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The African Strategy of Fundamental and Applied Physics

Report of the 2020–2024 Community Study on the Current and Future of Fundamental and Applied Physics in Africa

Organized Through Broad Grassroots Community Consultations

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Acknowledgements

The African Strategy of Fundamental and Applied Physics brought together over 600 participants worldwide to develop a strategic vision, with practical recommendations, to enhance physics research and education in Africa.

Foreword

In this space, the ASFAP Steering Committee will describe their view of the Study, and thank everyone who needs to be thanked.

Executive Summary

Fundamental and applied physics draws on worldwide efforts with a small yet steadily increasing presence of developing countries from Asia, South America and Africa. While we can be proud of African countries such as Morocco, Egypt and South Africa gaining footholds in major international projects at the Large Hadron Collider, the cooperation among African countries and between them and the rest of the world is not well developed. This is especially the case for sub-Saharan Africa, which is one of the most rapidly developing regions in the world with great educational needs. In order to extend—or augment—the existing international scientific ties to this continent, in the development of the strategic visions for fundamental and applied physics, engagement in physics education, communication and outreach, toward developing countries, should be strengthened and sustained also in targeted programs toward Africa. The success of these targeted programs would be sufficiently encouraging to provide motivation for a review of goals and for consideration of mechanisms of sustainability. The central long-term objective—to be integrated in the development of strategic visions for science and technology—would be to help improve higher education in Africa across national borders and in so doing, to contribute in a significant way to the development of this continent. We believe that maintaining the leadership of the organization of targeted education programs in Africa, in partnership with other interested institutes and African governments and policy makers, presents a unique opportunity for the international community to pioneer the scientific and technological development of a region of more than a billion people with large unmet needs but vast human potential.

Africa, a rich continent in natural resources, is still lagging behind in innovation, transfer of knowledge, mass education, and its economies are not growing as expected to meet the needs of its fast-increasing populations. The African youth represents more than 70% of the population, and is, very often, unskilled, unemployable, falls back into poverty, and struggles to cope. Africa further faces the issue of the retention of its qualified young people.

However, African initiatives promoted by African countries with their own resources—in some cases in partnerships with international institutes—are numerous. Among them in our field, to name a few, we cite the East Africa Institute for Fundamental Research (EAIFR), the Egyptian Network of High Energy Physics, the similar one, RUPHE, in Morocco, the excellent infrastructure of HESS experiment in Namibia, not to forget the prestigious universities in South Africa and its high-level research laboratories.

To help address the aforementioned issues effectively, we believe that African educational and research institutes should develop their own strategic discussions and planning of fundamental and applied physics, for the short, medium and long terms. We feel that Africans, developing their own strategy for science and technology, will have major benefits. This would allow the international partners interested in capacity development and retention in Africa to integrate inputs from Africans themselves, rather than to default to their own views of how they may want to "help" Africans. In addition, the help—in whichever form it is delivered—will have more impact. In addition, the process to define an African strategy will bring together the African scientific communities and more pan-African scientific collaborations may emerge. Furthermore, we hope that the African strategy will help to inform African policymakers.

The African Strategy for Fundamental and Applied Physics (ASFAP) further fosters social transformation and economic competitiveness, through human capital development and innovation—Africa having the capacity to use science for the benefit of its people. It is therefore vital for Africans to contribute to long-term sustainable training in Africa that can only be ensured through committed investments in research and development (R&D) with African-led local and international partnerships. International cooperation is a large common denominator of the culture of scientific activities. However, there is a lack of skilled curriculum developers, insufficient resources for effective implementation, persistent shortages of trained science researchers, and ineffective planning. Hence, the related scientific disciplines should be gathered through a coherent program by establishing a strong connection between the network of academic institutions and the associated partners, including the private sectors.

Scientific competence and understanding is required to increase the numbers of professionals. It is therefore timely and strategically important to undertake a strategy that could help. Since the scientific research in Africa includes the development of human resources, it is critical to ascertain what macro policy perspectives frame decisions on its nature. We must mobilize and include the involvement of the relevant policymakers of African science research and education, to develop strategies and participate in Africa's science and technology projects. Africa must harvest its population demographic dividend, especially the women and youth, whose energy, creativity and courage must drive its continental development strategy.

Considering scarce resources, it is important for the world community of scientists, engineers, technicians, funding agencies and policymakers to come together and define a concerted physics education and research strategy. To arrive at the definition of a strategy, many inputs from the regional community are collected in the form of proposals, letters of interest and white papers (welcoming input from the world community as well) and then discussed and debated in plenary sessions and topical parallel sessions. It is a process that may take a few years to culminate into a report—to advise the scientific community, funding agencies and policymakers on strategic directions to improve research and education. The process to define an African strategy is a true spirit of international cooperation that forms the common denominator of today's culture of scientific activities, defining priorities for domestic and inter-regional projects to be supported. In pursuing the grassroots physics strategy, the African scientific communities emphasize the importance of building synergy between fundamental physics and practical applications which is crucial for a solid education in Africa. Investments in education, technical competences and training, and in science, technology, research and innovation remain critical.

Physics strategies, driven at grassroots levels by the community of physicists, are carried out periodically in other regions. Europe updated its strategy (Update of the European Strategy for Particle Physics, CERN-ESU-013, June 2020) [1], taking into account inputs from the international community. Later, the United States of America updated its strategy for particle physics [2]. Latin America completed its first strategy for research infrastructures for high energy physics, cosmology and astrophysics [3].

Participation in activities to develop or update a physics strategy is voluntary; it is a non-legal collaboration by physicists to work and develop a scientific plan or vision. However, the development of a strategy ought to be mandated by an authority recognized by the physics community. In the USA, the Division of Particles and Fields (DPF) of the American Physical Society is the mandating authority of the USA particle physics strategy. The final report of the DPF strategy serves as an input to P5 (Particle Physics Project Prioritization Panel), an authoritative body that develops "a strategic plan for U.S. particle physics, plan that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field." In Europe, the mandating body of the European strategy for particle physics is the CERN Council. The Latin American strategy was mandated by the Council of Latin American Science Ministers. Similar to the case of the USA, ASFAP was mandated by—and developed in consultation with— the African Physical Society (AfPS). Furthermore, ASFAP received support from many institutes, the logos of which are shown Figure 0-1.

The final report of ASFAP will be submitted to the mandating body (AfPS), the international Advisory Committee and the supporting institutes. When the strategy report is submitted, the work of the physics

Figure 0-1: Institutes that endorsed of the African Strategy.

community is completed and the physics groups that developed ASFAP will disband. After the report is delivered, the relevant authorities (funding agencies, policymakers and governments) may appoint a prioritization panel similar to P5 in the USA to define actionable items that can be executed within ten years in the context of a longer-term global vision. The African strategy will not be repeated again until ten years later when an update will be performed as done in other regions.

ASFAP is a voluntary scientific collaboration among grassroots physicists for the purpose to study, discuss and document the needs for physics research and education in Africa. The process of ASFAP has taken a few years to terminate with a strategy report that contains a summary of the inputs received from the physics community in Africa and beyond. The physicists involved in ASFAP have done so as volunteers committed to the benefits of Africa-wide community consultations towards a concerted pan-African strategy for physics. To carry out the strategy development efficiently, we self-organized by setting up a steering committee, an international advisory committee, working group conveners and observers as shown in Figure 0-2.

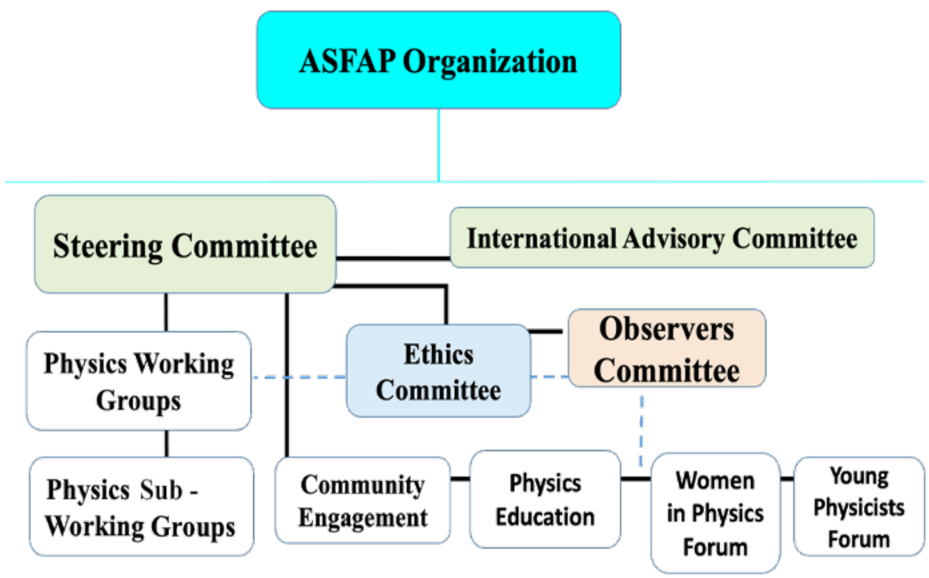

Figure 0-2: The organizational structure of people involved in ASFAP.

ASFAP has sixteen physics working groups and six engagement groups as shown here [5]. The group conveners organized meetings and workshops as necessary to review progress and maintain focus.

The process of ASFAP consist of:

1. Physicists to self-organized into working groups according to their research fields;

2. The groups solicited of community inputs through surveys, short documents—Letters of Interest (LOI)—and discussions; The groups analyzed of the inputs received from the community and categorized these inputs into a few major physics topics of importance to Africa;
3. The groups studied the topics that emerged from the community inputs and consultations, to develop scientific narratives—white papers—that form the basis of the strategy report;
4. The group summaries contain the major strategic directions extracted from analyzing the white papers.

The aforementioned steps required efforts within physics working groups, to reach out to the community at large and draw more volunteer physicists, encourage physics communities to contribute LOI, and encourage folks with similar interest to self-organize into white paper study groups. Each physics working group within ASFAP has 3-5 group conveners to organize the activities within the group, encourage progress and ultimately deliver a report of their working group. The working groups were designs along the major physics areas of interest to Africa, as defined by AfPS:

- Particles and related applications: nuclear physics, particle physics, medical physics, (particle)astrophysics & cosmology, fluid & plasma physics, complex systems;
- Light sources and their applications: light sources, condensed matter & materials physics, atomic & molecular physics, optics & photonics, earth science;
- Cross-cutting fields: accelerator physics, computing, instrumentation & detectors.

Topics in quantum computing & quantum information and machine learning & artificial intelligence were also on the agenda. Furthermore, ASFAP included the fields of societal engagements, namely: topics related to physics education, community engagement, women in physics and early career physicists. The timeline of the activities is shown in Figure 0-3.

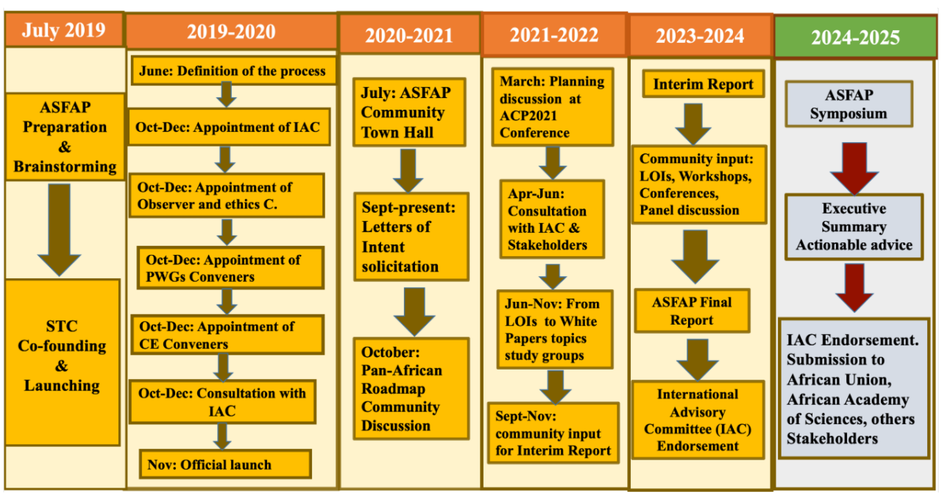

Figure 0-3: ASFAP roadmap timeline.

The final report will be presented to the international community in a dedicated symposium, planned in October 2025 in connection with the fourth African Conference on Fundamental and Applied Physics, ACP2025, at the University of Lome, Togo. The report will contain the summaries of each working group with their recommendations and actionable items. Through the symposium, we will collect final feedback from the international community. After the symposium, the community feedback will be integrated to prepare the final version of the report. For effective impact, we will need travel coverage so that many of the working group conveners would attend the symposium in person. The report will benefit from professional editing and formatting help, towards publication. We will also need help to disseminate the report to interested parties that may be interested in its recommendations and actionable items.

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Contents

1

Ethics in Physics

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1.1 Introduction

Ethical behavior within the African Strategy on Fundamental and Applied Physics (ASFAP) has been governed by a code of conduct (COC) [1], which is a set of core principles and community guidelines to which members of the ASFAP community must adhere. Registration to any working group implies that the member has read and accepted the ASFAP COC. The COC was drafted by the ASFAP steering committee but it subsequently fell under the responsibilities of a four-member ethics committee, which had been established to review and act as custodians of this document. It has been the task of the ethics committee to amend this document whenever necessary, while ensuring that ASFAP remains a community where everyone feels welcome and respected. In addition, members of the ethics committee have been mandated to serve as ombudspersons if need arises. We're pleased to report that, so far, we have not received any reports of conflicts within the ASFAP community requiring our intervention. Therefore, this report only outlines amendments we have made to the COC to date.

1.2 Amendments to the code of conduct

Between June 2021 and March 2022, we held several meetings to review contents of the COC and made adjustments and addendums in addition to some general textual editing. We also incorporated a few suggestions received from the steering committee. The current version of the COC was implemented in March 2022. Highlighted below are some of the "major" edits/addendums to the document.

1.2.1 Authorship

Very often there are ethical questions raised around large authorship papers in terms of each author's contribution to the body of work that has been published. In some cases, names are included as authors 'only because it was always done'. Therefore, the ethics committee decided that this matter needed to be covered in the COC. The following text was thus added to section 3(d) of the COC [1].

"Authorship offers credit for an individual's contributions to a study. It also holds the author accountable for the content in a published paper. All individuals who carried out the work are responsible for the decision on who should be listed as an author when that work is published. Any individual who makes a significant contribution to the work (as agreed by everyone contributing to the paper) should be listed as an author. Any other individual or organization should be acknowledged accordingly. In case of conflict, working group conveners should be contacted in order to help resolve the conflict. If the conveners and the contributors are unable to reach a consensus, the ethics committee should be contacted."

1.2.2 Email Communication

For a community involving hundreds of people, poor use of email communication could be problematic if not addressed. For example, one member could send a personal email to another member (e.g to congratulate them on an important achievement) but adding a larger email group in cc. This may be an issue if several other members reply to this email with everyone in copy. The ethics committee felt that this borders on the "unethical use of email communication". Hence, the text below was added to the COC as a bullet point in section 3(c).

"**Ethical use of email communication**: If your email concerns an individual person or a closed group of individuals, do not write to or reply to everyone in a general list. In addition, email communication should be done in a respectable manner, respecting the rest of this document's guidelines. Be also conscious of the fact that members of the ASFAP community are in different time zones. Therefore, prompt responses should not always be expected."

1.2.3 Guidelines on Virtual Meetings

Given that ASFAP meetings were mostly virtual and a number of them were held during the covid-19 pandemic, the steering committee advised the ethics committee to add a section on guidelines for such meetings to the COC. The text below was thus added to section 3(e).

"As members of ASFAP are located in various places across the globe, virtual meetings are inevitable. In addition, due to the ongoing pandemic, virtual or hybrid conferences/workshops may also be inevitable. To facilitate the smooth running of such meetings, members of the ASFAP community and invited guests should adhere to the guidelines listed below:

- Meeting times should accommodate participants from all time zones. Meeting minutes and/or recordings should also be made available on the meeting web page.
- Meeting hosts should ensure that only the speaker's microphone is ON at any given time.
- Participants should use the raise hand feature found in online meeting solutions (e.g. Zoom), or type their comments/questions in the chat box. Otherwise, participants should wait for an appropriate opportunity to comment or ask questions without interrupting other participants.
- Conveners should ensure that each participant receives an equal opportunity to participate in the discussion.

- Given that many individuals are currently working remotely, conveners should ensure that the meeting durations are respected. Virtual meetings tend to go overtime, but participants' time zones and personal lives should be respected."

Even though we have now gone past the pandemic, many individuals have continued to work from home for various reasons. Therefore, we believe that the last bullet point above still applies, and we have decided to keep it in the COC.

1.2.4 General Edits

- In section 5(b), we replaced "moderator/host/code of conduct committee" by "convener/host/observer/ethics committee" because we believe that members of the observers committee should also be able to speak up in case of violation.
- Throughout the COC document, we removed parts that mention contacting an individual's institution if the individual violates the COC. We believe this is unnecessary as in many cases, members of ASFAP are by no means representing their institutes

1.3 Conclusion

We have highlighted the major addendums and edits that we have made to the COC document since our engagement as its custodians. To date, no violations to the COC that needed our intervention have come to our attention. We believe that we would have done our job very well if there are zero complaints that come to us. Therefore, rather than being passive about these matters, our plan was to implement a way to constantly educate the community about these issues in a smart and non-intrusive manner. This could, for example, be a five minute slot at every meeting with conveners to remind them of the COC and its importance. However, we have not been able to enforce this during this strategy and we hope that future custodians of ASFAP's COC will keep these ideas alive and discussed in the public domain from time to time.

Bibliography

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2

Observers Committee Report

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[1]Cheikh Anta Diop University Senegal)
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2.1 Introduction

The Observers Committee is an intermediate body providing an additional link between the working groups and fora, and the Steering Committee. Members of this committee are people with experience in long term planning but also an outstanding involvement with projects in and with Africa. Members participate in WG discussions, they help to review papers, attend meetings and participate in the editing of the reports together with the WGs they are assigned to follow. The job of the Observers Committee during the first stage is to help the working groups get running efficiently and smoothly. At a later, the committee can help to review LOIs and White Papers, and with the editing of the Group Reports [1].

2.2 Hands-on

The interaction between the Observers Committee and the WGs was highly reduced. This has to do with the commitment of the committee members (together with an agenda that often did not fit the schedules) but also to a lack of visibility in the importance of an Observers Committee in such a major initiative.

In some specific cases, especially in the beginning of the ASFAP process, members of the Observer Committee facilitated initial contacts between the WG convenors and senior colleagues in their respective communities. This was arguably the most tangible benefit from the scheme, as at least perceived by individual Observers.

2.3 Next stage

At this stage of the initiative, the Observers Committee is expected to bring its know-how to the project through the reviewing of the different documents that have been produced by the Working Groups for the final report. This role has been implemented and was useful at least in some WGs.

2.4 Comments

The concept of inviting independent Observers with a broad background in science strategies is a very interesting approach. However, its effectiveness remained rather short of the initial expectations, and it has to be rethought for future strategy exercises, The Observers did in fact not interact formally among themselves, so no common actions were developed, nor was there any internal motivation generated that could have been useful. The Observer Committee actions remained with the initiatives of its individual members, both with respect to their assigned WGs as well as with the Steering Committee. Nevertheless, given the willingness of individual Observers to enhance the ASFAP process, one may still underline some positive contributions overall.

Committee email: ASFAP-Observers@cern.ch

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3

Accelerators Working Group

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3.1 Introduction and Motivation

Accelerator physics is the study of the design, operation, and applications of particle accelerators, which are devices that use electromagnetic fields to accelerate and manipulate charged particles. Particle accelerators have many uses in science, medicine, industry, and security, such as producing beams of high-energy photons, electrons, protons, or ions for nuclear physics, nuclear medicine, materials science, radiation therapy, and nuclear security. This field holds the key to transformative advancements in various scientific and technological domains. While this discipline has made significant strides globally, the landscape of accelerator physics in Africa presents a unique set of challenges and opportunities.

In recent years, accelerator facilities have become indispensable tools for fundamental research, material science, medical applications, and industrial processes. However, despite the increasing importance of accelerator-based technologies, Africa faces distinctive hurdles in establishing and maintaining state-of-the-art accelerator facilities. The demand for accelerator physics expertise in Africa is experiencing remarkable growth, fueled by the continent's ambitious pursuit of scientific and technological advancements. However, this progress is met with considerable challenges that arise from limited resources, infrastructure, and research funding. Despite these barriers, notable strides are being made in accelerator science across the continent. With over 578 accelerator facilities that support scientific research and offer some analytical or irradiation services to diverse community of users, distributed in 59 countries around the world, several accelerator facilities have been established in Africa, showcasing a commitment to advancing nuclear and particle physics research [1]. In particular, Algeria hosts one electrostatic accelerator at the Center de Recherche Nucleaire d'Alger [2], while Tunisia operates an Accelerator-Based Neutron Source at the Centre National de Sciences et Technologies Nucleaires [17]. In Egypt, the Atomic Energy Authority oversees one Electrostatic Accelerator, and Zagazig University houses an Accelerator-Based Neutron Source [18]. Ghana boasts an Electrostatic Accelerator at the Accelerator Research Centre, while Nigeria is equipped with an Electrostatic Accelerator at the Centre for Energy Research and Development [19]. South Africa leads the continent with six accelerator facilities, including three Accelerator-Based Neutron Sources at Nesca and iThemba, and three Electrostatic Accelerators at the University of Pretoria, iThemba Labs in Johannesburg, and iThemba Labs in Cape Town. These installations stand as beacons of scientific progress, contributing to the broader landscape of accelerator physics in Africa (see Fig. 3-1).

The field of accelerator physics in Africa has also experienced a steady increase in research output over recent decades. Fig. 3-2 shows a review of publication trends from 1967 to 2024 reveals minimal activity during

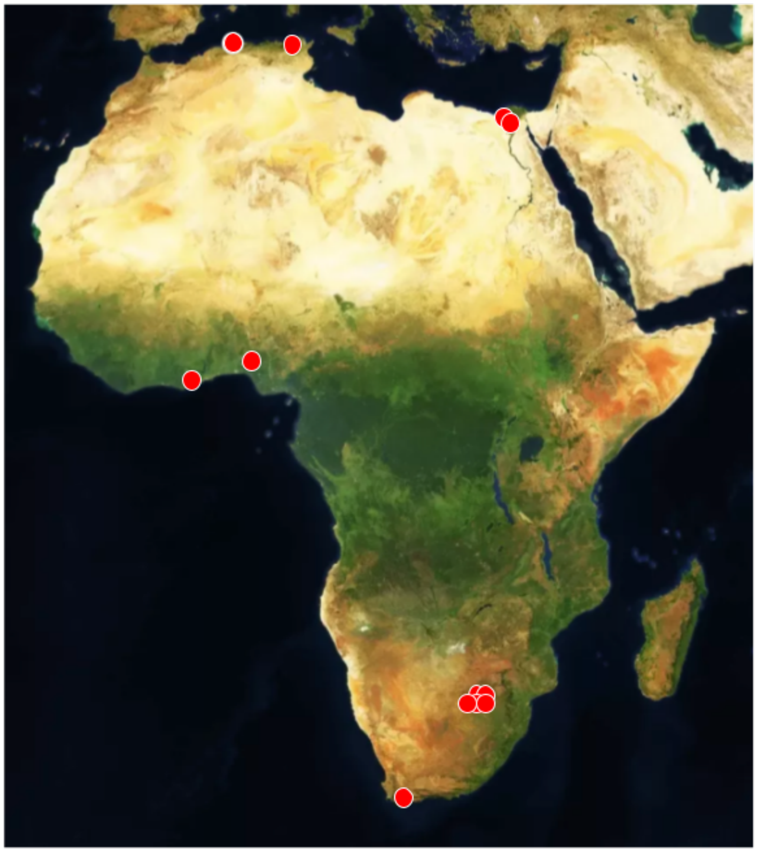

Figure 3-1: IAEA Physics Section's Developed and Maintained Interactive Map Showcasing Accelerators Across Africa [1]

the early years, with significant growth beginning in the late 1990s. The 2012s marked a peak in publication activity, reflecting the impact of international collaborations, regional initiatives, and the establishment of new facilities. Although fluctuations are evident, particularly after 2020 due to factors like the COVID-19 pandemic, recent years show a strong upward trajectory, underscoring the continent's expanding role in the global accelerator-physics community. This growing body of research demonstrates Africa's potential to contribute to fundamental and applied science, despite the challenges of limited infrastructure and funding.

Collaborative efforts among African nations and international partnerships have further accelerated progress, fostering the establishment of facilities aimed at addressing both local and global challenges. From fundamental research in nuclear and particle physics to applications in medical diagnostics and materials science, African scientists are actively involved in pioneering initiatives that will pave the way for transformative advancements in science and technology.

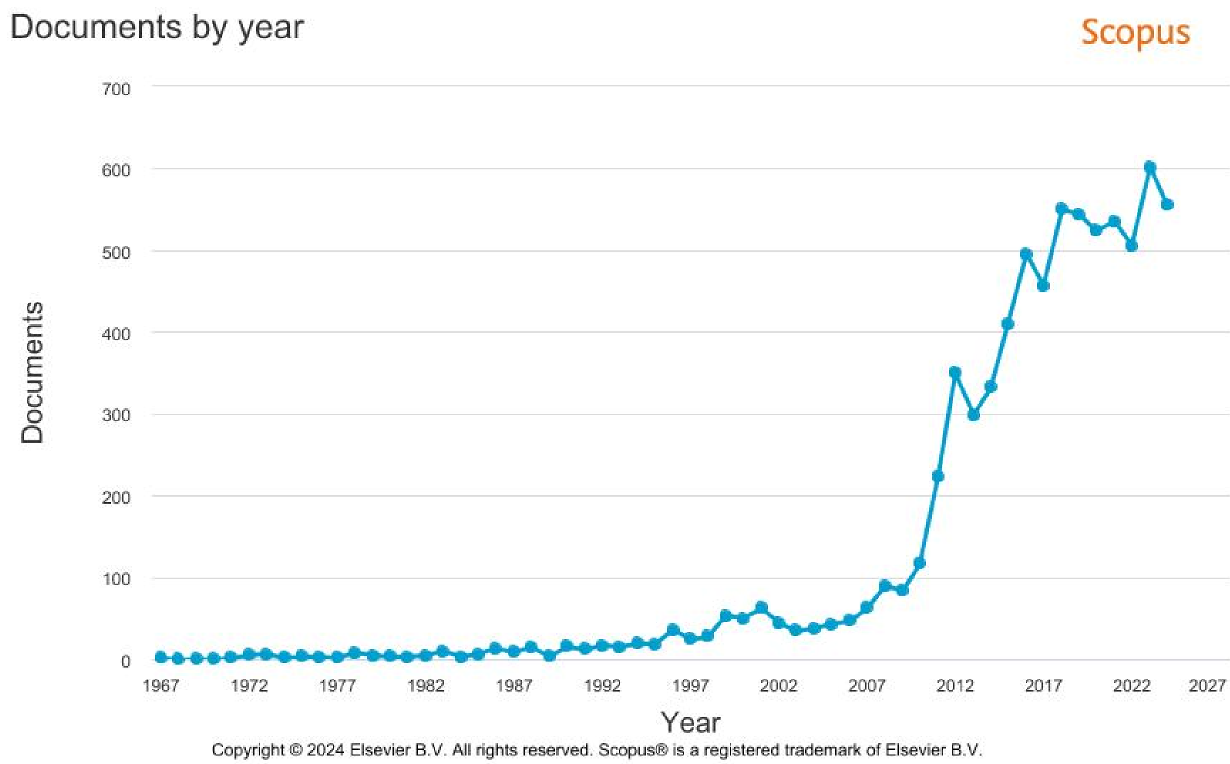

Figure 3-2: Annual Research Output in Particle Accelerator Physics in Africa (1967–2024) (Source: Scopus [6])

3.2 Accelerator Physics Capacity in Africa

Within the realm of accelerator physics in Africa, a spectrum of scientific activities unfolds, reflecting a diverse range of research endeavors. Countries such as South Africa, Nigeria, and Egypt, among others, have emerged as focal points for accelerator-based investigations. These endeavors encompass fundamental studies in nuclear and particle physics, exploring the fundamental building blocks of matter, and unraveling the mysteries of the universe.

One notable example is the iThemba LABS facility in South Africa, a prominent accelerator center that serves as a hub for nuclear and particle physics research. Researchers at iThemba LABS are engaged in investigations spanning nuclear structure, astrophysics, and materials science, contributing valuable insights to both fundamental science and applied technologies.

Collaborative efforts are a hallmark of the accelerator physics landscape in Africa. Initiatives like the African School of Fundamental Physics and Applications (ASP) bring together physicists from across the continent to share expertise, foster collaborations, and train the next generation of scientists. ASP not only facilitates knowledge exchange but also strengthens the scientific network within Africa, positioning the continent as an active participant in the global scientific community. Moreover, accelerator applications extend beyond theoretical explorations to practical solutions for societal challenges. Medical physics research, utilizing accelerators for cancer treatment and diagnostic imaging, is gaining momentum in several African countries.

These initiatives aim to enhance healthcare infrastructure and address pressing medical needs, showcasing the tangible impact of accelerator physics on improving lives.

In energy research, accelerator-driven systems are explored as potential solutions for sustainable power generation. African researchers are actively involved in studying accelerator-driven subcritical systems for nuclear energy applications, contributing to the quest for cleaner and more efficient energy sources.

As we delve into the scientific activities of accelerator physics in Africa, this section will provide a comprehensive overview of key projects, collaborative initiatives, and advancements that underscore the vibrant and dynamic landscape of accelerator research on the continent.

3.2.1 The iThemba LABS

The main facility for accelerator physics research and facilities in Africa is iThemba Laboratories for Accelerator Based Sciences (LABS), which is a business unit of the National Research Foundation (NRF) in South Africa. iThemba LABS operates one of the most significant and advanced cyclotron facilities in the African continent and the separated sector cyclotron is the largest accelerator facility in the Southern Hemisphere. The k-200 separated sector cyclotron can accelerate protons to energies of 200 MeV, and heavier particles to much higher energies. iThemba LABS provides access to state-of-the-art research infrastructure, both locally and globally, to facilitate activities that probe the nature, structure and properties of matter and materials, and to produce radioisotopes that can be used for diagnostics, imaging and therapy in nuclear medicine applications.

iThemba LABS has embarked on a recapitalization program, the overall objective of which is to safeguard the long-term sustainability of Africa's most unique Accelerator Based research facility. The first pillar of this program is the South African Isotope Facility (SAIF) [22], which is dedicated to research infrastructure renewal whose accomplishment is geared to achieve the twin objectives of increase in radioisotope production and research on the one hand, and the freeing up (on the other hand) of beamtime from the 200 MeV Separated Sector Cyclotron which will be dedicated for sub-atomic physics research and applications [8]. The first phase of SAIF is centred around the acquisition of a 70 MeV Cyclotron to enhance research and production of radioisotopes for nuclear medicine. In addition, iThemba LABS has two laboratories dedicated to research at the atomic scale using particle beams from a 3-MV Tandetron and a 6-MV Tandem accelerator [10]. These laboratories offer various techniques for ion beam analysis, ion implantation, subatomic physics, and environmental isotopes. iThemba LABS also collaborates with other international facilities and networks, such as the African light Source (AfLS), which is an initiative to build a synchrotron light source on the African continent [9, 11].

3.2.2 CERD Nigeria

The Particle Accelerator Facility located at the Centre for Energy Research and Development (CERD) within Obafemi Awolowo University, Ile-Ife, Nigeria, was inaugurated on September 28, 2008, primarily for Ion Beam experiments utilizing a single beam line [12, 13]. The establishment of this facility was made possible through the collaborative efforts of the Federal Government of Nigeria and the International Atomic Energy Agency Technical Cooperation (IAEA TC) Project NIR 1010. The accelerator itself is a NEC 5SDH 1.7MV Pelletron Accelerator, a product of the National Electrostatics Corporation (NEC) based in Middleton, WI, USA. Notably, in 2016, a significant enhancement was made to the facility by introducing a second beam line, complete with an NEC RC43 end-station, thus further augmenting its capabilities and research potential.

The Ion Beam Analysis (IBA) facility at CERD revolves around the utilization of a NEC 5SDH 1.7 MV Pelletron Accelerator, incorporating an RF charge exchange ion source capable of generating both proton and helium beams [4]. Although the accelerator can accommodate up to five beam lines, our current configuration focuses on maintaining two operational beam lines. One of these lines is furnished with a versatile End Station designed for four distinct analytical techniques: Particle Induced X-ray Emission (PIXE), Rutherford Backscattering (RBS), Elastic Recoil Detection Analysis (ERDA), and Particle Induced Gamma-ray Emission (PIGE). Meanwhile, the second beam line houses an NEC RC 43 End Station, similarly equipped with these four techniques, with added capabilities for conducting grazing experiments on thin samples, thereby enhancing our capacity for material studies. The application spectrum of our facility spans across a multitude of fields, encompassing mineralogy, geological analysis, agricultural assessments of soil and plant samples (including leaves, fruits, and seeds), biomedical and biological research, environmental pollution monitoring, air quality assessments, materials science investigations, thin film studies, as well as archaeological and cultural heritage analyses.

3.2.3 PELLETRON Accelerator in GHANA

The Ghana National Accelerator Project, initiated in 2008, aimed to acquire and install a 1.7MV Pelletron Accelerator in Ghana, facilitated through cost-sharing with the International Atomic Energy Agency (IAEA) [14, 15, 16]. This endeavor saw the generous donation of the accelerator, complete with Ion Source and high-energy end components, from the Government of the Netherlands. The refurbishment of the accelerator and the procurement of a complete beamline, as well as its subsequent installation, were financed by the IAEA. In turn, Ghana contributed by providing essential local infrastructure, including the construction of the facility building, electrical installations, air conditioning, and water and compressed air systems. Furthermore, the project prioritized human capacity building, with support from the IAEA. This included sponsorship for staff training in accelerator technology and applications, such as through the IAEA sandwich PhD program in advanced accelerator laboratories. Additionally, technicians received specialized training in accelerator systems maintenance, fostering local expertise in maintaining and operating the facility. Staff members also actively participated in the refurbishment of the accelerator in Groningen and were involved in the installation process alongside NEC Technicians, culminating in an Acceptance Test conducted by IAEA experts. This concerted effort not only realized the establishment of the Pelletron Accelerator in Ghana but also empowered local personnel with the necessary skills and knowledge to effectively utilize and maintain this advanced scientific infrastructure.

The accelerator was commissioned on March 2016, while its performance since its installation has been generally satisfactory, there have been some challenges and breakdowns encountered along the way. However, most of these issues have been successfully resolved, in some cases with or without the assistance from the NEC supporting Team. This collective effort not only ensured the establishment of advanced scientific infrastructure in Ghana but also facilitated the development of local expertise in accelerator technology and operations. Through continuous maintenance and improvement efforts, the accelerator continues to contribute significantly to scientific research and educational initiatives in the region, further solidifying Ghana's position in the field of accelerator physics and related disciplines.

3.3 Instrumentation and Control Systems Capacity in Africa

South Africa leads the continent in instrumentation and control systems with several institutions and initiatives driving advancements in this field. iThemba LABS, SARAO (South African Radio Astronomy Observatory), SKA (Square Kilometer Array), Necsa (Nuclear Energy Corporation of South Africa), and St. James Software are key players, each contributing expertise and infrastructure to various scientific endeavors. iThemba LABS, for instance, not only houses advanced accelerators but also excels in instrumentation and control systems crucial for monitoring and managing these facilities. It has advanced control systems for its cyclotrons and Tandetron accelerators, employing frameworks like EPICS (Experimental Physics and Industrial Control System). Recent developments include integrating EtherCAT-based hardware for distributed control and developing advanced user interfaces using tools like CS-Studio and React Automation Studio. These systems ensure real-time monitoring and high-performance operation across its facilities. SARAO and SKA are at the forefront of radio astronomy, deploying cutting-edge instrumentation and control systems to operate telescopes and process vast amounts of astronomical data [31]. Necsa, South Africa's Nuclear Energy Corporation, focuses on instrumentation and control systems for nuclear applications, ensuring safety and efficiency in nuclear facilities and research. Moreover, entities like St. James Software provide innovative solutions such as the JlogBook e-log-book, enhancing data management and collaboration across scientific disciplines. Furthermore, African countries actively participate in international collaborations like CERN, where they engage in technology transfer, operations, upgrades, and instrumentation development, using advancements in areas such as artificial intelligence to drive scientific progress and innovation both locally and globally. These efforts collectively demonstrate Africa's growing expertise and capacity in instrumentation and control systems, essential for driving scientific research and technological innovation across various disciplines.

3.4 Diverse Applications of Accelerator Physics Across Various Fields

More than 50.000 accelerators are used in a wide range of applications that span various scientific disciplines and industrial sectors [21, 23, 24]. From fundamental research in nuclear physics to practical applications in medicine, materials science, and beyond, accelerator-based techniques play a pivotal role in the advancement of scientific knowledge, technological innovation, and social progress. In this section, we explore the diverse array of applications enabled by accelerator physics.

- **Nuclear Physics**: Nuclear physics research facilities often have multiple accelerators for various purposes, including particle physics experiments and nuclear research. Large research institutions like iThemba LABS in South Africa [20, 10], CERN in Switzerland, Fermilab in the United States, and KEK in Japan host numerous accelerators, including cyclotrons, synchrotrons, and linear accelerators. The number of accelerators dedicated specifically to nuclear physics worldwide is estimated to be from 500 to 1000. The Egyptian Atomic Energy Authority (EAEA) operates several facilities equipped with accelerators for nuclear physics research [25]. These facilities include cyclotrons and linear accelerators used for nuclear research, medical isotope production, and radiopharmaceutical development. EAEA also collaborates with international institutions on nuclear research projects.

- **Medical Physics**: Accelerators in the medical field are primarily used for radiation therapy in cancer treatment. Thousands of medical linear accelerators (LINACs) are installed in hospitals and clinics worldwide for delivering external beam radiation therapy. More details about the ones in Africa can

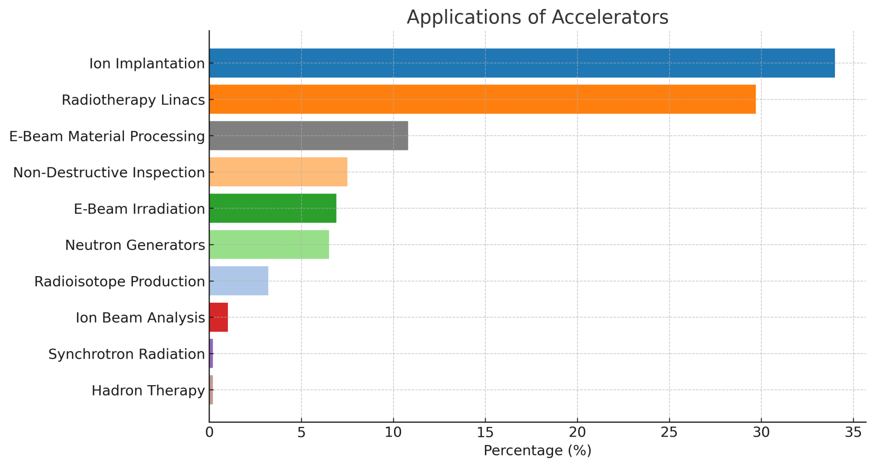

Figure 3-3: Distribution of accelerators worldwide by common applications. Data sourced from [21]

be found in Section 3.8. In addition to LINACs, advanced treatment techniques such as hadron therapy, which utilizes protons or heavier ions, are being increasingly adopted to target tumors with greater precision, though it currently represents a smaller share of applications. iThemba LABS uses its accelerators for proton therapy which makes it one of the few centers in Africa offering advanced radiation therapy using proton beams, in addition to its standard radiotherapy treatments.

- **Materials Science**: Synchrotron radiation facilities are widely used for materials science research. Major synchrotron facilities, such as the Advanced Photon Source (APS) in the United States, the European Synchrotron Radiation Facility (ESRF) in France, and the Diamond Light Source in the United Kingdom, host thousands of researchers annually conducting experiments on materials properties, crystallography, and structural biology. Moreover, ion implantation, which accounts for 34% of accelerator use, is a crucial technique in the semiconductor industry for doping materials, essential for manufacturing integrated circuits. Researchers use the accelerators at iThemba LABS to modify and analyze materials at the atomic level, contributing to the development of new materials and the improvement of existing ones.

- **Energy**: Accelerators are utilized in environmental and energy research for various purposes, including nuclear waste management, environmental monitoring, and alternative energy research. Facilities such as the European Spallation Source (ESS) in Sweden, which is under construction, aim to advance research in areas like nuclear energy, materials for energy storage, and environmental science. Beyond research, accelerators are used in non-destructive inspection (7.5%) and neutron generation (6.5%), critical in energy applications for ensuring the integrity and safety of materials and systems. The EAEA in Egypt operates several research centers that use accelerators for energy research. Their work includes studying materials for nuclear reactors, improving the efficiency of energy production from nuclear sources, and exploring alternative energy solutions. The EAEA also focuses on research to advance nuclear energy technology and its applications in Egypt and the broader region. NCERD in Nigeria also focuses on energy research [26]. The center conducts studies on nuclear energy, including the development of nuclear reactors and the application of nuclear techniques in energy production. NCERD's work is essential for advancing nuclear energy technology in Nigeria and supporting the country's energy needs.

Accelerators are versatile tools with applications extending beyond these traditional areas (see Fig. 3-3). For example, ion beam analysis (1.0%) and E-beam material processing (10.8 %) play important roles in quality control and material modification in various industries. Radioisotope production (3.2%) supports medical diagnostics and treatments, contributing to advancements in nuclear medicine, while synchrotron radiation (0.2 %) continues to drive forward cutting-edge research in structural biology and materials science. These diverse applications highlight the critical role accelerators play in both industrial and medical advancements.

3.5 Building a Pan-African Accelerator Network: Bridging Innovation, Collaboration, and Scientific Growth

The motivation for establishing dedicated accelerator divisions across African countries stems from the transformative potential these facilities hold for science, technology, and sustainable development. A pan-African vision for accelerator technology would involve strategic placement of accelerator divisions in different regions, bolstering local capacity and fostering regional collaboration. This network would not only elevate Africa's research capabilities but also create a platform for shared expertise, enabling scientists from across the continent to collaborate and push forward high-impact projects like the development of African light sources.

Morocco's strategic geographic position offers significant advantages for establishing an accelerator division that could lead to deeper collaboration with European research centers like ALBA (Spanish 3rd generation synchrotron light source) in Spain [36] and the STAR (Southern European Thomson back-scattering source for Applied Research) facility in southern Italy [35]. The proximity to these centers allows for easier exchange of expertise, joint projects, and access to advanced infrastructure. Such collaboration would contribute to a robust ecosystem where Moroccan researchers can engage in international partnerships, leveraging the experience of these established projects to develop new capabilities in accelerator technology and light sources. The broader context includes existing strong trade and scientific ties between Morocco, Spain, and Italy, as shown by Morocco's position as a significant partner in EU trade and research agreements. This mutual relationship underlines the potential for beneficial scientific exchanges and infrastructure projects in fields such as accelerator physics and light source development. Collaborative efforts would help establish the foundations for a comprehensive Pan-African network of research facilities, reversing the brain drain by providing African scientists with the necessary tools and resources at home. Such initiatives could pave the way for the future development of larger, more advanced light source projects across Africa, including in South Africa and Morocco, building on initial steps with compact light sources.

Currently, South Africa's iThemba LABS stands as a strong research facility in the field of nuclear physics and accelerator-based sciences. However, creating a specialized accelerator division within iThemba LABS and replicating similar divisions in north countries like Morocco and other African nations would significantly strengthen the continent's research infrastructure. Such divisions would serve as hubs for training, innovation, and collaborative research in accelerator physics and related disciplines.

The establishment of multiple accelerator divisions would accelerate the continent's progress toward building compact light sources. These sources are feasible starting points due to their relative simplicity and lower costs compared to large-scale synchrotrons or colliders. Compact light sources can still deliver impactful results in applications ranging from medical imaging and materials analysis to cultural heritage conservation and environmental studies. This vision aligns with reversing the brain drain that has historically affected Africa's scientific community. By providing advanced research facilities and opportunities, African accelerator physicists and engineers who work abroad could be motivated to return, bringing their skills and experiences to bolster the development of domestic research ecosystems. Such initiatives could lead to the eventual establishment of full-scale light source facilities—potentially one in South Africa and another in North Africa, such as Morocco. These facilities would create a robust research network that promotes scientific excellence and positions Africa as a leader in the global research landscape.

Furthermore, the creation of accelerator divisions supports economic development, as it attracts investments and partnerships with international research organizations. By investing in accelerator technology, African countries can foster local innovation, build highly skilled workforces, and strengthen regional and international scientific collaborations, laying the groundwork for long-term development and scientific leadership.

3.6 High-priority future needs

- **Infrastructure Development**: Accelerator physics in Africa faces a crucial need for the development and enhancement of research infrastructure. Investing in state-of-the-art accelerator facilities, upgrading existing ones, and establishing new centers will be pivotal for conducting cutting-edge experiments and staying at the forefront of global scientific advancements.

- **Human Capital Development**: The shortage of skilled personnel poses a significant challenge. Initiatives for training and capacity building in accelerator physics are essential. Collaborative programs, workshops, and educational partnerships can play a vital role in nurturing the next generation of African physicists, engineers, and technicians.

- **International Collaboration**: Strengthening collaboration with international partners is a high-priority need. This involves fostering partnerships with established accelerator centers worldwide, participating in joint research projects, and facilitating knowledge exchange. International collaborations with organizations like CERN, Fermilab, and SESAME (in Jordan) can accelerate progress, including funding Support from governments, private sector, and international agencies that should invest in accelerator research for African scientists to contribute meaningfully to global scientific endeavors.

- **Outreach Programs** Increasing outreach programs to introduce accelerator physics to students is critical for fostering interest and cultivating talent in this field. Organizing workshops, seminars, and summer schools targeted at high school and undergraduate students can raise awareness about accelerator physics and its applications. Additionally, mentorship programs and internships at accelerator facilities can provide hands-on experience and inspire students to pursue careers in this specialized area of science. As an exemplar, the ASP Outreach Program, which took place in Marrakech, Morocco, from April 15th to 19th, 2024. This initiative was meticulously designed to ignite and sustain learners' interests in Physics and its diverse applications. A significant segment of the program was exclusively dedicated to Accelerator Physics, aimed at acquainting students with its fundamental principles and cutting-edge technologies. Under the guidance of esteemed experts, Dr. Sanae Samsam from INFN (Istituto Nazionale di Fisica Nucleare) and Dr. Christine Darve from ESS (European Spallation Source), the program unfolded with a blend of comprehensive lectures and engaging practical sessions. These sessions were meticulously curated to provide participants with a holistic understanding of accelerator physics, ranging from its theoretical underpinnings to its real-world applications. Through interactive discussions and hands-on activities, students were not only introduced to the intricacies of particle acceleration but were also inspired to explore its interdisciplinary connections and potential for scientific innovation. The report which resume all the activity can be found in this Ref. [7].

In summary, Africa has immense potential to develop accelerator physics for scientific research, medical applications, and socioeconomic growth. By investing in education, infrastructure, and collaborations, African nations can contribute significantly to this field.

3.7 Synergies with neighbouring fields

Accelerator technologies play a pivotal role in medical physics and healthcare, contributing to cancer treatment through radiation therapy and medical imaging. Moreover, accelerator-based techniques in materials science and nanotechnology significantly impact research and development, offering powerful tools for ion-beam analysis and materials characterization. Environmental science and geophysics benefit from accelerator applications, particularly in studies related to archaeology, climate change, and geological processes. The intersection of accelerator physics with nuclear physics and astrophysics is evident in research exploring nuclear structure, reactions, and astrophysical phenomena. Accelerator technologies also drive technological innovation and industry applications, influencing semiconductor manufacturing, ion implantation, and non-destructive testing. Furthermore, accelerator initiatives contribute to education and capacity building, offering training programs and workshops that empower the next generation of scientists and technologists. Collaborations with international research institutions underscore Africa's role in global scientific endeavors, fostering knowledge exchange and joint projects. Through these synergies, accelerator physics emerges as a catalyst for holistic scientific progress, bridging diverse fields and expanding the frontiers of knowledge in the African context.

3.8 Clinical Linacs Driving Cancer Treatment Across Africa

Clinical Linacs, short for Clinical Linear Accelerators, are sophisticated medical devices primarily used in the treatment of cancer through a process called radiation therapy. These machines generate high-energy X-rays or electrons, which are directed towards the patient's tumor to destroy cancerous cells while minimizing damage to surrounding healthy tissues.

The proliferation of clinical Linacs across Africa marks a significant advancement in the region's capacity to provide essential cancer treatment services. According to the IAEA DIRAC (DIrectory of RAdiotherapy Centres), there are approximately 432 Linacs dedicated to MV Therapy spread across the continent [5]. Notably, North Africa boasts the largest share with 237 Linacs, followed by 107 in the southern region and 88 in the central part of the continent (see Fig. 3-4).

This distribution underscores the commitment of African nations to improve access to radiotherapy services, addressing the pressing healthcare needs of their populations. With Linac technology widely available in different regions of Africa, more patients can receive timely and effective treatment, contributing to better cancer outcomes and improved healthcare infrastructure throughout the continent.

Country	RT Centers	MV Therapy	Light Ion Therapy	kv Therapy	Brachytherapy
Algeria	16	37	0	0	13
Egypt	75	124	0	1	23
Libya	5	8	0	0	0
Morocco	30	48	0	0	10
Tunisia	15	27	0	1	4

Table 3-1: Clinical Linacs in North Africa

Tab. 7-1 provides an overview of the distribution of clinical linear accelerators across North Africa, highlighting the infrastructure for cancer treatment in the region. Egypt emerges as a leader in this regard,

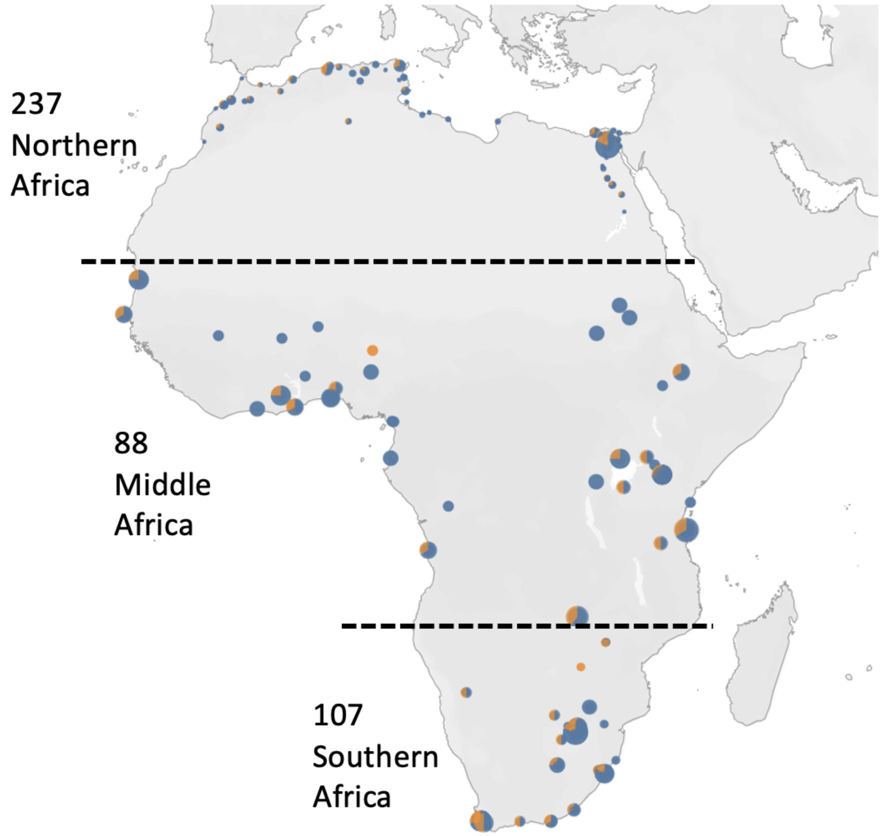

Figure 3-4: Status of Radiation Therapy Equipment in Africa

boasting the highest number of Linac centers (75) and offering the most diverse range of treatment modalities, including megavoltage (MV) therapy and kilovoltage (kV) therapy. Additionally, Egypt stands out as the sole provider of light ion therapy among the countries surveyed, indicating a more advanced level of radiation oncology infrastructure.

Following Egypt, Morocco demonstrates a significant presence in Linac facilities with 30 centers, although its range of treatment modalities is slightly more limited compared to Egypt. Algeria and Tunisia also exhibit substantial Linac infrastructure, albeit with fewer centers. Algeria notably has a considerable number of brachytherapy facilities (13), indicating a focus on this targeted treatment method.

Conversely, Libya appears to have the most limited infrastructure among the surveyed countries, with only five Linac centers and minimal representation in other treatment modalities.

In Middle Africa (see Tab. 3-2), several countries demonstrate modest but emerging capabilities in cancer care. Kenya is distinguished with a notable presence of 10 Linac centers, indicative of its commitment to expand the accessibility to cancer treatment. Nigeria follows closely with seven Linac centers, reinforcing its position as a regional hub for healthcare services.

Country	RT Centers	MV Therapy	Light Ion Therapy	kv Therapy	Brachytherapy
Angola	2	3	0	0	1
Burkina Faso	1	2	0	0	0
Cote D'Ivoire	1	2	0	0	0
Cameroon	3	2	0	0	0
Congo	1	1	0	0	0
Ethiopia	3	3	0	0	1
Gabon	1	2	0	0	0
Ghana	3	6	0	0	3
Kenya	10	16	0	0	5
Madagascar	2	3	0	0	1
Mali	1	1	0	0	0
Mozambique	1	1	0	0	0
Mauritania	1	4	0	0	1
Mauritius	1	3	0	0	1
Malawi	1	1	0	0	0
Niger	1	1	0	0	0
Nigeria	7	9	0	0	2
Reunion (France)	1	5	0	0	0
Rwanda	1	2	0	0	0
Sudan	4	6	0	0	0
Senegal	4	4	0	0	1
Togo	1	1	0	0	0
Tanzania	4	8	0	0	4
Uganda	1	3	0	0	1
Zambia	1	3	0	0	2

Table 3-2: Clinical Linacs in Middle Africa

Ghana, Tanzania, Sudan, and Senegal also show significant progress in Linac installations, reflecting efforts to enhance cancer treatment capacities. These countries not only possess multiple Linac centers but also offer various treatment modalities, including megavoltage (MV) therapy and brachytherapy.

In contrast, several countries in the region have limited Linac infrastructure, with only one or a few centers. Despite this, there is potential for growth and collaboration to address the gaps in cancer care accessibility.

In South Africa, as shown in Tab.3-3, South Africa emerges as a prominent player in cancer care, boasting a substantial number of Linac centers (62) and offering a wide range of treatment modalities. With more than 100 units of MV therapy and significant representation in brachytherapy.

Botswana and Namibia show promising developments in cancer treatment infrastructure, with two Linac centers each. These countries also provide brachytherapy services, indicating efforts to diversify treatment options. Zimbabwe, while having a more limited number of Linac centers, still contributes to the regional landscape of cancer care with three facilities. The presence of brachytherapy services underscores efforts to provide holistic cancer treatment approaches.

Country	RT Centers	MV Therapy	Light Ion Therapy	kv Therapy	Brachytherapy
Botswana	2	2	0	0	1
Namibia	2	2	0	0	1
South Africa	62	102	0	8	23
Zimbabwe	3	1	0	0	2

Table 3-3: Clinical Linacs in Southern Africa

The distribution of clinical Linacs facilities in Africa reveals varying levels of cancer treatment infrastructure. While Egypt leads in North Africa and South Africa in the south with substantial Linac centers and diverse treatment modalities, Kenya emerges as a notable player in Middle Africa. These findings underscore the imperative for continued investment and collaboration to strengthen cancer care infrastructure across the continent and ensure equitable access to quality treatment options.

Overall, the data underscores the need for continued investment and collaboration to strengthen cancer treatment infrastructure across Middle Africa, ensuring that all individuals have access to quality care regardless of geographic location.

3.9 Cyclotrons Capacities for Medical and Reserach applications

3.9.1 Current Landscape of Cyclotron Facilities in Africa

While accelerators are primarily known for their large-scale applications in research facilities like iThemba LABS, cyclotrons play an essential role in various sectors across Africa, particularly in nuclear medicine and medical isotope production. Several African countries (as shown in Fig.3-5), including Egypt, Morocco, Algeria, South Africa, Kenya and Tunisia, host cyclotron facilities, which are pivotal for the local production of medical isotopes used in diagnostics, imaging, and radiation therapy [27, 28]. These isotopes, such as fluorine-18 used in PET scans, are critical for early disease detection and treatment planning.

In addition to their medical uses, cyclotrons in Africa are also utilized for fundamental research. iThemba LABS, in South Africa, operates one of the largest cyclotron facilities on the continent, producing isotopes for medical and industrial applications. The facility's separated sector cyclotron, which accelerates protons to energies of up to 200 MeV, serves as a cornerstone for both regional research and medical applications. Other countries, such as Egypt and Tunisia, utilize their cyclotrons for nuclear physics research, where they contribute to scientific advancements in areas such as material science and radiation physics.

These smaller, standalone cyclotrons are not only crucial for local healthcare advancements but also represent a growing infrastructure that supports collaborative scientific efforts across the continent. Their expansion in Africa reflects the increasing importance of accelerator-based technologies in improving public health, advancing scientific research, and contributing to technological innovation.

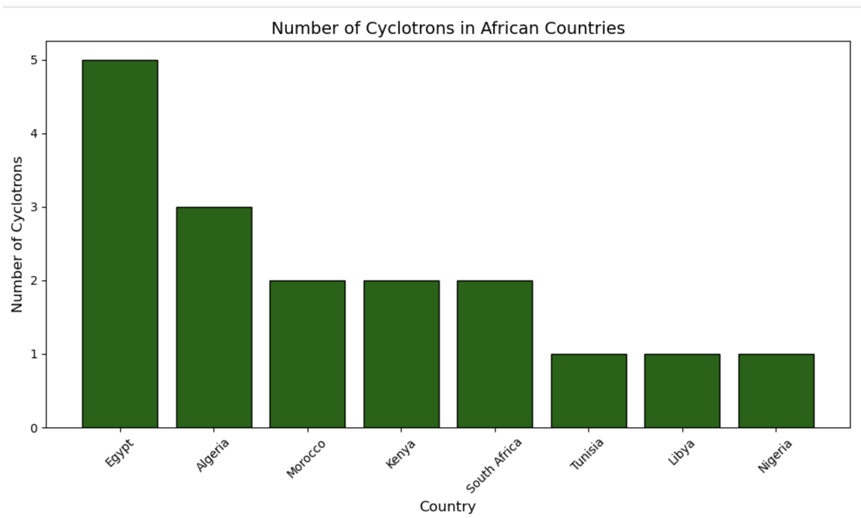

Figure 3-5: Database of the Cyclotrons used for radionuclide production in Africa[28]
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3.9.2 Challenges in Cyclotron Access and Usage

Despite their importance, many African nations still face challenges in expanding their cyclotron facilities. Key barriers include:

- High initial costs: The infrastructure for cyclotron facilities is expensive, and many countries lack the financial resources or investment mechanisms to develop them.
- Limited technical expertise: Cyclotron operation and maintenance require highly specialized technical skills. There is a need for training programs and capacity-building efforts in this area.
- Geographic concentration: Cyclotron facilities are currently concentrated in a few countries, creating disparities in access to these critical technologies across the continent.

3.9.3 Strategic Recommendations for Enhancing Cyclotron Use in Africa

To address these challenges and expand the role of cyclotrons in Africa, the following strategies are recommended:

- Establishing Collaborative Networks: Strengthening regional collaboration between countries with existing cyclotron facilities (such as South Africa, Egypt, and Tunisia) can help share knowledge, resources, and best practices. Regional hubs could be developed to provide services to neighboring countries with limited access to such facilities.
- Increasing Investment in Cyclotron Infrastructure: Governments and international organizations should consider allocating more funds to the establishment of cyclotron facilities in countries that do not yet

have them. Public-private partnerships could be explored to reduce the financial burden on national governments.

- Building Local Expertise and Training Programs: Developing specialized training programs in accelerator physics, cyclotron operation, and medical isotope production is critical. This could involve collaborations with existing facilities like iThemba LABS, as well as international training programs offered by institutions such as the IAEA.
- Expanding Medical Applications: There is an opportunity to scale up the production of medical isotopes for both domestic use and export. This would involve improving the production capabilities of existing cyclotron facilities and expanding their medical isotope portfolios to include isotopes for cancer therapy, diagnostic imaging, and radiopharmaceuticals.
- Promoting Research and Development: Encouraging the use of cyclotrons for both medical and scientific research in Africa is essential for advancing fields such as nuclear physics, materials science, and environmental research. Collaborative international research projects could boost the scientific capabilities of African cyclotron facilities, making them more attractive for global research initiatives.

3.10 Energy Recovery Linacs: A Pathway for Sustainable Particle Accelerators in Africa

3.10.1 Introduction and Motivation

Energy Recovery Linacs (ERLs) represent a transformative technology in the field of accelerator science, offering unparalleled energy efficiency, high beam quality, and the potential for sustainable operation. Globally, ERLs have demonstrated their ability to address diverse challenges in particle physics, materials science, and medical applications [29]. However, their adoption remains limited in regions lacking the infrastructure and expertise needed to develop advanced accelerator facilities.

Africa, despite its growing contributions to global science, faces significant barriers to building a robust accelerator science ecosystem. The absence of dedicated accelerator divisions and research facilities has hindered the development of cutting-edge technologies such as ERLs. Yet, this challenge presents an opportunity: by leveraging international collaborations and focusing on sustainable technologies like ERLs, Africa can lay the foundation for a future of self-sufficient and impactful accelerator research.

This section explores the motivation for pursuing ERL technologies in Africa. It highlights their potential to address pressing regional needs such as advancing healthcare diagnostics, supporting industrial innovation, and fostering scientific collaboration while providing a pathway for building capacity and expertise in accelerator science. By integrating ERLs into Africa's scientific roadmap, the region can align with global trends, contributing to and benefiting from advancements in accelerator technology.

3.10.2 History

The concept of an energy-recovery linac (ERL) was first proposed by Maury Tigner in 1965 , as a way to enhance the current in a collider for high-energy physics [30]. Traditional methods, where two beams are accelerated, collided, and then discarded, were highly inefficient. Tigner suggested recovering the energy of the beams using the same cavities that accelerated them, significantly improving machine efficiency and simplifying the design of the beam dump. However, implementing this idea required the development of reliable superconducting RF (SRF) accelerating cavities, which advanced over the following decade. The first major application of SRF cavities occurred at the High Energy Physics Lab at Stanford University, where researchers introduced a recirculation loop capable of varying the path length. This allowed electrons to either be accelerated or decelerated during a second pass through the cavities both processes were successfully demonstrated [32]. This marked the first ERL with SRF cavities , referred to as ”same-cell energy recovery”. Although the beam was neither used for experiments nor operated in continuous mode, energy recovery was clearly observed in the RF power requirements during the beam pulses.

3.10.3 The Role of ERLs in Africa's Research Landscape

Energy Recovery Linacs (ERLs) offer a transformative opportunity to address Africa's research challenges by providing energy-efficient, compact accelerator systems suited for diverse applications. These systems can drive advancements in synchrotron-based research for materials science, drug development, and energy technologies, while also enabling medical imaging and nondestructive testing in industrial applications. The sustainability and cost-efficiency of ERLs make them a practical choice for regions with limited resources, offering a pathway to align with global trends in environmentally conscious scientific infrastructure. Moreover, integrating ERLs into Africa's research landscape can foster capacity-building through training programs and collaborations with global institutions, such as CERN or Cornell University, creating a new generation of accelerator physicists and engineers. This development can bridge the gap between fundamental and applied sciences, enabling Africa to contribute to global accelerator projects and establish a leadership role in sustainable accelerator technology. By prioritizing ERLs, Africa can simultaneously address pressing regional needs and lay the groundwork for a self-sufficient and impactful research ecosystem.

3.10.4 Challenges and Opportunities in Adopting ERLs

The adoption of Energy Recovery Linacs (ERLs) in Africa presents both significant challenges and exciting opportunities. One of the primary challenges is the lack of existing infrastructure and technical expertise in accelerator science. Building ERL facilities requires specialized knowledge in superconducting technology, high-gradient RF structures, and beam dynamics, which are currently limited in many African countries. Additionally, the high initial costs of setting up such advanced technologies, along with the need for ongoing operational support, pose financial barriers. Moreover, there is a need for specialized facilities and laboratories, which require substantial investment in research and development (R&D), as well as in training personnel capable of designing, operating, and maintaining ERL systems.

However, these challenges also create significant opportunities for Africa. The development of ERLs offers the potential for leapfrogging traditional accelerator technologies, providing a more energy-efficient and cost-effective solution for scientific research and applications. By starting with compact ERL systems, Africa can focus on smaller, more manageable projects that can serve as a foundation for future growth. The long-term benefits of adopting ERLs include reduced energy consumption, the ability to support a wide range of scientific applications, and the creation of high-tech job opportunities in accelerator physics and engineering. Furthermore, international collaboration with established ERL research centers could facilitate technology transfer and knowledge sharing, helping to overcome the resource and expertise gaps. As the global demand for sustainable accelerator technologies increases, Africa's involvement in ERL development could position the continent as a key player in the future of accelerator science, with the potential for both local impact and global collaboration.

3.10.5 R&D Objectives and Capacity Building

To successfully adopt Energy Recovery Linac (ERL) technology in Africa, focused research and development (R&D) objectives must be established alongside capacity-building initiatives. The primary R&D objectives for ERL adoption include developing cost-effective, energy-efficient accelerator systems tailored to Africa's specific scientific and technological needs. These systems should prioritize sustainability, with a focus on reducing operational energy consumption and integrating renewable energy sources, making ERLs ideal for the continent's infrastructure challenges. Additionally, advancing key areas such as high-gradient RF structures, superconducting materials, and beam dynamics will be critical to ensuring the long-term performance and reliability of ERLs in diverse applications.

Simultaneously, capacity building must be at the core of ERL adoption in Africa. This includes training the next generation of accelerator physicists and engineers through specialized programs, workshops, and collaborations with established global ERL research centers. Building local expertise will not only support the development and operation of ERLs but also foster innovation in accelerator science. Partnerships with institutions like CERN, Jefferson Lab, and Cornell University could play a vital role in facilitating knowledge transfer, providing hands-on training, and supporting the establishment of research hubs in Africa. Furthermore, creating educational pathways, such as graduate programs and internships focused on accelerator physics, will be essential in developing a skilled workforce capable of supporting ERL projects. The R&D efforts should also involve collaborative projects with industry to ensure that the technologies developed are commercially viable and can be scaled to meet local needs. Through these initiatives, Africa can create a robust scientific and technical foundation for the successful integration of ERLs, driving both regional and global advancements in accelerator technology.

3.10.6 Potential Applications of ERLs in Africa

Energy Recovery Linacs (ERLs) offer a wide range of potential applications that could significantly impact various sectors in Africa, driving both scientific progress and socio-economic development. One of the most promising applications is in medical imaging and radiotherapy. ERLs can provide high-quality electron beams for advanced imaging techniques such as X-ray and CT scans, potentially improving healthcare access and diagnostics in underserved regions. The high beam quality of ERLs also makes them ideal for precise cancer treatments, offering a non-invasive, highly effective method for radiation therapy, which could enhance medical capabilities across Africa's growing healthcare sector.

In materials science, ERLs could enable the development of advanced synchrotron light sources. These light sources are crucial for the analysis of materials at the atomic level, supporting innovations in industries such as energy storage, nanotechnology, and environmental science. By establishing regional synchrotron facilities powered by ERLs, African researchers could contribute to the global effort to develop more efficient batteries, renewable energy technologies, and environmentally friendly materials, fostering economic growth and technological independence.

ERLs could also play a significant role in industrial applications, such as non-destructive testing of materials, which is essential for sectors like mining, construction, and manufacturing. The precision of ERL-driven electron beams can be used to detect structural weaknesses and improve quality control without damaging the materials. This application is particularly valuable in Africa, where industries such as mining and infrastructure development are rapidly growing, and where cost-effective, reliable testing methods are essential for ensuring safety and durability.

Finally, ERLs could serve as a foundation for training and education in accelerator physics, enabling the development of a highly skilled workforce. Establishing ERL facilities could serve as a hub for knowledge exchange, attracting students and researchers from across Africa and beyond. These facilities would not only enhance scientific capacity but also create opportunities for international collaboration, positioning Africa as a key player in the global accelerator science community. Through these diverse applications, ERLs can drive innovation, improve public health, and support sustainable economic development across the continent.

3.10.7 Collaboration and Implementation Roadmap

The successful adoption and implementation of Energy Recovery Linacs (ERLs) in Africa will require a coordinated approach that integrates local, regional, and international efforts. A robust collaboration framework is essential to overcome the challenges of limited infrastructure and expertise, while also ensuring that the benefits of ERL technology are realized across multiple sectors. This roadmap outlines key steps for fostering partnerships, guiding the phased implementation of ERL projects, and ensuring sustainable growth in Africa's accelerator research landscape.

- **Building International Partnerships:** Collaboration with established global ERL research centers, such as CERN, the Thomas Jefferson National Accelerator Facility (TJNAF), and Cornell University, will be pivotal for technology transfer and knowledge sharing. These institutions can offer both technical expertise and training programs, facilitating the development of local competencies in accelerator science. International partnerships will also enable access to shared resources, joint research projects, and participation in global accelerator initiatives. Strategic alliances with countries that have successfully developed ERLs will provide critical insights and guidance, ensuring that Africa can leapfrog some of the early-stage challenges faced by other regions.

- **Developing Local Collaborations:** Collaboration among African nations will be key to maximizing the impact of ERL technology. The establishment of regional research consortia, involving universities, national laboratories, and industrial partners, will allow for pooling of resources, talent, and expertise. These consortia can spearhead the design, development, and operation of small-scale ERL demonstrators, serving as training hubs and pilot projects for larger facilities in the future. Additionally, local industries and stakeholders, such as those in the healthcare, energy, and materials sectors, should be engaged early in the process to identify specific applications for ERL technology and ensure that the resulting infrastructure meets regional needs.

- **Phased Implementation Approach:** The roadmap for ERL implementation in Africa should follow a phased approach, starting with the establishment of small-scale ERL prototypes and progressing towards larger, more complex facilities. In the initial phase, the focus should be on building the technical capacity needed to design and operate ERLs, including the development of laboratory space, the acquisition of key components, and the training of local staff. This phase could also involve establishing collaborations with international partners to create a knowledge-sharing platform, such as workshops and joint research projects, aimed at building a sustainable ERL ecosystem in Africa. The next phase should focus on scaling up to pilot facilities capable of supporting applications in materials science, medical imaging, and industrial testing. These facilities would serve as a demonstration of ERL's potential impact and would help attract further investment and collaboration. The final phase would involve the establishment of full-scale ERL-based research centers with broader applications, including synchrotron light sources, particle physics research, and advanced medical facilities. These centers would be integrated into the global scientific community, contributing to collaborative international research and ensuring long-term sustainability.

- **Resource Mobilization and Funding:** Securing adequate funding for the development and operation of ERL facilities will require a combination of national, regional, and international investment. Governments should recognize the long-term value of ERL technology for scientific and economic development, and prioritize funding for accelerator research as part of broader science and technology initiatives. International funding agencies, such as the African Union, the United Nations, and the European Union, can play an important role in supporting the establishment of ERL infrastructure through collaborative research grants and joint programs. Additionally, private sector involvement, particularly from industries that would benefit from ERL technology, should be explored to ensure a diverse and sustainable funding base.

Through strategic collaboration, phased implementation, and resource mobilization, Africa can overcome existing barriers and lay the groundwork for a thriving accelerator research ecosystem powered by ERLs. This roadmap will enable the continent to not only benefit from the global advancements in accelerator technology but also contribute meaningfully to the future of sustainable science and technology.

3.10.8 Towards a Sustainable Future

The development and adoption of Energy Recovery Linacs (ERLs) in Africa represents a significant step toward building a sustainable and self-sufficient research infrastructure. As the global scientific community increasingly prioritizes sustainability, ERLs offer a promising pathway for Africa to address its unique challenges while contributing to international efforts to reduce the environmental impact of large-scale research facilities. By leveraging the inherent energy efficiency of ERLs, Africa can establish accelerator-based technologies that not only drive scientific progress but also align with global sustainability goals.

ERLs are particularly well-suited for Africa's needs due to their energy-efficient design, which recycles the energy from electron beams, significantly reducing operational energy consumption compared to traditional linear accelerators. This characteristic makes ERLs an ideal technology for regions with limited energy resources or those seeking to minimize the environmental footprint of scientific infrastructure. By integrating renewable energy sources into ERL operations, such as solar or wind power, Africa can further enhance the sustainability of these systems, making them resilient to energy supply challenges.

In addition to their energy efficiency, ERLs can contribute to Africa's sustainable development by supporting applications that address critical regional needs. For example, ERL-driven synchrotron light sources can aid in the development of cleaner energy technologies, such as more efficient solar cells or advanced materials for energy storage, directly contributing to Africa's transition to renewable energy. Similarly, ERLs used in medical imaging and radiation therapy can improve healthcare outcomes across the continent, providing access to state-of-the-art technologies without the high operational costs typically associated with traditional accelerators.

The sustainable impact of ERLs in Africa will also extend beyond energy and health. By fostering local expertise in accelerator technology and creating a skilled workforce, ERL projects will generate long-term educational and economic opportunities, helping to build a knowledge-based economy. International collaborations, knowledge-sharing platforms, and the establishment of regional research hubs will ensure that ERLs serve as a catalyst for broader innovation and scientific advancement across the continent.

Ultimately, the adoption of ERLs in Africa has the potential to create a sustainable and forward-looking accelerator science ecosystem that addresses both local and global challenges. By embracing this technology, Africa can contribute to the global pursuit of sustainable, energy-efficient research infrastructure while building a foundation for scientific and technological leadership in the 21_{st} century.

3.11 Recommendations

To ensure sustainable progress in accelerator physics in Africa, we propose the following key recommendations:

- **Strengthening Research Networks and Consortia**: It is crucial to establish pan-African research consortia dedicated to accelerator physics (see Section 3.5). These networks should facilitate collaboration between African institutions, pooling resources, expertise, and infrastructure. Such consortia can also act as a platform for engaging with global partners, securing funding, and coordinating large-scale research initiatives. By including Africa's needs in international conferences, we can amplify the importance of developing accelerator physics on the continent. For instance, during the recent EuPRAXiA PP Annual Meeting in Italy, the mission of the African School of Physics was presented, followed by a roundtable discussion pointing out that the number of accelerator physicists in Africa is critically low, stressing the urgent need to train more in order to benefit from their expertise in the future [33]. The mission had also been presented earlier in April 2024 during the 3rd Accelerator Days (TERZA Giornata Acceleratori) at the Frascati National Labs of INFN [34], which inspired the idea of including more outreach activities in conferences like EuPRAXiA and inviting members of the IOC to strengthen the relationship between INFN and ASP.
- **Creating Structured Training Programs**: Governments, universities, and research centers should prioritize the creation of structured educational programs like Ph.D positions focused on accelerator physics. This includes developing graduate programs, certification courses, and specialized training sessions. Additionally, expanding opportunities for African students and professionals to receive training abroad, through scholarships and exchange programs, will help in skill-building and knowledge transfer.
- **Expanding Public and Private Sector Funding**: A strong push for increasing financial support from both the public and private sectors is needed. Governments should recognize the strategic importance of accelerator physics in driving scientific and technological innovation, and allocate more resources to research and development in this field. Partnerships with industry could also be leveraged to attract private investments in accelerator-related technologies, particularly those with commercial potential, such as medical accelerators or renewable energy applications.
- **Enhancing Digital Infrastructure and Access to Computational Tools**: With many accelerator physics experiments requiring advanced simulation software and computational tools, it is important to ensure that African institutions have access to the necessary digital infrastructure. This includes high-performance computing facilities and access to software platforms such as CAIN, WHIZARD, and others. Support for training researchers in using these tools effectively should also be prioritized.
- **Encouraging Knowledge Dissemination and Scientific Publications**: It is essential to promote knowledge sharing within the African accelerator physics community and beyond. Initiatives should

be developed to encourage researchers to publish their work in peer-reviewed journals, participate in international conferences, and contribute to open-access platforms. Creating an African accelerator physics journal or repository could further enhance visibility and collaboration in this field.

- **Long-term Strategic Planning**: Governments and research institutions should formulate long-term strategic plans to guide the growth of accelerator physics in Africa. This could include roadmaps for infrastructure development, timelines for achieving specific research goals, and frameworks for integrating accelerator technologies into national priorities, such as healthcare, energy, and education.
- **Encourage Policy Support for Accelerator Research:** Policy frameworks that support the growth of accelerator science and technology in Africa should be established at the national and regional levels. Governments should create policies that promote investment in R&D, facilitate international partnerships, and provide incentives for private sector involvement. By recognizing the strategic importance of accelerators in advancing science and technology, policymakers can create an enabling environment for innovation and ensure the long-term success of ERL projects. Furthermore, policies that encourage the use of ERLs in various sectors, including healthcare, materials science, and industrial applications, will ensure that the technology has a broad and lasting impact.
- **Promote Sustainability in ERL Design and Operation:** Given Africa's unique environmental and energy challenges, sustainability should be a central consideration in the design and operation of ERL facilities. The integration of renewable energy sources, such as solar and wind, should be explored to power ERL operations, reducing their environmental footprint and enhancing their resilience to energy shortages. Additionally, energy-efficient technologies, including those for cooling, power supply, and waste heat recovery, should be prioritized in the development of ERL systems. By focusing on sustainability, Africa can position itself as a leader in environmentally responsible accelerator technology and contribute to global efforts to reduce the carbon footprint of scientific infrastructure.

By following these recommendations, African nations can build the necessary infrastructure, expertise, and partnerships to harness the full potential of an accelerator division, advancing not only scientific research but also economic and social development. With careful planning, international collaboration, and a focus on sustainability, ERLs can become a cornerstone of Africa's future in science and technology.

3.12 Preliminary Results of the ASFAP Survey on Accelerator Physics

3.12.1 Educational Background and Awareness

The survey revealed significant gaps in the educational exposure of African students and researchers to accelerator physics. in Fig.3-6, only 46.3% of respondents had accelerator physics or technology included in their academic curriculum, and 53.7% were unfamiliar with fundamental accelerator concepts. These results highlight the urgent need for integrating accelerator-related topics into undergraduate and graduate programs across Africa.

Moreover, 57.1% of respondents were unaware of existing accelerator facilities in Africa. Among those familiar, 69% cited iThemba LABS in South Africa, indicating the limited recognition of existing resources. These findings point to the need for awareness campaigns to showcase the relevance of accelerators and their applications in various fields.

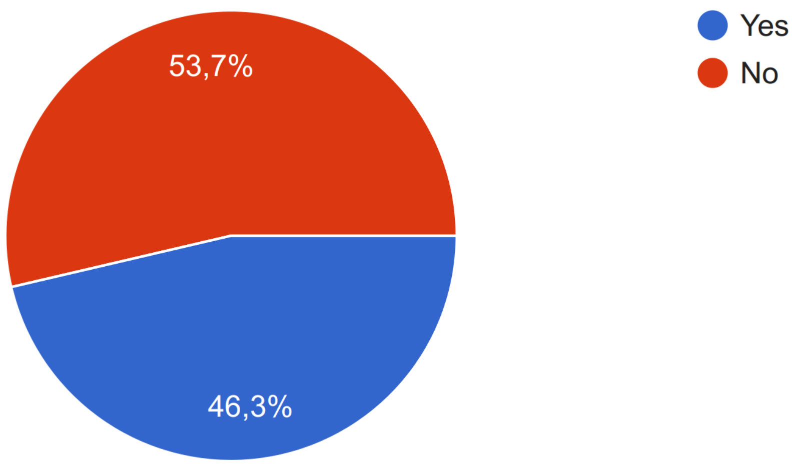

Figure 3-6: Inclusion of Accelerator Physics or Technology in Academic Curricula

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3.12.2 Aspirations for Accelerator Physics Development

The survey highlighted widespread support for developing accelerator divisions in Africa, with 88.1% of respondents expressing the belief that such divisions are necessary (see Fig. 3-7). Furthermore, Fig. 3-8 shows that 77.4% strongly agreed that the establishment of accelerator facilities would significantly enhance research opportunities on the continent.

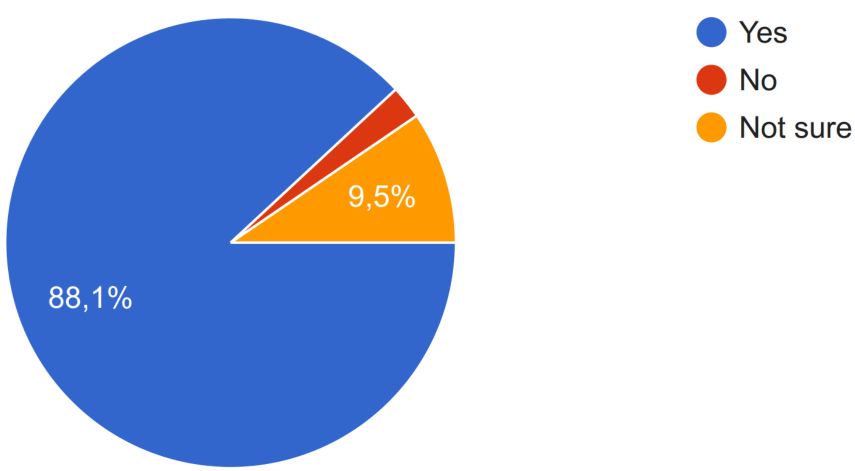

Figure 3-7: Perception of the Need for Accelerator Divisions in Africa

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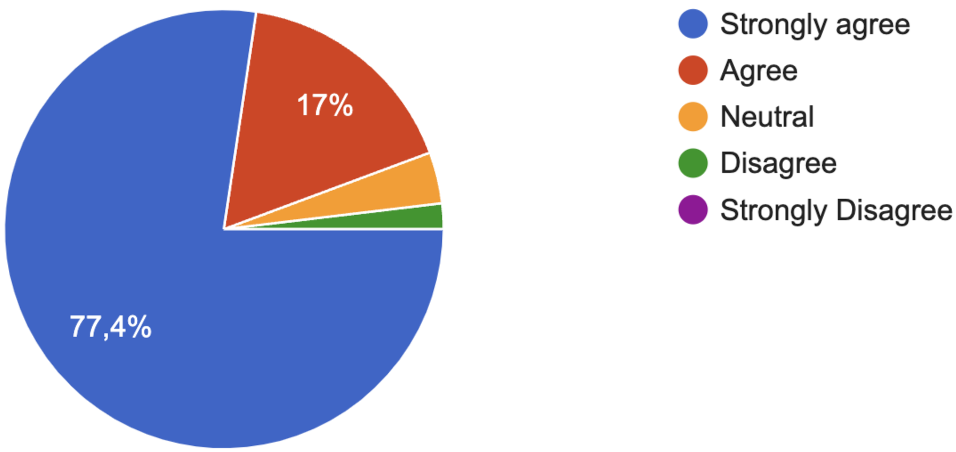

Figure 3-8: Impact of Accelerator Facilities on Scientific Research Opportunities in Africa
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Respondents also identified compact accelerator technologies as a promising starting point for Africa. 92.3% viewed compact accelerators favorably, emphasizing their cost-effectiveness and accessibility compared to larger facilities. These preliminary results suggest a clear interest and readiness within the African scientific community to embrace accelerator technology.

3.12.3 Barriers to Progress

Respondents identified several key challenges to establishing accelerator divisions in Africa:

- Lack of funding: Identified by 64.3%, this was the most significant barrier.
- Insufficient expertise: Highlighted by 57.1%, this reflects the need for more trained professionals.
- Limited education and training opportunities: Reported by 57.1% of participants.
- Political and logistical obstacles: A lack of political will and infrastructural support further compounds the difficulty of establishing such facilities.

These barriers underscore the need for focused strategies to address funding, skills development, and infrastructure deficits.

3.12.4 Potential Solutions and Strategies

Participants proposed several actionable strategies to overcome these challenges:

- Increasing funding through international partnerships: Supported by 78.6% of the respondents.
- Strengthening regional and global collaborations: Highlighted by 57.1%.
- Developing smaller, cost-effective facilities (e.g., compact light sources (CLS): Suggested by 54.8% as a practical entry point for Africa.

Respondents also emphasized the importance of capacity building through training programs and the involvement of the African diaspora. In particular, 57. 5% expressed willingness to return to Africa to work in accelerator divisions if opportunities arise, providing a strong basis for diaspora participation initiatives.

3.13 Conclusion and perspectives

Although accelerator physics in Africa may not be as developed as in some other regions, there is a growing recognition of its importance for scientific research and technological advancement, leading to increased investment and collaboration in this field across the continent. Africa's accelerating interest stems from a collective understanding of the transformative potential that accelerator-based facilities offer across diverse scientific domains. This burgeoning acknowledgment has spurred a notable uptick in investment and collaboration within the accelerator physics realm throughout Africa.

This momentum is not merely confined to the establishment of accelerator facilities but encompasses a broader spectrum of initiatives aimed at nurturing indigenous expertise, fostering collaborative networks, and leveraging international partnerships. Through strategic capacity-building programs, educational outreach endeavors, and knowledge exchange platforms, African countries are actively cultivating a skilled workforce capable of driving accelerator-based research forward.

Moreover, the increasing integration of accelerator physics into national scientific agendas reflects a broader commitment to harnessing science and technology for sustainable development objectives. By leveraging accelerator-based tools, such as synchrotron radiation facilities and particle accelerators, African nations are poised to address pressing societal challenges, ranging from healthcare and materials science to environmental conservation and renewable energy.

In essence, while accelerator physics in Africa may currently be in a nascent stage compared to its counterparts in more developed regions, the trajectory is undeniably upward. As investment and collaboration continue to amplify, Africa's accelerator physics community is poised to make increasingly substantial contributions to global scientific discourse, innovation, and societal well-being, solidifying its place on the international stage of scientific endeavor.

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Astrophysics & Cosmology Working Group

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4.1 Abstract

This report summarises the current status, challenges, recommendations, and future needs of Astronomy in Africa, developed within the framework of the Astrophysics and Cosmology Working Group (WG) of the African Strategy for Fundamental and Applied Physics (ASFAP). It provides a brief introduction to the developments in astronomy in Africa over the past ten years, showing that astronomy is one of the emerging fields of science on the continent, and the importance of astronomy for socio-economic and environmental development, in line with the United Nations Sustainable Development Goals (SDGs) and the African

Union's Agenda 2063 (MDGs).~~ It provides a list of challenges facing the professional community and a list of recommendations for policy and decision-makers.~~ It also highlights the challenges faced by the professional community and a list of recommendations for policy and decision-makers. Finally, it describes the highest priority future needs and plans in line with the Letters of Interest received and general activities.

4.2 Introduction and motivation

Astronomy is currently one of the emerging scientific fields in Africa. This can be seen through different activities, from institutional development, strong infrastructure development with new observatories and site testing, human capacity building through new postgraduate programmes and training, research and publications, the creation of professional societies and networks, to the growth of outreach activities, amateur astronomical societies, and increased political engagement. ~~Moreover,~~ In addition, astronomy is an important tool for socio-economic and environmental development for instance through job creation in the astrotourism industry and, as such, can be used to combat poverty in Africa and globally and to reduce inequalities between countries.

4.2.1 Current status of astronomy in Africa: brief summary

The last ten to twenty years have seen a strong institutional development in astronomy, with the creation of numerous space agencies, research centres, and astronomy departments within universities. Some examples include (see Figure 4-1 below): Nigeria with the strengthening of the Centre for Basic Space Sciences (CBSS) and the strong development of the National Space Research and Development Agency (NASRDA) since 1999, Algeria with the launch of the Algerian Space Agency (ASAL) in 2002, Botswana with the establishment of astronomy research and infrastructure under the new Botswana International University of Science and Technology (BIUST) in 2006, Morocco with the strong development of the Oukaimeden Observatory since 2007, Gabon with the Agency for Space Studies and Observation (AGEOS) since 2010, South Africa with multiple strong institutional developments, such as the South African Radio Astronomical Observatory (SARAO), the South African Astronomical Observatory (SAAO) and the South African National Space Agency (SANSA) since 2010, Ghana with the launch of the Ghana Space Science and Technology Institute (GSSTI) in 2012 and the Ghana Radio Observatory in 2017, Sudan with the launch of the Institute for Space and Aerospace Research (ISRA) in 2013, Ethiopia with the establishment of the former Ethiopian Space Science and Technology Institute (ESSTI) in 2016, now the Space Science and Geospatial Institute (SSGI), and the Entoto Observatory, Kenya with the launch of the Kenya Space Agency (KSA) in 2017, Egypt with the establishment of the Egyptian Space Agency (EgSA) in 2018 and the strengthening of the National Research Institute for Astronomy and Geophysics (NRIAG), Zimbabwe with the launch of the Zimbabwe National Geospatial and Space Agency (ZINGSA) in 2019, Rwanda with the launch of the Rwandan Space Agency (RSA) in 2020, etc. [8]. ~~Algeria with the launch of the Algerian Space Agency (ASAL) in 2002, Angola with the establishment of the National Space Programme Management Office (GGPEN) in 2010, Botswana with the establishment of astronomy research and infrastructure under the new Botswana International University of Science and Technology (BIUST) in 2006, Egypt with the establishment of the Egyptian Space Agency (EgSA) in 2018 and the strengthening of the National Research Institute for Astronomy and Geophysics (NRIAG), Ethiopia with the establishment of the former Ethiopian Space Science and Technology Institute (ESSTI) in 2016, now the Space Science and Geospatial Institute (SSGI), and the Entoto Observatory (see below), Gabon with the Agency for Space Studies and Observation (AGEOS) since 2010, Ghana with the launch of the Ghana Space Science and Technology Institute (GSSTI) in 2012 and the Ghana Radio Observatory (see below), Kenya with the launch of the Kenya Space Agency~~

~~(KSA) in 2017, Morocco with the strong development of the Oukaimeden Observatory (see below) since 2007, Nigeria with the strengthening of the Centre for Basic Space Sciences (CBSS) and the strong development of the National Space Research and Development Agency (NASRDA) since 1999, Rwanda with the launch of the Rwandan Space Agency (RSA) in 2020, South Africa with multiple strong institutional developments, such as the South African Radio Astronomical Observatory (SARAO, see below), the South African Astronomical Observatory (SAAO, see below) and the South African National Space Agency (SANSA) since 2010, Sudan with the launch of the Institute for Space and Aerospace Research (ISRA) in 2013, Zimbabwe with the launch of the Zimbabwe National Geospatial and Space Agency (ZINGSA) in 2019, etc. [8]~~. In the African Union (AU) Science, Technology and Innovation (STI) strategy and the Common African Position (CAP) on the Post-2015 Development Agenda, astronomy and space science have been selected as some of the priority fields for achieving the goals of the development agenda. Taking into account the importance of astronomy and space science, the AU established in 2018 the first African Space Agency based in Egypt and developed the first African Space Strategy [1].

The development of infrastructure with new observatories and the construction of new telescopes, including site testing, has also been remarkable, growing from small to some of the largest telescopes in the world. Figure 4-1 (central map) shows some of the existing and future telescopes and observatories in radio, optical and gamma-rays.

In radio astronomy, the Square Kilometre Array (SKA)[1], one of the most ambitious scientific projects of the 21st century that aims to reproduce the entire radio universe since the Big Bang, together with the African Very Long Baseline Interferometry (VLBI) Network (AVN)[2] are some of the major initiatives in Africa, with South Africa being the main host of the SKA in partnership with Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia. All these countries signed a memorandum of understanding in 2019 to work together to develop SKA and radio astronomy. As part of this collaboration, Ghana was the first country to convert the former telecommunication dish antenna into a radio telescope and established Ghana's first Radio Observatory at Kuntunse in 2017. The MeerKAT[3] radio interferometer, the precursor to the African SKA, with 64 dishes located in South Africa in the Karoo Desert, became operational in 2018 and is currently producing some of the best and most detailed radio data in the Universe. With participation in the SKA, the South African SKA and the HartRAO Observatory joined forces in creating SARAO. In addition, South Africa is working on the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX)[4] radio interferometer. Namibia is currently building the African Millimetre Telescope (AMT [2, 3]), the first millimetre-wave radio telescope on the African continent, as part of the European Research Council (ERC) Synergy Grant named 'BlackHolistic' obtained in collaboration with Finland, the Netherlands and the United Kingdom. Once completed, the AMT will join the global telescope network of the Event Horizon Telescope (EHT) project, which aims to observe and study supermassive black holes at the centres of galaxies [5, 6]. Other countries are developing radio astronomy infrastructures, such as Nigeria, and/or testing sites, such as Tanzania, to establish small dishes in the near future and join some of the international networks, such as the EHT. All the radio telescopes mentioned are part of large international collaborations.

In optical astronomy, South Africa hosts the 11 m South African Large Telescope (SALT)[5] and more than 15 smaller optical telescopes at the South African Astronomical Observatory (SAAO)[6] in collaboration with different countries. SALT is currently the largest optical telescope in the world, offering the possibility to obtain various types of photometric, spectroscopic and polarimetric data, including near-infrared (NIR) and optical integral field spectroscopy with the two newly developed instruments. Morocco also established

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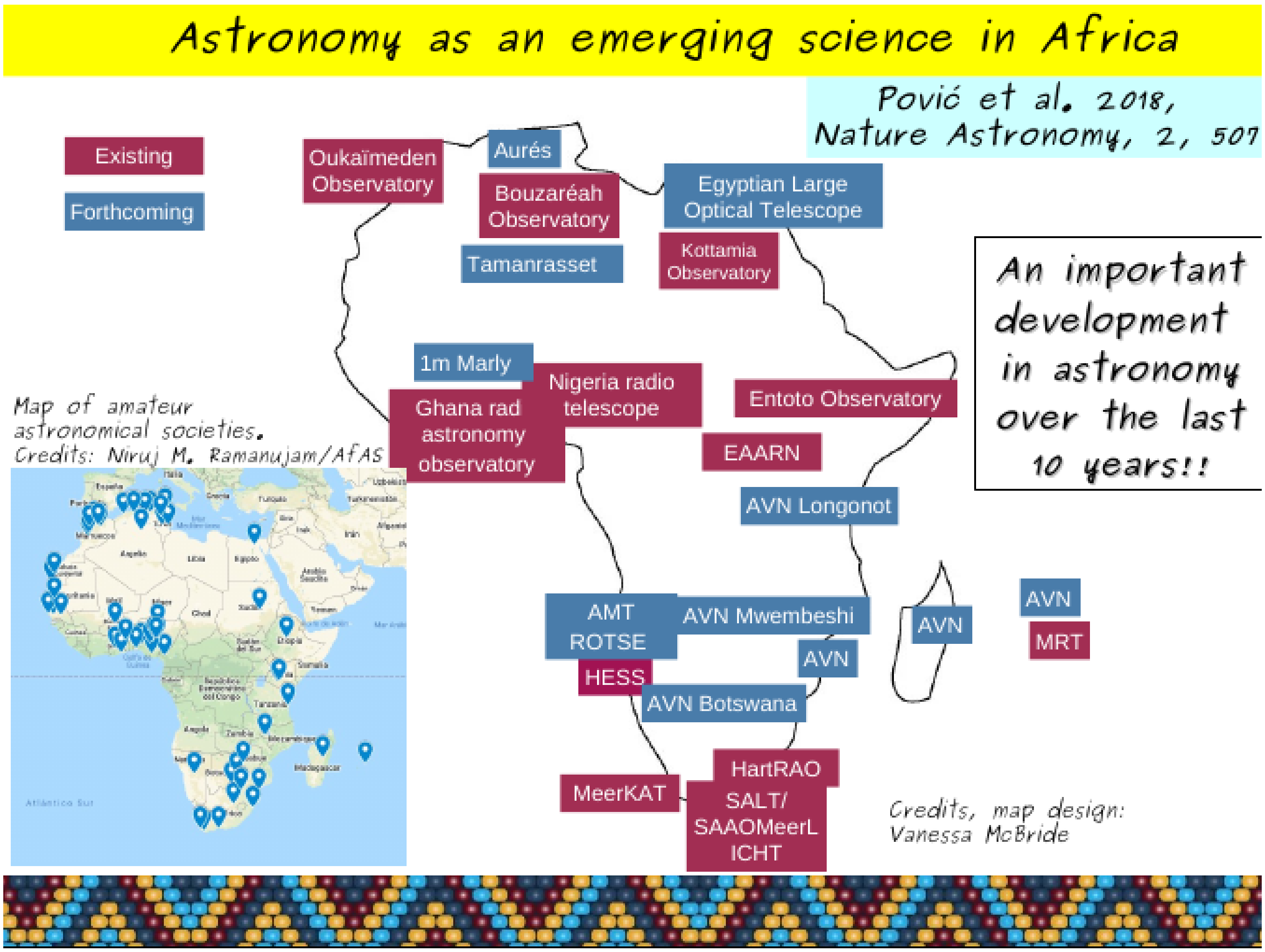

Figure 4-1: Central map: Existing and forthcoming telescopes and observatories in optical, radio, and gamma-rays, produced by Vanessa McBride using the data from Ref. [8]. Left bottom map: Amateur astronomical societies in Africa produced by the Niruj M. Ramanujam, under the African Astronomical Society (AfAS).

through different international collaborations several small telescopes at the Oukaïmeden Observatory[7] that are effectively used for observations of small bodies, extrasolar planets, stars, nearby galaxies, and space debris [4]. This includes the TRAPPIST-North 60cm telescope that is actively used in the detection of extrasolar planets. Small optical telescopes (approx. up to 2 m) have also been installed in several other countries and/or are in the process of being established soon, such as in Algeria with the old Bouzaréah Observatory, Burkina Faso with intentions to install the 1m Marly optical telescope (a project that has been affected by political instability and conflict), Egypt with the Kottamia Astronomical Observatory (KAO), Ethiopia with the twin 1 m telescopes at the Entoto Observatory (see [8] for more information), and Namibia with the re-establishment of the ROTSE telescope. All these facilities in optical, aim to create in the future a network of connected robotic observatories called the African Integrated Observing System (AIOS), to strengthen continental and international collaborations and research in optical astronomy and make better use of small telescopes. In addition, several countries are conducting site testing to build optical telescopes in the future. These include Algeria, in collaboration with the European Virgo consortia, Egypt, to establish the 4-6 m Egyptian Large Optical Telescope, Ethiopia, to establish a 3-4 m telescope, and Kenya, to build a small telescope in collaboration with the United Kingdom.

Finally, in gamma-rays, Namibia hosts, in collaboration with Germany, the High Energy Stereoscopic System (H.E.S.S)[8] Cherenkov telescope for the study of cosmic gamma rays, and there are also research groups (in particular in South Africa and Namibia) involved in the development of the next-generation Cherenkov Telescope Array (CTA).

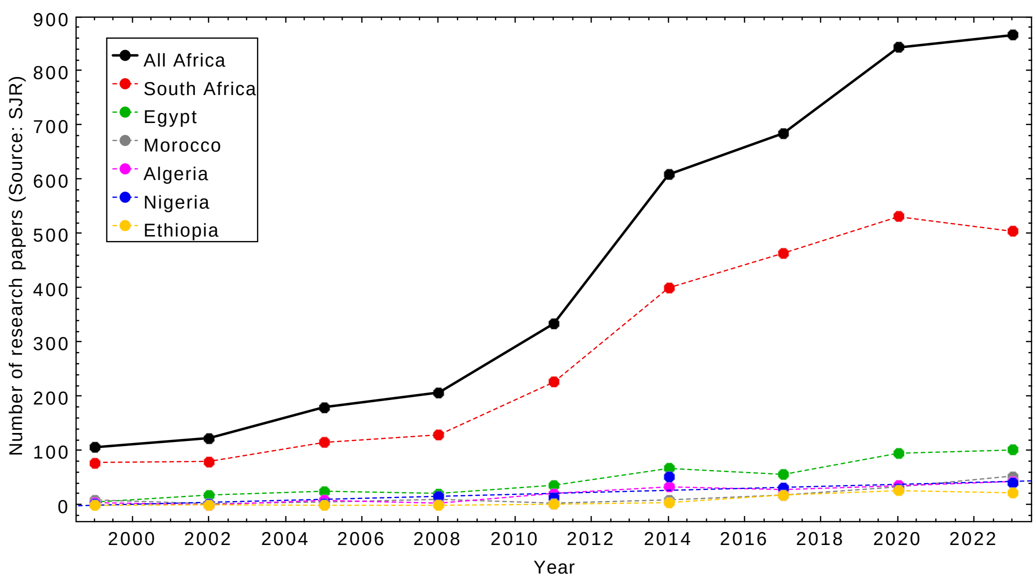

Figure 4-2: Number of publications in astronomy and astrophysics in the last 25 years in all African countries (black), and in six countries with the highest number of published research papers. These are South Africa (red), Egypt (green), Morocco (grey), Algeria (pink), Nigeria (blue) and Ethiopia (yellow). The data were obtained from the Scimago Journal Country Rank (SJR).

New postgraduate programmes (masters and PhD) in astronomy and astrophysics increased across the continent in the last 10-15 years, as well as the number of professional astronomers (e.g., in Algeria, Botswana, Burkina Faso, Cote d'Ivoire, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Madagascar, Mauritius, Morocco,

[7] http://moss-observatory.org/
[8] https://www.mpi-hd.mpg.de/hfm/HESS

Namibia, Nigeria, Rwanda, Senegal, South Africa, Sudan, Tunisia, Uganda, Zambia, Zimbabwe, etc.). This brought a strong development in astronomy research across the continent (e.g., the number of published research papers tripled from 2011 to 2021; source SRJ-Scimago Journal and Country Rank). Figure 4-2 shows the increase in the number of refereed publications in astronomy and astrophysics in Africa (in black) over the last 25 years and the six countries with the highest number of published research ~~papers~~articles. ~~South Africa is the leading contributor to astronomy and astrophysics research, followed by Egypt. In all cases, it can be seen that there has been a strong development in research since 2010.~~ It is evident that there has been a steady development in research since 2010. Currently, all fields of astronomy research are present on the continent ~~. This can also be~~as seen in Figure 4-3, which was obtained ~~as a result of~~ from a survey conducted within the ASFAP Astrophysics and Cosmology WG with 130 professional astronomers from 20 countries in Africa, who expressed their professional interests in different fields of astronomy. It can be seen that the majority of the participants ($>60\%$) are interested in the use of astronomy for the development of our society. Astronomical methods and data are the second most popular interest, followed by cosmology and gravitational astronomy, and galactic and extragalactic astronomy. Figure 4-3 also outlines which fields of astronomy are less developed in Africa and have fewer experts, such as solar physics, transients and pulsars, or ethno-archaeoastronomy (cultural astronomy) and the history of astronomy.

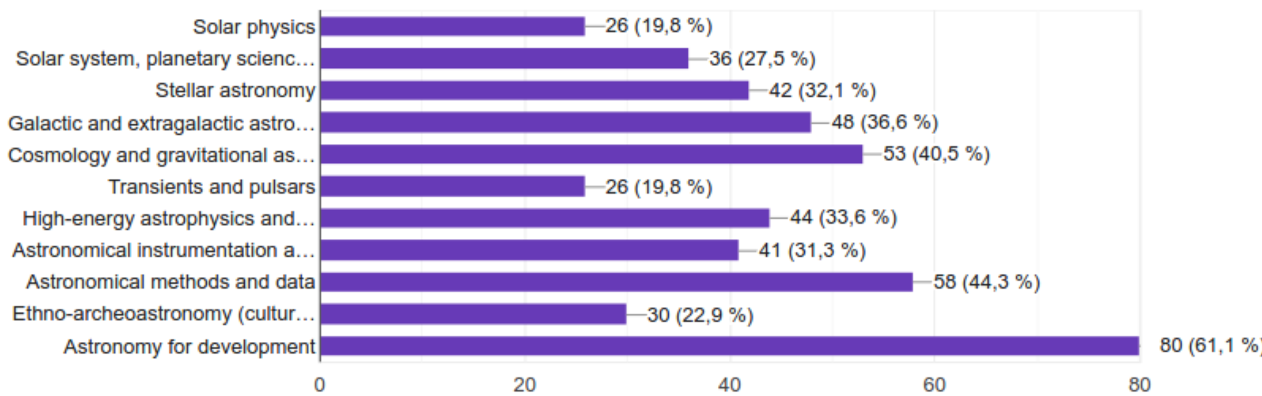

Figure 4-3: Interest in different fields of astronomy among the professional community in Africa. This figure was derived from the feedback of 130 professional astronomers in Africa.

Increased research activities brought strong international collaborations, including long-term initiatives such as the Development in Africa with Radio Astronomy (DARA)[9], the Africa Initiative for Planetary and Space Sciences (AFIPS)[10], the Europlanet Society[11], and mobility programs in research such as the Pan-Africa Planetary and Space Science Network (PAPSSN)[12]. Finally, taking into account all aspects of professional development, such as research, institutional development, infrastructure development and site testing, and human capacity building (with masters and PhD programmes), most African countries are conducting activities in professional astronomy, as shown in Figure 4-4. Tunisia is missing in the map

The number of astronomy schools, workshops and training, as well as professional conferences and meetings, has increased considerably. This includes the organisation of regular astronomy schools, such as the Pan-African School for Emerging Astronomers (PASEA), some of the first International Astronomical Union (IAU) symposia, such as IAU 356 and IAU 386 held in Ethiopia, the 3rd and 4th symposia organised in

[9]https://www.dara-project.org/
[10]https://africapss.org/
[11]https://www.europlanet-society.org
[12]https://www.papssnmobility.org/

Figure 4-4: African countries with professional astronomy present, including research, human capacity building, institutional development, infrastructure development with new observatories and telescopes, and site testing.

Africa in the last 100 years of the IAU, and the organisation of the 1st IAU General Assembly (GA) in Africa, held in August 2024 in Cape Town, South Africa. This first GA, organised in line with Vision 2024[13], was a truly unique and historic event that will have a long-term legacy in terms of improved research, infrastructure development, education, outreach and stronger collaborations around the world, and particularly in Africa.

Consequently, with the support of the South African Department of Science and Innovation (DSI), the African Astronomical Society (AfAS)[14] was re-established in 2019 with the aim of becoming the voice of astronomy development in Africa. AfAS is now a vibrant and active professional society, with more than 350 members, and different established committees, including the Science Committee and the Education and Outreach Committee, which lead a number of initiatives, including the annual research conference ~~and~~, awards and prizes for postgraduate students and early-career researchers. In close collaboration with AfAS, and with support from DSI, other initiatives such as the African Planetarium Association (APA)[15], the African Network of Women in Astronomy (AfNWA)[16], the African Science Stars (ASSAP)[17] and the Africa-Europe Science Innovation and Collaboration Platform (AERAP)[18] have emerged. In addition, AfAS established strong connections and initiated long-term collaborations with several professional societies and organisations such as the European Astronomical Society (EAS), the American Astronomical Society (AAS), the Square Kilometre Array Observatory (SKAO), the Breakthrough Listen initiative, etc. Africa also hosts the Office of Astronomy for Development (OAD)[19] of the IAU, which includes the main Office in South Africa and three OAD Regional Offices in Ethiopia, Nigeria and Zambia. Finally, public awareness and outreach activities have increased exponentially across Africa in the last ten years, including the creation of more than 70 amateur astronomical societies, as can be seen in Figure 4-5 ~~(bottom left map)~~.

[13] https://astronomy2024.org/vision-2024/
[14] https://www.africanastronomicalsociety.org/
[15] https://africanplanetarium.org/
[16] https://afnwa.org/
[17] https://assap.co.za/
[18] https://aerapscience.org/
[19] https://www.astro4dev.org/

Figure 4-5: Amateur astronomical societies in Africa as per 2021 produced by the Niruj M. Ramanujam, under the African Astronomical Society (AfAS).

4.2.2 Astronomy for development

The impressive advances in astronomy in Africa described above now increase the possibility of achieving the ~~the United Nations (UN)~~ Sustainable Development Goals (SDGs) of the United Nations, and the African Union's Agenda 2063 Millennium Development Goals through astronomy, which have proven to be an important tool for socio-economic and environmental development (e.g., [10, 7, 9, 11]). Indeed, never before has it been more possible to use astronomy for development than now. Astronomy is one of the most multidisciplinary sciences, and has proven to be a powerful tool to promote education and inspire young people and children (including girls) to do science through the beauty of the Universe, contributing directly to SDG4 (Quality education) and SDG5 (Gender Equality) (e.g., see OAD annual reports). Astronomy is one of the leading sciences in bringing highly skilled people into the sector through fundamental research and instrument and data development, in line with SDG8 (Decent work and economic growth), and technological development and innovation through the continued construction of next-generation telescopes and instruments, in line with SDG9 (Industry, innovation, and infrastructure). Astronomy helps advance medical diagnostic techniques (e.g., X-ray imaging, magnetic resonance, thermal sensors, etc.) thus directly contributing ~~directly~~ to SDG3 (Good health and well-being). Astronomy is a major contributor to the development of renewable and green energies, through fundamental research in solar physics and the development of ground- and space-based missions, in line with SDG7 (Affordable and clean energy) and SDG13 (Climate action). Astronomy can be used to promote diplomacy and peace, through the message that 'We all live under the same sky', in line with SDG16 (Peace, justice and strong institutions). Astronomy is also one of the scientific fields that contributes significantly to long-term international collaborations through fundamental research, data sharing, and the building of next-generation telescopes and instruments, in support of SDG17 (Partnerships for the goals). Many of the high- and middle-income countries have benefited significantly from their dark skies and investment in astronomical research and infrastructure, and it is time for African countries to use astronomy as one of the tools to achieve the

UN SDGs. Finally, empowering Africa through astronomy and other fields of science will in the long term reduce inequalities between countries, in line with SDG10, and help to combat poverty (SDG1).

4.3 High-priority current and future initiatives

Until the date of this report, ~~we received 13 LoI (out of 68, ~20%) with Astrophysics and Cosmology being indicated as the primary physics WG~~out of the the 68 LoI received by the ASFAP community, 13 belonged to the Astrophysics and Cosmology WG.. The received LoI cover radio astronomy, gamma-rays and optical observational astronomy, cosmology, and astronomy for development. Most of them~~,~~ describe ~~the~~ initiatives/projects that are already running, but there are also several LoI with new proposed developments. In continuation, we are providing a summary of the received LoI and their suggestions:

- African Radio Astronomy Network ~~(James Chibueze, UNISA/South Africa),~~ suggests building a network of small and cheap radio telescopes, with an aim to provide training in radio astronomy across Africa and to undertake research with the ultimate aim of getting African astronomers to participate in the SKA science.

- Astro-particle and cosmology potential in the underground of Africa ~~(Fairouz Malek, CNRS/France, and Yasmine Sara Amhis, IJCLab/France),~~ addresses the opportunity for African countries to contribute to the enhancement of the knowledge and understanding of the fundamental aspects of the Universe by building and leading underground experiments similar to IceCube, ANTARES, Kamioka neutrino observatory, SNOLAB, etc.

- Continued gamma-ray observations with H.E.S.S ~~(Michael Backes, UNAM/Namibia),~~ addresses the importance of H.E.S.S telescopes for the current gamma-ray observations, and for the development of the future CTA telescope.

- Development in Africa with Radio Astronomy ~~(Melvin Hoare, University of Leeds/UK), describes the~~ (DARA) project that has provided basic training in radio astronomy to over 300 young graduates across eight African countries, and scholarships to 26 MSc and 9 PhD African students, with perspectives to continue with the work in future. Recently, DARA started the 3rd phase of its development and human capacity building in radio astronomy and data science in Africa.

- Furthering the sustainable development goals in Africa by exposing young children to the beauty, excitement and perspective of astrophysics ~~(George Miley, Leiden University/The Netherlands),~~ suggests that ASFAP incorporates into its strategy the use of physics in the education of very young children (4 - 10 years old), particularly those in underprivileged communities.

- Gamma-ray astronomy in the context of multi-wavelength astronomy and multi-messenger astrophysics ~~(Markus Boettcher, NWU/South Africa),~~ summarises opportunities for Africa to take on a driving role in the field of multi-wavelength and multi-messenger astrophysics.

- Low-frequency ($<$ 1GHz) radio interferometric arrays and radio astronomy/cosmology ~~(Patrice Okouma, Rhodes University/South Africa),~~ suggests the development in space science and low-frequency ($<$ 1.2 GHz) radio astronomy and cosmology.

- Observational astronomy in North Africa ~~(Fairouz Malek, CNRS/France, and Mourad Telmini, University of Tunis El Manar/Tunisia),~~ addresses the opportunity for North African countries to unite in contributing to build and lead a series of local observatories and/or one large facility.

- The first millimetre-wave radio telescope in Africa: the Africa Millimetre Telescope ~~(Michael Backes, UNAM/Namibia),~~ introduces the AMT and its impact on human capacity development in Namibia and Africa.
- The importance of the financial and technical support for the improvement of cosmology in Cameroon and in Africa ~~(Ragil Ndongmo, University of Yaoundé I/ Cameroon),~~ addresses the current difficulties in Cameroon regarding the studies in cosmology and brings some suggestions on how to overcome the existing challenges.
- The Lofar global citizenship radio array "GLORAY" ~~(George Miley, Leiden University/The Netherlands),~~ summarises a proposal to be submitted to ASTRON and to the International LOFAR Telescope Board to carry out a design study for a project that would transform LOFAR into a multidisciplinary facility that would span 3 continents, including Africa (in particular North Africa).
- The South African Radio Astronomy Observatory (SARAO) ~~(Rob Adam, SARAO/South Africa),~~ describes SARAO's vision, mission, objectives, and research infrastructure for radio astronomy developments in South Africa and Africa, particularly through the SKA.
- Using Astronomy for Development in Africa ~~(Kevin Govender, OAD-IAU/South Africa),~~ summarises the activities, vision, and strategy behind the OAD, and suggests to ensure the growth of astronomy in Africa and to use the experience of the OAD to ensure that developmental impacts are fully realised.

These LoI received ~~LoI~~ present some of the high-priority initiatives, and provide the starting point for the development of White Papers in the future. ~~A number of~~Several additional initiatives and projects are listed in section 4.2.1, with the main priorities focusing on institutional development, human capacity building through master and PhD programs and general trainings, and infrastructure development, in particular in optical astronomy and radio astronomy.

4.4 Major challenges and needs

Despite the ~~strong~~enormous developments in astronomy in Africa, there are still many challenges and needs to be addressed. In the framework of the AfAS Scientific Committee, a survey was conducted among 60 experienced researchers from 21 countries with professional astronomy. Most of the researchers who filled ~~in~~out the survey are high-level experts who know very well the state of development of astronomy in their country. In addition, the Vision 2024[20] online document ~~has been~~was developed by the community in ~~line with the~~preparation for the 2024 IAU GA in South Africa. The following difficulties and challenges ~~have been~~ were identified (in no particular order) to be considered for future improvement and to be taken into account in the development of future policies and strategies:

- Most countries are starting from scratch in the development of astronomy, so they need considerable support in all aspects.
- There is a limited number of human resources, in addition to the limited skilled sector, to carry out all activities and satisfy all needs.
- In many countries, the lack of ~~astronomy~~ master and PhD in astronomy fellowships and job vacancies forces people to look abroad for opportunities, leading to ~~a~~ severe brain drain and ~~the~~ loss of talent and qualified people.

[20] https://astronomy2024.org/vision-2024/

- Supporting infrastructures for astronomy and scientific development, in general, are often lacking, often including access to basic tools such as adequate computers, external disks, etc.
- There is a lack of funding, especially secured long-term funding, and a lack of support from local governments. This includes a lack of funding to hire master and PhD students, or postdocs, to set up research groups and for various facilities, including computers.
- Many researchers face daily difficulties in carrying out their work due to a lack of uninterrupted power supply and poor Internet connection.
- Astronomy in Africa is still not accessible to everyone, as can be seen above ~~and in particular~~ in Figures 4-1 and 4-4.
- Work overload is common among African astronomers due to the still small number of experts in most countries compared to the needs, including teaching and lack of time for research. In addition, the administration of higher institutions has grown exponentially in many countries in the last decade, taking much time away from research and teaching.
- Attracting new students is not an easy task, particularly attracting well-prepared students.
- Many researchers face great uncertainty due to non-permanent positions.
- The telescope time available for African researchers at the larger telescopes is limited.
- Mobility of African researchers is a major problem, due to funding problems, but also visa problems, even when funding is secured.
- Many African astronomers live far from their home country (in Africa, especially in South Africa), which often puts additional stress on them, especially if funding is limited and they cannot travel home frequently.
- Low salaries have been identified as a major problem and the reason why people leave the field and/or the country.
- Publication fees for prestigious international journals are high, as are subscription fees.
- ~~There is a need for~~ More awareness is needed~~to be done~~ among the general public, policy- and decision-makers regarding the importance of astronomy and science for African growth and socio-economical and environmental development [7].
- Political instability, conflicts, and wars pose a serious problem for the development of astronomy and science and all other aspects of a society's well-being.

Considering all of the above, ASFAP is timely to address the enormous developments in astronomy in Africa, but also to highlight the current challenges and needs.

4.5 Systemic inequalities and recommendations

The main challenges listed above can be grouped into systemic inequalities that exist in current scientific practices in astronomy and cosmology in Africa and the world. This section lists some of the main systemic inequalities and recommendations to be considered in ~~the~~ future developments in astronomy and cosmology at the policy level to foster a more equitable science system.

- **Global perception of importance of astronomy for development and for achieving the UN SDGs.** There is a lack of awareness of how different science fields are perceived when we speak about development and SDGs. Astronomy and cosmology are in particular exposed to such lack of awareness, being cutting-edge sciences. This leads then to conscious and/or unconscious bias towards investment in astronomy and cosmology in Africa that leads to systemic inequalities in science development and its impact on socio-economic and environmental development in short- and long-term.
  Recommendation. Develop the methods that will efficiently bring awareness at all levels, from decision makers to general public, that investing in astronomy, cosmology, and science in general, is not a question of luxury but a fundamental need if we want to bring more equal opportunities to everyone. ~~The~~ Future science, technology, and innovation (STI) policies should raise better the impact and importance of different science fields, including astronomy/cosmology for development in short- but also long-term.

- **Systemic funding inequalities** in astronomy at all levels between Africa and other continents, and more generally between the global south and north. This includes systemic inequalities in access to national (internal) but also external funding. Moreover, if funding is not available, we cannot talk about advances in astronomy and cosmology and their use for STI and for achieving the SDGs. Furthermore, access to external funding often comes with conditions that follow the agenda of donors, and not necessarily the needs of African countries. This leads to systematic inequalities between countries in terms of progress in astronomy and STI in general.
  Recommendation. There is a need to secure increased funding at the national levels across Africa for all aspects of astronomy and cosmology development (from research, through human capacity building, institutional development, to infrastructure development and communication of astronomy and science to the public). External funding structures/modalities need to be designed at the global level to be more flexible, more inclusive (in all aspects), broad (considering all fields of science and that can be easily adapted to the needs of each country), to consider not only current challenges/needs and short-term benefits in line with rapid economic growth, but also long-term impact on society and more sustainable development.

- **Systemic inequalities in human resources and the number of qualified experts in the fields of astronomy and cosmology** between most African countries (except possibly South Africa) and countries in other continents, or between the global south and north, with significantly more limited human resources in low-income countries. This leads to a number of problems, such as the overburdening of senior researchers (between research, teaching, leadership/management activities, administration, etc.), on the cost of research, and the strong brain drain of younger researchers due to lack of opportunities.
  Recommendation. Design models to strengthen postgraduate programs and recruitment in the fields of astronomy and cosmology at master's, PhD and post-doctoral level. The generation of more permanent positions in astronomy and cosmology (in universities and research centers) and the creation of more research opportunities are required to avoid/minimize the brain drain. This should be accompanied by funding modalities for the creation of new research groups. Develop modalities to strengthen human capacity building through international collaborations (e.g., through mobility programs in astronomy research, joint supervision of students, organization of scientific meetings in Africa, etc.).

- Because of the points raised above, there are **systemic inequalities in the quality of the activities carried out** in the fields of astronomy and cosmology, and thus in their efficiency and impact on the SDGs. In addition, there are also **systemic inequalities in metrics** and in how the quality of work done in astronomy and cosmology is measured between Africa and the rest of the world and between different African countries.
  Recommendation. The last two recommendations above will have a direct impact on improving the

quality of research and other activities carried out in the fields of astronomy and cosmology. More diverse and inclusive metrics need to be developed in the near future to assess advances in astronomy and cosmology and their impact on our society across Africa.

- **Inequalities in the means of communicating astronomy** and presenting quality work to others, e.g., through publication. Publication fees in Q1 impact factor journals are high, and most African researchers cannot afford them.
  Recommendation. Implementation of open science policies are necessary for authors, not just readers in astronomy and cosmology in Africa.

- **Systemic inequalities in access to basic infrastructure**, such as electricity (power cuts are common in many African countries), internet connectivity (which remains poor in many countries, particularly in landlocked countries), computers (this remains a major challenge for many African researchers), other computing facilities (e.g. supercomputers, grids, clusters), etc.
  Recommendation. Develop strategies to ensure access to power and internet connectivity to all academic centers in the future, and improve access to personal computers and computing infrastructure. Improve access to shared computing infrastructures through national and international collaborations.

- **Systemic inequalities in access to world-class infrastructure and data in astronomy and cosmology**, including new generation telescopes and instruments. This improved with open science policies, at least in terms of access to public data, but significant inequalities remain between African countries and the rest of the world in access to high-quality data.
  Recommendation. Strengthen open access policies in astronomy and cosmology, and give more visibility to already available resources, strengthen international collaborations around infrastructure and available astronomical data. Include more African researchers in the large international collaborations developed around the latest and next generation telescopes and instruments.

- All of the above, particularly affects **under-represented groups** such as women, minorities and the astronomical community in conflict- and crisis-affected areas.
  Recommendation. Special attention ~~shall be~~shoud be given to each of the above (funding, recruitment, capacity building, leadership development, etc.) when dealing with under-represented groups and at-risk scientists to ensure equity. This should be taken into account in all astronomy-related policies and in the overall development of STI in Africa.

4.6 Conclusions

Astronomy has developed in Africa at an astonishing pace in the last 10-15 years, including research, human resources, infrastructure, etc. Africa needs to participate in international projects together with international partners, to ensure that it is not left behind. Such involvement should be in projects that include scientific discovery, technological development and innovation, as well as projects involving training, including for women and minorities. There are still important systemic inequalities when comparing the status of astronomy in Africa and in other continents. These include the perception of astronomy for African development, funding, human resources, the quality and metrics used to measure it, the means to communicate astronomical research, access to basic infrastructure, access to the latest and next-generation telescopes and instruments, and the challenges faced by under-represented groups. The STI policies will need to develop particular strategies to address all these systemic inequalities in the future for the benefit of all.

Acknowledgements

We acknowledge the hard work and efforts of all colleagues and students who in one way or another contributed to the development of education, science and technology in Africa through astronomy, and all those who will continue to do so in the future.

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5

Atomic & Molecular Physics Working Group

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5.1 Foreword

Recent advances in experimental and theoretical scanning probing methods at the atomic scale have led to tremendous applications in biology, medicine, electronics, quantum technologies, spintronics or heterogeneous catalysis. For example, insight into the structure of living cells, the single molecule transistor, the minute working of catalytic reactions allowing the rational design of catalysts and improvement of properties, just to cite a few. However, probing matter at the nanoscale on the African continent is still challenging, both theoretically and experimentally. This stems from the various limitations in research facilities.

Despite the population of about 1.3 billion, which are mainly youth, the research and development output of Africa is quite low in virtually all areas of physics. To quantitatively understand this abysmal performance, we analyse the amount of research articles published by African scientists (based in African institutions) from 2000 – 2021, see Figure 5-1. Over the last two decades, the total research output from Africa stands shy of 70,000 articles with about 6,000 per year in recent times. It will be interesting to know that these are comparable to the Brazil scientific research output over the same period. However, the dramatic rise of India over the same period clearly shows the need for understanding the problem facing African scientists. This graphical illustration could readily be linked to the poor economic performance of the Africa continent, the world's poorest inhabited continent according to the World Bank. This is basically demonstrated by the difficulty to access energy for community services (health, education and so on) as well as the lack/inadequate information and communication technologies among others [1]. Moreover, only Egypt and South Africa made it in the Top 40 of the world's research and development index in 2021 [2]. However, Africa Union Agenda 2063 has identified Physics – fundamental and applied as a key solution to address the developmental problems facing the continent [3].

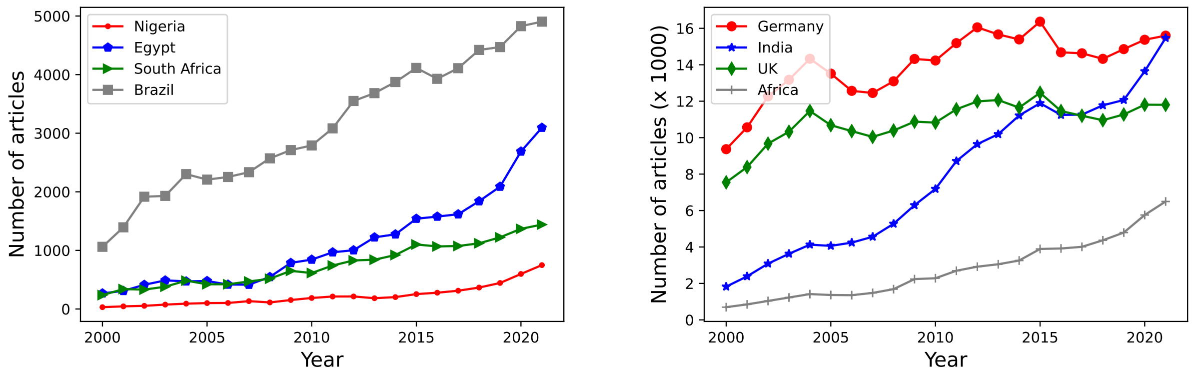

Figure 5-1: Research output per year from 2000 – 2021 for search keywords: atoms, atomic, molecular, molecules, or ions. **Left panel** – The number of articles published by some African countries (Egypt, Nigeria, South Africa) compared to the Brazil. **Right panel** – The total articles published by African scientists (Algeria, Cameroon, Congo, Egypt, Ethiopia, Ghana, Kenya, Morocco, Nigeria, South Africa, Tunisia) compared western countries (Germany and UK) and India. Source: Scopus – accessed October 8, 2022.[6]

5.2 Challenges facing African scientists/physicists

On a theoretical point of view, electrical power instability in many countries does not allow sustainable computing and computational facilities are scarce, see Ref.[4] for more discussion. Most sub-saharan countries barely have supercomputers available for research. The few available facilities on the continent are concentrated in Northern Africa and South Africa. Researchers rely on the latter and on external partners such as the Abdus Salam International Centre for Theoretical Physics, Italy. A dependence that limits the productivity but also the size of the system to study simple molecules. Experimentally, resources are also scarce. For example, it is only recently that central Africa got its first operational AFM apparatus in what is likely the first nanotechnology laboratory in the Republic of Congo. Besides, the light source community is still to build the first synchrotron on the continent and relies on external sources and networks like the Synchrotron-Light for Experimental Science and Applications in the Middle East (SESAME) and the free and open-source software such as Large-scale Atomic/Molecular Massively Parallel Simulator (LAAMPS). Unfortunately, for Africa, international organizations often support research of their interest and are compounded by the government's ill-advised policies towards education.

5.3 Current support towards enhance research output

During the last decades, various research groups and networks have been active on the continent, thanks to some foreign collaborations/donors. These include Physics Department, Marien Ngouabi University (Brazzaville, Congo), CEPAMOQ (Douala, Cameroon), Lasers Atoms Laboratory, Cheikh Anta Diop University (Dakar, Senegal), Atomic Molecular Spectroscopy and Applications Laboratory, University of Tunis El Manar (Tunisia), Medical University of Southern Africa (South Africa), African Laser Atomic Molecular and Optical Science Network. In addition, there is growth in the study of materials sciences in Africa through the African School for Electronic Structure Methods and Applications (ASESMA).

As an extension of these efforts, African physicists from a variety of specializations are developing an African strategy for basic and applied physics, see https://africanphysicsstrategy.org/ [5]. Organized into several working groups, committees, and forums, they are working to produce a report to inform the African and broader community of strategic directions that can positively impact physics education and research over the next decade [7, 8].The report is intended to help African policy makers, educators, researchers, communities, and international partners prioritize resources and activities for physics education and research at the national, regional, and pan-African levels. As part of this group of African physicists, we have the task of coordinating the activities of the Atomic and Molecular Physics working group.

5.4 Atomic and molecular physics working group – journey so far and way forward

In the spirit of the ASFAP, the Atomic and Molecular Physics (AMP) working group aims at reporting on the state of research and knowledge transfer of these groups and their derivatives on the continental level but also on the various research carried by African scientists in AMP performed all over the world and that align to sustainable development goals. From the above-mentioned research groups and networks, we have identified and have traced the various African scientists still active in the field, their research interests and compiled their various achievements.

As part of this, we have successfully organised meetings and had an online workshop on Atomic and Molecular Physics in January 2022 during which the discussion is cantered on identifying challenges facing different research groups across the continent among others. These efforts, in conjunction with other ASFAP working group, have resulted in some letter of intents (LOIs) submitted for the strategies. In addition, after deliberation with the ASFAP Steering committee members and the Photonics and Optics working group during the second African Conference of Fundamental and Applied Physics ACP2021, there is a unilateral decision to merge the two working groups – *Atomic, Molecular and Optical Physics.* We believe that this will synergise interdisciplinary activities towards industrial and technological advancements.

To conclude, we advocate for physics-based policies in the various country, region and the continent at large. These will be geared towards development of human capital as well as engaging the private sectors for support. Finally, with the support of international collaborations, qualitative increase in the research output of Atomic, Molecular and Optical Physics in Africa will become a fruition.

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6

Biophysics Working Group

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Abstract

This report is a serious call to scientists, innovators, investors, and policymakers to invest in the development of biophysics in Africa. The complex problems of our day demand multidisciplinary approaches, and biophysics offers training in much-needed multi- and cross-disciplinary thinking. Biophysics is a research field at the forefront of modern science because it provides a powerful scientific platform that addresses many of the critical challenges humanity faces today and in the future. It is a vital source of innovation for any country interested in developing a high-tech economy. However, there is woefully little biophysics educational and research activity in Africa, representing a critical gap that must be addressed with urgency. This report suggests key research areas that African biophysicists should focus on, identifies major challenges to growing biophysics in Africa, and underscores the high-priority needs that must be addressed.

6.1 Introduction and Motivation

Since the COVID-19 pandemic, many governments have expressed the need for Africa to be able to make its own therapeutics and vaccines. The first step for that to happen is investing in the basic and applied sciences and engineering research, and that especially means biophysics.

Why biophysics? This unique interdisciplinary field brings our understanding of biological processes to an unprecedently detailed level. Only when we understand nature's processes at a sufficiently deep level can we make reliable predictions and obtain sustainable technological solutions.

This is realised by numerous pharmaceutical companies, where biophysics forms an indispensable component of drug discovery [1]. Dr. Martin Friede from the World Health Organization's Initiative for Vaccine Research took it a step further by stating, "It is impossible to develop the next generation of vaccines without biophysics" [2]. Consider Structural Biology, a subdomain of biophysics that aims to resolve and study the structure and dynamics of biological macromolecules such as proteins — the molecular machines of biological cells. Knowing the protein structure at the atomic level has enormous commercial potential in areas such as industrial enzymology and drug discovery. A fully resolved protein structure enables us to engineer proteins that can make new chemicals and to design molecules that interfere with the life-giving reactions of harmful pathogens or pests (i.e., drugs and pesticides). Structural Biology is, therefore, an important step to the global economic success of a country. It is particularly telling that over 80 Nobel Prizes have thus far been awarded in the field of Structural Biology: 70 prizes for scientific discoveries and 11 prizes for experimental methods that enabled these discoveries [3].

Biophysics is not only concerned with scientific research. An integral component of scientific discovery in biophysics involves technological development. Innovative experimental and computational methods pave the way for new scientific discoveries and provide practical solutions across the broad domain of biological sciences. Therefore, biophysics is more than a basic science that feeds innovation, because innovation is an integral part of research in biophysics.

Biophysics revolutionised medical research and technology in the 20th century. It provided both the tools and the understanding for treating various diseases. These developments are accelerating in the 21st century. Biophysics addresses not only human health challenges but also plant and animal health. By understanding the minutiae of photosynthesis through decades of scientific research, rice, and soy plants were recently engineered with 20–30% enhanced crop yield [4, 5, 6].

Biophysics research features in various aspects of the global effort to combat climate change. An important area of research and technological development in this regard is biomimetics, which originates from biophysics [7]. The design of environmentally friendly materials such as biodegradable plastics is one example. Another example is how biomimetics offers a useful perspective in addressing food security and sustainable energy, two of the great challenges of our time: we can gain inspiration from the efficacy and adaptability of photosynthetic organisms to produce food or fuel from sunlight using materials that are very abundant in nature (i.e., inexpensive and scalable) [8]. In addition, meeting food, water, and energy demands is not limited to mankind, but it is a basic need of essentially every cell of every living organism. It is therefore prudent to investigate how other living organisms meet these demands at various levels.

Quantum Biology is a new, emerging research field with enormous potential for science and technology. This field of research investigates how biological organisms use the principles of quantum mechanics to gain a physiological advantage in executing their physiological functions [9, 10]. Through quantum sensing, quantum computing, and quantum-inspired algorithms, this field has the potential to revolutionise our understanding of biological processes and lead to new technological innovations. During the past few years, several research programmes focussing on Quantum Biology have been launched across the world [11]. It is important that Africa actively contributes to the development of this promising field of research. Applications of Quantum Biology could impact many technologies, such as energy, environment, health, sensing, and information technologies [9, 10, 12]. Learning from life will not only lead to new technologies but also to new fundamental insights in physics, chemistry, and biology. For example, in the medical field, it is known that light enhances wound healing and effectively treats different types of cancer, and when applied to the brain it can have a range of physiological effects such as improved attention, memory, executive function, and rule-based learning [12]. Identifying how quantum effects might play out in the brain could offer a completely new way of imagining medical intervention beyond the purely chemical.

The term "century of biology" was coined for the 21st century in the context of biotechnological development [13] to address several critical global challenges. Biophysics plays an indispensable role both in establishing the crucial scientific basis and in bridging the gap between science and technology.

A strong and diverse biophysics research and commercial sector is essential for the success of the African economy. The importance of the bioeconomy has been recognised by numerous countries. For example, the UK [14], EU [15], USA [16] as well as South Africa [17] have formulated strategies to move away from the traditional industrial base and instead develop a strong bioeconomy. Notably, biophysics is an indispensable component of these bioeconomy strategies.

6.2 Biophysics and the UN SDGs

Biophysics research and education have the potential to make significant contributions towards achieving several of the United Nations' Sustainable Development Goals (SDGs). The most direct connections are with SDG 2: Zero Hunger and SDG 3: Good Health and Wellbeing. Furthermore, biophysics also indirectly supports other SDGs, such as SDG 1: No Poverty, SDG 8: Decent Work and Economic Growth, SDG 9: Industry, Innovation and Infrastructure, SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 14: Life Below Water, and SDG 15: Life on Land. Additionally, the development of biophysics in Africa requires a strong commitment to SDG 4: Quality Education.

SDG 2: Zero Hunger

Biophysics research in agribusiness and food security plays a crucial role in addressing SDG 2: Zero Hunger. Key areas of biophysics research that contribute to this goal include:

- Understanding the complex process of photosynthesis to engineer crops with enhanced yield [4, 5, 6];
- Developing innovative biosensing technologies to detect and prevent plant diseases;
- Exploring alternative, less toxic treatments for plant pests and diseases to ensure sustainable agriculture.

By advancing our scientific understanding of plant biology and developing practical technological solutions, biophysics can help improve food production, nutrition, and security across the African continent.

SDG 3: Good Health and Wellbeing

Biophysics research in the medical field is essential for achieving SDG 3: Good Health and Wellbeing. Relevant areas of biophysics research include:

- Structural biology to understand disease mechanisms and guide the rational design of new drugs and vaccines [1, 2, 3];
- Biosensing and quantum biology for sensitive disease diagnostics [9, 10, 11, 12];
- Biophotonics for light-based therapies and diagnostics;
- Computational approaches to complement experimental work and deepen our understanding of diseases.

Addressing the significant health challenges faced by Africa, such as poverty-related diseases, neglected tropical diseases, malaria, and cancer, requires innovative biophysics-driven solutions.

SDG 4: Quality Education

Underpinning the development of biophysics in Africa is the need for a strong commitment to SDG 4: Quality Education. Investing in biophysics education, training, and research opportunities is crucial to build the necessary human capacity and expertise to drive innovation in this field. By aligning biophysics research priorities with the UN SDGs, Africa can leverage this powerful scientific discipline to address some of the continent's most pressing challenges and contribute to a more sustainable and prosperous future.

Indirect Contributions to Other SDGs

In addition to the direct links to SDG 2, SDG3, and SDG 4, biophysics research also indirectly supports several other SDGs:

- SDG 1 (No Poverty): Improved food security and access to affordable healthcare can help alleviate poverty.
- SDG 8 (Decent Work and Economic Growth): Biophysics-driven innovations can foster economic development and create new job opportunities.
- SDG 9 (Industry, Innovation and Infrastructure): Biophysics research is essential for building a strong bioeconomy and developing new technologies.
- SDG 12 (Responsible Consumption and Production): Biophysics-inspired solutions, such as biomimetic materials, can promote sustainable production.
- SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land): Biophysics research can contribute to understanding and addressing environmental challenges.

6.3 Key Research Areas Requiring Biophysicists

Biophysics research in Africa should focus on several key areas that address the continent's most pressing challenges. These areas are crucial for advancing the field and ensuring that biophysics contributes meaningfully to the development of Africa.

6.3.1 Medicine

We wish to focus specifically on diseases that constitute the most significant health, social, and economic burden to the African continent. These include (i) poverty-related diseases such as HIV/AIDS and tuberculosis, which kill millions of people annually, (ii) neglected tropical diseases that affect in the order of 400 million people on the continent according to the World Health Organization, (iii) malaria with an annual mortality rate of about half a million African people, and (iv) cancer, for which the mortality rate increases every year and is predicted to reach ca. 1.4 million annual deaths in Africa by 2040 [18].

Most of these mortality cases can be linked to the patient having limited access to treatment or the inability to afford the treatment. African countries, therefore, have a desperate need for robust, cost-effective diagnostics and low-cost innovations to address local needs — and biophysics plays a crucial role in the development of these technologies.

Another key area of research is the development of drugs and vaccines for which research in Structural Biology is indispensable. By resolving molecular structures of macromolecules, Structural Biology provides the tools to understand the molecular basis of diseases, which guides the rational design of new drugs and the optimisation of existing medicines. Tangible areas in which biophysicists can contribute include the following:

Disease Diagnosis and Treatment

- Biosensing: Developing sensitive diagnostic tools for diseases prevalent in Africa, such as malaria, tuberculosis, and HIV/AIDS.
- Biophotonics: Applying biophotonics to enhance light-based therapies and diagnostics for various diseases, including cancer and neurological disorders.
- Quantum Biology of Disease Mechanisms: Investigating how quantum effects contribute to disease mechanisms and developing new therapeutic approaches.
- Computational Approaches: Using computational methods to complement experimental work and deepen our understanding of diseases, enabling more effective treatments.

Drug Discovery and Development

- Structural Biology: Understanding the molecular mechanisms of diseases through structural biology to guide the rational design of new drugs and vaccines.
- Microfluidics: The capability to miniaturise and automate biophysical experiments enables high throughput screening, which can be further enhanced using artificial intelligence.

6.3.2 Agribusiness and Food Security

Biophysics can also contribute significantly to agribusiness in several ways, in particular by scientific and technological solutions to improve plant health. Growing food insecurity and sustained malnutrition are a major concern in the developing world. The rapidly growing food demand is due to the combination of a growing African population and a reduction in fertile farmland. This requires drastic agricultural intensification, which means that plant health becomes an increasingly important demand every year.

Currently, at least half of agricultural loss occurs due to biotic or abiotic stressors. Biotic stressors are stress factors of a biological origin, for example, pathogens, insects, fungi, parasites, worms, and weeds. Abiotic stressors are non-biological factors such as non-optimal soil salinity, nutrient deficiency, drought, extreme temperature, and excess light.

Early Disease Detection

Early plant disease detection is an emerging area of research, constituting non-invasive methods — typically remote sensing technologies — that enable early, pre-symptomatic diagnosis of plant stress [7, 20]. These methods enable the farmer to treat diseases or optimise abiotic factors at the earliest stages, which can be several days before the plants would show symptoms that are observable by the eye. Early treatment curbs the spread of diseases, increases the chances of successful treatment, and reduces the resources required for treatment. The non-invasiveness of these methods also enables precision agriculture and plant phenotyping for resistance breeding [21, 22]. Remote sensing includes numerous promising spectroscopy-based methods, such as hyper- and multispectral imaging and pulse-amplitude-modulation fluorometry. Owing to their deep understanding of spectroscopy, modelling, and device development, biophysicists are apt to enhance the sensitivity of these technologies, devise ways to relate spectroscopic changes to particular stress factors, and translate the detected signals between different environments (e.g., from indoor to outdoor) and across different scales (e.g., from the leaf to the canopy level). This is a largely unexplored area of research, but crucial for maintaining crop productivity and food security.

In summary, biophysicists can contribute specifically to the following research area:

- Biosensing: Developing innovative and inexpensive biosensing technologies to detect and prevent plant diseases, ensuring sustainable agricultural practices.

Sustainable Agriculture and Pest Management

Another promising area of biophysics research is to provide a basis for finding alternative treatments for plant diseases. Reducing chemical use for pest management is an urgent need in Africa for cost, food safety, and environmental sustainability. Key problems of using pesticides and fungicides are the growing resistance of pests and fungi, and their toxicity to humans, animals, and the environment. We therefore urgently need to develop alternative ways to enable more accurate use of fungicides in the short term and explore less toxic alternatives in the long term. An example is to control spore dispersal from fungi, which can only be done when understanding the mechanics of fungal dispersal [23]. Again, biophysicists are needed to provide such a mechanistic understanding. This is one of numerous underexplored areas of research.

Biophysics is also paramount to obtaining a deep understanding of the complex photosynthetic process. The onset of biotic and abiotic stressors triggers a series of photoprotective mechanisms. It has been demonstrated that the genetic modification of some of these mechanisms can significantly improve crop yields [4, 5, 6]. Biophysics contributes to sustainable agriculture and pest management in various ways, including the following:

- Photosynthesis and Plant Biology: Understanding the complex process of photosynthesis to engineer crops with enhanced yields and improved nutritional content.
- Biomimetics: Designing environmentally friendly materials and technologies inspired by nature to reduce chemical use and promote sustainable agriculture practices.
- Biophysics of Plant-Microbe Interactions: Understanding the interactions between plants and microorganisms to develop more effective and sustainable pest-management strategies.
- Quantum Biology of Plant Processes: Investigating how quantum effects influence plant processes and developing more efficient agricultural practices.

Climate Change and Sustainability

Climate change is one of the most pressing global challenges of our time. Rising temperatures, melting ice caps, and extreme weather events are all symptoms of a planet in distress. Biophysics plays a crucial role in addressing this crisis by providing innovative solutions that can mitigate the effects of climate change and promote sustainability.

Biophysicists can contribute to the following specific areas:

- Biodegradable Materials: Developing biodegradable plastics and other materials inspired by nature to reduce waste and promote sustainable practices.
- Quantum Biology and Energy: Investigating how biological organisms use quantum physics to gain physiological advantages in energy production and storage.
- Biophysics of Environmental Processes: Understanding the biophysical processes that govern environmental systems to develop more effective strategies for sustainability.

6.4 Major Challenges to Growing Biophysics in Africa

The best way to grow and establish biophysics on the continent is to create adequate opportunities for state-of-the-art research on home soil. The major challenges to this goal are discussed here. It is important to note that these challenges feed one another. In other words, addressing one requires addressing them all.

6.4.1 Vastly Inadequate Infrastructure and Resources

All research and development require appropriate infrastructure and resources. This is even more so for biophysics research operating at the forefront of science and technology. There are a handful of research centres scattered across Africa that house relevant infrastructure [24]. This is a good start but undoubtedly markedly insufficient. Most African countries do not have even basic equipment for biophysics research, while the equipment hosted by the rest of the countries is vastly inadequate [24]. The severe lack of equipment is a very demotivating factor for aspiring biophysicists on the continent.

Acquisition of equipment is only one side of the coin. Equally important is the need to maintain technical infrastructure by equipping our own people and providing sufficient funds. It has happened too often that state-of-the-art specialised equipment gets wasted because of inadequate resources to sustain it — due to a lack of expertise or funds for maintenance or both.

Consider as an example the infrastructure required for Structural Biology. Determining the structure of biological macromolecules requires the establishment of a workflow that includes the ability to prepare the material, test its functionality, obtain the data necessary for structure determination, process this data, and interpret the outcome. Both X-ray crystallography and cryo-electron microscopy lead to directly interpretable, near-atomic-resolution visualisations of biomolecular structures and are currently the most widely used structure determination techniques. The value of structural insights is recognised internationally to the extent that industries as well as governments abroad have invested billions in building and staffing shared, large-scale, centralised infrastructure for Structural Biology. In comparison, due to the high cost of the technology and the critically scarce skills required to operate such equipment, only limited structural investigations are possible at select sites in Africa, all of which are currently in South Africa. The technology and thus critical insights remain elusive to both local industry and academic researchers. Where resources have been committed, appropriate equipment and skills have been spread over many sites, and this has meant that a productive critical mass that could lead to development and innovation has never been established. Trained students have in general not been retained, and many have found employment in the field abroad, where they have been highly successful.

It is also important that one or more of the societal activities in which structural biology is needed must exist in a country interested in developing this field of research. For example, there should be companies researching novel agrochemicals, medicines, or industrial enzymes for which protein structural information is a sine qua non. Given the poor state of development of the discipline in Africa, it is unlikely that entrepreneurs will invest without substantial government intervention.

From the above, the two main keys points are:

- Equipment and Facilities: Biophysics research requires state-of-the-art equipment and facilities. However, most African countries lack the necessary infrastructure and resources to support biophysics research. This includes basic and advanced experimental equipment, as well as high-performance computers for theoretical investigations.

- Maintenance and Sustainability: Even if equipment is acquired, it is crucial to ensure that it is properly maintained and sustained. This requires a steady supply of funds and technical expertise, which is often lacking in Africa.

6.4.2 Very Low Critical Mass

Awareness and Funding

The present state of affairs is that very few students and research scientists in Africa venture into biophysics. One major reason is a lack of awareness of the importance of this field of research. This leads to limited funding opportunities supporting biophysics research and development, which, in turn, discourages scientific work in this area.

Exodus of Skilled Scientists

Another major reason for Africa's low critical mass in biophysics is the exodus of skilled scientists. Most Africans interested in biophysics study abroad and do not return to Africa, while most of those who returned to their home countries have remained in biophysics for short periods. The primary reason for this is the severe shortage of infrastructure and resources for biophysics research. These scientists have the necessary knowledge and skills, but they lack the capacity to execute the research. Opportunities are urgently needed to support and help these scientists to excel in their research.

Limited Educational, Training, and Mentorship Opportunities in Africa

Going hand-in-hand with the previous two challenges is the need to educate, train, and mentor our current and aspiring biophysicists in Africa. Only a few African universities offer biophysics courses, and even fewer offer biophysics degrees. In addition, general and specialised biophysics schools and workshops in Africa are organised too infrequently.

Mentorship is crucial for encouraging and nurturing aspiring and established biophysicists on the continent. However, this is often lacking due to the limited number of experienced biophysicists in Africa.

6.5 High-Priority Future Needs

6.5.1 Capacity Building

An earnest investment in educational opportunities is a low-hanging fruit for the growth of critical mass and knowledge in biophysics. This must be done through the development of biophysics curricula and the hosting of general and specialised biophysics schools, workshops, seminars, and expert lectures. Biophysics programmes and degrees would need to be established as a pipeline in developing curricula along both academic and vocational lines. Both Africans and non-Africans can help significantly to address these needs. In this regard, the International Union for Pure and Applied Biophysics (IUPAB) and the Biophysical Society (BPS) have ample resources that can be tapped into.

The development of biophysics research should be a natural outflow of biophysics education and training. Again, support from IUPAB and BPS as well as numerous other international societies would be of immense help, for example, to bring international experts to Africa through the organisation of workshops and conferences. Collaboration with well-established biophysicists in other continents through multinational research programmes and consortia is an excellent way to boost research quality and opportunities. This becomes a realistic opportunity when African researchers strive for excellence.

Lastly, the severe lack of awareness of biophysics on the continent must additionally be addressed through public awareness activities such as popular science literature, news reports, science festivals, roadshows, and school visits and demonstrations. In general, the profile of scientists must be raised in the public eye. They are the people expending great effort in training the next generation of leaders and developing innovative technological solutions. If scientists — and biophysicists in particular — could be elevated to the same level as sports stars, this would immediately attract significant attention from the public and governments. In addition, if scientists do not actively define their role in society, their relevance will be determined by society — and this will be a vastly underappreciated role.

From the above, the key points are:

- Education and Training: Establish biophysics curricula and degrees at African universities. Host general and specialised biophysics schools, workshops, seminars, and expert lectures to educate and train aspiring biophysicists.

- Mentorship: Provide mentorship opportunities for aspiring and established biophysicists. This includes pairing experienced biophysicists with younger researchers and encouraging collaboration between African and international biophysicists.

- Public Awareness: Organise public awareness activities such as popular-science literature, news reports, science festivals, roadshows, and school visits and demonstrations to elevate the profile of biophysicists and the importance of biophysics research.

6.5.2 Investment in Infrastructure and Equipment

As motivated above, the acquisition and maintenance of modern infrastructure and equipment is key to the development of biophysics research and innovation. Funding for this requires governmental support, which should grow through policy development and high-level discussions with governments convincing them of the need to support the work of African biophysicists, build the necessary infrastructure, and encourage African industries to invest in the bioeconomy strategy.

Governing bodies and investors must make adequate funding available for the procurement of necessary facilities for biophysics research. Funding incentives should also be provided to researchers to establish and develop biophysics research in important areas. To this end, governments may develop multiple-department initiatives to support the work of biophysicists. They should incentivise our universities to build infrastructure in all the fields that support biophysics and make funding available for basic and advanced equipment.

African home countries need to invest in their own research. Currently, the weakest link is the fact that we get most funding from outside Africa and no or very limited buy-in from our own continent. Africans must be convinced that their support is indispensable.

Investment in infrastructure and human capacity development must be seen for what it is: an investment — not for a limited number of elite persons but for the country and ultimately for the whole continent! A growing body of expertise will attract industrial development, which, in time, will inevitably lead to direct foreign investment and the development of intellectual property and products. Consider as an example the study of protein structure. Proper investment in the development of infrastructure and scientists to do cutting-edge Structural Biology research will enable the development of local industries concerned with drug discovery and development, advanced agrochemicals, and fourth-generation industrial biotechnology.

Biophysics research depends on a very broad spectrum of experimental techniques, and it is therefore impossible to house all the necessary equipment on the African continent. But it is also unnecessary to try and collect all types of equipment. Firstly, we must be selective in our focus, specifically addressing the key research areas stated above. Secondly, we must follow the example of European countries that similarly do not house all the necessary equipment but, instead, form consortia to share expensive equipment, which can also be accessed by scientists from non-member countries.

In summary, we recommend:

- Acquisition and Maintenance: Acquire and maintain modern infrastructure and equipment for biophysics research.
- Funding: Secure funding for the procurement and maintenance of necessary facilities for biophysics research. This includes government support and incentives for researchers to establish and develop biophysics research in important areas.
- Collaboration: Collaborate with international organisations and experts to access shared, large-scale, centralised infrastructure for biophysics research.

6.5.3 Low-Cost Innovations to Address Local Needs

Although the importance of acquiring and maintaining expensive equipment for state-of-the-art biophysics research and development cannot be understated, a particularly pressing need for Africa is to find inexpensive technologies for the vast majority of its people who cannot afford expensive solutions. In this regard, it is important to note that for most applications, only a dedicated technology is needed, not a versatile one. This requirement may significantly decrease the price of the technology. Connected with this is the need to develop methods that are specific to particular contexts. Such affordable solutions require innovative thinking.

Consider as an example a quantum light imaging device to improve the resolution of medical images for people living in remote areas. This technology is out of place for its target group because, firstly, such equipment is very expensive; secondly, it requires a well-isolated (vibration-free) environment and reliable electricity supply; and, thirdly, it requires highly skilled staff to operate and maintain. Instead, a significantly cheaper instrument can be used to acquire an image at a lower resolution, after which machine-learning techniques can be employed to optimise the image resolution.

Another example of an inexpensive innovative instrument is a homebuilt multispectral camera, which can be a few orders of magnitude cheaper than state-of-the-art commercial ones. Such a camera can be built using a 3D printer and Raspberry Pi kit, the latter of which is then used to control inexpensive camera sensors and filters. Running the output through a machine-learning algorithm can again improve the image and spectral resolution. The cost of this instrument can be cut further when dedicated to a specific application. Possible applications are diverse and may include the sensing of particular stressors in plants, drug sorting, detection of tainted drugs, diagnosis of traditional medicines, food diagnosis to determine its safety for consumption (e.g., detection of pesticides, rot, or diseases), or investigation or detection of plastics.

These examples highlight the importance of translating scientific work from the laboratory to society by finding inexpensive, dedicated solutions. This is in line with the World Health Organization's set of criteria for ideal diagnostic test development based on the acronym REASSURED, which refers to **R**eal-time connectivity, **E**ase of specimen collection, **A**ffordable, **S**ensitive, **S**pecific, **U**ser-friendly, **R**apid and robust, **E**quipment-free or simple, and **D**eliverable to end-users.

In summary, we recommend:

- Affordable Solutions: Develop inexpensive technologies for the vast majority of Africans who cannot afford expensive solutions. This includes dedicated technologies for specific applications and innovative thinking to find affordable solutions.
- Artificial Intelligence: Utilise artificial intelligence such as machine learning and techniques to optimise and enhance biophysics research and applications.

6.6 Synergies With Neighbouring Fields and Multinational Research Programmes

The broad scope of biophysics demands a broad range of experimental and modelling approaches. Even within a focused area of biophysics, numerous experimental and modelling approaches are often used to obtain a holistic picture and a deep understanding of the complex system at hand. Therefore, biophysics has synergy with many other fields of physics. ASFAP subgroups with which there is significant overlap include Accelerators, Atomic & Molecular Physics, Computing & 4IR, Instrumentation & Detectors, Light Sources, Condensed Matter & Materials Physics, Medical Physics, Optics and Photonics, and Complex Systems. In addition, some research areas within biophysics have synergy with the ASFAP subgroups Earth Science, Energy, and Fluid and Plasma.

Adopting a broad definition of biophysics here, biophysics has a strong overlap with many other disciplines such as biochemistry, bio-computing, bio-mathematics, biomedical engineering, biotechnology, botany, chemistry, crystallography, genetics, genomics, molecular biology, neuroscience, oceanography, pharmacology, physiology, structural biology, synthetic biology, systems biology. Professional African Societies for many of these disciplines already exist, and biophysics initiatives must cooperate with these societies [24].

Cross-pollination of biophysics with the various sub-disciplines of physics and the other related scientific disciplines is strongly recommended because this encourages lateral, cross-disciplinary thinking.

In summary, we recommend:

- Interdisciplinary Approaches: Encourage interdisciplinary approaches by collaborating with other fields of physics and related scientific disciplines.
- Professional Societies: Cooperate with professional societies for various disciplines to leverage synergies and cross-pollination of ideas.
- Establish Initiatives: Establish multinational research programmes and consortia to share expensive equipment and expertise.
- Training Events: Organise training events and workshops to enhance research quality and opportunities.

6.7 Conclusion and Perspectives

Biophysics offers a powerful scientific platform that addresses many of the critical challenges humanity faces today and in the future. It is a vital source of innovation for any country interested in developing a high-tech economy. However, there is woefully little biophysics educational and research activity in Africa, representing a critical gap that must be addressed with urgency.

This report identifies key research areas that African biophysicists should focus on, including medicine, agribusiness, and climate change. It also discusses major challenges to growing biophysics in Africa, including inadequate infrastructure and resources, low critical mass, and limited educational, training, and mentorship opportunities.

To address these challenges, the report recommends capacity building through education and training programs, investment in infrastructure and equipment, and public awareness activities. It also emphasizes the need for multinational research programs and consortia to leverage synergies and cross-pollination of ideas.

By addressing the challenges and leveraging the opportunities for biophysics research and development in Africa, the continent can build a strong foundation for biophysics research and innovation, ultimately contributing to the continent's economic and social development.

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7

Computing Working Group

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7.1 Introduction and Motivation

Research nowadays needs strong computing services to analyze big data, extract results, make discoveries, and improve the lives of citizens.

What we define as a computing service is comprised of many layers, ranging from the underlying hardware including network resources, computer systems, and storage, to the applications and software implemented on the hardware. For decades, we have observed the advent of new computing fields such as Artificial Intelligence and Deep Learning that have revolutionized data processing.

Even though computing is itself a science and a field of research and technology, we consider here the application of informatics to other science research fields. We should also not forget Quantum Computing, which will give a major advantage to countries and organizations that master this field.

A large fraction of the information collected in this report is based on a survey launched in March 2022, including ASFAP participants and attendees of the 2nd African Conference of Fundamental and Applied Physics ACP2021 [1] held in March 2022 in Casablanca, Morocco. More details can be found in ref. [19]. This survey was launched to evaluate the status of computing resources in the field of African Physics Research. The panel was mainly made up of participants who worked and lived in Africa (more than 82%); the rest being largely what we call Africans from the diaspora. 26 countries were represented in the panel.

7.2 Computing capacity in Africa

Africa has made significant strides in developing high-performance computing (HPC) infrastructure, with some systems earning recognition in the TOP500 rankings—a biannual list evaluating the world's most powerful supercomputers based on their Rmax performance (measured in petaflops) [3]. Countries such as South Africa, Morocco, Egypt, Algeria, Rwanda and Nigeria host some of these HPC systems, which are used to handle complex simulations and data-intensive tasks. However, Africa's presence in the global rankings remains limited, with only a few HPC systems making notable appearances. While many data center facilities operated by private companies, telecom operators, or governments exist in the region, this section discusses the leading centers providing research support through high-performance computing, focusing on both scientific and academic needs.

7.2.1 Centre for High Performance Computing (CHPC) – South Africa

The Centre for High Performance Computing (CHPC) in Cape Town, South Africa, operates the Lengau Cluster, which achieved a peak performance of 1.029 petaflops. Lengau made its debut on the TOP500 list in June 2016, ranked 121st, but it last appeared in the rankings in 2019. The system has supported various scientific and engineering applications, including climate modeling, material science, bioinformatics, and engineering simulations [4]. CHPC has also extended its resources to commercial projects, supporting initiatives across the Southern African Development Community (SADC) region and other African countries, including Ghana and Kenya [5].

7.2.2 Africa Supercomputing Center (ASCC) – Morocco

The fastest supercomputer in Africa is the Toubkal Supercomputer, hosted by the University Mohammed VI Polytechnic (UM6P) in Morocco within the Africa Supercomputing Centre [6]. Launched in February 2021, Toubkal was ranked 246th, 277th, and 316th in the Top500 list for November 2023, June 2024, and November 2024, respectively, making it the highest-ranked supercomputer in Africa currently. Toubkal plays a critical role in handling complex simulations and data-intensive research tasks such as climate modeling, physics simulations, material science studies, and drug discovery.

7.2.3 Bibliotheca Alexandrina High-Performance Computing Center – Egypt

BA-HPC C1 - was installed in 2009 and continued to serve researchers in Egypt for years and well into 2016. In August 2016, BA-HPC C2 was commissioned to continue the mission of the BA Supercomputing Facility to serve as High-Performance Computing platform for research projects at Egypt's universities and research institutes [7]. The Bibliotheca Alexandrina HPC Center offers HPC services to researchers, with a peak performance of over 100 teraflops.

Other notable centers include, but are not limited to, the Rwanda High Performance Computing Centre in Rwanda, the HPC Centre at the University of Cape Town in South Africa, and the National Institute for Theoretical and Computational Sciences (NITheCS) in South Africa. These centers offer extensive research support through high-performance computing, addressing both scientific and academic needs. They play a crucial role in advancing computational science across the continent and empowering African researchers to contribute to global scientific initiatives.

HPC System	Location	Peak Performance (Rmax)	Latest TOP500 Ranking
Toubkal (UM6P - ASCC)	Morocco	3.16 petaflops	316th (Nov 2024)
Lengau Cluster (CHPC)	South Africa	1.029 petaflops	Not listed
BA-HPC-C2	Egypt	0.118 petaflops	Not listed

Table 7-1: Leading HPC Systems in Africa

Tab. 7-1 shows the top HPC facilities for research purposes in the region. Beyond the mentioned centres, other countries may also host HPC facilities dedicated to research purposes. However, these often remain under-publicized due to lower performance capabilities, operational challenges, or limitations to local or domestic applications without global benchmarking. In addition, some facilities are underutilized due to a lack of collaborative research initiatives and funding constraints.

7.3 Computing Challenges for Scientific Activities in Africa

The scientific fields that rely on data processing to extract knowledge are numerous. They span various fields including physics, astronomy, biomedical and environmental research, etc. The survey cited above has gathered participants belonging to more than 30 different fields. Most of them highlighted the scarcity of computing infrastructure and often the lack of stakeholder understanding about the extent of the need for computing in their field.

In recent decades, the importance of providing robust computing resources and services has become increasingly evident. For instance, the discovery of the Higgs Boson at the Large Hadron Collider (LHC) at CERN [9, 10] would not have been possible without such resources. To put this in perspective, the CRAY X-MP/48 computer, used at CERN around 1985, would take approximately 3.5 million years to process just one year's worth of data from the LHC today. Even the high-performance computing infrastructure from around 1995 would still require 11,000 years to achieve the same task [11].

The sheer size and complexity of the LHC's data, the stringent selection process required to find the "needle in a haystack," and the necessity of generating billions of simulated events to compare against theoretical models required an unprecedented level of computing power. This example underscores the need for computing resources that are not only vast, but also shared, distributed, and interoperable across a global community of scientists.

Another computational challenge is the need to simulate increasingly more complex physical phenomena that require different heterogeneous architectures and a level of coding that allows better exploitation of new architectures such as GPUs (Graphical Processing Units). Active research, in particular using Deep Learning, Natural Language Processing, Graphical Networks and other AI-related techniques is ongoing to produce code that would be optimized for specific infrastructures. Simulations require substantial processing performance for computational physics, and other research applications in Physics involving large datasets require high computational power to produce precise and timely results (Navaux, et al.,2023 [13]). To process large datasets and perform complex calculations, researchers can use High Performance Computing (HPC) resources. The main challenge in Africa is the limited availability of HPC facilities for researchers, hindering research in the African region.

Not all fields demand such a large amount of computing resources; but as modest as the data sample may be, it may need complex processing that cannot anymore be done by hand.

If we focus on the Africa region, lack of commitment from African governments toward advancing scientific and technological innovation is also a key challenge to the scientific research in the region. The ASFAP community report (2020-2024) reveals that African countries have been spending less than 1% of their gross domestic product (GDP) on research despite the increase in the number of scientists in the past five years. South Africa and Egypt allocate the highest budgets for scientific research which are respectively 0.83% and 0.72% of their GDP [12].

More so, the significant costs associated with acquiring, operating, and maintaining higher-performance computing systems could be overwhelming and challenging in the regions with the poorest economy.

Another challenge would be the insufficient number of skilled computational scientists and engineers to support and operate the computing resources. This may hamper the effective and efficient use of computing resources in the region.

7.4 Synergies with neighboring fields

The need for more computational performance in many fields of science is driving the search for more powerful architectures and applications. We have seen above that very close neighboring fields can and will develop with the need for powerful computing for Physics. The most obvious ones are the fields related to Artificial Intelligence and Quantum Computing. These two fields are providing and will provide an unprecedented boost in the power of computing for any research thematic.

7.4.1 Artificial Intelligence

Artificial Intelligence (AI) is already widely used in many domains in industry, research, communications, etc., and it is difficult to fully capture and describe the role it has taken on in our every day life.

Particle physics was one of the first fields of science in the late 1960s to study and use AI, in particular Neural Networks, to discriminate more accurately between signal and background, and also Deep Learning to increase analysis performance of the immense amount of data delivered by powerful colliders.

It is used in many other fields, some of them being security, machine control, work in extreme environments, and in particular in medical sciences: early diagnostics of pathology, second opinion for doctors, drug discovery and personalized treatment. Accordingly, the broader adoption of AI in healthcare systems in Africa would be of significant benefit for the continent.

Although AI techniques are still in their early stages, they have accelerated the progress in research, penetrated all facets of our life, and they contribute to considerable resource savings.

The 2024 Nobel Prize in Physics Went to AI Research and recognized John Hopfield and Geoffrey Hinton for foundation research in neural networks. The Nobel Prize Committee has awarded the 2024 Nobel Prize in physics for their fundamental discoveries in machine learning, which is key to artificial intelligence as it develops how a computer can train itself to generate information (Matthew S. Smith, 2024. IEEE Spectrum [14]).

7.4.2 Quantum Computing

Quantum computing is one of the most trending and promising chapters of all quantum technologies. The basic idea behind its development is the possibility to rely on the quantum properties of matter at the microscopic scale, mainly quantum superposition and quantum entanglement, in order to build up computing hardware (quantum circuits) and software (quantum algorithms), that can handle complex problems which are out of reach of conventional computing resources, in a reasonable amount of time.

Quantum superposition has been demonstrated a long time ago and routinely used in several applications such as atomic clocks and interferometry, using inter alia the basic Rabi oscillations phenomenon. However, quantum entanglement was by far a more elusive phenomenon that has required significantly more effort from the physics community to provide fully accepted evidence of it. This field was triggered by the groundbreaking experimental work of A. Aspect in the 1980's, which demonstrated the violation of Bell's inequalities and proved the existence of quantum entanglement. Further research conducted by A. Zeilinger and others was able to implement quantum teleportation, based on quantum entanglement, opening up the possibility to effectively consider technological applications of these quantum properties.

Quantum Computing uses qubits, similar to the bits in classical computing, but offering the advantage of multiple outputs, as opposed to just 2 outputs, 0 and 1, for the standard electronic bit. This quantic quantum property, if embedded in a quantum computer, would enable the resolution of complex problems in an exponentially faster time than with a classical computer. In 2019, Google claimed that it solved a sampling problem in 200 seconds which would have taken 10,000 years on a classical computer. Notably, the engineering of qubits has proven to be very challenging, and many governments and private corporatations worldwide are heavily investing in this research. Not only is it very difficult to build a processor based on qubits, but another related challenge is to build software and algorithms to exploit its capabilities. Progress in AI, Quantum Computing, and in general in Computing Sciences is one of the most important approaches to deal with the avalanche of data in all fields of science, and to speed up the process of discoveries that impact our everyday lives. Synergy between the work of research scientists and computing experts is essential to explore the quantum world. The rapidly growing field of quantum information and quantum engineering will require quantum-aware engineers [8].

In Africa, Quantum technologies, and especially quantum computing, have been recognized by the physics community as important fields, and several teams across the continent engaged significant efforts and means for research and capacity building accordingly. It is important to mention the pioneering role of South Africa in this field. The country has several universities working on quantum computing and related topics, and has already endorsed a national quantum road map, on the same footing as most of the developed countries in the world. Several other countries are following this path, including Morocco, Egypt and Tunisia.

Numerous initiatives have been implemented to foster collaborations across Africa. It is worth citing the series of Quantum Africa Conferences, initiated in 2010 in South Africa and held every two years. A number of other informal networks, either national, regional or continental, are actively organizing on-line events in the field of quantum computing, in addition to training schools and workshops.

The African School of Physics (ASP) has included Quantum computing as part of its training program regularly and the lectures are appreciated by the young attendees, showing their interest in this field. It is highly recommended to keep the momentum on this topic and to continue the efforts for capacity building and stronger involvement of African physicists in this emerging and trending discipline.

7.5 High priority Future Needs from Scientific Community Consultations

We have consulted a scientific community belonging to more than 15 research fields about their experience accessing computing facilities and their training and education in computing sciences. Parts of the answers are summarized in figure 7-1: the largest number of responses stress the lack of budget for computing, the lack of technical support, and the fact that the management does not understand the need of computing for research.

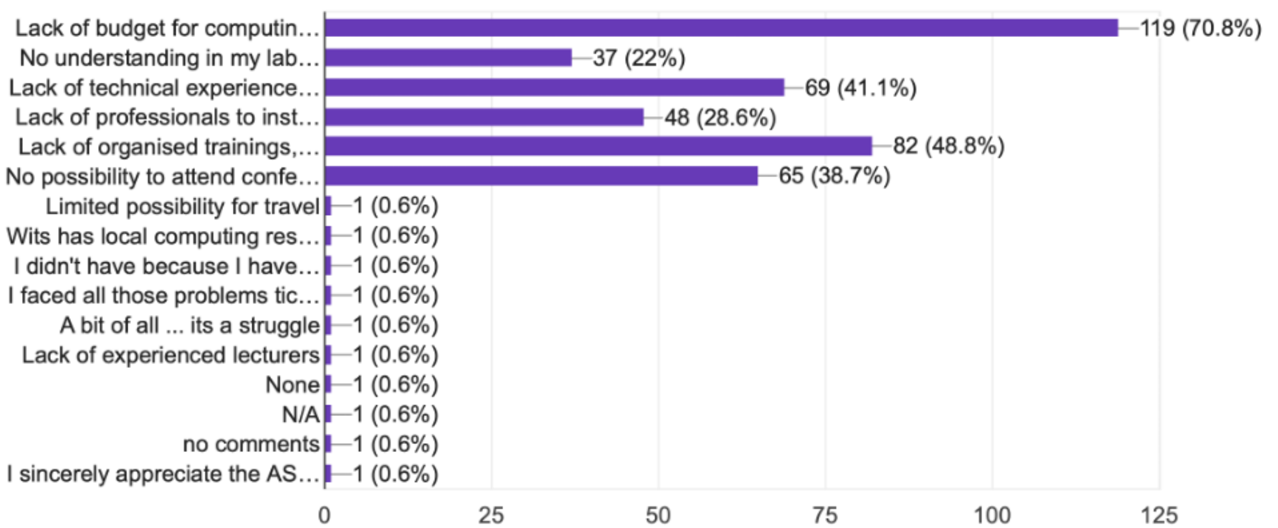

Figure 7-1: Main obstacles to the use of computing by scientists: the largest bottleneck is the lack of budget for computing in physical sciences. The problem might arise from the lack of funding as well as from the wide spread opinion that scientists do not need computers and computing infrastructures to perform their research. This last point is also raised as we see in the graph that 22% of the answers highlight a "No understanding in their lab" of the necessity of computing.

On computing resources available to achieve their work, the largest number of responses – more than 50% – find the computing resources to be highly insufficient and the percentage goes up to 66% when counting only scientists using their local resources. They point at the lack of budget for computing, the lack of technical support and the fact that the management does not understand the need of computing for research.

On Education and Training, the participants stress the lack of organized training and workshops and the difficulty to attend those meetings organized abroad. Concerning this specific point, more detailed information is found in figure 7-2: 74.4% of the scientists are not provided with courses and lectures, or an insufficient level thereof. Comprehensive analysis of the survey from which the statistics are extracted can be found in [19].

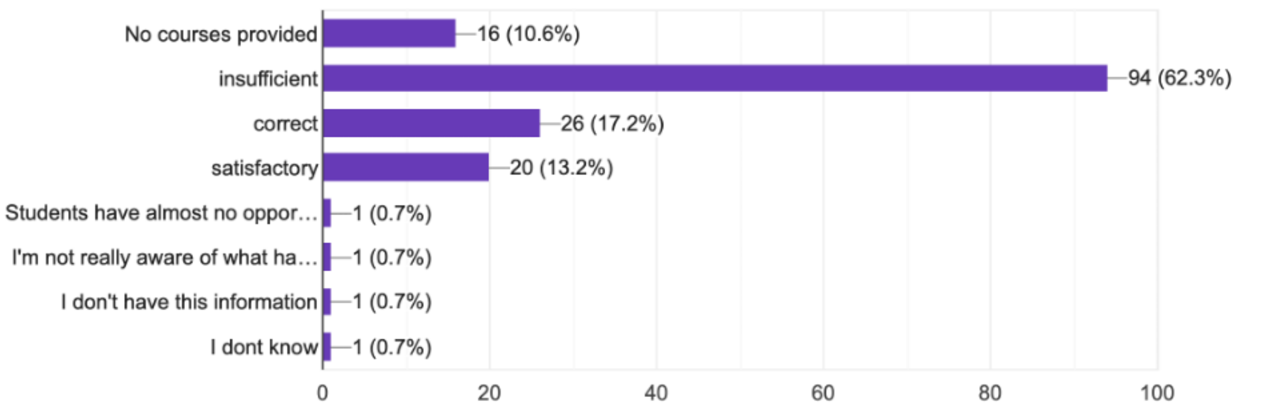

Figure 7-2: Teaching and Training: details are provided about the status of the computing know-how: more than 70% of the answers point to a nonexistent or insufficient level of courses and training.

7.6 Recommendations and perspectives

Considering the answers provided by the survey cited above and to improve the situation and boost the scientific research in Africa, we draw the following guidelines:

- **Develop computing infrastructure and build a knowledgebase**: Infrastructure should be made available and, if already existing, improved by a significant level in order to provide easy access to data and enough computing performance to process the massive and/or complex data samples. Major components of the underlying infrastructure are:
  - **Network**: Since networks are vital for the access to data and information, an essential part of Computing services is the access, availability and performance of the network, i.e., Academic and Research Network in Africa. This is not only true at the local level in universities and research centers, but even more so at the national and international level with connections to other countries. Most of the countries have, at scientific level, a poor network and slow connections to each other: one needs to get a global picture of the existing situation and compile the needs of all constituents in order to draw up a strategy for improvement. It is imperative for all countries to share their knowledge. An African coordinated initiative would be a real asset to the continent. There has been significant developments from the Ubuntunet Alliance in building research Networks across the continent. Currently, most of the countries have developed the National Research Networks and are looking at possibility of cross-country connectivity. In addition, the undersea cable investment has seen emergence of new cables to the continent such as the Equiano, Google, Facebook, WACS and SEACOM. This will enable participation of African countries in accessing resources in the continent and globally [**?**].
  - **Storage and Computing Power**: these are necessary to store and process the data, which is the only way to produce results and advance science. The computing needed is more and more sophisticated now that Artificial Intelligence and Deep Learning have entered the game in all fields of science. As suggested by some of the participants, large data centers shared within a country or with other countries within Africa would certainly be a solution that would federate the resources, and decrease the costs and disparities between universities and countries.

  - **Qualified technical staff** is necessary to deploy and run these computing resources and make them available to the physics research scientists that would not be able to deal with Cloud deployment or computer storage access by themselves. Here a collaboration between different countries (within Africa and beyond) could be a fruitful initiative to share IT technicians, setup a few test sites, and start setting up an infrastructure on site. The SADC Cyberinfrastructure Initiative has started a process of developing expertise around the region, by deplying small scale HPC systems in SADC countries and training the System Administrators in those countries. This has enabled countries such as Botswana, Namiboa, Mozambique, Zambia, Ghana etc.., to build the necessary skills for deploying and managing HPC system and provisioning them for the rest of the research communities.

- **Build Knowledge and include computing in Education**: The poll has highlighted the insufficient level of education in computing. Many solutions should be envisaged simultaneously:
  - **Increase the number of computing courses** in the courses of physics and other science students.
  - **Train IT professionals** to prepare and operate the infrastructure. These professionals are an important piece of the game as they are the ones that can deploy the complex infrastructure and follow up on the progress in the field.
  - **Organize regular workshops and trainings**. This would be highly beneficial for knowledge sharing and to stay at the forefront in computing where evolution is very fast. But this also would have an important positive side effect: Researchers have highlighted the fact that they quite often work isolated. These workshops are the best place to meet their peers and initiate collaborations that would be very beneficial to raise research productivity.
  - **Establish Communities of Practice.** Many research computing facilities in Africa face the common problems of isolation and staff retention. Most groups operate in relative isolation and struggle to engage with peers. This is largely owing to the lack of financial resources to facilitate in-person engagements since the vast majority of scientific computing workshops occur outside of Africa. Another contributing factor towards isolation is simply the lack of awareness of any accessible broader communities in Africa.
  - **Establish sustainable workforce development pipelines**. While there is an identified need to train and upskill the technical workforce in Africa to operate and maintain advanced research computing resources, any workforce development pipelines must be sustainable. Research institutes that manage to upskill their technical staff face a subsequent challenge of retaining the newly-skilled staff who now have opportunities to migrate to higher-paying industries with more attractive resources.
  - Last but not least, **national and international collaboration** with peers more experienced in these fields would provide accelerated knowledge transfer and build mutually beneficial collaboration.

- **Harnessing Cloud Computing for Africa's Scientific Research Infrastructure:** The rapid evolution of computing capabilities to meet the growing demand for data processing presents a significant challenge to Africa's scientific research infrastructure. To keep pace with the computing requirements for today's vast amounts of data, there is a critical need for constant optimization of computing resources. Cloud computing offers a cost-effective solution to this challenge. While traditional High-Performance Computing (HPC) systems require substantial investment in acquisition, operation, and maintenance, cloud computing provides a viable, lower-cost alternative. Although cloud computing has its limitations, as there are challenges of data sovereignty and sometimes the latency issues on applications that are I/O intensive, its adoption by African researchers and institutions could bridge the gap in accessing essential computing resources for high-quality research. Another alternative is to develop OpenStack Cloud which are located within the African countries. For examaple, South Africa has deployed the OpenStack Cloud, named SEBOWA, which is used by the various research communities. The HPC system in Morocco, is also designed to be run on OpenStack. These are possibilities of advancing the deployment of Cloud platforms in the continent. Additionally, embracing this technology has the potential to stimulate further research and advancements in cloud computing and data center management, fostering innovation in these fields.

- **Prioritizing Sustainable Investments in HPC Centers for Africa's Development:** Instead of providing financial aid or loans to African nations, developed countries should prioritize direct investments in sustainable projects, such as the establishment of HPC centers within the region. These efforts should include the training of personnel to operate and manage such centers, ensuring long-term success. This approach would contribute to achieving the Sustainable Development Goal 9 (Industry, Innovation and Infrastructure) included in the 2030 Agenda for Global Education of the UNESCO (ref. to be added here) and significantly enhance the region's computing capabilities to meet present and future demands.

- An example of an initiative to address a sustainable HPC development pipeline is South Africa's HPC Ecosystems Project [?]- A project that oversees a now ten-year partnership between Southern African countries and international computing facilities which has led to the establishment of more than thirty-five HPC systems in eleven African countries and provided technical training to over 700 participants. Through the Project's engagements, a virtual community of practice for emerging HPC Administrators has grown to incorporate more than 350 members from five continents, which prioritises sustainable workforce development and adoption of advanced research computing best practices.

7.7 Conclusion

The unavoidable and exponential increase of computing in all science fields including fundamental and applied sciences necessitates the availability of computing resources, the growth of computing awareness in the scientific communities and the inclusion of computing in education. Although certainly not extensive and complete, some key recommendations are drawn in the section above that might fill the gap that is visibly present when one compares African research with that of other continents. Investing in computing is one of the highest return on investment that a country can expect. It would provide to the youth of all countries an opportunity at the level of their hopes and ambitions.

The top priority is raising the awareness of governing bodies and stakeholders at each level; continent, state, university, and research centers about the crucial role of computing in research and sciences. But beyond sciences, it would have a large societal impact and would keep Africa in the race for knowledge, better living and peace.
Global and long scale planning is necessary as this evolution needs building networks, facilities and educating new generations of women and men to adopt the rapidly evolving computing landscape.
Budget should be expressly dedicated to computing: it would include all equipment needed for scientists, students and technicians for education, research, and R&D (Research and Development) and the budget to build, connect and run large-scale facilities to host and access the exponentially increasing volume of data.
As the demand for computing capacity is growing enormously, close collaboration between countries is the most efficient way to provide the needed resources. None of the main discoveries of the last decade would have been made possible without the collaborative work effort and the setup of closely connected powerful data centers distributed all over the world.

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8

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8.1 Introduction and Motivation

The earth sciences represent a major and interdisciplinary field that is fundamentally underpinned by physics and physical principles. The term 'Earth Sciences' is thus a broad umbrella term that encompasses scientific investigation a variety of different scales (sub-micrometer through to planetary scale), and which focusses on a variety of different environments. These environments include those located at earth's surface (the so-called critical zone which includes the biosphere, the hydrosphere, and the geosphere), but also extends inwards deep into the earth's mantle and core, and outwards through the atmosphere and out to the cryosphere. Although the specific scientific sub-disciplines that fall within the realm of the earth sciences are too many to enumerate, those that are most reliant on a strong physics foundation include: hydrogeology, geophysics, geophysical fluid dynamics, atmospheric physics and aeronomy, ocean physics, space physics and astronomy, environmental physics, meteorology, climatology, tectonics, seismology, gravity and magnetism, mineralogy and petrology, geochronology, ecotoxicology, among others. Additionally, almost all sub-disciplines or the earth sciences rely on measurements of physical properties to characterize and understand observed phenomena (e.g., Syono and Manghnani, 1992 [1]; Doel, 2013 [2]; von der Heyden et al. 2020 [3]). As such, inclusion of the Earth Sciences is a crucial addition to any documents or policies related to the future of physics on the African continent (e.g., the African Strategy for Fundamental and Applied Physics (ASFAP)).

As anthropogenic impacts continue to change the planet in which we live (e.g., Cracknell and Krapivin, 2008 [4]), it is becoming ever more important to understand how natural processes are being affected by this change. This understanding will help both to inform the design of any mitigation measures that are put forward, and to predict the environmental responses in a case where human activity continues under a 'business-as-usual' scenario. Multiple references have highlighted that Africa is particularly vulnerable to environmental change (Stige et al. 2006 [5]; Nkomo et al. 2006) especially given that a vast proportion of its inhabitants live life at, near, or even below the bread-line (Nkomo et al. 2006 [6]). For these reasons, a road map detailing the current state of affairs and future (envisaged) directions of the Earth Sciences is of both highly timeouts and of distinct geographic importance.

8.2 Challenges

Two considerations posed moderate challenges towards the overarching goal of uniting the earth sciences as a single entity under the greater umbrella of the African Society for Fundamental and Applied Physics (ASFAP). The first of these is the sheer number of sub-disciplines and communities that identify as earth scientists (see an incomplete list of sub-disciplines detailed in section 11.1). To identify and develop rapport with key individuals situated within each of these sub-disciplines required some effort from the two conveners of the working group, whose respective networks were somewhat limited to those of geology, geochemistry and environmental sciences. The second challenge relates to the multi-disciplinary nature of the earth sciences, which results in some workers struggling to identify their affiliation to physics, versus to other key disciplines that underpin earth sciences. For example, a geochemist may feel that his or her field is more closely aligned with chemistry rather than with physics. An important aspect that should be included in any physics policy document, that encompasses earth sciences, is a formal definition that delineates the relationship between the two.

8.3 Scientific activities

The activities of the Earth Sciences working group have arguable not been as prolific as those undertaken by several of the other ASFAP working groups. Despite this, the working group has experienced some successes and highlights. These include:

- Ongoing scientific and strategy related interactions with the broader ASFAP community (Haddad et al. 2022 [7]);
- A planned mini-symposium to coincide with International Earth Week 2021 (ultimately postponed to avoid a clash in dates with the African Geophysical Society);
- Development of a mailing list comprising twenty-three email addresses of individuals who are passionate about the future of earth sciences on the African continent;
- Successful presentation of the Earth Sciences working group achievements at a major regional earth sciences conference (Geocongress 2023 (11-13 January 2023; Stellenbosch, South Africa));
- Successful design and distribution of a targeted survey investigating the perceived future needs of the African earth sciences community (see Section **??**).

8.4 Survey design and responses

The developed survey comprised ten questions of which four probed insights into the meta-data of the respondent (e.g., experience level, field of study, country of habitation), and four questions provided the main source of data for further scrutiny. These four questions were open-ended, and sought to elucidate which issues are most prevalently impacting the African earth sciences, and how additional funding would serve to further improve the status of this important field of science. These four questions were:

- Please detail any barriers (e.g., access to students, funding, analytical equipment, researcher support, etc.) that currently hinder your abilities to conduct earth science research on or for the African continent?

- If you were awarded US$ 1000 towards advancing the physics-related needs or future goals of the earth sciences, kindly explain how you would best spend it?

- If you were awarded US$ 1 million towards advancing the physics-related needs or future goals of the earth sciences, kindly explain how you would best spend it?

- Please leave any other remarks which may serve to advise future physics strategy development for advancing the status of earth sciences on or for the African continent.

An advantage to this open-ended style of questioning is that it opened up opportunity for unforeseen responses (i.e., the responses are not limited to those on a prescribed list). Over thirty respondents completed the survey, with respondents comprising a broad array of nationalities including 30% of respondents each from west Africa and southern Africa, 20% from east Africa, and 10% each from north African and other countries outside of Africa, as shown in Figure 8-1.

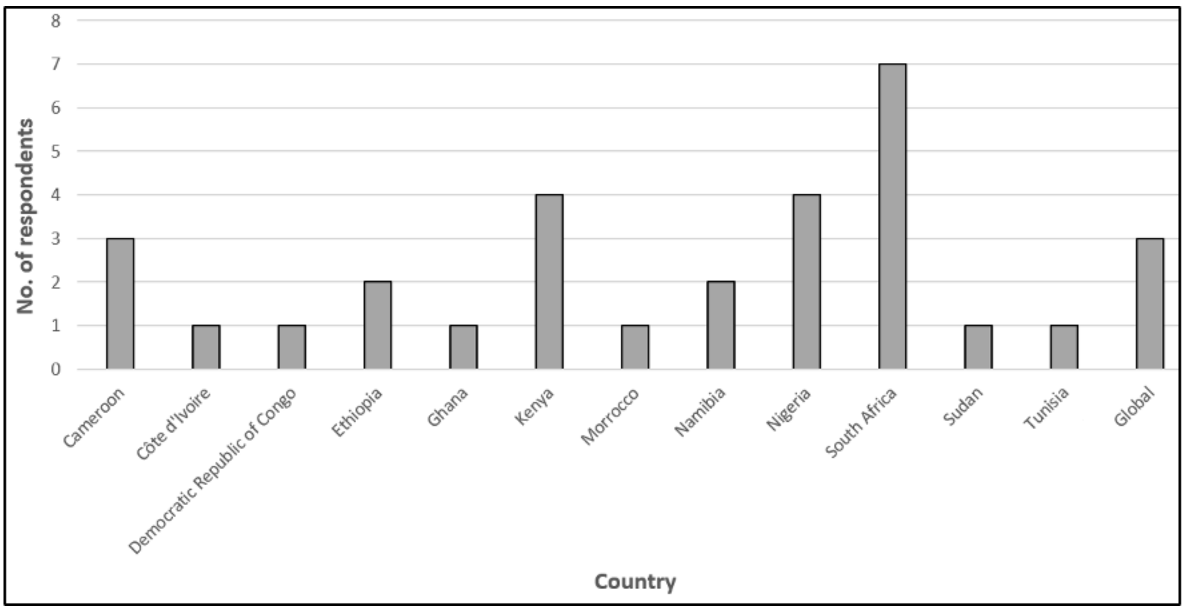

Figure 8-1: A summary of the respondents' countries of employment. 'Global' refers to countries outside of Africa.

Moreover, there was a good spread of experience levels and earth science sub-fields represented in the survey, Figures 8-2 and 8-3. Survey responses were interpreted following qualitative data analysis protocols, using the 'data that glows' methodology of MacLure, 2013 [?].

8.5 High priority future needs

Based on survey responses, the needs of the African Earth Sciences community can be divided broadly between those requiring high monetary inputs, those requiring smaller monetary inputs, and those that require other forms of support or incentivisation.

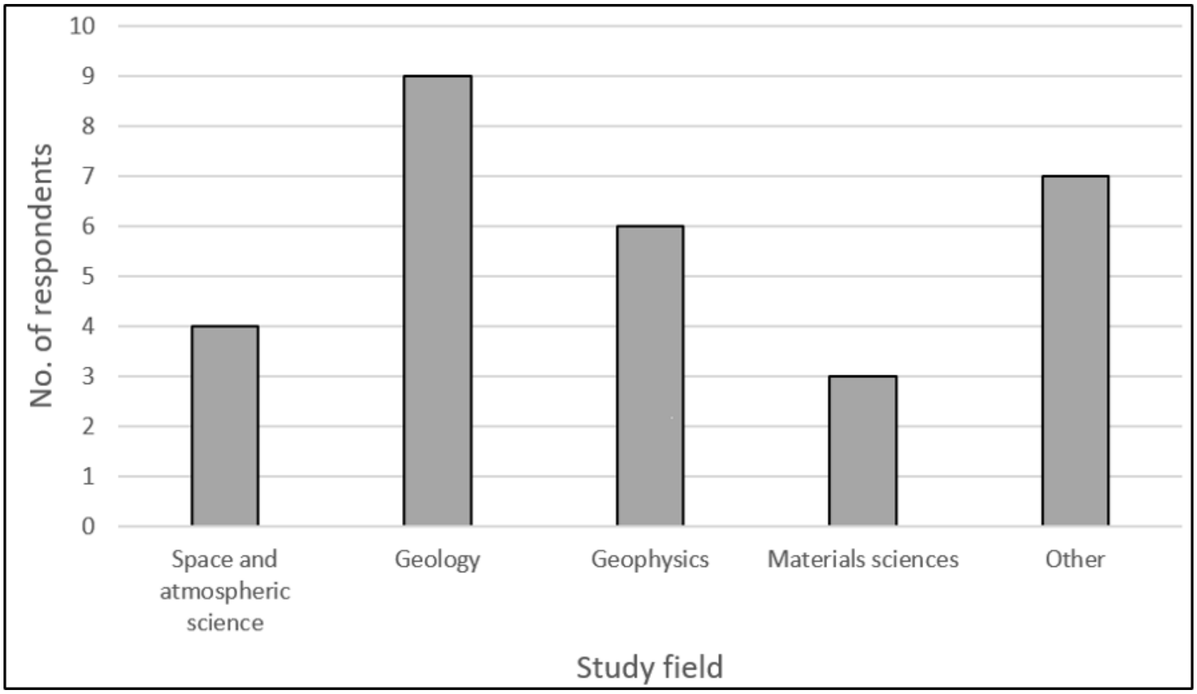

Figure 8-2: A summary of the respondents' study fields. 'Other' includes a diverse array of study fields including remote sensing, geoscience education, particle physics, among others.

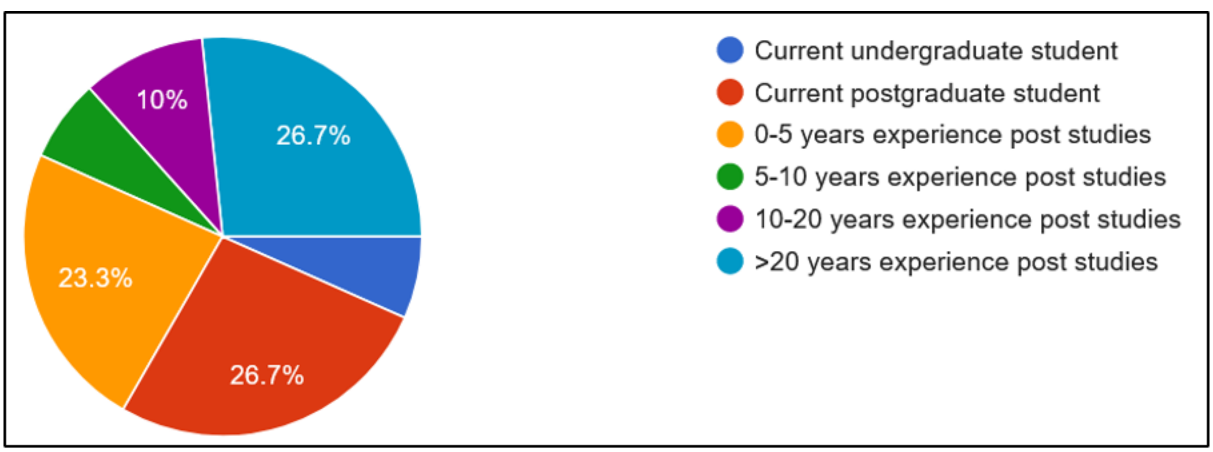

Figure 8-3: Summary of the indicated experience levels of the different respondents, showing a good mix in experience.

8.5.1 Needs requiring high degrees of financial support

In a hypothetical scenario in which survey participants were offered one million USD towards achieving their research goals, the majority of respondents indicated that they would utilize this money towards setting up high-end laboratory facilities that could be utilized towards investigating local- and global research questions. This response was received from respondents ranging across all of the different sub-disciplines of the earth sciences, and across all of the nationalities and experience levels. Examples of the types of large analytical labs suggested include broad-band and short period seismic equipment; a flume for fluid dynamics research; multiple meteorological mini-weather stations; among others. Interestingly, two different models for research equipment were proposed. Some respondents felt that large research equipment should be housed at a centralized and stable research facility (e.g., a well-established and reputable university). This is captured by the following statement:

Anonymous respondent A: “Provide critical research equipment to one of the universities that has the capacity to house and operate it, provided that the facility be available to other researchers within the country.”

An alternative model suggested a series of small laboratories set up across a more expansive geographic area, importantly comprising rural regions where labs must necessarily be run by off-grid e.g., photovoltaic power solutions. Most respondents highlighted that for any funding awarded towards a new laboratory, a subset of the funding needs to be set aside for technical staff training, for operating expenses and for funding of associated student projects. Some respondents also highlighted that large amounts of financial support could also be split into smaller tranches for utilization towards enhancing student and researcher training. Suggested training vehicles included bursaries for undergraduate and post-graduate students, overseas visits and conference/workshop attendance for researchers, and towards attracting international post-doctoral research fellows to African laboratories.

8.5.2 Needs requiring lower degrees of financial support

In line with the responses received for the larger grants, most respondents highlighted that smaller grants (i.e., 1000 USD) would be best utilized towards acquiring smaller items of equipment or towards funding student bursaries. Concerning the latter point, several respondents indicated that these bursaries should be awarded on a competitive basis and according to merit-based criteria. Surprisingly, several respondents indicated that the funding would be used to repair or upgrade existing equipment, with the concerning implication being that these items are currently not operating at their optimum performance levels. Other uses for the small grant awards included field trips, capacity building through local workshops, publication costs, and towards partnering with science communication companies to help develop ongoing popular media such as apps, comics, TV, etc. that advocate for the earth sciences.

8.5.3 Other needs and suggestions arising

The final open question of the survey attracted a range of other recommendations, all geared towards enhancing the status of earth sciences on or for the African continent. A large proportion of these focused on the need for enhanced collaboration and networking between African researchers. Collaboration, and vehicles that drive collaboration, need to be enhanced both for intra-country and intra-continent interactions.

Vehicles identified that would help facilitate collaboration include improved across-border data sharing, and development of more enabling government policies, funding and academic/research support. It was also suggested that improved industry-university linkages should be facilitated and nurtured, since these linkages are mutually beneficial (e.g., Heath, 2000; Agrawal, 2001; von der Heyden, 2019 [10, 9, 11]).

A second key focus area relates to ensuring a sustained talent pipeline for future generations of African earth scientists. This may be achieved by establishment of outreach programs aimed at attracting High School students to our important discipline. Dedicated investment into Geoscience education initiatives would also be useful, particularly if they are underpinned by good educational research, and designed to have longevity. As indicated in previous sections, offering bursaries to dedicated and hard-working students will also help to ensure a sustained supply of future thought leaders and industry professionals who will drive the science and its various practical applications forward. Also indicated previously, these students will need to be trained in good laboratories, of which there are currently a dearth. This again underpins the need for financial investment into state-of-the-art equipment.

Anonymous respondent B: "Doing Research in physics needs quality equipment."

Anonymous respondent C: "It is necessary to modernize the laboratories of the earth sciences to supervise many students for their Ph.D."

Other approaches that would serve to strengthen the standing of earth sciences on the African continent would be through focus on issues that are topical both to the continent and globally. For example, topics such as green energy, global climate change and critical metals all fall within the focus area of the earth sciences and are all relatively easily supported by large international funding bodies. Linked to accessing large grants, an important skillset that needs better development among local researchers is the ability to write strong and competitive research grants. This is succinctly captured in a statement by Anonymous Respondent D: "Spread, democratize as aggressively as possible the skills of successful writing of large grant proposals."

8.6 Conclusions and perspectives

Based on the somewhat limited feedback received from a survey initiative set up by the ASFAP earth sciences working group, the largest and most inhibitory barriers affecting the African earth sciences are 1) a perceived dearth of funding and, 2) limited access to high-end analytical facilities. Towards negating the first inhibitor, funders are encouraged to open up new funding vehicles that explicitly aim to advance the African earth sciences, particularly if the research areas are topical and of societal and environmental relevance to our continent (and globally). Furthermore, African researchers need to be better equipped to write, defend and deliver on large grant proposals. There is a great opportunity to introduce greater circularity into the training provided to upcoming researchers. That is, not only should next generation scientists deliver good science, but they should also be trained to write highly-competitive grants.

Anonymous Respondent E: "Postgraduate Students willing to work on the use of physics and physics concepts and methods will be encouraged and drawn into the multidisciplinary research consortium which will be established with a solid foundation/background underpinned by Physics. The above mentioned research and education consortium will then apply and submit research funding proposals for more research funds. Physics education and research, physics concepts and methods will be used as background for a greater societal and industry impact leveraging of localized and decolonized African realities."

Towards mitigating the perceived dearth of analytical facilities, a worthwhile departure point would be to compile a list of all earth sciences analytical facilities located on the African continent. This list should be augmented with details of the associated research costs and the availability/openness of the unit to intra-continental collaborative efforts. Collaboration can be stimulated by developing strong and mutually-beneficial research agreements between countries, laboratories, research institutions and industry on the continent. Whereas other parts of the world are engaging in anti-globalisation movements, a general absence of this attitude on the African continent will be beneficial towards preferential and expedited local advancements.

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9

Energy Working Group

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9.1 Introduction

Access to modern energy services is essential to achieving basic social needs by promoting economic development. Modern energy services, particularly electricity and gas, affect productivity, health, education, safe water, and communication [1]. Energy has a significant impact on socio-economic development in any country because it encourages investment, innovation, and the formation of new businesses that promote the creation of jobs, inclusive growth, and shared prosperity throughout the entire economy [2]. This fact, along with the strong links between energy and the Millennium Development Goals (MDGs), makes it even more important to address the challenges and prospects of energy service provision in Africa. Developing countries' decisions on the growth of their energy sectors will significantly impact future energy consumption trends, fuel preferences, trade patterns, and other relevant aspects in addition to their development. Over the past two decades, Africa has exhibited a significant increase in energy consumption, with a reported 45% increase [3]. However, the energy infrastructure in many areas remains underdeveloped, leaving the demands of the population unmet. Despite the wealth of energy resources available to cater to domestic needs, many countries continue to lack access to modern energy services. Approximately 620 million Africans, which account for two-thirds of the population, do not consume electricity, and a further 730 million rely on traditional biomass for cooking. Even for those with access to energy, the quality and cost of supply are often found to be subpar [3].

The energy sources used in Africa vary from country to country. However, the most commonly utilised energy sources on the continent are oil, coal, natural gas, hydroelectricity, and renewable sources such as solar, wind, and geothermal power. It is worth noting that the International Energy Agency (IEA) states that Africa possesses 60% of the world's best solar resources, yet only 1% of the installed solar PV capacity. Furthermore, the IEA predicts that solar PV will be the most cost-effective power source in many regions of Africa by 2030. Affordable and dependable energy are key factors in Africa's economic and social progress. The COVID-19 pandemic has highlighted the importance of a stable energy supply. Without electricity, the measures put in place by the government to contain the virus would have been unbearable. Access to electricity allowed people to work from home; schools continued functioning through online classes; and governments continued their operations (e.g., through virtual court systems). Electricity also facilitated water utilities to continue supplying clean water for handwashing, which was an essential guideline for reducing the spread of the virus [4], [5]. Increased access to affordable and dependable energy can play a significant role in mitigating economic disruptions caused by the pandemic. As countries prepare for economic recovery, African governments must focus on creating more job opportunities and stimulating economic growth. Investing in energy access can help achieve both goals[6].

The transition towards clean energy on a global scale presents promising prospects for the economic and social growth of Africa. As of May 2022, countries committed to achieving net zero emissions accounted for more than 70% of the century. This includes 12 African nations contributing to over 40% of the continent's total CO2 emissions [7]. The commitment of these nations to achieve net zero emissions contributes to the transformation of the global energy sector due to the declining costs of clean technology and shifting global investments. African nations, the majority of which are signatories to the Paris Agreement on Climate Change, are well-positioned to benefit from technological advancements and attract increasing amounts of climate finance [6].

For the African government to ensure greater energy access to its population, diversification of energy sources will play a key role, which will include investing in new sources of energy, especially renewables such as wind and solar energy, as well as pooling them together to ensure sufficient supply.

9.2 Sources of energy and resources in Africa

Africa is endowed with various resources that meet the energy needs of different countries. Different countries in Africa have different energy mixes as their sources of energy, including

- Hydroelectric energy: in Africa, several countries are tapping hydroelectric as part of the source of utility energy; the following are some of the biggest in Africa.
  - The Grand Ethiopian Renaissance Dam (GERD) – 6,450 MW: Previously known as the Millennium Dam, the Grand Renaissance Dam in Ethiopia has been under construction since 2011 and is set to become the largest dam on the continent upon completion. Located on the Blue Nile, the dam will generate an estimated 6, 450 MW per year in the Benishangul–Gumuz region near Ethiopia's border with Sudan.
  - Aswan High Dam – 2,100 MW: Located near the city of the same name in southern Egypt, the Aswan High Dam ranks as the continent's second-largest dam. Built across the Nile, the dam is the largest embankment dam in the world, with a height of 111 m and length of 4,000 m. By powering 12 generators, each at a rate of 175 MW, the dam has a total generation capacity of 2,100 MW.
  - Cahora Basa Dam – 2,070 MW: One of the two major dams on the Zambezi River, the Cahora Bassa Dam in Mozambique is the largest hydropower plant in southern Africa. Power was generated through five 415 MW turbines with a combined capacity of 2,070 MW. Most of the power generated by the Cahora Bassa Dam is exported to South Africa through the Cahora Bassa high-voltage direct current (HVDC) line system, with two conversion stations located in Songo, Mozambique, and Apollo, South Africa.
  - Gilgel Gibe III Dam – 1,870 MW: The Gilgel Gibe III Dam located southwest of Ethiopia's capital, Addis Abeba, is a roller-compacted concrete dam and hydroelectric power plant built on the Omo River. The Gibe III power station forms part of a cascade of dams, including the Gibe I dam, with a capacity of 184 MW, and the Gibe II power station, with a capacity of 420 MW. Plans are currently underway to add Gibe IV and V dams with capacities of 1,472 MW and 560 MW, respectively, to the Gibe Cascade. Currently, during its commissioning process, the future electricity generated by the plant is expected to provide half of its capacity to Ethiopia, with the other half expected to be exported to Kenya (500 MW), Sudan (200 MW), and Djibouti (200

MW). Under the country's current development plans, Ethiopia has pledged to generate 95% of its energy generation from hydropower.

- Inga Dams – 1,775 MW: Comprised of two single dams, the Inga 1 (351 MW) and Inga II (1,424 MW), Dams in the Democratic Republic of Congo (DRC) currently operate at a combined capacity of 1,775 MW. Built on Inga Falls, one of the largest waterfalls in the world, hydroelectric dams currently work at merely half of their potential capacity. The expansion of the dam has generated interest from nations and power companies all over Africa that have expressed interest in the pursuit of a Grand Inga project estimated to cost $80 billion, which would become the largest power station in the world with a capacity of up to 70 GW.
- The Kariba Dam, 1,626 MW, is located between Zimbabwe and Zambia. It is 128 m tall and 579 m long and is the largest man-made dam in the world. Currently, with a total installed capacity of 1,626 MW, the dam is under expansion to increase its yield. Power stations located on the north and south banks of the dam provide Zambia and Zimbabwe with their respective energy sources.
- Merowe Dam – 1,250 MW: In terms of its size, with a length of 7km and height of up to 67 meters, the Merowe Dam in northern Sudan is the largest contemporary hydropower project in Africa by size. Situated on the Nile, the hydropower dam consists of 10 turbines, each with a capacity to produce 125 MW for a combined total of 1,250 MW.
- Tekezé Dam – 1,200 MW: With a height of 188 meters, the Tekezé Dam in Ethiopia is the tallest dam on the continent. Situated on the Tekezé River, a tributary of the Nile, the $360 million dam is one of the largest public works projects in the country. The dam's powerhouse contains four 75 MW turbines, each generating 300 MW of electricity for a combined total of 1,200 MW. Akosombo Dam – 1,020 MW: Located at the base of Lake Volta, the Akosombo Hydroelectric Dam in southeastern Ghana draws its hydropower from the world's largest person-made lake in the world, with a surface area of 8,502km2. Initially constructed to provide electricity for the country's aluminum industry, the power plant currently has an installed capacity of 1,020 MW, and provides electricity to Ghana, Togo, and Benin.
- Kainji Dam – 760 MW: Built on the Niger River in Nigeria, the Kainji Dam provides electricity to all of the west-African country's major cities. Despite the intention of designing a dam with an installed capacity of 960 MW, only eight of the proposed twelve turbines have been installed, reducing the capacity of the plant to 760 MW. The Kainji Dam, with a length of 10km, is one of the longest dams in the world.

- Thermal energy
- Wind power
- Solar power
- Geothermal energy

9.3 Energy pooling in Africa

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10

Fluid and Plasma Working Group

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Abstract

Abstract: In physics, a fluid is a liquid, gas, or other material that continuously deforms under an applied shear stress, or external force. They are substances which cannot resist any shear force applied to them. Meanwhile, plasma refers to an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles produced when the atoms in a gas become ionized. In this report, the concept of fluid and plasma physics is briefly outlined, followed by an overview of the status and impact of fluids and plasma physics education and capacity development in Africa.

Keywords: Fluids and plasma physics; Magnetohydrodynamics; Education and capacity development in Africa

10.1 Introduction

Adequate knowledge in fluid and plasma physics is a necessary prerequisite for development of technology and innovation, and thereby constitutes a key input into the transition to a knowledge-based economy [1]. Applications of fluids and Plasma physics range from energy production by thermonuclear fusion to laboratory astrophysics, creation of intense sources of high-energy particle and radiation beams, and fundamental studies involving high-field quantum electrodynamics [2]. Plasma is being used in many high tech industries. It is used in making many microelectronic or electronic devices such as semiconductors. It can help make features on chips for computers. Plasma is also used in making transmitters for microwaves or high temperature films. Fluids and Plasma research are leading to profound new insights on the inner workings of the sun and other stars, and fascinating astrophysical objects such as black holes and neutron stars. The study of fluids and plasma enable prediction of space weather, medical treatments, and even water purification [3]. Majority of plasma phenomena observed in real experiments can be explained by a fluid model, in which the identity of the individual particle is neglected, and only the motion of fluid elements is taken into account [4]. The theoretical study of plasma as fluids are governed by the concept of magnetohydrodynamics which involved a combination of conservation of conducting fluid mass, charges and momentum equations coupled with state equation and Maxwell equations of electromagnetism [5]. Plasma may involve the dynamics positively charged ion fluid and negatively charged electron fluid. In a partially ionized gas, for the dynamics of fluid of neutral atoms may also be involved. The neutral fluid will interact with the ions and electrons only through collisions. The ion and electron fluids will interact with each other even in the absence of collisions, due to the generation of the electric and magnetic fields [6]. The magnetohydrodynamic approach treats the plasma as a single fluid with mass density $\rho_m = n_e m_e + n_i m_i$, charge density $\sigma = q_e ne + q_i n_i$, mass velocity $V = (n_e m_e v_e + n_i m_i v_i)/\rho_m$, current density $j = q_e n_e v_e + q_i n_i v_i = q_e n_e(v_e - v_i)$ and total pressure $p = p_e + p_i$ as outline in the equations below [7, 8, 9]:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (nV) = 0 \;\; \text{(Mass conservation);} \tag{10.1}$$

$$\frac{\partial \sigma}{\partial t} + \nabla \cdot (nj) = 0 \;\; \text{(Charge conservation);} \tag{10.2}$$

$$\rho \left(\frac{\partial V}{\partial t} + V \cdot \nabla V \right) = \sigma E + j \times B - \nabla P \;\; \text{(Momentum conservation);} \tag{10.3}$$

$$P = C n^{\gamma} \;\; \text{(Equation of state);} \tag{10.4}$$

with the addition of Maxwell equations.

where the subscripts i and e represent the ions and electrons, respectively, C is a constant, γ is the ratio of specific heat C_p/C_v, t is the time, B is the magnetic field strength, E is the electric field, T is the temperature, n is the particle density, η is the resistivity.

10.2 Status of Fluids and Plasma Physics Internationally

Fluid and plasma research is advancing rapidly, with fluid dynamics focusing on computational methods like CFD, turbulence modeling, and microfluidics, benefiting industries such as aerospace, automotive, and medicine. Plasma research is highlighted by efforts in fusion energy, particularly ITER, alternative confinement methods, and applications in space propulsion, medicine, and materials processing. Global collaborations and funding are key drivers, with AI and machine learning accelerating simulations in both fields. Emerging technologies like quantum computing hold promise for more complex simulations, while sustainable energy solutions and space exploration remain critical application areas. ITER (International Thermonuclear Experimental Reactor) is a large-scale international project aimed at demonstrating the feasibility of nuclear fusion as a sustainable, safe, and virtually limitless energy source. It is designed to be the world's largest tokamak—a device that uses magnetic fields to confine and control plasma, the hot, charged gas where fusion reactions occur, similar to those in the sun. Located in southern France, ITER is a collaborative effort involving 35 countries, including the European Union, the U.S., China, Russia, Japan, India, and South Korea. The main goal of ITER is to achieve a sustained fusion reaction where the energy output exceeds the energy input, paving the way for future fusion power plants. It is expected to produce 500 megawatts of thermal power from 50 megawatts of input power, demonstrating the practicality of fusion as a reliable energy source without the carbon emissions or long-lived radioactive waste associated with nuclear fission. Though ITER won't generate electricity directly, it will serve as a crucial stepping stone for future commercial fusion reactors.

10.3 Status of Fluids and Plasma Physics in Africa

Due to the lack of necessary research laboratories infrastructure, technical support, and so forth in many academic and research institutions in Africa, relatively few scientists in the field of fluids and plasma physics have managed to perform at a level competitive with the best in the world. The figure 1 below depicts the level of research output in the fluids and plasma physics in Africa [10].

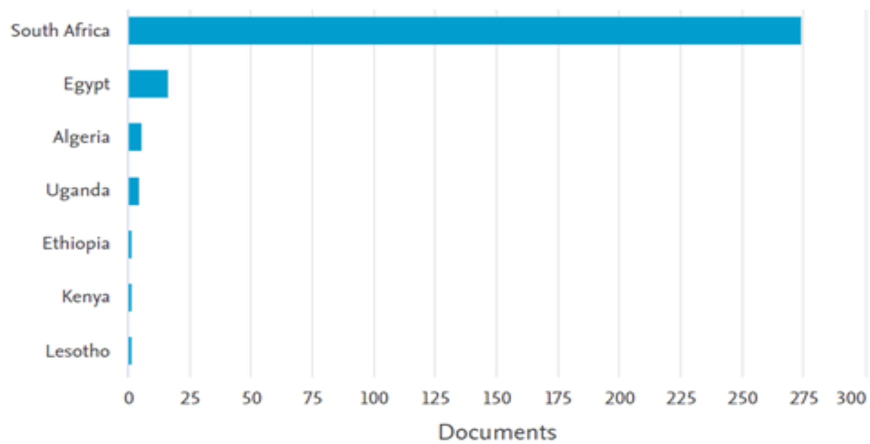

Figure 10-1: Fluids and plasma physics research output in Africa (source-SCOPUS database [10])

From figure 10-1, it is obvious that very few countries and scientists within Africa are engaging in productive research in the field of fluids and plasma physics. The largest visible research output on fluids and plasma physics comes from the institutions in South Africa, followed by the institutions in Egypt, Algeria, Uganda, Ethiopia, Kenya and Lesotho. Moreover, Fluid and plasma physics research in Africa is emerging, with growing importance in areas such as environmental management, renewable energy, healthcare, and space science. Fluid dynamics research is primarily focused on addressing challenges related to water resource management, hydrology, and climate modeling, as well as optimizing renewable energy systems like wind and hydropower, with South Africa, Egypt, and Kenya being key contributors. In the biomedical field, fluid dynamics is being applied to healthcare solutions, particularly for cardiovascular diseases and drug delivery systems. Plasma physics research, though still in its infancy, is expanding, with South Africa playing a leading role in fusion energy research and space propulsion. Plasma applications in medical fields, such as sterilization and wound healing, are also being explored across the continent. Countries like Nigeria and Algeria are contributing to plasma physics research, especially in areas like satellite propulsion and environmental remediation. International collaborations and regional partnerships are essential for building research capacity and infrastructure, with future directions focusing on sustainable energy solutions, climate adaptation, and healthcare advancements to address Africa's socio-economic challenges. Meanwhile, research and academic institutions in several African countries may be engaging in some research activities in fluids and plasma physics, however, their output may not be visible on the SCOPUS database.

10.4 African Participation in ITER Fluid & Plasma Physics Research

Fluid and Plasma research, especially in fusion energy, offers the potential for clean, limitless energy, while also contributing to space propulsion, advanced manufacturing, and medical applications like sterilization and cancer treatment. African participation in ITER (International Thermonuclear Experimental Reactor), led by South Africa, is particularly important for the continent's involvement in cutting-edge plasma physics and fusion energy research, enabling knowledge transfer, capacity building, and contributions to global scientific efforts. This involvement not only supports Africa's energy sustainability goals but also fosters international collaboration and technological growth in areas such as satellite propulsion and environmental remediation. As African countries engage in global scientific initiatives, they position themselves to address critical socio-economic challenges through these advanced research fields.

10.5 Fluid & Plasma Physics Education and Capacity Development in Africa

The challenges of education and capacity development in the field of fluids and plasma physics in Africa include inadequate funding of science education at secondary and tertiary levels, lack of infrastructure, absent of physics-based industries, poverty, etc. [11]. To excel in physics & science education and training in Africa is to conquer Mount Everest without the aid of additional oxygen. Meanwhile, scientific advancement cannot occur without quality education; to achieve that quality, African countries will require significant investment at all educational levels. African scientists have to convince their governments, businesses, and the public that investment in physics education is beneficial and will lead to economic development and an enhanced quality of life [1]. Physics curricula should emphasize project work and problem solving, with a complement of activities in entrepreneurship. Figure 10-2 below depicts a strategy that African countries' may adopt for education and capacity development in fluid and plasma physics.

The proposed capacity development strategy envisages a close and mutual interaction between the African educational institutions, research institutions, and industries. Moreover, post-doctoral research activities should be encouraged in the field of fluid and plasma physics in African tertiary and research institutions, scientists in Africa should be encouraged to publish their research outputs in mainstream peer-review academic journals for global visibility.

10.6 Recommendation and Conclusion

To improve fluid and plasma research, international collaboration, and education in Africa, policymakers should increase investment in Research & Development by boosting public funding and incentivizing private sector involvement. They need to build and modernize research infrastructure by creating centers of excellence and upgrading university labs. Strengthening education in STEM (Science, Technology, Engineering, and Mathematics) fields is crucial, with updated curriculums, graduate scholarships, and vocational training. Fostering global and regional collaborations, including partnerships with initiatives like ITER, will provide African researchers access to cutting-edge technologies. Industry-academia linkages should be promoted to translate research into practical applications, while innovation hubs and incubators can support startups. Retaining talent through competitive salaries, funding, and return programs for African scientists abroad is

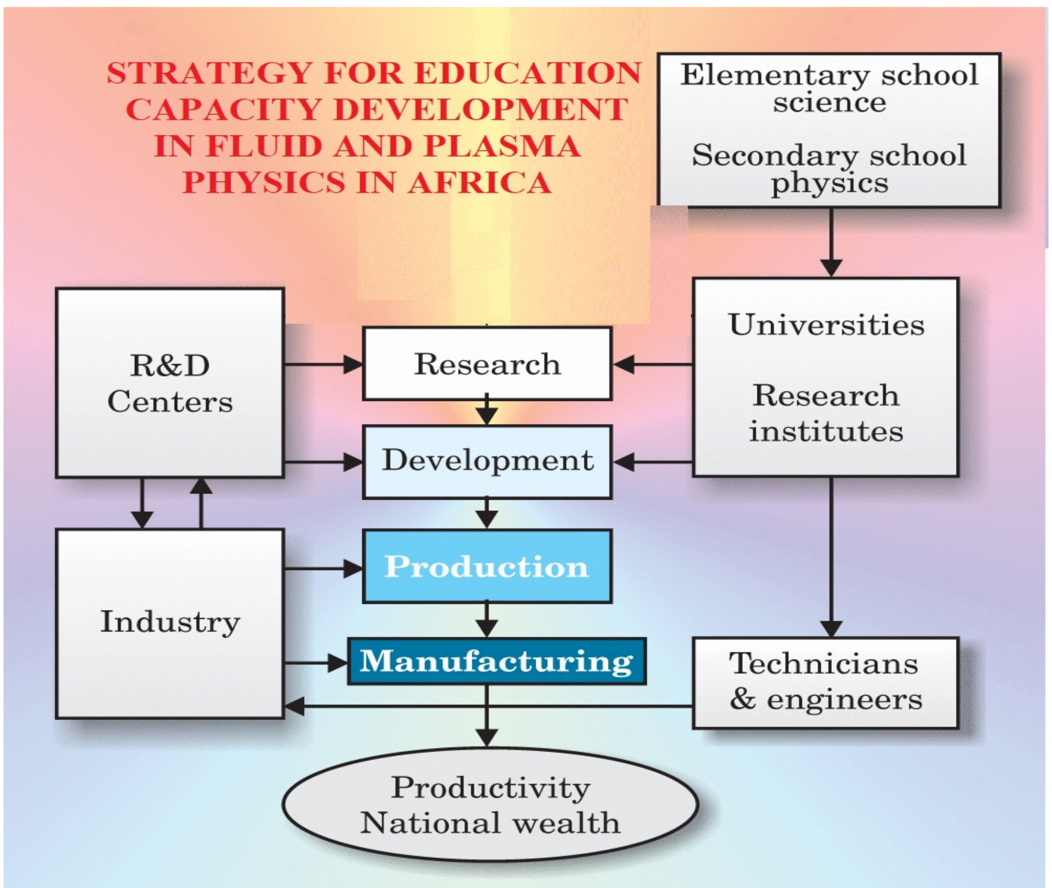

Figure 10-2: Strategy for education capacity development in fluid and plasma physics in Africa

essential to combat brain drain. Finally, public awareness campaigns and youth STEM engagement initiatives will help build a strong scientific culture and drive future research in fields critical to Africa's development, like clean energy, space technology, and healthcare.

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11

Instrumentation and Detectors Working Group

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11.1 Introduction and Motivation

By construction, this working group is transversal and multidisciplinary, and its activities are related to all other physics groups. The Instrumentation and Detectors Working Group aims to identify existing or new initiatives and projects within a wide range of instrumentation, which should be further developed in order to become valid proposals to provide access and/or create new facilities across Africa. The role of this WG is to coordinate and encourage such initiatives and to provide assistance in the process of writing concrete proposals towards the so-called "white papers."

11.2 Major challenges for scientific activities

In the early phase of the WG, a small and probably insufficient attempt was made to generate an approximate overview of existing (active) facilities in Africa by scanning through web pages, conference proceedings and other miscellaneous sources of information. This process turned out to be fairly difficult, especially in the physics domains outside of the competences of the WG conveners. However, the prejudice that most of the instrumental centers are concentrated in very specific regions on the continent, e.g., South Africa, Namibia and in the Northern part of Africa, seemed to be confirmed, while very few are located in the sub-Saharan countries of central Africa.

Some of the large research activities are also described in chapter 4 on various instrumentation used in astronomy and cosmology across the whole continent, in chapter 3 on accelerator technologies and in chapter 16 with respect to the participation of several research groups in particle physics experiments, especially at CERN[1] in Geneva, Switzerland: Researchers from universities and laboratories in Morocco, Egypt, and South Africa are members of these large international collaborations like ATLAS, ALICE, and CMS and are contributing to High Energy Physics Experiments. Recently, physicists from Nigeria, Algeria, and Tunisia have joined these collaborations.

In the US, the university of Antananarivo has joined the DUNE[11] long base line neutrino experiment and the new facility of an electron ion collider[12] at Brookhaven National Laboratory in New York has attracted researchers from Egypt, Tunisia, and Zambia. Lastly, Senegal is involved at the Thomas Jefferson National Accelerator Facility in Virginia[24] and the Facility for Rare Isotope Beams in Michigan[25].

African countries can contribute to the field of experimental physics, thanks to the international character of this field of physics. In the development of these collaborations, African laboratories profit from knowledge transfer and the installation of new facilities, which opens up further possibilities for future activities.

Examples of relatively large centers with an important activity in instrumentation are the nuclear facilities with accelerators at iThemba Labs[2] and several astrophysics observatories such as the South African Astronomical Observatory (SAAO)[3] and Square Kilometer Array (SKA)[4] in South Africa, the High Energy Stereoscopic System (HESS)[5] in Namibia, and larger research centers such as the Center National de l'Énergie, des Sciences et des Techniques Nucléaires (CNESTEN)[6] in Morocco and the Center for Development of Advanced Technologies (CDTA)[7] in Algeria. Other smaller instrumentation-focused centers exist also in other countries, that includes the Lasers Atoms Laboratory at Cheikh Anta Diop University and the Radiocarbon Laboratory of the Institut Fondamentale d'Afrique Noire (IFAN)[8] in Senegal, the Atomic Molecular Spectroscopy and Applications Laboratory at the University of Tunis El Manar in Tunisia, and the Center for Energy Research and Development (CERD)[9] in Nigeria, among others. Various small research groups established a multi-country collaboration to establish a larger network of complementary scientific capabilities like the African Laser Center[26]. There are many other laboratories on the continent with various instruments to conduct research, however, not only a large fraction are known to be inactive due to lack of resources to repair some key components, albeit with some needed minor repairs, but also the large majority being unknown to the African scientific community.

A first meeting of the WG took place in November 2021, with the principal goal of helping in the submission of Letters of Intent (LoIs) designed to be a call to the African scientific community to obtain inputs for the African Strategy for Fundamental and Applied Physics (ASFAP). These LOIs were further analyzed by structuring the collected information on existing facilities. This initial survey was complemented with other information collected from presentations at various scientific meetings, conferences, and workshops such as ACP2021[10] and others. Two main issues were raised repeatedly:

- There is a strong consensus that the main problem researchers face is the need and easy accessibility of experimental facilities to conduct their research; and
- The second essential need is to overcome the lack of educational training centers in instrumentation for basic and advanced experimental physics.

11.3 Analysis of submitted Letters of Intent (LoIs) related to instrumentation

After the first set of submitted LoIs, several were identified that possibly relate to instrumentation needs. These LOIs were grouped in three categories as listed below (the numbers in the brackets refer to the submission identification of the LoI). A graphical representation is provided by Fig.11-1:

1. Extensions of existing facilities:
    - (Radio)-Astronomy (51, 54, 56, 67)

- Accelerator centres (17, 24)

2. New facilities
   - Astronomy: local observatories for North Africa (14)
   - Astroparticle underground (15)
   - African millimetre telescope (33)
   - Am-Be neutron source (39)
   - AfLS (not a special LoI)
   - Instrumentation for AfLS (58, 59, 61,66)
3. Centers of Excellence (within which the instrumentation part was not always explicit or clear)
   - Graphen Flagship (4)
   - Energy centre of excellence (5)
   - NANOAFNET(10)
   - Quantum physics and biology (19, 23, 27, 49)
   - Education, ICEPA (68), Internet of Things

Three types of LoIs spanning over many fields of physics emerged, some proposing extensions of already existing facilities, others the creation of new facilities. A third category of LoIs concentrated on centers of excellence to address specific topics, emphasizing collaboration between African countries.

In the spring 2022 the conveners of the WG started to approach the authors of the existing LoIs directly with two goals: (1) to compile more details pertaining to instrumentation and (2) to encourage a plan for the organization of a global collaborative effort; the latter aiming to coordinate concrete action items and to assist in instrumentation needs. However only two meetings could be held, on May 5^{th} and June 9^{th}, gathering a total of 21 and 14 participants, respectively. Further meetings were planned but canceled due to problems identifying dates accommodating the speakers and conveners' availability. The beginning of the summer 2022 break put an end to that round of meetings.

On May 5^{th} three LoIs were discussed, namely letter #39 (Am-Be neutron source), #54(Low Frequency($<$ 1 GHz) RadioInterferometric Arrays), and #33 (The first millimeter-wave radio telescope). The following meeting on June 9^{th} centered on two existing facilities at iThemba Labs (#17, #24) and #10, UNESCO-UNISA[22] and NANOAFNET[23]. Brief summaries for the former are listed below.

LoI #39: Am-Be neutron source proposes to extend the use of Am-Be neutron sources for teaching and applied research beyond Nigeria to other African countries. Transferring this technology will stimulate new collaborations. Neutron sources are technically much easier than research reactors to probe materials with thermal neutron reflection technique or neutron activation analysis. Only 8 African countries have research reactors: Algeria(2), DR Congo (2), Egypt (2), Ghana (1), Libya (1), Morocco (1), Nigeria (1), and South Africa (1).

LOI #54: Low Frequency($<$ 1 GHz) RadioInterferometric Arrays which is an already growing international collaboration between Gabon, New Zealand, and South Africa that explores the time dependent density of the ionosphere, which has a large impact on many communication channels with satellites but also on radio-astronomy. Arrays of GPS stations can monitor the Total Electron Content (TEC) of the ionosphere. Transient Array Radio Telescopes (TART) or a scaled-down version of The Long Wavelength Array (SDLWA) address astrophysical topics.

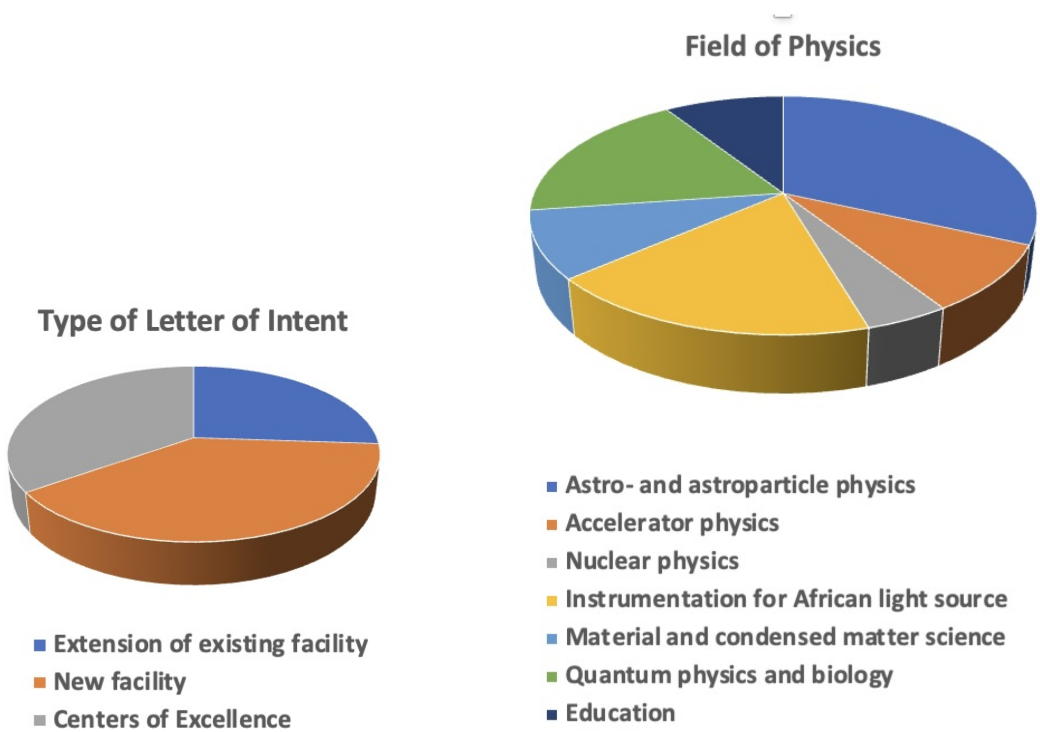

Figure 11-1: The Letter of Intents submitted by the African scientific community grouped by type (left) and sub-field of physics (right).

LOI #33: The first millimeter-wave radio telescope which is a "single dish" radio telescope currently being built in Namibia. It will open new perspectives for astrophysics in Africa as well as new international collaborations, especially if the telescope is incorporated in the world wide Event horizon telescope[27].

All the above mentioned projects are built on some already existing experimental activities and have the potential for the future to create African-wide collaborations. The existing facilities at iThemba Labs do already attract scientists from other countries like Algeria, Senegal, Burkina Faso, and Nigeria; however, there is quite some room to further increase such collaborations.

In the discussions following the presentations, it became evident that one of the most important shortcomings was in fact the problem of finding enough person power to widen the scope of these projects beyond the country where these activities are located presently. Especially for the astrophysical related projects this is a bit surprising because Africa has a fairly large astronomy community, particularly in East Africa.

One of the projects, namely the proposal for an underground laboratory in a tunnel in South Africa (LoI #15) took a very positive development during the last years into a strong collaboration now called PAUL (for Paarl Africa Underground Laboratory) and is described in more detail in chapter 17. It has been published[14] and presented at several conferences[13]. Unfortunately, because of difficulties to find a convenient time slot, this project could not be reviewed by the Instrumentation and Detector Group. The proposal consists in the creation of a new underground facility in the existing Huguenot tunnel similar to existing underground laboratories in the world. If realized in the future, it will create unique research possibilities in many fields of physics for the African continent. It is a prime example of successful collaboration building between many African and international scientists.

Unfortunately, the start of the LoI-review could not be continued after the summer break, for various reasons, mainly manpower, and the lack of participation and resonance within the community.

11.4 High priorities

Several ideas of how to improve the lack of know-how in instrumentation and experimental facilities were discussed in many meetings. The existence of more such facilities would certainly also increase the number of people interested to extend their experimental research activities. As mentioned already in the previous section, difficult communication between the researchers and engineers over the vast African continent is a further obstacle to progress in the fields. While it is difficult to prioritize any of the ideas presented in the LOIs, the Instrumentaiton and Detecor Working Group identified three areas that could serve as a basis for improving the state of scientific excellence in Africa.

11.4.1 A proposal for an International Center for Experimental Physics in Africa (ICEPA)

Within the Instrumentation and Detector working group a proposal for an "International Center for Experimental Physics in Africa (ICEPA)" was discussed in order to address the lack of experimental training facilities in Africa. Some ideas were sketched and then submitted as a LoI (#68). The LoI was also presented at a meeting of the Physics Education working group. The idea for such a school was born from the apparent lack, but high need for experimental education and know-how in most African countries. The concept is very much inspired by the African Institute for Mathematical Sciences (AIMS[15]) and the US Particle Accelerator School[28], as well as other educational centres like the Southern African Institute for Nuclear Technology and Sciences (SAINT[16]) or the Sèmè City[17] in Benin.

The proposed center would consist of a master-like curriculum of typically one and a half year, including a 6-month research project and would include high-level lectures with a major component on hands-on experiences. A final examination and a recognised diploma (the association to a university will be required in such case) would conclude the cursus. While the proposed training centre is conceptually very similar to AIMS, it focuses on experimental techniques used in physics and is strongly oriented towards instrumentation. For the latter, the idea is to build experimental installations and facilities at strategic locations on the African continent. The instrumentation could partially be contributed or donated by international collaborators and universities. These donors ideally should also take the responsibility to maintain the equipment, at least for the first years, until a local staff has been trained and qualified.

11.4.2 Small physics experimentation and the Internet of Things

Another very interesting and potentially powerful possibility with the goal to foster experience in instrumentation, is the intense use of micro processors and controllers for education. Furthermore, it is much easier to establish.

Most of today's physics experiments use sensors converting measured physical quantities into electronic signals, which are finally acquired and treated with computers. This means that skills in electronics, computer interfacing and programming are essential for an experimental physicist. Micro-controllers are mass produced[19] and for this reason they have become extremely cheap. This is a major advantage for countries with small budgets. On the other hand, these micro-controllers have become very powerful with many low-cost standardized interfaces like GPIO, I2C, I2S, Can bus etc.[20], but still with high precision. Examples of sensors easy to implement are:

- sht30: temperature and humidity sensor
- PlanTower pms5003 (sensor with laser technology measuring light deflection through dust particles)
- Analog devices MAX 2769 GPS receiver
- MPU6050 accelerometer and gyroscope
- and many, many more

Very divers experiments can be made for a few dollars using these devices such as:

- Medical measurements like ECG, heart rate, oxygen content in the blood etc.
- Environmental measurements like air or water quality
- Meteorologic measurements of air temperature and humidity, soil moisture, wind speed etc.
- Smart farming experiments
- and many more.

Some of the micro-controllers integrate network interfaces (Ethernet or WiFi, BlueTooth or GSM) allowing them to be connected to the Internet. Measured data can be transferred to servers and further analyzed and displayed there. These servers can give world-wide access to the measurement results. These are systems of type "Internet of Things"[18]. It is easily possible to provide documentation of experiments on the Internet using Wiki pages. The software needed for data readout, readout, analysis and communication with the Internet can be made available through github[21], allowing easy collaboration between groups of physicists working on similar subjects across borders. Unfortunately there are very few universities in Africa providing courses on the Internet of Things, despite the very limited budget needed to set up such a course and the great potential for the students they would have. Teaching digital electronics, data analysis, micro-controller programming of WEB programming would give the student chances in a wide range of industries also outside of physics.

11.4.3 Regional instrumental conferences

Regional conferences focused on instrumentation and detectors across different fields could be one way of enhancing the exchange of knowledge and expertise between scientists of neighboring countries and to stimulate new collaborations.

11.5 Conclusion, synergies with other fields and perspectives

After an enthusiastic start in 2021/2022 in the context of the ASFAP townhall meeting in the Spring 2022, the activities of the Instrumentation and Detector working group came to an apparent hold during the Summer 2022. Therefore the group could not guide the proponents of LoIs to generate White Papers. The activities also suffered from a lack of interaction with the other working groups, whose input is urgently required because instrumentation can only be developed in a global context of physics and education. Examples for the latter are the proposed instrumentation school (ICEPA) and the implementation of "The Internet of Things" into universities curricula. The mobilization of the African scientific community itself is still insufficient to develop a strategy and the proposed projects and to find African leaders as spokespeople for these.

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gpio: https://en.wikipedia.org/wiki/General-purpose_input/output
i2c specs: https://www.nxp.com/docs/en/user-guide/UM10204.pdf
spi: https://www.analog.com/en/resources/analog-dialogue/articles/introduction-to-spi-interface.html
i2s: https://www.nxp.com/docs/en/user-manual/UM11732.pdf
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12

Light Sources Working Group

SESAME Light Source (Synchrotron Light for Experimental Science and Applications in the Middle East), Allan, As-salt, Jordan- on leave from: Department of Physics, Helwan University, Cairo, Egypt

Preface

"Immeasurable studies have been implemented, many reports, models and calculations strikingly revealed that the atmosphere is warming, 16 of the 17 warmest years on record occurred since 2001 according to NASA, one 8^{th} of all species on the planet are at risk of being lost, 2.2 billion people do not have regular access to clean fresh water [1], forests disappear [2], oceans are polluted [3]."

Major catastrophes are queuing on clean water, food security, disaster management models, human health, climate change, sustainable energy, environment. In a recent article by Antje Vollmer [4], the author signifies that the most important focus is to be on how to answer the so many evolving questions and challenges facing the mankind, on how to get actions from science and in particular from the large-scale infrastructures. Vollmer summarizes the nature and importance of these facilities: as intrinsically international, inter-, multi- and cross-disciplinary and excellence driven – have possession of a fantastic triangle core of research, education, and innovation.

Light sources among such large-scale infrastructures present a spectacular scientific portfolio spanning from physics, chemistry, biology, new materials, energy research, pollution, food, medicine and pharma, engineering and smart materials research, to art restoration, cultural heritage, and paleontology. As a consequence, a growing user community is monitored both in numbers and in acquired skills and experiences, which paves the way to further developments and cooperation with a common goal to address the imposing challenges of the years to come.

Africa is not an exception in the human race of advancing science and technological grounds towards the implementation of the Sustainable Development Goals. Many challenges are accruing with an accumulative mode such as establishing and/or consolidating cutting-edge large scale research infrastructures, addressing the so many local and/or regional concerns, as well as strengthening industrial development for a sustainable economy. Into the discussion point, is an African Synchrotron light source offering plentiful scientific techniques to support extensive capabilities in basic science and applied science. This has been under-valued and under-resourced over the years. It is time to revive the vision that Africa must take its equal place as a co-leader in the global scientific process, along with all the social-economic benefits thereto. With a global prospective, a light source in Africa presents an ambitious international project that will provide a high-impact multi-disciplinary science and technology, and would represent a major step of science diplomacy towards the Pan-African vision and play an important role in stopping the African scientific diaspora, and perhaps even reversing it as the diaspora returns.

This report sheds some light on the vital importance of establishing an African light source facility that is projected to serve Africa -and beyond- with a strong involvement of young scientists and African diasporas. Consecutively, this aims at stimulating new partnerships between countries and organizations to together address the several mutual concerns of science, education, and economic development, with an impact that will robustly go beyond any "national" science.

12.1 Introduction and Motivation

12.1.1 General overview on Science Missions, challenges, and impact

In March 2024, the International Science Council, ISC, has launched the “Global Call for Pilot Missions and for Visionary Funders to support Science Missions for Sustainability” [5]. The Call aims at a universal action that is collectively projected to realize the United Nations Sustainable Development Goals, SDGs, as per the 2030 Agenda (Fig.12-1). The Call signifies a strategic proposal towards a transformative future for science and humanity. Such a determined objective towards collaborative and sustained actions necessitates a standardization of priorities [5].

Figure 12-1: United Nations Sustainable Development Goals, SDGs, as per the 2030 Agenda [13].

Additionally, a joint measure that can significantly alter science funding systems is intended in strengthening the science’s impact on realizing the SDGs. This imposes a fundamental transformation in our scientific thinking and practices on how we do conduct research, utilize and apply scientific findings, and how can we prioritize and allocate funding to tackle the most persistent challenges.

The ISC Call underlines the instance for which the science funders can play a leadership role in funding specific science grounds encouraging them to stepping out of “business-as-usual” approaches towards a worldwide renovation beyond traditional science models. This entails innovative strategies and collaborative actions on all levels. For instance, scaling up the investment in science to strongly support transdisciplinary and inclusive mission.

The ISC’s groundbreaking report - “Flipping the Science Model: A Roadmap to Science Missions for Sustainability” that was unveiled at the 2023 UN High-Level Political Forum, articulates such a looked-for visionary model. It points out at elevating tailored partnership between scientists and policy makers to new heights of rigid solutions that match the scale of the most critical challenges of complex sustainability via integrated and fully actionable knowledge [6].

Large-scale infrastructures supporting big science such as CERN was strongly supported by the scientific community. At the present time, the world needs to think with the same visionary CERN-mindset to tackle urgent existential risks, principally in the regions where the SDGs progress is lacking the most due to many inconsistent burdens arising from global encounters such as energy, water, food security as well as climate and health with the aim of advancing their equity and sustainability.

As per the ISC depiction, the "Science Missions for Sustainability" are defined as the scientific missions that vigorously engage with society to address multifaceted sustainability challenges by having defined goals, solution-oriented focus, and time-bound nature [6]. To endorse the anticipated transformational actions, the Science Missions are considered to be significant in scale, and by the determined application of inter- and transdisciplinary approaches (Fig.12-2). Furthermore, the conceived strategy that Science Missions must focus on societal, economic, and political aspects within each domain beside the technological innovations is also well-thought-out for which identifying the root causes and overcoming the several complications and obstacles are crucial steps towards a reliable and sustainable development.

Figure 12-2: Collective projection of Science Missions in realizing the UN Sustainable Development Goals [5].

Complex world situations require that both funding structures and time concrete plans are considered for a practical execution. With this, regional science hubs are expected to ensure that science is inclusive and up to standards. In its comprehensive report "Flipping the science model: A Roadmap to Science Missions for Sustainability", the International Science Council, has formulated a number of key messages: among them, taking the responsibility in funding science in a different way aiming at achieving long-term global sustainability goals. This entails furnishing supplementary mechanisms beyond the common practices of the traditional science model that is marked by the absence of trust with stakeholders, as well as toxic models of competition.

The ISC strategies regarding the criteria of Science Missions, and irrespective to their individual design and focus, present a set of objectives and expectations [5]. Illustrations of possible acts are listed below to contribute to the mission's co-design and implementation: a) Establishing mechanisms for regular exchange between all stakeholders, b) Building collaborations between science, decision-makers, and communities, c) Mobilizing existing scientific infrastructure and knowledge across disciplines and ensure the integration of the social sciences in shaping and implementing the missions, d) Enabling within- and cross-regional scientific collaborations.

In an attempt to cope with these objectives, the call aims at finding well-designed solutions convoluting local and global efforts which in turns requires extensive and inclusive collaborative schemes as well as an immense investment in multidisciplinary and interdisciplinary basic and natural sciences from the problem identification to the solution implementation [6]. The commission estimates "a collective investment of a billion dollars per annum that is not even 1% of global annual R&D investment would significantly accelerate the progress of the 2030 Agenda."

The tangible vision that Africa must receive its comparable spot as a co-leader within the global scientific arenas among its peers becomes more evident – in sharing equivalent responsibilities, commitments, and deliverables towards the global scientific societies. Africa is not an exception in the human race of advancing science and technological grounds towards the implementation of the Sustainable Development Goals. Many challenges are accruing with an accumulative mode such as establishing and/or consolidating cutting-edge large scale research infrastructures, addressing the so many local and/or regional concerns, as well as strengthening industrial development for a sustainable economy. Into the discussion point, are synchrotron light sources offering plentiful scientific techniques to support extensive capabilities in basic science such as physics, chemistry and biology, in consort with applied science arena including biomedicine, pharmaceuticals and drug design, agriculture, environment, air, soil, and water pollution, besides materials science and industrial applications, with an emerging focus on energy and climate change. Furthermore, comprehensive insights can be also identified in cultural heritage, archaeology and bio-archaeology domains [7].

In accordance with the above vision, it is fundamentally critical at this stage to signalize the unfair fact that Africa is the only continent that is being deserted without such an advanced technology of synchrotron light sources' infrastructures – this fact represents the core motivation of the Light Sources Working Group mandated by The African Strategy of Fundamental and Applied Physics, ASFAP [8, 9] to provide advice on strategies towards light sources in Africa, with considerations of compact light sources, synchrotron light sources, and other related topics relevant to an African context - e.g., capacity building. This reveals the importance of an African Light Source establishment to fulfill the vast scientific community's demands. Over and above, examining the major challenges and concerns in conjunction with the ASFAP relevant Working Groups wherever applicable.

A light source for Africa presents a rich opportunity for a regionally well-adjusted contribution within the worldwide economy (Fig.12-3). In the comprehensive report on light sources towards the Middle of the Century, Vollmer A. indicates that Africa will soon become the home to the best part of the world's youth expected to be a major part of revitalizing the economic circumstances in their respective regions [4]. A major statistic estimates that Africa as a whole has 169 scientists per 1 million people (cf. Europe 20 times more), undoubtedly infers that such a number has to be enlarged in order to realize a well-developed economy. A few orientations are furnished to attain that goal, such as a tangible investment in science and technology, facilitating international cooperation, and brain-drain circulation - at all levels.

Figure 12-3: The African light source is expected to promote local and regional research platforms, massive advanced human capacity building and employment in Africa. Additionally, it is foreseen to be a prominent mega-science techno-industrial and fundamental research facility. [10]

This reporting sheds some light on the vital importance of establishing an African light source facility that is projected to serve Africa -and beyond- with a strong involvement of young scientists and African diasporas, women scientists, as well as scientists from developing countries. Consecutively, this will stimulate new partnerships between countries and organizations to address the several mutual concerns of science, education, and economic development, with an impact that will robustly go beyond any "national" science.

12.1.2 Introduction to light sources, their scientific, economic, and societal impacts

Light sources, specifically, synchrotron light sources, have opened up vast opportunities for investigating different types of matter across numerous applications contributing to scientific progress and sustainable development.

Synchrotron radiation, emitted through the acceleration of particles at nearly the speed of light in a curved path, covers a wide range of electromagnetic radiation, including X-rays, ultraviolet, visible light, and infrared radiation. These properties make it a valuable tool for studying the microscopic world in various scientific fields, including physics, chemistry, biology, biophysics, life sciences, and material sciences. They also have practical applications in energy, pharmaceuticals, medicines, public health, agriculture, environmental studies, and energy storage. They not only offer insights into the present and future but also allow researchers to explore the past, including cultural heritage, archaeology, bio-archaeology, and palaeontology.

During the last decades, a huge increase in the use of accelerators-based techniques is witnessed in a wide range of scientific applications. In Europe alone, the number of synchrotron facilities has increased from only three facilities in the 1960s to 14 synchrotron sources and 7 Free Electron Lasers over 10 European countries in 2021 serving more than 24000 users per year leading to a drastic oversubscription of requested instruments [4]. Technically, light sources can foster initiatives and science missions that aim to dynamically involve developing regions mobilizing a broader community through larger international enterprises. This facilitates creating a healthy environment for joint collaborations, attracting scientists working abroad in an attempt to diminish – or to effectively reverse- the brain-drain gap, as well as, addressing local and/or regional concerns such as health, environment, water, pollution, human heritage among others. These facilities provide free access to scientific user communities that is exclusively based on the scientific excellence and merit. In this context, "light sources operate in a democratic mode, conventionally attained by using scientific cooperation to promote understanding between people from different traditions, religions, and political systems –Herman Winick".

The impact of advanced light sources on science and society in the developing world on addressing national and global concerns cannot be underestimated. In addition to facilitating awareness to benefit human well-being, science proved to be a valuable share of diplomacy — scientific cooperation to work on problems across borders and without boundaries, cooperation made possible by the international language and methodology of science. This strategy allows scientists to get beyond ideologies and form relationships that allow diplomats to defuse complicated political situations. Moreover, synchrotron light sources can frontward the traditional educational systems, the employment status, brain-drain reversal, besides the human capacity building which is alleged to be the backbone of any advanced society. Through collective brainpower and constructive partnerships and collaborations, establishment of light sources has begun in developing countries decades ago, now in operation, with upgrades, besides new facilities those are either under construction or in the planning phase.

With this, they advance, not only scientific discoveries, but also the predictable economic strength by developing different industries taking into account the scarce resources and incomes.

In Europe, almost all European synchrotron facilities have either recently done major up-grades or are planning to do so in the next decade. ALBA, BESSY II@HZB, DIAMOND, ELETTRA, PETRA III, and SLS (in alphabetical order) are planning up-grades, as well as MAX IV (Sweden), the ESRF (The European Synchrotron Radiation Facility) are back to service after a tremendous and innovative upgrade. As well, several non-European Synchrotrons are in the process of up-grading such as APS and ALS in the USA, CLS in Canada, SIRIUS in Brazil, SPring-8 in Japan [4].

Therefore, in an attempt to catch this wild evolving scientific and technical race of light sources around the world, African scientists – through collaborations, agreements and training fellowships – are also in a race with time to set up the first facility ever in the continent. In this contribution, the significant need of such facilities to the African continent is emphasized (Fig.12-4).

Figure 12-4: Distribution of synchrotron light sources around the world.

12.1.3 Motivation for establishing an African light source

The argument that Africa is facing numerous challenges cannot be misjudged. For several reasons, some of these challenges is common to the rest of the world, but others are distinctive and are regionally incomparable. This has affected all aspects of life and the future of the young generations together with an obvious underestimation of the standing of science grounds affecting thousands of African scientists and diasporas. In this regard, the establishment of an African Light Source (AfLS) can play a crucial role in the region, for the African community and elsewhere. The AfLS can open wide doors to scientists from all over the world to demonstrate their capacity and to overcome traditional and technical obstacles as much as they can. From this perspective, it can – and will- show credible contributions in improving and advancing societies towards the SDGs as well (Fig.12-5). In actual fact, African countries are already involved in numerous scientific activities and research programs in international light sources (Fig.**??**).

The straightforward objective of the ASFAP is to establish and to advance a capacity building in physics education and research being the case in other regions of the world. With no exception, scientific and economic challenges need to be addressed in African continent, with the dream that Africa, too, should take its equivalent identity as a co-leader in the global scientific arena. With this, the requisite of having the ASFAP has turned out to be indispensable for Africa. Among other working groups, there is the ASFAP Light Sources WG that is mandated to investigate, report, highlight, and advise on the necessity of establishing an African light source – the first of its kind in Africa.

One of the major outcomes, is the results of the assessment survey that was launched by the ASFAP Light Sources Working group. The survey aimed at collecting a considerate input from the African scientific community – and internationally-based community- on the case of founding an African light source. The subsequent purpose of the survey is to well prepare and establish collaborative research themes and angles.

Figure 12-5: Informative chart illustrating how an African Light Source can address all 17 United Nations Sustainable Development Goals, which are an urgent call for action by all countries. [10]

Recent statistics shows that one third of the survey's participants have previous experience in light sources facilities (Fig.12-6).

It is worthy to mention that 77.1% of the survey's participants are resident citizens in African countries, while 12.3% are African diasporas. Participants from nineteen African countries (Nigeria, Morocco, Kenya, Cameron, Senegal, South Africa, Ethiopia, Tunisia, Uganda, Algeria, Ghana, Sudan, Egypt, Ivory Coast, Zambia, Mozambique, Togo, Congo, and Sierra Leon. Participants from 13 non-African countries have also contributed to the survey. Specifically, from USA, India, Pakistan, Italy, Germany, Jordan, UK, France, Malaysia, Peru, Canada, Japan, and Portugal (Fig.12-7). The strong position of the African researchers having current/future synchrotron-related interest(s) is illustrated in (Fig.12-8).

In this reporting, some assembled inspirations out of the survey will be shared in the following sections. The expected scientific impacts of light sources have grabbed the attention of the participants, with this, their detailed motivations were provided into the survey as follows:

• Light sources technology must be more available and cheaper for all geographical areas in Africa and the world as it provides cutting-edge tools for advancing almost any branch of science,

• Highlighting the profile of the African Science, capacity building, local technology, local infrastructure, enhanced networks and participation in international collaborations, as well as bringing up a strong factor towards the African wealth,

• Supporting the Pan-African initiative of Africa having its own scientific light source,

• The critical requisite of new and practical solutions to human health and energy-related materials discovery and development,

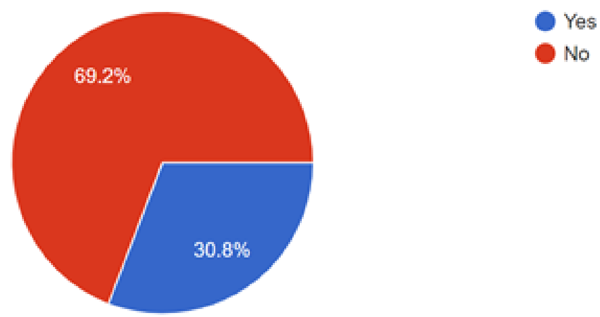

Figure 12-6: Outlook on the African scientists and researchers having previous experience in light sources facilities.

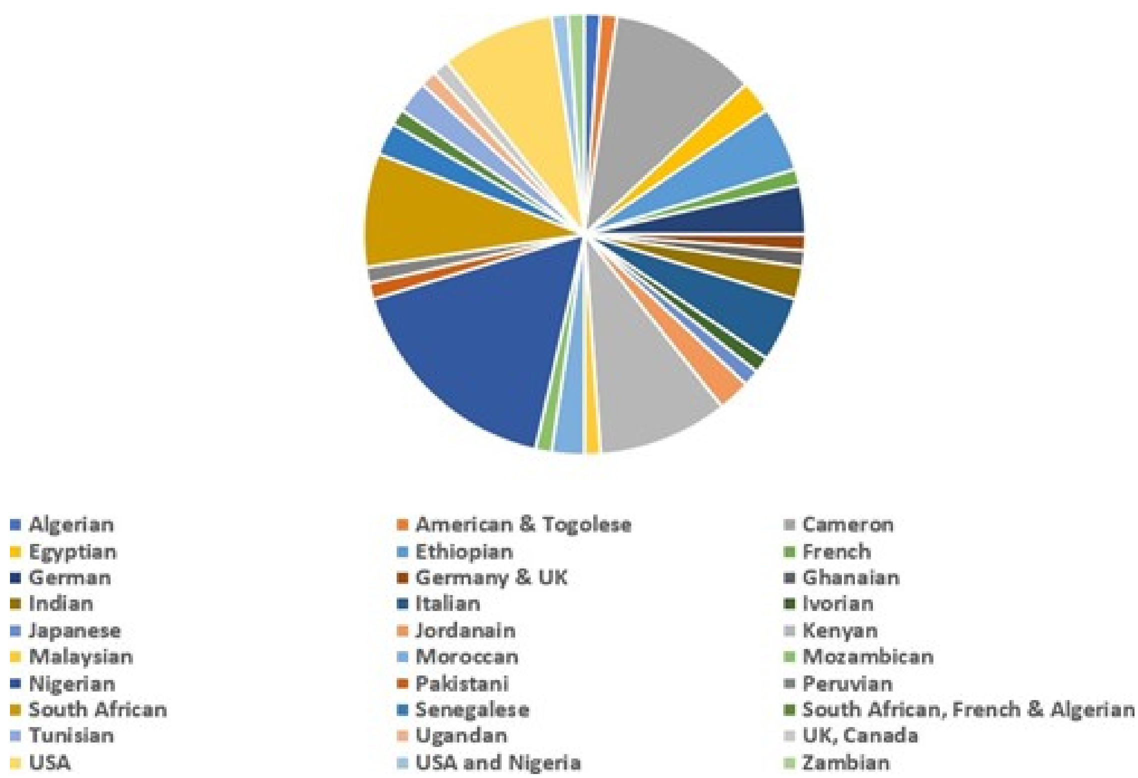

Figure 12-7: Nationalities of the participants responded to the ASFAP Light Source Working Group.

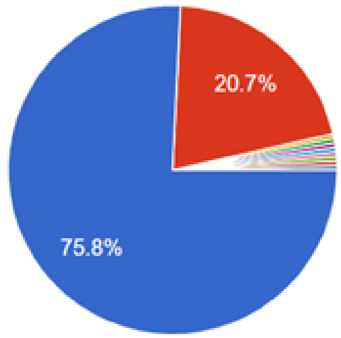

Figure 12-8: The position of the African researchers (75.8%) having current/future synchrotron-related interest(s).

- A light source facility will support many other research fields, providing a framework for central research and education in Africa. It will also attract the international community and boost the regional economy in providing jobs,
- Validating a sort of independence against exogenous markets and policy forces,
- Solving local problems with greater economic output, by means of light sources one can develop solutions and products to raise the balance of trade for Africa,
- Diversification of the types of research questions posed, particularly in medicine, energy and materials. Escape from European fixation on batteries and fusion,
- With the abundance of mineral resources in Africa, this is a great opportunity for further exploration and usage to get out of poverty. Additionally, discovering novel molecules capable of curing diseases and infections that affect the population,
- Fostering scientific and technological excellence; prevent or reverse the brain drain by enabling world-class scientific research; build cultural bridges between diverse societies, as well as education and capacity building,
- Increase number of publications in African countries,
- Addressing of brain drain and societal issues; Promotion of knowledge base economies,
- Transfer the know-how among the related countries, and bridging communities through collaborations.

12.2 Major challenges

There is no doubt that such global research infrastructures do have a strong impact on economy, food security, and disaster management. For this case study of the ASFAP Light Sources' survey, it was acknowledged that 73% of the participants expect societal impact of light sources in the form of establishing a common culture of knowledge, competitive local industry, entrepreneurship, and capacity building. 62.4% of the participants have declared an interest to be employed in a light source facility when established, which again, shows the genuine awareness and attentiveness to such an axis of national development (Fig.12-9).

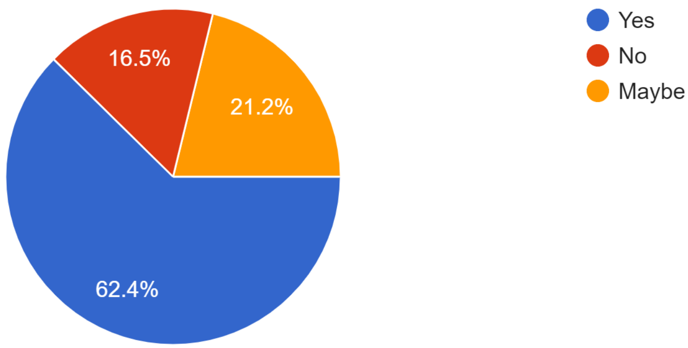

Figure 12-9: The segmented response of the African researchers showing interest in employment at light sources.

On the other hand, instituting a synchrotron light source often goes beyond the financial capacity and the allocated governmental budget to science - even with a dedicated initial budget- of a single country. Hence, it embodies a real bottleneck for the low economically-standing countries – for which is the circumstance of many African countries. Then again, the condition can be also deteriorating as a direct influence by the human capacity deficiency, that yet again, signifies the necessity to reverse the brain-drain issue.

Due to the absence of their national facility, some major obstacles and challenges are intensely facing the African Scientists when attempting to pursue scientific research in worldwide facilities in the interim of the making of the first African Light Source. Chief research requirements reported through the ASFAP survey on light sources are depicted in (Fig.12-10), and other challenges were communicated as follows:

- Lack of basic and/or preliminary research equipment in own country,
- Bureaucracy in the facility of destination, and/or bureaucracy in own country,
- Lack of funding schemes (travel and mobility, project expenses, etc.),
- Lack of training opportunities to develop the required professional skills,
- Lack of dedicated and qualified human resources.

12.2.1 Relevant scientific activities

Light sources provide free access to the scientific user community based upon scientific excellence and open data. Human health is a hot subject matter that requires multifold approaches and strategies from understanding the molecular basis of diseases, development of diagnostic approaches, and consequently to identify effective and affordable treatments. This is primarily initiated by studying to the development of diagnostic methods that leads to early preventive actions, to treatment involving innovative therapies.

Neurodegenerative diseases such as Alzheimer, Multiple Sclerosis, and Parkinson, degenerative medicine, diabetes and diabetic foot, Preeclampsia, cancer of all types, HIV, HCV, Malaria, wound healing, and

Figure 12-10: Difficulties facing scientists in Africa as has been raised by participants to the Light sources survey.

pharmaceutics are just a few examples to mention (Fig.**??**). Therefore, the challenge for the scientific community is to develop new and creative means for acquiring, processing and interpreting the complicated bio-molecular information involved with tissues, single cells or cells in a microenvironment, at cellular and sub-cellular resolution. Synchrotron facilities open the door for a huge number of biological and biomedical applications, where high spatial resolution and high-quality information are a must utilizing synchrotron radiation techniques such as Infrared microspectroscopy, structural biology, drug polymorphism, chemical and elemental mapping, micro-computed tomography as they and other techniques and modalities can render very specific, as well as, complementary information on relevant subjects.

For instance, the status of the human health in Africa represents a huge pillar of scientific research by African scientists and others. Many diseases are there to be investigated and treated. (Fig.12-11) sheds some light on some of the targets to be explored, while (Fig.12-12) indicates the leading causes of death in Africa recorded in 2019.

In addition to human health growing concerns not only in Africa but worldwide, it is also significant to retrieve some informative data on the prospect of the potential cross-disciplinary collaborations and links to light sources user-communities which may be achieved by creating multi-folds' links with academia and industrial sectors, as well as, initiating and/or strengthening the basic interdisciplinary collaborations in different scientific activities. Results of the survey showed the following aspects in which a light source facility can serve communities in various disciplines:

• Materials for Energy systems, biomedical engineering, and plant molecules exploitation,

• Drug discovery and materials development - including different vaccine development,

• Agriculture where chemists will synthesize and crystallize fertilizers for crop production, and new techniques to be applied to new fields such as imaging for paleontology, archaeology, optics and photonics, pharma, etc.

Amongst the research interests and scientific activities those were favored by the participants of the survey came on top the basic and/or applied science, followed by life sciences, materials sciences, cultural heritage and archaeology, accelerators' physics and technology, optical instrumentation, beamlines development, as well as experimental instrumentation and data analysis approaches. A thought-provoking input was also attained by the fact that 76% of the researchers and students opted for current and/or future synchrotron-related interests.

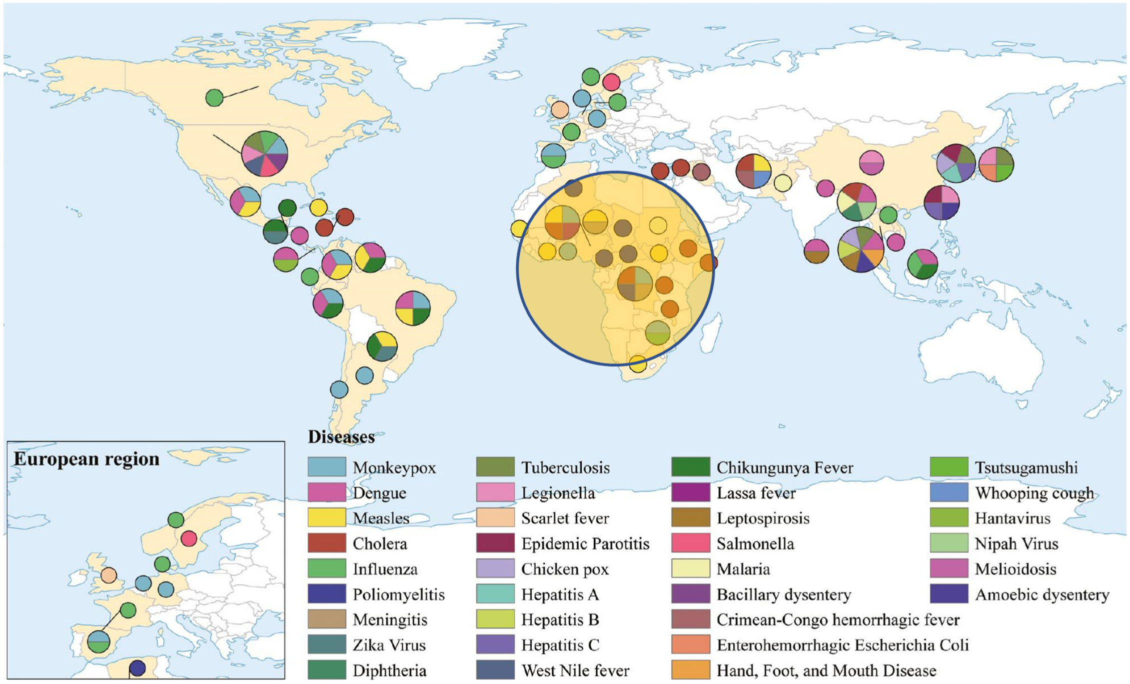

Figure 12-11: Global Infectious Diseases in January 2023.

(Fig.12-13) shows the required synchrotron techniques, which confirms the necessity of establishing such a facility. Moreover, geographical distribution, collaborations with other research institutions, access to remote databases and software, as well as advanced instrumentation, were assigned as higher priorities for research chief requirements. 70% of those who participated showed a previous experience in light sources facilities, while 61% opted for a looked-for employment given the opportunity and depending on qualifications.

Besides, 88% opted for their willingness to initiate interactions on different axes of collaboration and assistance with other African groups. Additionally, 81% marked their need for advanced training regarding the general use of such available infrastructures, with a descending order of financial, technical, and scientific support.

The participants were also invited to provide their insights on what sort of changes are essential to allow better use of networking facilities to improve the current scientific activities. Some collected opinions were as following:

• The urgent need to highlight the scientific impact of using synchrotron facilities and addressing what kind of research could be conducted in such facilities,

• Design specific outreach activities targeting the undergraduate students,

• Scientists everywhere have challenges with stable funding, it is likely more acute in Africa than in the US, EU and Asia,

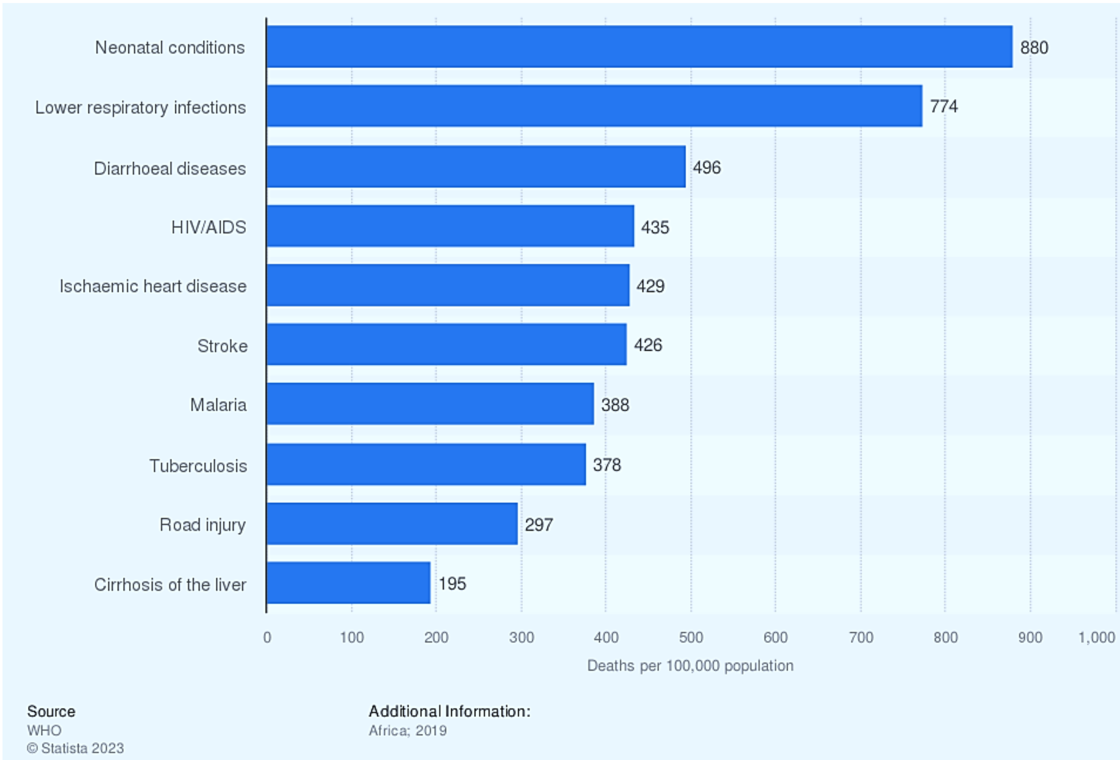

Figure 12-12: Leading 10 causes of death in Africa in 2019 (in deaths per 100,000 population).

- Establishment of more local facilities with clustered partnerships (Intra-continental and extra-continental), and sharing equipment available in Africa cross countries and/or within a single country through its different institutions,
- Launching dynamic collaborations to expose the underprivileged institutions,
- Building Bilateral/multilateral agreements within Africa via major international agencies.

12.3 High-priority future needs

Aligned on the broad perceptions indicated in the ISC reporting on the new models of science for sustainability, and in the context of the climate emergency and the imperative energy transition, a central question arises about the science-informed solutions if they are satisfactorily practical and acceptable by governments and society. This kind of challenges necessitates a sort of integration of technical and climate sciences alongside social sciences. However, a further critical question arises: are policy-makers, civil society, and the private sector sufficiently engaged with the science system to identify the most urgent research questions in the beginning? [6].

It is important to refer here to the report [6] in identifying the importance of "... committing resources to the process of co-defining issues and co-implementing solutions by scientists, policymakers, funders and other

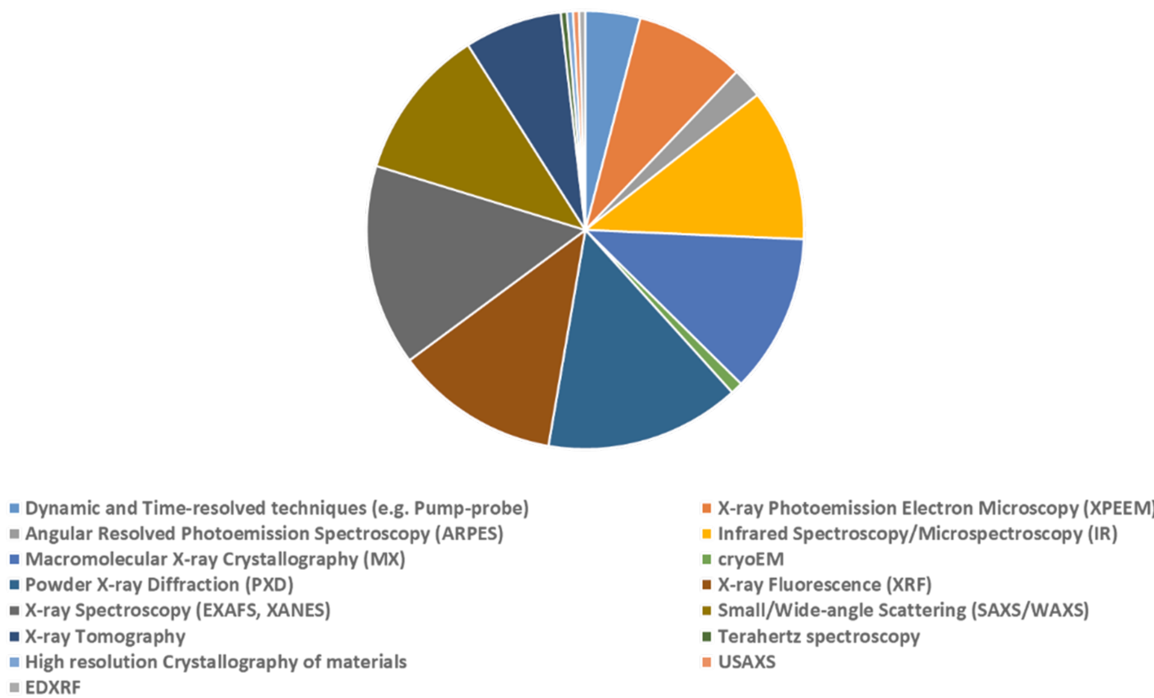

Figure 12-13: Favorable techniques reported through the ASFAP survey on light sources.

relevant stakeholders rather than focusing on narrow, predefined or singular outputs and outcomes alone by scientists alone. Ultimately, their goal is to deliver the 'how' not the 'what' of science for sustainability, by promoting a viable model for global cooperation which addresses complex local and regional challenges in service of a more sustainable planet and a dignified future for humanity." Accordingly, the focus of the discourse must now shift from 'what' to 'how,' identifying the mechanisms needed to fund and achieve the desired outcomes.

12.3.1 Prioritized domains and their motivations

The scale and long-term nature of the science missions would require pooling and matchmaking of financial support by different funders as demonstrated by the ISC reporting on flipping the traditional model of science [5, 6]. This would best be accomplished through a central fund created by all participating funders and partners, or regional funds, or instead, by dedicated hub funders. As it the case of founding an African Light Source, this implies a fundamental shift in how science is funded.

It is valid and binding more than ever to consider that engaging the end-users is essential to ensure the research is designed to generate actionable knowledge and develop a plan for its uptake. However, the evidence suggests that the existing funding mechanisms often fail to recognize and transform complex systems underlying sustainability challenges. That is, the detailed report of the ISC calls for stakeholders to unite around these challenges, and sends out another thought-provoking question: "Science has a vital brokering role in co-creating solutions to the current sustainability problems. The question is how." One possibility could be to bring together the best of global science in dedicated full-time multidisciplinary hubs that can serve as good facilitating environments for Sustainability Solutions Teams, with adequate financial support and institutional shielding to deliver not just knowledge outcomes, but also action outcomes.

As a general reflection, diverse considerations can embody the aforementioned case of establishing a light source in Africa as a high priority, such as the next major drives are elucidated in the next section.

12.3.2 How can light sources tackle priorities and the future needs of Africa aligned with the SDGs?

To address the above multiple challenges and more, a huge demand in the implementation of cooperative models is evidently viewed. In addition to their scientific and technological advancements, synchrotron light sources proved to convey a valuable segment of diplomacy — that is based on scientific cooperation ceasing complications across borders. Through them, collaborations were made possible only using the neutral language of science. This in line, can encourage new partnerships on the national and international levels to address mutual demands of scientific and societal challenges, and education and economic development as well. Additionally, there are indirect impacts that come along those cannot be underestimated. Some examples are illustrated as follows:

• Establishing a world-class and applied research interdisciplinary research laboratories,

• Addressing the many local and regional concerns (for instance; human health, environment, materials and energy, cultural and human heritage, etc.),

• Providing a vigorous environment for successful collaborations and allowing the essential space needed for individual career development,

• Attracting African diasporas thus drawing back the brain-drain alarm and in the same time resolving the internal brain-drain to other sectors as well, this is the case as the majority may tend to target other fields rather than natural sciences or engineering where the remuneration for jobs in economy for example are much higher than for scientists and with many excellent young scientists choosing such more profitable careers,

• Training and preparing graduate students who will no longer need to go abroad to industrialized countries, which implies a minimum of infrastructure and some interesting projects to take place and to be constantly developed in the home country and/or region,

• Promoting development of high¬-tech industry (capacity building),

• Based on several statistical figures, one of the most important aspects to be also tackled is the gender balance concern. Light sources have also shown to be effective in reducing such a gap as much as possible being an open and flexible environment that is based only on scientific merit and skills.

12.4 Synergies with neighbouring fields

"Science and research being intrinsically international will further intensify all efforts of interdisciplinary, multidisciplinary, cross boundary cooperation – also in an institutionalized way – to help solving the major challenges of the next decades" – Antje Vollmer.

Light sources are one of the best examples of an open and multidisciplinary research infrastructure. They provide strong opportunities for integration through networking and cost-sharing, as well as promote multi-disciplinary collaboration with the wider global community, while promoting science diplomacy and peace at large. Moreover, environmental problems, advanced materials, cultural heritage valorization are all complex issue intrinsically involving cross-disciplinary collaboration.

As depicted in (Fig.12-14), light sources can serve communities in various disciplines such as materials physics, atomic and molecular physics, biophysics, optics and photonics, pharma, materials and energy systems, biomedical engineering, and plant molecules exploitation. With this strong basis, it is well-comprehended and highly recommended to set synergies of collaboration and strategies between the neighboring fields of ASFAP Working Groups. To mention a few, the Light Sources WG has a great share of integrated activity planning with the ASFAP Accelerators, Biophysics, Earth Science, Energy, Materials, and Medical Physics working Groups [12].

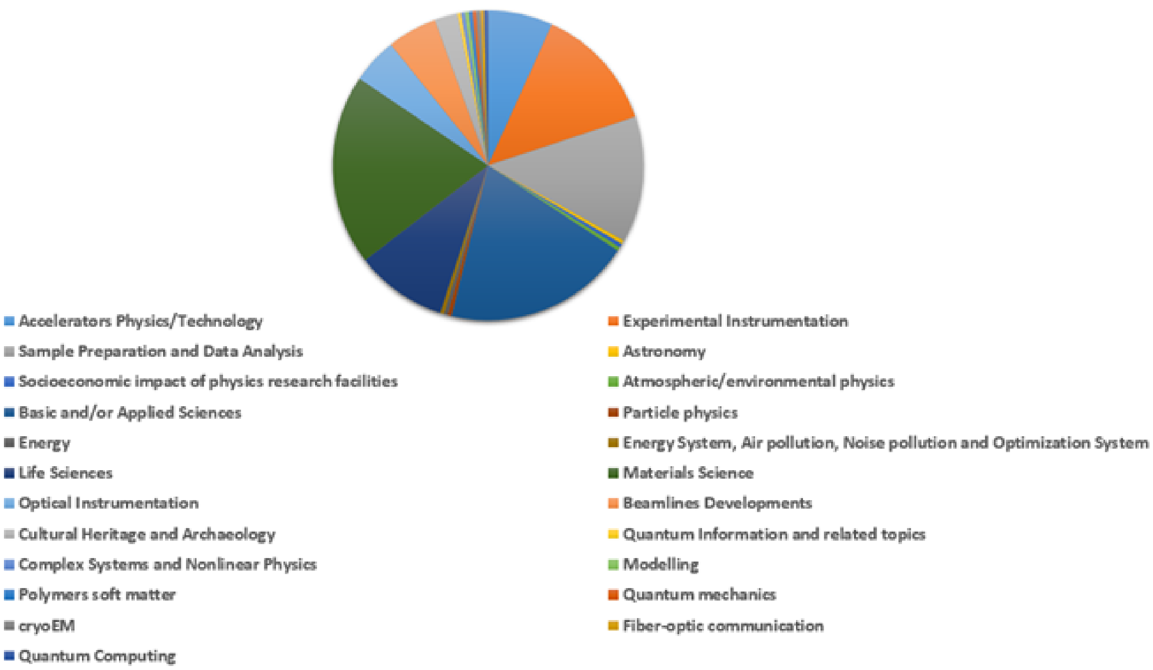

Figure 12-14: The scientific communities that light sources can be of great assistance, in addition to the ASFAP defined Working Groups.

Accordingly, there is a robust impact of convolution with close fields demonstrated by the clear need to have a research large-scale infrastructure in Africa, specifically an African light source to cope with challenges that Africa is facing. For such projects, it is always vital to gain some insights from the scientific community in all scientific domains on how can African countries join forces to overcome the major challenges to establish its own light source. Below are some of them:

• Reaching the Critical Mass. Ensuring mobility, training, and enrollment of large multi-skilled young scientists through workshops and conferences and funding,

• Establishing common and joint infrastructures to be that can be shared among all scientific communities, with this, instituting centers of excellence, sharing experiences and complementary equipment are also vital targets,

• Developing a concrete strategic vision for a light source facility - Engaging complementary domains which may better convince policymakers and the international community to support such a vision,

• Co-leading an intense educational system on the research capabilities of integrating light sources and their importance to scientific revolution in Africa,

• Investing in the science that drives light sources in the rest of the world, e.g., to solve local health challenges such as malaria, famine and technological advancement,

• It is only through scientific discoveries and common research activities that tackle preexisting problems and those raised by the side effects of technologies can be met.

12.5 Policy making and societal impact

Synchrotron facilities play a vital role in fundamental, applied, and industrial research, driving technological advancements and fostering collaborations across boundaries. Equally, the establishment of a synchrotron light source in Africa has significant potential for scientific progress and socioeconomic development.

Enormous potential lies at the very thin interfaces between governmental policy makers and the funding agencies/sectors and between science and its users.

Based on the launched survey, the participants have provided some insights on the high priority needs, for example, the participants have demonstrated a number of concerns that may be considered for setting a practical strategy for founding an African light source in Africa:

• In Africa, this might have to be done on region basis to develop a major science facility policy in general (as part of STI policies, respectively), and a light source policy in particular, which can be then developing joint policies given other conditions, e.g. transportation routes. Such policies may be furnished in cooperating with the African Union and/or other African institutions,

• Designing collaboration themes as well as joint funding programs to meet the expenses of such a huge infrastructure to establish the first African Light Source,

• African governments can also seek joint funding partnerships that involve the private sector,

• Mutual cooperation in top-down and bottom-up organizational patterns. Herein, the participants point towards the fact that it would be hard to strongly justify ”bottom-up” approach without the realization of the concrete evidence of current and/or near-future demands - The multinational aspect of such a project should not be forgotten - coming under the umbrella of a Pan-African society such as the AU or perhaps a regional one like SADC, ECOWAS, etc. is an important parameter in setting up mutual/eventual decisions,

• Raising awareness among African Heads of State and the African Union on the need to implement their light source for controlled and therefore sustainable development. With this, a scheme of mutual cooperation in bench-marking degrees, entry visas, mobility programs and exchange funds is highly beneficial.

12.6 Conclusion and perspectives

Science is striving to keep pace with the sustainability challenge, yet it has largely relied on a traditional model. As expressed in numerous reports and studies, more must be done. Additional modalities and tailored strategies are yet needed for science to effectively lead to actions.

Aligned with this pattern, it was thoughtfully expressed and planned in the new ISC Global Commission calling for Science Missions to design practical models to ensure the integration of science within other perspectives and with different domains to better achieve the 2030 Agenda.

As demonstrated in the previous sections, light sources are the best example of an open and multidisciplinary research infrastructure that can effectively deliver the required incorporated themes. They provide strong opportunities for integration through networking and cost-sharing, as well as promoting multi-disciplinary collaborations with the wider global community, while promoting science diplomacy and peace at large. Moreover, environmental problems, advanced materials, cultural heritage valorization are all complex issues those intrinsically involve cross-disciplinary collaborations.

Nevertheless, and as tremendously displayed, thousands of science examples can demonstrate the massive contributions of light sources to solving the challenges of the years and decades to come. However, these facilities do not see themselves as self-sufficient. For thousands of users from academia and industry, with intense cooperation between research institutions and universities throughout a wide range of scientific disciplines, they can be considered as crystallization seeds for multi- and interdisciplinary work, as well as acting as hubs for transnational scientific liaison.

This is highly considered -and without exception- for light sources-related methods with relevant techniques based on microscopes, ion and other particle beams, neutrons, lasers and high magnetic fields.

In conclusion, there is more to science than theories, experiments, and abstract knowledge. There is the responsibility to bring the world closer together for the benefit of humanity for - at least- the next generations in Africa and the whole world - if not for us as well. For peace. For justice, fairness and equal opportunities. Light sources are sources of radiation, yet, they are also sources of hope for a better future – where only the scientific merit does control our fate.

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13

Condensed Matter and Materials Physics Working Group

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13.1 Introduction and Motivation

In 1956 John Bardeen, Walter Brattain, and William Bradford Shockley were awarded the Nobel Prize in Physics *for their research on semiconductors and their discovery of the transistor effect.* Their discovery is considered as a milestone in Human civilization as it opened the way to the development of the modern technology. Without the chips manufactured from semiconducting materials, one needs to imagine life without computers, communication systems, healthcare and medical devices, transportation and automotive technologies, energy generation, home appliances among others.

Humanity is now entering a new technological era marked by the quantum revolution including but not limited to quantum computing, quantum sensing and quantum encryption. *The quantum era is arriving, and it will be transformational!* [56].

Regarding its huge industrial and security impact, quantum technology has rapidly reached the realms of policymaking. A Furious international race will soon emerge to master the fundamental concepts of quantum computing and to find suitable platforms to build quantum-bits (qubits) the elementary block of a quantum computer. Recently, many countries and international organizations have adopted their national quantum strategies, where a key policy objective is manufacturing quantum computers with improved error correction. To achieve this multidisciplinary objective, worldwide Condensed Matter Physics (CMP) community is devoting great efforts to study existing material candidates and predict new possible materials including two-dimensional (2D) systems, superconductors, topological materials... Beyond the realization of quantum computers, CMP community is mainly focusing on the fundamental concepts of quantum computing, quantum sensing, quantum metrology...encompassing various efforts in engineering, computer sciences, atomic-molecular and optics (AMO) and photonics.

Condensed Matter Physics is a highly interdisciplinary field of research attracting more than 46% of the Physicists in the world [57]. It aims to understand the properties of the condensed phase of matter characterized by a large number of interacting constituents, which covers solid, liquid, soft matter, optical lattices of cold atoms, classical and quantum matter, complex systems including economical, biological systems... CMP is at the basis of the modern and nano-technology and is a keystone in the development of new technological era. Based on fundamental and innovative applied research, CMP provides not only new fundamental Physical concepts but also cutting-edge experiments to explore and control matter at different scales ranging from the atomic and nano-scale to the mesoscopic and macro-scale.

CMP is a tumultuous evolving field with a strong overlap with Materials Physics (MP), a Physics branch focusing on the synthesis, characterization and exploration of materials for applications in diverse fields as energy, biology, medicine, environment...

Beside the quantum computing race, many countries across the world are heavily investing in CMP&MP, to realize on-demand semiconductors, so-called the New Oil [58], and which are required for the cutting-edge technological devices. This *Chips* race, led by the United States and China, is not limited to silicon-based semiconductors but includes emergent 2D materials and in particular graphene[1] and its heterostructures, transition metal dichalcogenides, etc.

To stay in this chips race, Europe has mounted a variety of flagship and reserach supporting programmes including the European Alliance on Semiconductors [59], the Graphene Flagship [60], Research & Innovation programmes on Chemicals and advanced materials [62], European Chips Act [61], etc.

The natural question which arises at this point is about **the position of Africa in this global tech race**.

As mentioned in Ref. [63] *Africa is far behind in semiconductor technology, despite some glimmer of hope in countries such as Kenya and South Africa.* But, ironically, *many of the minerals used in semiconductor chips are indeed from Africa.* [63]

Africa is lagging behind in the global research activities in CMP and advanced materials which are intentionally designed materials with on-demand properties meeting the technological requirements of specific applications [64].

Africa needs to catch up with the worldwide tech race to avoid a further marginalization and to take advantage of its natural resources which are still exploited by non-African countries without benefits for the Continent [65].

Therefore, **fostering CMP and MP research for tech applications becomes crucial** not only for the economy development of the Continent and its sustainability but also for geopolitical challenges raised by countries heavily investing in technology.

Consequently, establishing an **African strategy for the future CMP and MP research policy** is substantially required as an evidence for Africa commitment in joining the global tech race and insuring its economical sovereignty and geopolitical security.

In this contest, the working group on CMP and MP (WG-CMP&MP) has been created within the ASFAP to come out with a **road-map for the future research plans in Africa in the area of Condensed Matter Physics and Advanced Materials**. This road-map is based on the outcomes of several open meetings and workshops with researchers from different African countries and from diaspora, and on the analysis of the received LOIs and responses to surveys. The long-term discussions involved more than one thousand African researchers at different career levels: Heads of research centers, stakeholders, startup founders, permanent researchers, postdoc fellows, Ph.D, Master and Bachelor students, etc.

The objectives of the present strategy can be summarized as follow

[1] Graphene, known as the wonder material, is the first 2D crystal discovered in 2004 by Geim and Novoselov who have been awarded the Nobel Prize of Physics in 2010...

- Identifying the challenges forming the greatest barriers to promote research and innovation in CMP, Advanced Materials, quantum technologies and related topics.
- Identifying the strategic areas of research in CMP and MP where Africa should invest to join the global technological race.
- Identifying the priority actions to bridge the gaps at the Educational and research levels.
- Setting a clear guideline for the future development of research and innovation in CMP and MP in Africa within a scientific and economic win-win approach.

13.2 Major challenges

Condensed Matter Physics research is critical for technological advancement and economic development globally. However, many African countries face challenges in investing adequately in CMP due to limited resources. The main challenges faced by physicists across the continent in the field of CM and MP can be categorized as follows:

- **Education**
  - Unreliable educational background

    For a successful catch-up, learning is the key for African countries considered as the 'late-latecomers' to industrialization and technology [66]. However, learning in CMP&MP with an international standard requires strong background in Physics, Mathematics, computing, and good knowledge in chemistry for students willing to pursue an experimental research career. However, in the most African countries the curricula in the Bachelor and Master levels are far below the international standard requirements [67].
  - Limited Master and Ph.D programmes

    In Africa, the majority of Bachelor students in Physics have not the opportunity to be enrolled in Master and Ph.D programmes in CM and MP. Except South Africa and certain North African countries (Algeria, Tunisia, Morocco, and Egypt), teaching Physics in several African countries is limited to basic concepts without any connection with ongoing international research activities [73]. The gender balance is also an issue. Girls are less likely to pursuit a Master or a Ph.D programmes in CM and MP as it is depicted in Fig. 13-1 showing the gender and age distributions of the participants to the survey launched by the WG-CMP&MP. All the African grouping regions have been represented in the survey as shown in Fig. 13-1(c).
  - Limited number of qualified researchers/trainers

    When African universities decide to set-up programmes in CMP&MP at the graduate levels, there may often not be qualified teachers and trainers fulfilling the international standard requirements. Several topics, including quantum information, modern computational techniques, advanced materials, etc. cannot be covered in the curricula of the majority of African universities. These topics, among others, are already included within the Master programmes running since several years in several international universities.

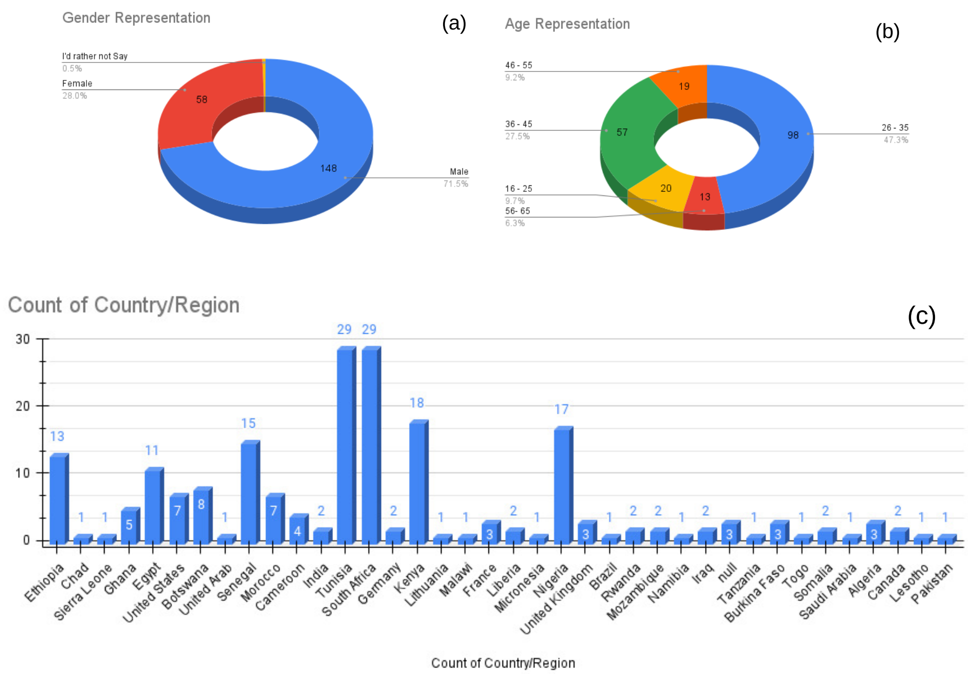

Figure 13-1: Statistics of the online mini-workshop organized by the CM-WG. (a) The gender participation ratios. The age (b) and country (c) distributions of the attendees [74].

Some African countries may propose training terms in international institutes for their teachers and students to perform themselves in specific topics. However, travel and visa application can be a nightmare for an African researcher and in particular students. On the other hands, it is usually difficult to raise funds to cover such visits. When grants are available, they are often not sufficient to cover the life-cost in US, Europe and Asia and researchers need to undertake endless bureaucratic procedures.

– Limited teaching equipment

Offering a successful Master and Ph.D programmes in CMP&MP requires several hands-on sessions in computation Physics, lab sessions, training in materials synthesis and characterization using research equipment etc. With the exception of South Africa, these key-stone training programmes cannot be implemented in the most of the African universities regarding the irregular power supply, the lack of computer facilities, the unsteady internet connectivity, the absence of clean rooms and the basic research equipment for Materials Science.

– Unemployed Physicists with Ph.D in CMP&MP

In most of the African countries offering Ph.D programmes in CMP&MP, the majority of the PhD holders end up unemployed. As noted in one of the submitted LOIs, *"this can be linked to a lack of innovations: most graduates nearly add no value to the companies they are employed in, regardless of whether they graduated with upper honors from the university or not. This is*

due to the fact that the quality of our research facilities is going low and the time taken by most university professors to offer quality research is low since the learner-teacher ratio is high" [103].
Some of African PhD holders in CMP&MP manage to have postdoc positions in North America, China and other Asian countries but most of them may remain jobless for several years.
At the international level, there is *"a PhD factory"* in developed countries and *"supply has outstripped demand although few PhD holders end up unemployed"*. [68]. However, there rarely unemployed physicists [69, 70, 68] since if they do not manage to have a full time job in academia, they are absorbed in industry which is the largest employment base for Physics Ph.D holders. This change in career pathway is made possible since Ph.D students, in developed countries, acquire during their academic journey several skills opening the way for well-paid jobs beyond academia [70].

– Career Progression Barriers

The primary role of lecturers in government-funded universities is teaching, leaving limited time and resources for research activities. This teaching-centric approach hampers the development of a vibrant research culture within academic institutions. Furthermore, most African countries suffer from limited or absent research positions, which creates barriers to career progression. Without recognition and support for research contributions, lecturers face challenges in advancing their academic careers and gaining international recognition.

– Brain Drain
Most African countries allocate minimal resources to scientific research, resulting in underinvestment in CMP infrastructure, equipment, and human capital. The lack of such funding and career opportunities drives talented CMP researchers to seek employment abroad, leading to a loss of expertise and a brain drain phenomenon.

- **Research**

– Challenges with existing research infrastructure

For experimentalists in CMCMP&MP, there is a big need for synthesis and characterization facilities, including equipment for producing nanostructured materials.
In Africa, there are a few hot spots with upgraded instrumentation as

∗ **In South Africa**:
The Centre of Excellence in Materials, Energy and Nanotechnology (CoE-MEN) is hosted by the University of the Witwatersrand (South Africa) and set-up by the African Research Universities Alliance (ARUA) Materials, Energy and Nanotechnology (CoE-MEN) - ARUA [79].
The CSIR-hosted National Centre for Nanostructured Materials (NCNSM) focuses on the modelling, synthesis, characterisation and fabrication of new and novel nano-structured materials with specific properties National Centre for Nano-structured Materials — CSIR [80].
NRF - iThemba Laboratory which is a national facility for pure and applied research, development and training in Accelerator based Sciences. It's Materials Research arm hosts the UNESCO-UNISA Africa Chair in Nanosciences and Nanotechnology and the 3MV Tandetron laboratory for research, modification and characterization of materials using low energy ion beams, add other centres in ZA. Home — iThemba LABS (tlabs.ac.za)
Department of Science and Technology/Council of Mineral Technology (DST/MINTEK).
Nanotechnology Innovation Centre (NIC) [25] which is geographically spread across the country with activities aimed at addressing national priorities highlighted by both the national

nanotechnology strategy and the national research and development strategy. The Mintek NIC structure was built on the foundation of the national system of innovations (NSI) to focus on driving South Africa's transformation from a resource-based economy towards a knowledge-based economy using nanotechnology.

∗ **In Egypt** The centres for Imaging and Microscopy and for Nanotechnology at Zewail City of Science, Technology and innovation (Egypt) [81]

∗ **In Morocco** The Advanced Materials Pole at the Moroccan foundation for Advanced Science, Innovation and Research (MAScIR) where research activities in the fields of materials and nanomaterials are oriented towards applied research and innovation [82].

∗ **In Algeria** The Research Center in Semiconductors Technology for Energetic (CRTSE) devoted to materials sciences and technology with applications in energy conversion, photovoltaic and storage, sensing, optoelectronics and photonics [83].

∗ **In Tunisia**: The Research and Technology Centre of Energy (CRTEn) is a R&D structure focusing on semiconductors Sciences for applications in photovoltaic cells [84].
The centre of Research in microelectronics and nanotechnology foreseeing the synergy between Materials science and microelectronics [85].

∗ **Botswana**: The Botswana Institute for Technology Research and Innovation (BITRI) which hosts the Centre for Materials Science (CMS) [32]. BITRI hosts a state of the art facility for conducting research and development in mineral beneficiation, biotechology, materials science and nanotechnology.

∗ **Mauritius**: The Centre for Biomedical and Biomaterials Research (CBBR)[37]. It is the University of Mauritius Pole of Innovation for Health which hosts the biomaterials, drug delivery and nanotechnology units.

∗ **Uganda**: African Centre of Excellence, Centre of Materials, Product Development and Nanotechnology (MAPRONANO ACE) at Makerere University. The Center was developed out of the need to strengthen research and training in the thematic areas of materials science and engineering, nanotechnology and nanomedicine in order to develop human resource capacity in applied science engineering disciplines for the development of the great lakes region. http://www.mapronano.mak.ac.ug/

∗ **Rwanda**: East Africa Institute for Fundamental Research (EAIFR) which is a partner institute of the Abdus Salam International Centre for Theoretical Physics (ICTP) and it is also a Category 2 UNESCO institute. The institute is located at the University of Rwanda. Its main areas of research and teaching include Condensed Matter Phyiscs, Physics of the Solid Earth, High Energy, Cosmology and Astroparticle Physics. About Us — EAIFR (ictp.it)

∗ **The African Materials Research Society (AMRS)** [104] was launched in 2002 to establish and strengthen collaboration between the USA and Africa to promote the materials research capacity in Africa. Among other initiatives, the main meeting of the AMRS is a series of biennial international Conferences that are hosted in the different countries within the five regions of Africa to bring together scientists, industry researchers and Government representatives from the USA, Africa and the rest of the world. The objectives of the society are;

  · To promote excellence in all aspects of materials research in Africa through creating a platform for maximizing collaboration that will ensure that experts in the field work together.

  · To ensure that materials research contributes significantly to the various national strategies for social equity and poverty alleviation in a constructive and sustainable manner by engaging the governments, industry, universities and entrepreneurs among other organizations that can promote awareness of the benefits of materials science in everyday life.

- To work closely with governments and state structures to develop appropriate policy and support for materials research and development.
- To build a network of materials researchers which encourages multinational and multi-disciplinary collaboration in materials research both with in Africa and between African Researchers and the rest of the world.
- To identify and foster specific areas of materials research as appropriate in the different countries or regions of Africa.
- To promote information and resource sharing, exchange and development in materials science by actively engaging the representatives of the five regions of Africa so that they can provide information to the secretariat office which will communicate through the website and newsletters.
- To regularly host meetings, symposia and conferences with a view to promoting dialogue between materials researchers within Africa as well as with researchers outside the continent.
- To encourage downstream materials manufacturing and value adding activities in all countries in Africa.
- To strengthen the facilities and other resources for materials science in the further and higher education sectors. [105].

However, the available equipment, in most African countries, is old or defective, this is compounded by the fact that there is a shortage of trained technicians for maintenance. Getting dysfunctional equipment fixed is often unduly cumbersome and bureaucratic. Furthermore, African laboratories cannot afford upgraded instrumentation due to a lack of funds [73].

For theorists using computational techniques, the main challenge is finding computational facilities as high performance computers (HPC) or at least powerful workstations, to perform computationally intensive calculations. Such facilities are not available in the most of African countries. On the other hand, many numerical calculations need to be operated with commercial codes which are not affordable to many research laboratories. To use such codes, researchers need also to be enrolled in training programmes and workshops to keep being updated related computing techniques. However, African researchers are mostly left to their own resources and backgrounds, which is at the origin of the large gap between the research outcomes in computational Physics of African labs and other international research institutes.

There are a few attempts to boost computational Physics in Africa.

* HPC facilities are provided to researchers in South Africa [86], Egypt [87], Algeria [88]. The National Center for Scientific and Technical Research (CNRST) provides the Moroccan scientists with a remote-access to HPC [89].
* The annual African School on Electronic Structure Methods and Applications (ASESMA), organized by ICTP, offer the young African researchers an introduction to the computational electronic band structure and other atomistic simulation methods[75, 76, 77]

Figure 13-2 clearly shows the huge lack in equipment for African researchers in experimental and theoretical CMCMP&MP.

– Challenges with communication and dissemination

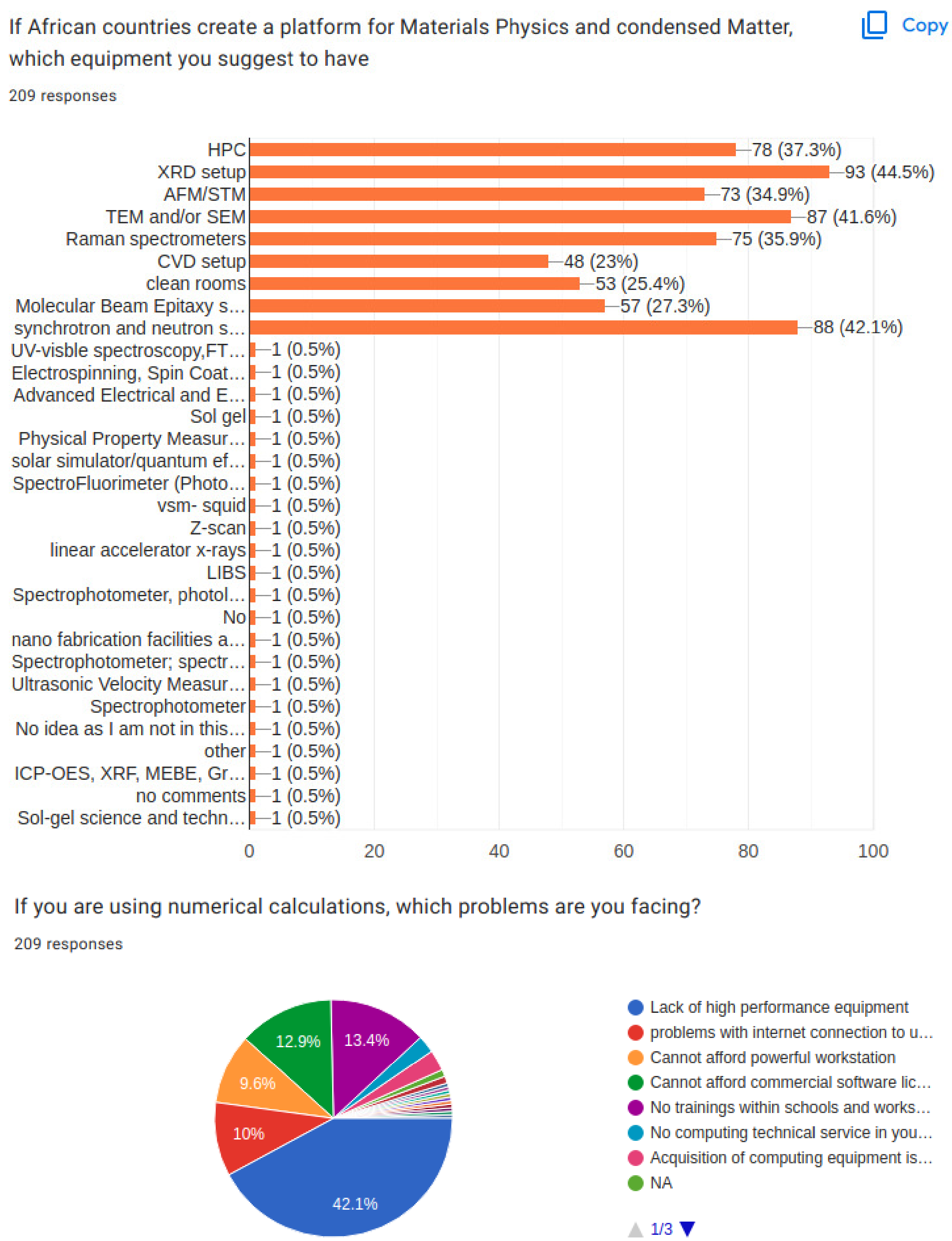

Figure 13-2: Survey responses concerning the equipment needed for experimentalists (top) and theorists (bottom) working in CMCMP&MP. [74].

* Participation to international research events

Taking part to international events is a key ingredient in the development of the research activities. There are plenty of scientific events in CMCMP&MP during the year in different countries all over the world, where outstanding researchers are invited, including Nobel prize laureates. These events offer the opportunity for African scientists to be in touch with the ongoing international research activities, to discuss their results, build-up networks, establish collaborations etc. However, access to such events is generally not possible for African researchers for many reasons

1. Due to the lack of funds in their home institutes and their low incomes, African attendees cannot afford to cover the conference registration fees (which are usually around 500 Euros).
2. Visas issues often plague African participation to international events even if the funds are available [73].
3. Many African researchers are isolated from the international networks and they do not receive event announcements, in addition to problems with internet connectivity.

* Research paper publication

Publishing the research results in outstanding scientific journals opens the way to researchers to be recognized at the international level and to be part of the global networks. In CMCMP&MP there is broad panoply of outstanding journals, but many of them reject preprints from African labs because the obtained results do not meet the journal standards. Let us put bias aside and look for the reasons of the rejection.
Regarding their poor infrastructure, African researcher cannot obtain results competing with those of their peers in other international institutions. On the other hand, they do not often have access to the data base nor to published papers. Most of the African institution libraries are not subscribed into international journal publishers which require unaffordable registration fees.
Recently, many journals in MCMP&MP converted, fully or partially, to the open access scheme, which allows African researchers, among others, to have access to the published papers. However, the downside of the open access journals is the high publication charges (around few thousands dollars per paper) which cannot be covered by African labs. Some international institutions offer a free access to many journals for researchers from low-income countries. In particular the American Physical Society (APS) [90] and ICTP within its eJournals Delivery Service [91]. Nevertheless, the access to is limited to a few researchers due to problem with information access,
As shown in Table 13-1, the African countries with high publication rates in Materials science and nanotechnology are those granted with a good infrastructure as discussed in the previous section.

In figures -5, -6, -7 (see Appendix) we depicted the publication records, during the lats two decades, of different African countries categorized by regions. The last panel shows a comparison between two Africa countries with the highest African records (South Africa and Egypt) and some other countries in the world with a comparable. This figure clearly shows that, despite its huge natural and human resources, Africa is lagging behind the rest of the world in terms of research in CM&MP, which explain why Africa is far behind in technology and industrialization.

It is worth to note that despite the large community of African researchers working in CM&MP, there are only four classified journals in the field and are low-ranked as shown in Fig. 13-3.

Country	Worldwide Rank
Egypt	31
South Africa	41
Algeria	47
Tunisia	49
Morocco	54
Nigeria	62
Ethiopia	75
Cameroon	89
Senegal	107

Country	Worldwide Rank
Egypt	33
South Africa	45
Tunisia	55
Algeria	56
Ethiopia	62
Morocco	64
Nigeria	68
Ghana	86
Cameroon	93

Table 13-1: Publication country ranking in Materials Science (left) and nanoscience and nanotechnology (right) during the period 1996-2022, after Scimago classification [78]

	Title	Type	↓ SJR	H index	Total Docs. (2022)	Total Docs. (3years)	Total Refs. (2022)	Total Cites (3years)	Citable Docs. (3years)	Cites / Doc. (2years)	Ref. / Doc. (2022)
1	Journal of Nanotechnology	journal	0.577 Q2	39	25	55	2070	253	51	4.07	82.80
2	International Journal of Polymer Science	journal	0.411 Q2	50	56	276	3367	909	269	3.29	60.13
3	Advances in Tribology	journal	0.368 Q3	22	0	13	0	39	13	2.82	0.00
4	Journal of the Southern African Institute of Mining and Metallurgy	journal	0.242 Q3	43	73	289	2348	244	272	0.75	32.16

Figure 13-3: African journals on Materials Sciences with WOS classification [78].

– Challenges with international collaborations

Being a partner in an international research project breaks the scientific isolation of African countries and facilitate substantially their cross-border activities. There are several joint programmes boosting the participation of African countries in international consortia. In particular, EU proposes several collaboration schemes [92, 93, 94] as Euraxess Africa [95], Horizon-Europe [96], etc. Within such collaboration, many African students can have the opportunity to carry out internship in international labs.
Since international consortia brings together countries with complementary expertise, the African members need to bring a relevant contribution to the research activities of the consortium within a win-win approach. With the exception of South Africa and some North African countries, the participation of Africa to international projects is very limited. This is, basically, due to the unbalance between the international and African infrastructures and research outcomes, the lack of information on available collaborating opportunities, the absence of administrative structure

for the project management in the African institutions etc.

– Challenges with limited budgets

As noted in Ref. [97] African countries are spending less than 1% of its gross domestic product (GDP) on research despite the increase in the number of scientists in the past five years. South Africa and Egypt allocate the highest budgets for scientific research which are respectively 0.83% and 0.72% of their GDP [97].
Setting-up a research lab in CM&MP requires investment in high performance equipment as those indicated in Table 13-2. Regarding their limited budget, most of the African institutes cannot manage to get one of these facilities.
In international labs, experimental research in CM&MP involve many Postdocs, Ph.D and Master students, in addition to trained technicians for machine maintenance. This is not the case of the majority of African labs due to the lack of funds which prevent the recruitment of students and postdocs, pushing Ph.D holders to unemployment. It is worth to stress that the stipend of Ph.D student in Africa is in general much lower than the minimum wage.

Equipment	Price (in $)
Lithography System	220 million – 500 million
Scanning electron microscopes	70,000 to 1,000,000
Transmission Electron Microscopes (TEM)	100,000 to 10,000,000
Molecular beam epitaxy (MBE)	minimum 1,000,000
Physical Property Measurement System (PPMS)	100,000 to 10,000,000
Clean room (per square metre)	1,500 to 6,000

Table 13-2: Average price range of some equipment used in CM&MP [99, 98]

13.3 High-priority future needs

The current landscape of CMP research in Africa reveals a significant gap in infrastructure, funding, and human capital. While some individual research efforts exist, the **absence of coordinated initiatives** limits the impact and scalability of these endeavors. Furthermore, the lack of state-of-the-art equipment and facilities hampers research progress and inhibits collaboration. Thus, to enhance the continent's scientific capabilities and address pressing societal challenges, some high-priority future needs for an African strategy, focusing on maximizing impact with limited resources, are identified as follows:

1. Education and capacity building

   Catching the tech race requires an immediate investment in Education which should not be limited to teaching but should also include continuous training for teachers and researchers. There is an urge to improve the curricula of CM&MP taught at different levels: Bachelor, Master and doctorate. Based on the received LOIs and the outcomes of different meetings with African researchers in CM&MP, we propose to reshape the teaching of CM&MP in Africa as follows:

   (a) Start teaching of CM&MP at the Bachelor level to raise the awareness of students about the technological impacts of Condensed Matter Physics. The curricula should include an introduction to solid states physics with lab and computation hands-on sessions. A teaching by project approach is strongly recommended with input from industry.

(b) Build up **Pan African Master and related Ph.D programmes** an with exchange student program. The Master should involve African and International universities to insure training of African teachers and students. The African countries involved in such hub should be able to handle visa issues to facilitate the exchange of staff and students. Each Master programme could have a nodal point in an African country with a suitable teaching/research infrastructure. The teaching will focus on the fundamental and applied aspects of CM&MP as required by the participants to the survey launched by the ASFAP CM&MP working group (see figure 13-4). The proposed Master programmes are in following areas

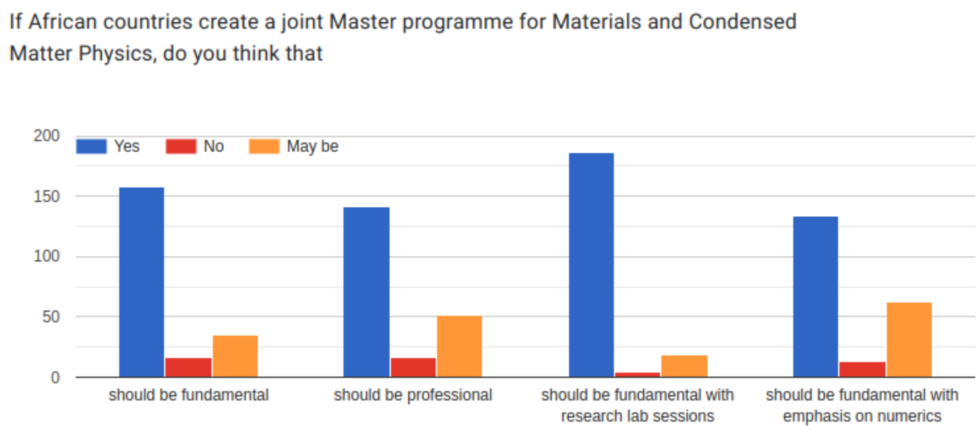

Figure 13-4: Survey responses concerning their preferences about the nature of a possible joint African Master programme in CMCMP&MP. [74].

- **Master in Theoretical & computational CM:** with a strong focus on the fundamental aspects of solid states Physics, quantum matter and the related computational methods, including machine learning, AI and quantum computing. The students will be able to combine numerical and analytical skills to undertake Ph.D projects in advanced CM topics including but not limited to advanced materials and quantum information. This Master programme will lay on the existence of HPC infrastructure or at least powerful workstation to carry out numerical calculations. The teaching will be based on workshops and seminars organized with ICTP and other international research institutes. A pre-master year could be planned to students with major gaps in relevant background.
After getting their Master degree, students should also be able to carry out a career in data science or quantum computing.
- **Master in Experimental and applied CM&MP:** devoted to the fundamentals of experimental CM&MP and the technological applications. This is a key Master programme for the promotion of research in CM&MP. The students will learn the different techniques of synthesis, characterization of advanced materials and the methods to control their properties. The teaching should be mostly based (80%) on lab-courses carried out in research centers or labs with suitable equipment. The students will be able to master the key experimental methods to undertake Ph.D projects in experimental CM&MP or in R&D focusing on applied MP. After getting their Master degree, students should also be able to carry out a career in industry.

- **Professional Master degree in Materials Physics and applications:** with a focus on energy, water purification, food agriculture etc The students will also be trained on entrepreneurship within startups and technology business incubators to help them setting-up their own Materials Physics based-business.
- **Master in quantum technologies:** This Master is already implemented in many international institutes. It will be an interface between three pathways: physics, engineering and mathematics where students from different paths can interact within multidisciplinary research projects and workshops. The topics include Quantum Computing, Quantum Sensing, Quantum Simulation, Quantum Materials and Quantum Cryptography with advanced practical training on quantum computing platforms, photonic quantum computers etc. The details of the Master curricula could be discussed within an African strategy for Quantum technologies.

The Pan African University Institute for Basic Sciences, technology and Innovation (PAUSTI) can be the engine to boost such joint education programmes in Africa [107, 106]. PAUSTI mission focuses on forming leaders and innovators in the fields of Mathematics, Molecular Biology and Biotechnology; Civil Engineering; Mechanical Engineering; Mechatronic Engineering and Electrical Engineering.

(c) Set-up an **International Centre for Experimental in Africa (ICEPA)** with a focus on CM&MP. *"This is an educational centre for the training of young African students, postdocs and junior faculty members in instrumentation for fundamental and applied experimental physics. The educational programme foreseen would be equivalent to a Master curriculum at a university. Many African universities do not have the necessary number of experimental facilities and instruments at their disposal for training in experimental techniques and tools.The concept of the proposed centre (named provisionally ICEPA in the following) has been inspired by the successful AIMS centres for mathematical sciences and ICTP for theoretical physics. But for ICEPA the focus is on experimental physics, strongly oriented towards instrumentation. The attachment to or at least a very close link to a university or to an existing research centre will be necessary to train and recruit qualified staff for the supervision of the experiments and to be able to issue an international recognised diploma" [102].*

(d) Strengthen the teaching activities at the Master and Ph.D levels by organizing regular schools in specific on-demand topics as computational CM&MP, quantum matter, 2D materials, quantum information etc. *"The Case of the African School for Electronic Structure Methods and Applications (ASESMA) shown that it is possible to build a network across sub-Saharan Africa with world-class research with world-class research with a relatively low budget." [76]*

2. Research

Research on MP in African is generally limited to local natural materials and their applications in particular area like construction, food, biology. To bridge the technological gap between Africa and At the international level, the key research areas in CM&MP are, but not limited to, 2D and advanced Materials for chips technologies, quan....

- Enhance existing and establish new collaborative networks between universities, research institutions, and industries within and outside Africa. These networks facilitate knowledge exchange, joint research projects, and technology transfer.
- Encourage public-private partnerships to provide funding, industry expertise, and market access, fostering innovation and entrepreneurship in CMP.

- Upgrade existing research infrastructure and establish new facilities equipped with state-of-the-art instruments as well as facilitate access to advanced experimental and computational tools.
- Invest in training programs, mentorships, workshops, and international collaborations to enhance the capacity of African researchers in CMP.
- Develop comprehensive and interdisciplinary curricula tailored to CMP by integrating theoretical knowledge with practical skills.
- Invest and fund advanced laboratories, research grants, and scholarships to attract and retain top talent. This funding should support both basic and applied research, as well as capacity-building activities.
- Create dedicated research positions for CMP researchers within universities and research centers to provide sufficient time, resources, and institutional support for conducting impactful research without compromising teaching responsibilities.
- Promote a culture of research excellence by incentivizing and rewarding research contributions. This includes recognizing research outputs in performance evaluations, providing research-related training and mentorship.

13.4 Synergies with neighbouring fields

Condensed Matter and Materials Physics exhibit numerous synergies with neighboring fields, fostering interdisciplinary collaboration and driving scientific innovation across various domains.

This can be illustrated through their intersection with Photonics and Optoelectronics in studying the interaction of light with condensed matter systems and the development of optical and optoelectronic devices [100]. CMP techniques, such as spectroscopy, nonlinear optics, and photonic crystal engineering, are used to investigate the optical properties of materials and design photonic devices, such as lasers, LEDs, and photodetectors, for communication, sensing, and imaging applications. Conversely, advances in Photonics and Optoelectronics contribute to CMP research by providing tools and techniques for manipulating light-matter interactions and harnessing optical phenomena for controlling and manipulating condensed matter systems at the nanoscale.

Besides, CMP relies on light sources, such as synchrotrons and free-electron lasers, for spectroscopy and imaging experiments [101]. These techniques provide valuable insights into the electronic and structural properties of materials at the atomic scale. Advances in light sources technology, such as high-brightness beams and ultrafast lasers, enable CMP researchers to study dynamic processes in condensed matter systems with unprecedented resolution and sensitivity. Furthermore, light sources offer a wide range of characterization techniques, including X-ray diffraction, X-ray absorption spectroscopy, and photoelectron spectroscopy, which are essential for studying the properties of materials in CMP. These techniques provide information about the crystal structure, chemical composition, and electronic structure of materials, facilitating the design and optimization of new materials for specific applications.

Biophysics also intersects with CMP in studying the physical principles underlying biological systems' structure, function, and behavior. CMP techniques, such as X-ray crystallography, spectroscopy, and microscopy, are used to investigate biomolecular structures, protein folding dynamics, and cellular processes. Understanding the physical mechanisms governing biological systems' behavior has implications for biomedical research, drug discovery, and biotechnological applications. Conversely, insights from biophysics inspire CMP research, leading to the development of biomimetic materials and devices that mimic biological systems' functionalities and properties.

On the other hand, Materials physics and Particle Physics researchers often share theoretical and experimental techniques. Concepts from Particle Physics, such as symmetry breaking, gauge theories, and renormalization, have found applications in CMP research, while techniques from CMP, such as effective field theory and renormalization group methods, have been adopted in Particle Physics to study strong and weak interactions.

Furthermore, collaboration between CMP and Condensed Matter Chemistry researchers enables a deeper understanding of chemical processes at the molecular level and the development of innovative materials with tailored functionalities.

13.5 Environmental and societal impact

Condensed Matter and Materials Physics is part of our everyday life as it plays a crucial role to describe matter. Therefore, improved education in CMMP of the current and future generation will help to have a more scientifically inclined and open minded society. This will help to ensure that Africa is well positioned to have a critical mass of physicists with the knowledge, skills, creativity and versatility to face any challenge. Due to the fact that CMMP embraces various fields, it instils interdisciplinarity in the mindsets of Scientists.

13.6 Conclusion and perspectives

In the past, availability of land, raw materials and labour were considered to be important economic factors for African development while the pursuit for scientific information and knowledge were less considered. This was primarily due to inward looking and short term thinking focused on tangible things in the short term without thinking about how the search for new scientific knowledge could change the future of Africa to move away from set ways of doing things. The late Professor John Desmond Bernal, a British Physicist in his book "Science in History" stated that "It is now evident that the real source of wealth of a nation lies no longer in the raw materials, the labour force or machinery, but in having a scientific, educational and technological base, education has become the real wealth of the new age". As a result of limited investment in scientific research by most African countries with almost all of them falling short of reaching the set minimum of investing 0.5% of their GDP in scientific research, economic development in Africa is still lagging behind that of the Western world. It is painful to note that Africa is still more of a consumer rather than a producer although a significant amount of mineral resources required for production of technological components are sourced from Africa. Physics is a foundational pillar for development of basic science and technology. Therefore, for Africa to advance to go beyond just catching up on the global scientific and technological race, it is necessary to fully integrate physics in the education system of Africa. In the context of our report that focuses on condensed matter and materials physics, it is critical that continental initiatives embrace its potential. For example, the African Union's Agenda 2063 "The Africa we want" which is Africa's blue print and master plan for transforming Africa into the global powerhouse of the future. For this to be fully realized, it is essential that continental science, technology and innovation policies are tailored to create an enabling environment for the successful harnessing of the immense potential that lies in condensed matter and materials physics. This cuts across a move towards elimination of limitations to access to education, access to equipment for research and fostering a strong relationship within the triple helix context. The need for advanced tools (experimental, computational and theoretical) to probe the structure and properties of materials is critical for the significant advancement of condensed matter and materials physics in Africa hence the need for significant investment and training. It should also be noted that having a improved understanding of the value of seeking answers for scientific questions, the link between theoretical and experimental research and their impact on current and future technological applications will contribute significantly to socioeconomic development of Africa. However, for this to be realized, the value of condensed matter and materials physics should be appreciated at the highest level of African governments hence the compilation of the African Strategy for Fundamental and Applied Physics. Africa is the future of the world because of the abundance of natural resources and having a significant percentage of a young population but it needs to speed up its approach to scientific thinking in order to capitalize on its advantages.

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Appendix

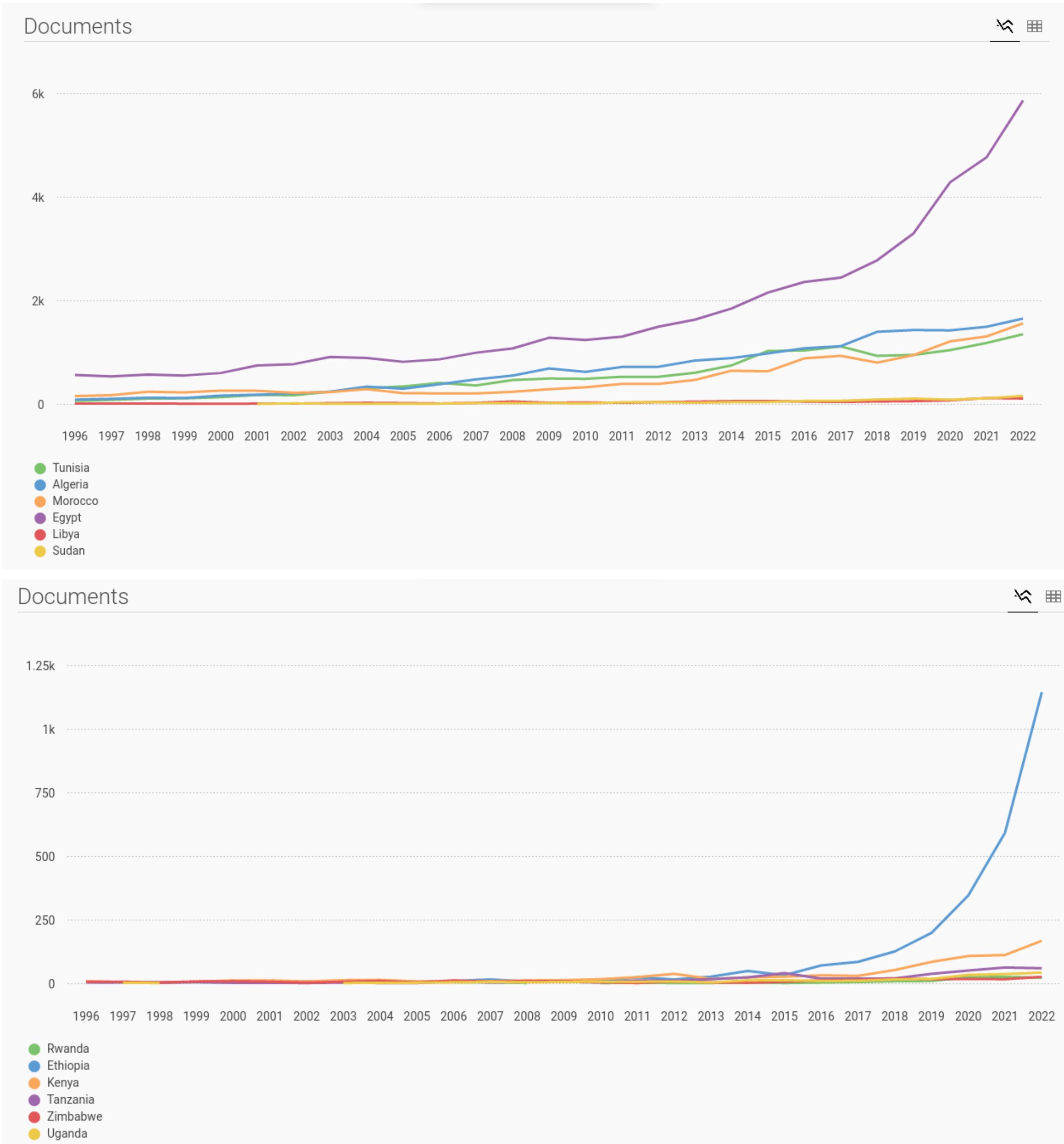

Figure -5: Number of publications per year in Materials Sciences for North and Eastern African countries, after Scimago Scimago.

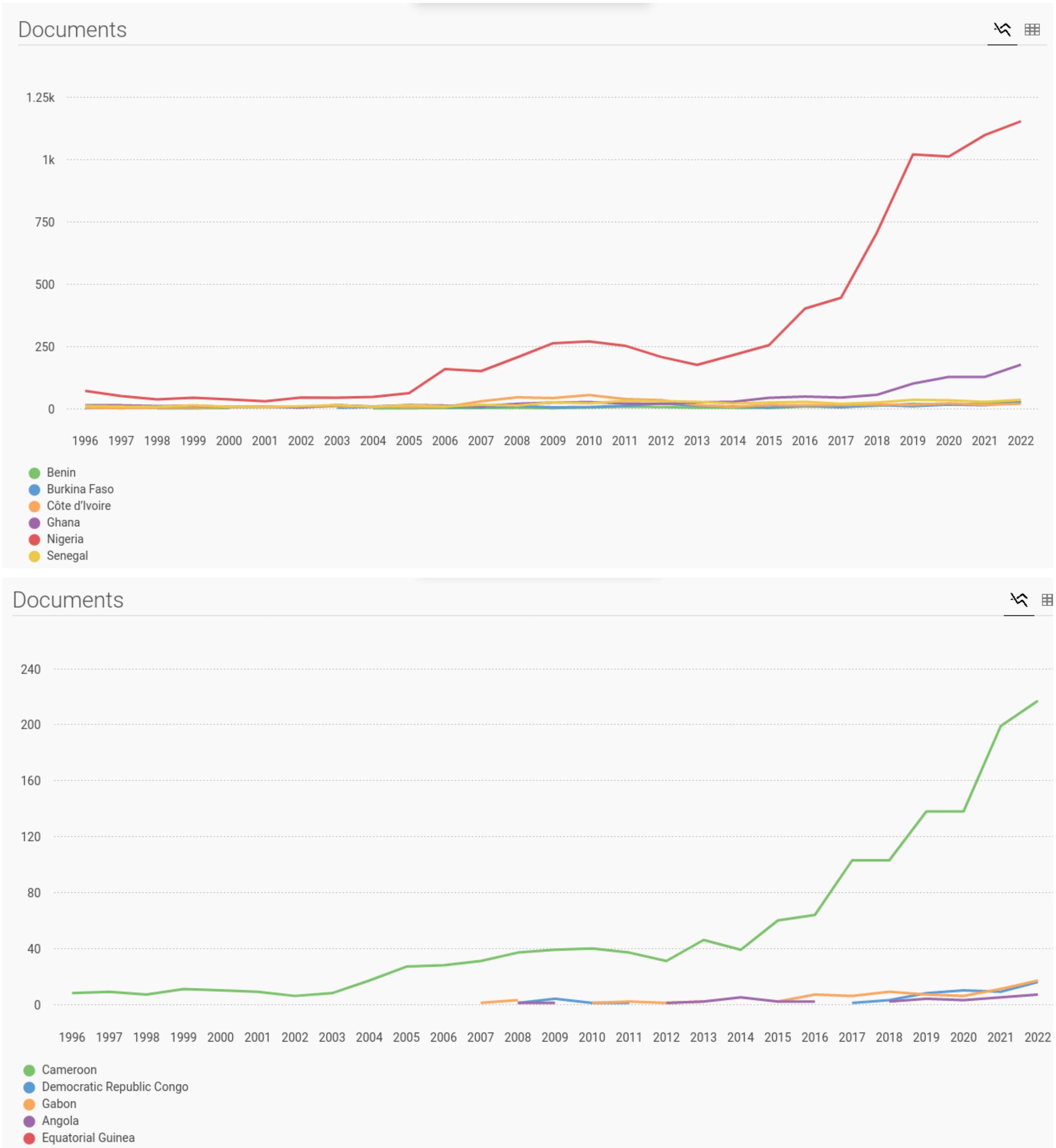

Figure -6: Number of publications per year in Materials Sciences for Western and Central African countries, after Scimago [78].

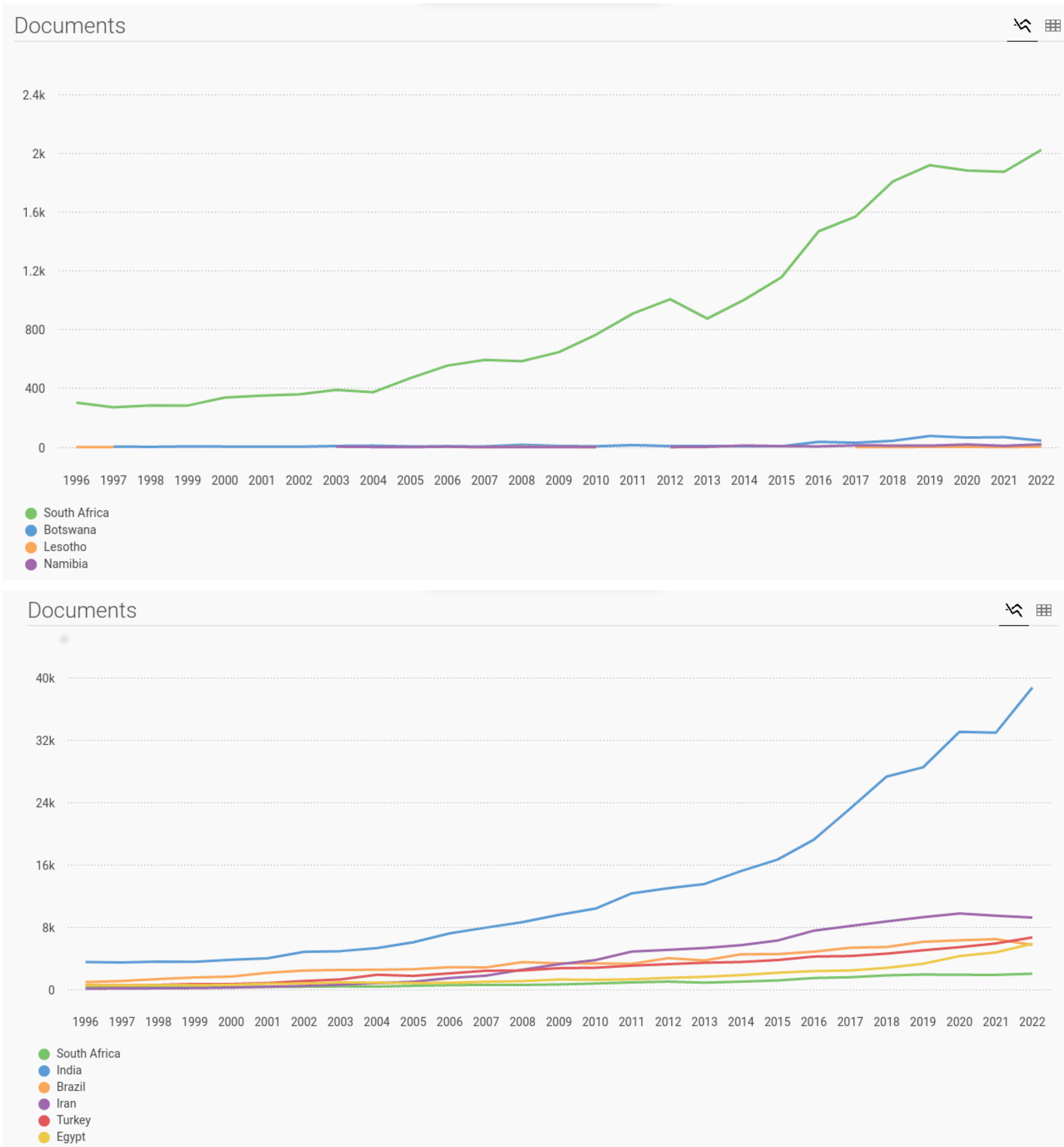

Figure -7: Number of publications per year in Materials Sciences for South African countries, Iran, Turkey, India an Brazil and countries in different continents, after Scimago [78].

14

Medical Physics Working Group

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14.1 Introduction and Motivation

Africa is rapidly acquiring high-tech medical imaging equipment such as multi-slice helical computed tomography (CT) scanners, MRI scanners, as well as hybrid imaging technologies like combining single photon emission tomography (SPECT) and positron emission tomography (PET) with CT. However, without proper specialized support, this advancement in technology has the potential of significantly increasing the population's exposure to ionizing radiation. The safe use of these technologies requires proper quality assurance procedures, calibration of imaging equipment and optimization of the radiation dose to the patient, which may not be properly done in the absence of a qualified medical physicist. The degree of involvement of the medical physicist is determined by the complexity of the radiological procedures and the associated radiation risks [1].

The essential responsibility of the Qualified Medical Physicist's clinical practice is to assure the safe and effective delivery of radiation to achieve a diagnostic or therapeutic result as prescribed in patient care [2,3,4]. The responsibilities of the medical physicist include: protection of the patient and others from potentially harmful or excessive radiation; establishment of adequate protocols to ensure accurate patient dosimetry; the measurement and characterization of radiation; the determination of delivered dose; advancement of procedures necessary to ensure image quality; development and direction of quality assurance programs; and assistance to other health care professionals in optimizing the balance between the beneficial and deleterious effects of radiation; and compliance with applicable federal and state regulations [5].

Unfortunately, in most African countries, there is a critical shortage or absence of qualified medical physicists in hospitals, clinics and other health care facilities that use radiation technology. This problem is particularly critical in diagnostic imaging units (either in diagnostic radiology or nuclear medicine) that usually have no qualified medical physicist in their workforce [6, 7]. This may lead to patients receiving non-optimized radiation procedures, resulting in inadequate diagnosis or treatment, or in extreme cases from the harmful effects of radiation due to overexposure.

14.2 Major challenges Scientific activities

Medical physicists play a vital role in ensuring the safe and effective use of radiation and imaging technologies in diagnostic and therapeutic medical procedures. However, several factors pose challenges to the field that can impact their work and the quality of healthcare services in the region requiring strategic solutions and priority actions. Some of the key challenges include the following.

14.2.1 Limited Resources

Many African countries face significant challenges in terms of limited financial resources, leading to inadequate funding for healthcare infrastructure, including radiation therapy and diagnostic imaging facilities. The funding constraints impact the acquisition and maintenance of advanced medical equipment, professional training programs, and research opportunities. Many hospitals struggle to meet the rising demand for cancer care and other medical physics services, leading to delays in diagnosis and treatment, which directly affect patient outcomes. Furthermore, limited resources hinder the growth and retention of skilled medical physicists, as funding for education, competitive salaries, and professional development remains scarce. Addressing these financial challenges is crucial to advancing equitable, high-quality healthcare across the continent.

14.2.2 Shortage of Qualified Personnel

Africa faces a critical shortage of qualified medical physics professionals, a gap that greatly affects the delivery of essential healthcare services, especially in oncology and diagnostic imaging. The limited number of trained medical physicists hinders the safe and effective use of radiation in medical applications, leading to delays in treatment and increased risks for patients. This shortage is further exacerbated by insufficient training programs, limited funding, and few opportunities for professional growth, which also drive talented individuals to pursue careers abroad (brain drain). Consequently, many hospitals lack the expert oversight needed to operate advanced equipment safely and efficiently. Bridging this gap requires strategic investment in education, training, and retention to build a robust medical physics workforce and improve healthcare outcomes across the continent.

14.2.3 Inadequate Infrastructure

Some regions lack the necessary infrastructure for advanced medical physics services. This includes a shortage of modern equipment, such as linear accelerators, CT scanners, and other advanced imaging devices such as MRI machines. In facilities where this equipment is available, outdated technology and insufficient maintenance further compromise their effectiveness, leading to frequent breakdowns and extended downtime. Additionally, a lack of dedicated spaces for training and research in medical physics hampers the development of a skilled workforce. This infrastructural deficit creates a reliance on external support and limits the ability of healthcare systems to offer timely and safe medical physics services. Expanding infrastructure is critical to empowering African nations to provide comprehensive, high-quality healthcare independently.

14.2.4 Education and Training Gaps

Insufficient training opportunities for medical physicists can lead to a lack of specialized skills. Comprehensive education programs, including postgraduate training and continuous professional development, are crucial to ensuring a competent workforce. Africa faces substantial education and training gaps in the field of medical physics, which limit the development of a skilled workforce equipped to meet the continent's growing healthcare demands. A few institutions offer medical physics programs within the region, with a number of them under-resourced, with limited access to state-of-the-art equipment, research opportunities, and specialized faculty. As a result, many medical physics professionals graduate with insufficient practical experience to make them clinically competent to practice independently. Additionally, continuing education and certification opportunities are scarce, leaving few pathways for professionals to upgrade their skills or gain expertise in emerging technologies. More investment in accredited training programs, partnerships with international institutions, and resources for hands-on experience are needed for building a self-sustaining medical physics workforce across Africa.

14.2.5 Regulatory Frameworks

The development of robust regulatory frameworks for medical physics in Africa is essential to ensure safe and effective use of radiation in healthcare, but many countries on the continent lack comprehensive policies in this area. Inconsistent or inadequate regulatory frameworks for radiation safety and medical physics exist in many countries. A robust regulatory system is essential to ensure consistent standards for equipment quality, radiation safety, and professional qualifications to ensure safe and effective use of radiation in medical procedures. In most of African countries, medical physics is not recognized as a profession and medical physicists are not required to register with a Health Professions Council. This could potentially have a negative effect on the practice standards, training adequacies and credentialing requirements for medical physics professionals.

14.2.6 Access to Continuing Education

Access to continuing education for medical physics professionals in Africa remains limited, posing a significant barrier to the advancement and quality of healthcare services that depend on up-to-date knowledge in this highly specialized field. Rapid advancements in medical technology mean that professionals require ongoing training to stay proficient in new techniques, safety standards, and equipment, especially in areas like radiotherapy, diagnostic imaging, and nuclear medicine. However, few African institutions offer structured programs for continuing education in medical physics, and international training opportunities are often cost-prohibitive. This lack of accessible professional development leads to skill gaps, impacting the quality of patient care and limiting the growth of medical physics as a field in the region. Increasing local opportunities for continuing education through workshops, certifications, and partnerships with global institutions like the IAEA and ICTP is crucial for building a competent, resilient healthcare workforce in Africa.

14.2.7 Geographic Disparities

Geographic disparities significantly affect the distribution of medical physicists across Africa, with most professionals concentrated in the Northern and Southern regions of the continent. At the country level, there are more medical physicists in the urban centers, leaving rural and underserved regions with limited or no access to their expertise. The uneven distribution means that advanced healthcare services, such as radiation therapy and diagnostic imaging, are predominantly available in a few major cities, creating a barrier for millions of people who live in remote areas. Contributing factors include a lack of infrastructure, fewer employment incentives in rural areas, and limited local training opportunities. Addressing these geographic disparities requires investment in rural healthcare infrastructure, the establishment of regional training centers, and policies that incentivize medical physicists to serve in underserved areas, ensuring more equitable healthcare access across the continent.

14.2.8 Lack of Research Opportunities

Medical physicists in Africa face a significant shortage of research opportunities, which limits their ability to contribute to scientific advancements and adapt innovations to the continent's unique healthcare challenges. Research is essential for developing tailored solutions in radiotherapy and medical imaging to address Africa's specific disease burdens, resource constraints, and demographic needs. However, funding for research is often sparse, and access to state-of-the-art equipment and collaborative networks is limited, hindering local professionals from pursuing studies that could improve patient care and safety. Additionally, without strong research programs, many talented medical physicists lack career development opportunities, leading some to seek positions abroad where they can engage in meaningful scientific work.

14.2.9 Technological Obsolescence

The rapid evolution of medical technology means that equipment may become obsolete quickly. Technological obsolescence poses a significant challenge for medical physicists in Africa, as outdated equipment limits the effectiveness of radiation therapy, diagnostic imaging, and other critical healthcare services. Due to limited funding, many healthcare facilities are unable to upgrade essential radiation therapy and medical imaging equipment which often operate beyond their recommended lifespan. As a result, these aging technologies provide lower-quality images, reduce treatment precision, and frequently break down, causing delays and compromising patient outcomes. For medical physicists, working with obsolete equipment restricts the ability to apply advanced techniques and stay current with global standards in medical care. Moreover, this situation can impede the training of new professionals who miss opportunities to gain experience with modern tools. Addressing technological obsolescence through investment in equipment upgrades and maintenance is crucial to enhancing treatment quality, supporting professional development, and ensuring that healthcare systems across Africa keep pace with advancements in medical physics. Equipment management, and in particular budgeting for preventative maintenance, is often only an afterthought, and this can lead to extended downtime.

14.2.10 Public Awareness

Public awareness of the role and importance of medical physicists in Africa remains limited, which affects the development of the field and its integration into healthcare systems. Many people, including patients and even healthcare professionals, are unfamiliar with how medical physicists contribute to the safe and effective use of radiation in cancer treatment, diagnostic imaging, and nuclear medicine. This lack of awareness leads to underinvestment in medical physics services, as the critical impact of these professionals on patient safety, treatment outcomes, and healthcare innovation often goes unrecognized.

Efforts to address these challenges often involve raising awareness through media, community health programs, partnerships with hospitals and educational institutions, collaboration between international organizations, governments, non-governmental organizations (NGOs), and educational institutions. These collaborations can focus on improving education and training opportunities, investing in infrastructure, and implementing effective regulatory frameworks to enhance the practice of medical physics in Africa.

14.3 Progress, Achievements, Solutions

While challenges exist, there have been notable progress, achievements, and ongoing efforts to address issues in the field of medical physics in Africa. Some positive developments are mentioned as follow.

14.3.1 Training Programs

Expansion of educational programs in medical physics: Several African countries have taken steps to establish or expand educational programs in medical physics at the postgraduate levels, contributing to a growing pool of qualified professionals [5,8]. The International Atomic Energy Agency (IAEA) and the International Centre for Theoretical Physics (ICTP) has supported the region with training of medical physicists through long-term fellowships and short-term training courses and workshops. The IAEA has developed an Academic and Clinical Training syllabus for the region which has been endorsed by the regional Medical Physics Federation (FAMPO), and this has largely harmonized the training regimes in Africa. However, access to remunerated training posts remains a challenge.

14.3.2 International Collaboration

Collaborative initiatives with international organizations: Partnerships with organizations such as the IAEA, World Health Organization (WHO), ICTP, and other international bodies have facilitated capacity-building, knowledge exchange, training opportunities, and resource mobilization for African medical physicists. Through these collaborations, there have been equipment donations, scholarships, exchange programs, and technical assistance, which help bridge resource gaps, provide access to best practices, and empower African medical physicists to contribute to and benefit from global advancements.

This is an area that could be expanded on, especially in view of the increased awareness around global health.

14.3.3 Capacity Building

Capacity-building projects: Various projects focus on enhancing the capacity of medical physics services. These projects often involve the donation or support for acquiring modern equipment and technologies. Medical physics capacity building is often part of a much larger national cancer strategy, for example. Other capacity building approaches include instituting training programs, workshops, and education initiatives. Capacity-building efforts have also led to the establishment of certification and accreditation programs, enhancing professional standards and fostering a more skilled and resilient workforce.

14.3.4 Research and Innovation

Growing research activities: Some African medical physicists are actively engaged in research, contributing to advancements in the field. Research can lead to innovative solutions tailored to the specific needs and conditions in the region. Strengthening research support, funding, and partnerships with global institutions is essential to enable Africa's medical physicists to innovate and drive progress within the field, fostering home-grown solutions and enhancing healthcare quality across the continent.

14.3.5 Advancements in Telemedicine

Utilization of telemedicine: Telemedicine applications have been employed to provide remote support, consultation, and training for medical physicists in underserved areas, overcoming geographic disparities. Through virtual platforms, medical physicists can receive real-time support for complex cases, collaborate on treatment planning, and gain insights into the latest technologies and protocols. Additionally, telemedicine facilitates ongoing training and professional development, allowing medical physicists to participate in webinars, workshops, and mentorship programs without the need for costly travel. These advancements are creating a more connected and resource-efficient healthcare network, which is crucial for addressing Africa's healthcare needs and advancing the field of medical physics across the continent. The potential impact of tools that employ machine learning strategies cannot be overstated. While there are still many open questions in this field, there is no doubt that machine learning has the potential to help address some of the staffing challenges in the region.

14.3.6 Public Awareness and Advocacy

Increasing public awareness: Efforts to raise awareness about the role of medical physicists and the importance of radiation safety have been made through public health campaigns and educational programs. Increased public education on the role of medical physicists have driven more support for training programs, funding, and recruitment initiatives.

14.3.7 Regulatory Enhancements

Strengthening regulatory frameworks: Some countries are working to enhance and enforce regulatory frameworks related to radiation safety and medical physics practices, ensuring compliance with international standards. Such strengthened regulatory frameworks of standardized protocols, certification requirements, and oversight mechanisms is vital for improving healthcare outcomes and ensuring patient and practitioner safety across Africa.

14.3.8 Professional Networks

Development of professional networks: Networking opportunities, both within Africa and internationally, have facilitated information sharing, collaboration, and mentorship among medical physicists. FAMPO has created a network of medical physicists in Africa to raise and maintain practice standards and promote collaboration and innovation. The Federation networks with national member organizations, individual medical physicists and global professional bodies like the International Organization for Medical Physics (IOMP) to promote the application of physics in medicine.

14.3.9 Support from NGOs and Foundations

Support from non-governmental organizations (NGOs) and foundations: Various NGOs and philanthropic foundations provide financial and technical support to improve medical physics services in Africa. The support includes equipment donations, technology upgrades, and funding for research, all of which help bridge resource gaps and improve the quality of patient care. The support fosters stronger, more resilient healthcare infrastructure in Africa, empowering local medical physicists to deliver high-quality, safe, and effective care to communities across the continent.

14.3.10 Focus on Sustainable Solutions

Emphasis on sustainable solutions: Initiatives are increasingly focusing on developing sustainable models for maintaining and upgrading medical physics infrastructure, considering long-term viability.

While progress has been made, ongoing efforts are necessary to sustain and expand these achievements. Key solutions involve continued investment in education and training, infrastructure development, regulatory enforcement, and international collaboration. Encouraging local leadership, empowering healthcare professionals, and advocating for policy changes are integral parts of fostering sustainable improvements in medical physics across the African continent.

14.4 High priority needs

As medical physics in Africa continues to evolve, several high-priority future needs have been identified to address challenges and enhance the quality of healthcare services. Some of these needs include increased the awareness and recognition of role of medical physicists in medical imaging, in addition to the following.

14.4.1 Capacity building for medical physicists in imaging

- Implement and extend the educational to reach across the continent to new Members who have requested assistance to move forward with national cancer control plans.
- Increase the frequency of teaching and formal training activities in the centers and abroad.
- Establishment an education and training programme in Zones and affiliated to the university to promote the education and training programme.
- training of the existing qualified therapy medical physicists to support Diagnostic Radiology and Nuclear Medicine.
- E-learning platform for training [5]
- Regional guidelines for academic education and training programs for imaging physicists e-learning [10].

14.4.2 Establish diagnostic reference levels (DRLs) for nuclear medicine(NM) and diagnostic radiology (DR)

- DRLs are considered a useful dose optimization tool, and medical physicists are an integral part of the team to determine DRLs and further optimize these
- Standardizing the procedures and optimizing the parameters affecting the dose delivered to patients.
- Focus on pediatric imaging by way of examination of a certain number of criteria linked to these practices.

14.4.3 Expansion of Training Programs

- Establish and expand educational programs in medical physics at postgraduate level, as recommended by the IOMP and IAEA, to meet the increasing demand for qualified professionals.

14.4.4 Continued Professional Development

- Develop ongoing training and professional development opportunities to ensure that medical physicists stay abreast of advancements in technology and best practices.

14.4.5 Research and Innovation

- Foster a culture of research and innovation within the field of medical physics to address local challenges and contribute to the global body of knowledge.

14.4.6 Infrastructure Development

- Invest in the development and maintenance of modern infrastructure, including upgrading existing equipment and acquiring new technologies for diagnosis and treatment.
- Harmonization of quality assurance/quality control programme in medical imaging in Africa [9].
- Facilities and technical equipment for quality control as well as radiology and nuclear medicine.
- Training on QA/QC in nuclear medicine and diagnostic radiology. Implement & develop QA Programme.

14.4.7 International Collaboration

- Strengthen and expand collaborations with international organizations, institutions, and professionals to facilitate knowledge exchange, training, and resource mobilization.
- Collaboration among African member states will be elevated regional guidelines for academic education and training programmes.

14.4.8 Telemedicine Integration

- Promote the integration of telemedicine solutions to provide remote support, consultation, and training, especially in under-served and remote areas.

14.4.9 Patient Safety and Quality Assurance

- Emphasize patient safety through the implementation and enforcement of rigorous quality assurance programs in medical physics practices.
- Training workshop on the acceptance testing and commissioning of diagnostic/interventional radiology machine used for pediatric patients.
- Increase the awareness about the radiosensitivity of pediatric patients by educating or having workshops with hospital managers, government policy makers and recruiters, radiologist, radiographers, clinicians about the need and role of the medical physicist.

14.4.10 Standardization and Certification

- Work towards standardizing medical physics practices and certifications across the region to ensure consistency and adherence to international standards.

14.4.11 Regulatory Framework Strengthening

- Strengthen regulatory frameworks related to radiation safety and medical physics practices to ensure compliance with international guidelines and standards.

14.4.12 Application for the official accreditation

- Implement registration of Medical Physicists by a national Health Professions Council or appropriate body to ensure that minimum training requirements are applied.

14.4.13 Public Awareness Campaigns

- Conduct public awareness campaigns to educate the public, healthcare providers, and policymakers about the critical role of medical physicists in healthcare and the importance of radiation safety.

14.4.14 Networking and Collaboration

- • Encourage the establishment of professional networks and collaboration platforms to facilitate information sharing, mentorship, and collaborative research initiatives.

14.4.15 Improve the quality of the service provided

- Continue to develop and implement quality procedures; request to the IAEA to support with manual and ICT material on the quality management system.

14.4.16 Sustainable Funding Models

- Develop sustainable funding models for medical physics services to ensure consistent access to resources for education, infrastructure development, and ongoing operations.

14.4.17 Local Leadership Empowerment

- Empower local leadership within the field of medical physics to take ownership of initiatives, advocate for policy changes, and drive sustainable improvements.

14.4.18 Capacity Building for Healthcare Providers

- Provide training and capacity-building programs for healthcare providers to enhance their understanding of medical physics concepts and the safe use of radiation in medical procedures.

14.4.19 Adaptation to Technological Advances

- Prepare for and adapt to technological advances in medical physics by incorporating new equipment, treatment techniques, and imaging modalities. By addressing these high-priority needs, stakeholders can contribute to the growth and sustainability of medical physics in Africa, ultimately improving patient care, enhancing safety, and advancing the field.
- Collaboration among governments, healthcare institutions, educational bodies, and international partners is essential to successfully meet these needs.

14.5 Conclusion

The field of medical physics in Africa presents both challenges and promising opportunities for improvement in healthcare delivery. Despite facing issues such as limited resources, a shortage of qualified personnel, and disparities in infrastructure, there are ongoing efforts to address these challenges.

Key solutions involve the expansion of training programs, international collaborations, infrastructure development, continuous professional development, and research support. Prioritizing capacity building, regulatory compliance, and public engagement are crucial for the sustainable growth of medical physics services across the continent.

As Africa works towards strengthening its medical physics capabilities, the concerted efforts of governments, healthcare institutions, educational bodies, and international partners will play a pivotal role in shaping a future where quality and safe medical physics practices contribute significantly to the advancement of healthcare in the region. Through these endeavors, the potential for positive impact on patient care, technological advancements, and overall healthcare infrastructure in Africa remains promising.

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15

Nuclear Physics Working Group

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15.1 Introduction and Motivation

Nuclear science, technology and research represent the underlying foundation of all nuclear applications. Nuclear applications contribute in many ways to health, development and security worldwide. They are used in a broad range of areas, from power production to medicine, agriculture, food safety, environment, forensics, industry, and the analysis of artefacts. Continuous research efforts and knowledge expansion in nuclear physics is necessary to further technological innovation, which in turn brings about new benefits for society. There are university level nuclear training facilities in many countries in at least 40 of the 55 countries in Africa. There are 432 clinical Linacs and throughout the continent and 5 countries have Accelerator facilities. Two countries have viable nuclear regulators, 8 have research reactors, and a total of 10 have or are seriously considering nuclear power. One would therefore imagine Africa should have a healthy platform from which to grow its capacity in nuclear related training, research and technological capacity. The IAEA is an important player in developing the nuclear science and technological capacity in Africa. It runs a nuclear science program through AFCONE and AFRA to help its Member States to benefit from the various existing radiation applications. It also assists and advises them on their needs for capacity-building, research and development in the nuclear sciences, for instance with regard to the utilization of particle accelerators, research reactors and nuclear instrumentation, including nuclear fusion research and technology, for the full suite of applications, including energy, medicine, agriculture and manufacturing industry. However, the existing capacity and facilities do not cover sufficiently the required opportunities for the African population. The absence of technological development needed for running nuclear facilities are still very insufficient excepted in very few cases. Therefore, future upgrade plans as well as their role in the socioeconomic development in Africa must be addressed. The nuclear physics research field is relatively old but very important research field with several journals dedicated to both the theoretical and experimental findings. It is a fundamental field from which many other fields of research have emanated and with very many spin-off applications.

15.2 Overview of Nuclear training in Africa

The countries in Africa which have nuclear training programmes include Algeria, Angola, Benin, Burundi, Cameroon, Central African Republic, Chad, Democratic Republic of the Congo, Egypt, Equatorial Guinea, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, The Gambia, Togo, Tunisia, Uganda, Zambia and Zimbabwe. This has been estimated from the participation in the AFRA-NEST programme and also via participation in the IAEA and its activities. AFRA-NEST was established by AFRA [2] in 2007 to support nuclear training and also nuclear knowledge management. The footprint of nuclear training is therefore the majority of African countries. This can be considered a good platform, and the AFCONE, AFRA and AFRA-NEST progammes already forming a good level of co-ordination for nuclear training.

Recently, The IAEA and South Africa's Laboratory for Accelerator Based Sciences, NRF-iThemba LABS, have signed a major agreement to collaborate on achieving major goals regarding accelerator-based sciences and training. But due to bad South African immigration policy, access to this facility is limited to only few nuclear researchers in Africa.

15.3 Overview of nuclear related facilities in Africa

The nuclear related facilities extend from Particle Accelerators, Nuclear Reactors, medical Clinical facilities that use radiation, Laboratories with smaller nuclear facilities and instrumentation, such as various nuclear radiation sources and detectors, and then implementations of the same in applications in other areas such as Agriculture and manufacturing industries.

15.3.1 Particle Accelerators : Research facilities and Medical Facilities

The following nuclear related research facilities exist, with their countries and also links to the facilities.

- Ghana:
  The Accelerator Laboratory at the Obafemi Awolowo University has a 1.7MV Pelletron Tandem Accelerator [3]
- Nigeria:
  Centre for Energy Research and Development (CERD)

Figure 15-1: The iThemba LABS has a 200 MeV separated-sector cyclotron (SSC) with two injector cyclotrons in South Africa [7].

Centre for Energy Research and Training(CERT)
The Accelerator Laboratory at the Obafemi Awolowo University has a 1.7MV Pelletron Tandem Accelerator [4].

- Egypt:
  The Nuclear Research Centre (NRC) has a MGC-20 cyclotron and a 3 MV Tandetron [5].

- Algiers:
  The Nuclear Research Centre of Algiers (CRNA) has a 3.75 MV Van de Graaff accelerator [6].

- South Africa:
  The iThemba LABS has a 200 MeV separated-sector cyclotron (SSC) with two injector cyclotrons, 6 MV Tandem accelerator, 3 MV Tandetron. The main campus view of the SSC is shown in figure 2 below [7].
  The Nuclear Energy Corporation of South Africa (Necsa) has a Van de Graaff accelerator, capable of going up to a terminal potential 4 MV and a Radio Frequency Quadrupole (RFQ) accelerator, capable of accelerating deuterons up to energies between 3.7 MeV and 5.1 MeV or protons between 1.8 and 2.5 MeV [8].
  The University of Pretoria as a 2 MV Van de Graaff Accelerator [9].
  National Metreological Institute South Africa:(NMISA).

The medical facilities make extensive use of electron linacs for clinical treatments. An audit has been performed by the IAEA and is available at the Directory of Radiotherapy Centres (DIRAC) [10] summarised graphically in figure 15-2 [1]. The total number found is 432. The literature on this topic indicates that Africa is in dire need of technical experts and increased investment to keep them many of them in an appropriate state of operation. Nonetheless, this can be considered a proxy for data indicating the penetration of nuclear medical technology in Africa. Most especially, in the use of modern facilities to validate and provide improved experimental information on nuclei across the periodic table, as well as providing new and balanced scientific interpretation for experimental observations. Researchers in nuclear field across Africa are few, despite the long historical development of nuclear technology in South Africa. Know nuclear facilities are:

In the present configuration, the accelerator facilities are organized into 5 main categories:

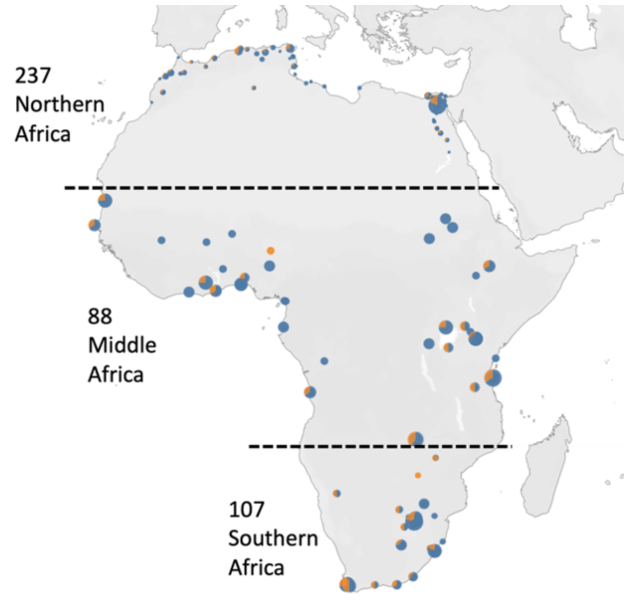

Figure 15-2: The footprint of medical LINACs in Africa from the Directory of Radiotherapy Centres (DIRAC)[1].

- Accelerator-Based Neutron Sources: Blue (146 with 3 in Africa)
- Boron Neutron Capture Therapy (BNCT) facilities: Orange (29 with 0 in Africa)
- Electrostatic Accelerators: Red (322 with 7 in Africa)
- Synchrotron Light Sources: Light Blue (60 with 0 in Africa)
- X-ray Free Electron Laser Sources: Yellow (14 with 0 in Africa)

15.3.2 Nuclear Reactors

Nuclear reactors are categorised into reactors for power generation and research reactors or so-called Materials Test Reactors (MTR). Eleven (11) research reactors currently exist across the African continent, covering a wide power range, from 0.1 kW to 22 MW. Common designs include General Atomics' TRIGA model and the miniature neutron source reactor (MNSR). The countries with Research Reactors include Ghana, Nigeria, Algeria, Egypt, Libya, Morocco, DRC and South Africa.

15.4 ASFAP related Activities for the Nuclear Working Group

The first mini-workshop organised by the ASFAP Nuclear Physics group took place on 2nd March 2022 with four contributions: i) "ASFAP introduction"; ii) "Nuclear Physics Activities at BIUST"; iii) "The Pan African Virtual Nuclear University"; and, iv) report from a student "Tanzania: challenges facing nuclear

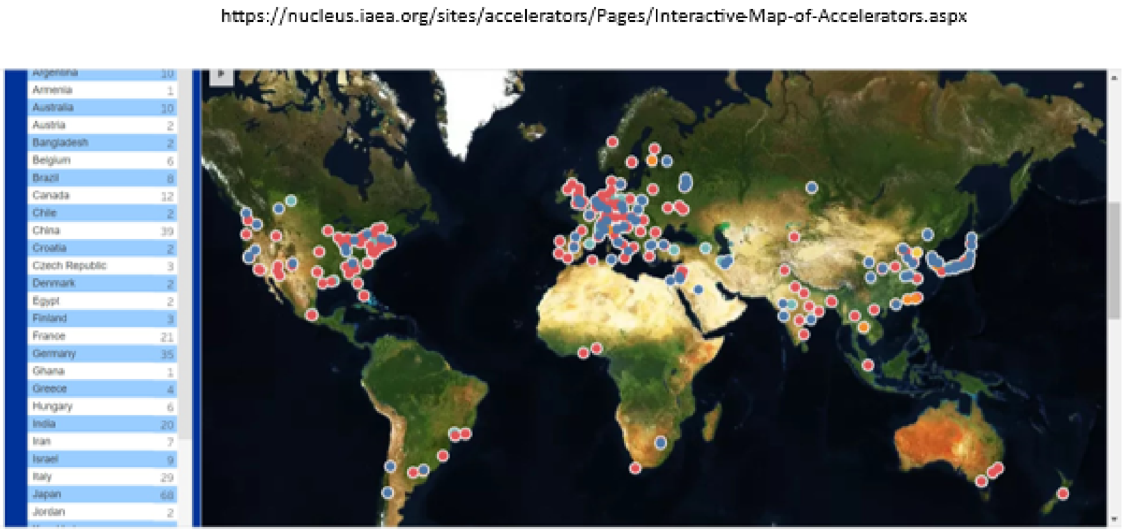

Figure 15-3: Accelerator-Based Neutron Sources: Blue (146 with 3 in Africa) [10]

physics research (lack of suitable and qualified personnel, laboratory equipment for nuclear research, etc.)". It followed with a discussion session in which few relevant aspects were brought-up, such as the need for a training session on Geant4 program (a nuclear and particle physics simulation software). So far, 4 LOIs have been received: three on experimental facilities and one about education and training.

15.4.1 Major challenges

South Africa is facing challenges with energy generation and everyone has to work around load shedding. This ongoing load shedding is negatively affecting nuclear physics research because the main instrument required to conduct experiments and collect data must be turned off during periods of high load shedding implemented by Eskom. For the past year or so, experiments have been postponed at iThemba LABS due to load-shedding. This is the major challenges facing African countries in the running of nuclear physics experiments without power interruption. The International Thermonuclear Experimental Reactor (ITER), is "arguably the most complex machine ever designed," according to Laban Coblentz, head of communication at the ITER Organization. More than 30 nations are working together to build the world's largest tokamak to demonstrate the feasibility of harnessing fusion at an industrial scale. However, no African countries were among those involved. In order to meet up with the evolving fusion research, we need to take more responsibilities in the ongoing fusion research activities, and not left behind. Other challenges that can be considered are intensive Outreach Activities through sponsorship by non-governmental and private organisations in Africa, Sustainability and Continuity of nuclear projects and research facilities across African countries, Effective communication through international collaborative projects, Hashtag "Physicists Without Borders initiative", Facilitation of exchange program among researchers, educational partnerships, workshop, seminars and training of Suitably Qualified and Experienced Personnel (SQEP) in nuclear science and technology to overcome aged workforce in African countries.

15.5 High-priority future needs

- Establishment of Regional Centres for Nuclear Physics Research Facility
- Development of Nuclear Physics Educational Program
- Human Recourses Capacity Development in Nuclear Science and Technology in Africa due to aged workforces and transfer of knowledge
- Outreach and Community Engagements/Interventions
- International collaborations
- Establishment of theoretical nuclear physics centre similar to ICTP-EAIFR Rwanda for each region in Africa for easy access and dissemination of information
- Government supports and funding towards Nuclear Education, Training and Research- From Policy Management to Implementation.

15.6 Synergies with neighbouring fields

While the direct impact on other fields might be less pronounced, the foundational knowledge generated through nuclear research can have interdisciplinary/multidisciplinary applications in fields such as materials science, astrophysics, and nuclear medicine and engineering.

15.7 Environmental and societal impact

Understandably, the foundational knowledge and advancements made in understanding nuclear structure can potentially have long-term implications. Some of these may include applications in nuclear energy development, materials science for radiation shielding, and fundamental insights into nuclear processes with implications for Astrophysics, medical imaging and treatments. While the immediate societal impacts might not be directly evident, the foundational knowledge generated holds promise for potential future applications. Majorly, the impact of nuclear physics research on the society lies majorly in fundamental and applied knowledge contribution and in training future generations for sustainable human capital development. That is, the production of new knowledge that will improve our understanding of the atomic nucleus and materials in general, and the training of those who will sustain the continued existence of the nuclear power industry, nuclear waste management and other allied nuclear industries. The COP28 climate conference has ended with a final agreement that highlights a need to transition away from fossil fuels and toward clean energy. The conference included a promise by more than 20 countries to triple nuclear capacity worldwide by mid-century. "The final COP28 text acknowledges the key role that carbon-free nuclear energy plays in putting the brakes on climate change," American Nuclear Society CEO Craig Piercy says. "We can only meet our net-zero emissions target by 2050 with a swift, large-scale deployment of new reactors worldwide." In the area of environmental impact, evidenced from the recently concluded COP28 where historic pledges and agreements considering nuclear energy as a viable solution to climate change were created towards achieving net-zero carbon, included Nuclear as part of global energy mix for sustainable development focussing on the deployment of Small Modular Reactors (SMRs) in African countries. The project aims to demonstrate a safe, clean and reliable nuclear source that operates autonomously for decades and generate stable energy for African grids.

15.8 Letters of Interests received

Meeting to discuss the ASFAP Nuclear Physics Letters of Interest (LOIs) was held on the 6th of July 2022 (Online). Below are the points raised on the 3 LOIs during the meeting:

15.8.1 NUPHAPHA-Nuclear Photonics Accelerated Physics for Africa

Kalambuka Angeyo (University of Nairobi, Kenya) presented the LOI on Nuclear Photonics using pulse lasers and novel sources based on African Union Agenda 2023. He further explained that similar facilities mostly in advanced developmental stage are taking place at ELI-NP in Bucharest Romania, MEGaRay at Lawrence Livermore USA, Nuclotron Based Ion Collider Facility NICA at Dubna Russia. Paving way out on how best African countries can benefited from this technology, suggestion was made that this initiative can be coordinated through African Laser Centre and iThemba LABS in South Africa.

15.8.2 The use of Am-Be neutron source for teaching and applied research

Sunday Jonah (Ahmadu Bello University, Nigeria) presented on the use of Am-Be neutron source for Physics education teaching, training and applied nuclear research purposes. He mentioned that similar set-up have been developed at Ghana Atomic Energy Commission (GAEC) through the financial supports from IAEA. Emphasis was placed that other African countries can benefited from this project through ASFAP education organising committee. There was a question raised by Mark on the actual cost implication and technical requirements for installation of this equipment at other African countries. This will include shielding, safety aspects as well as security of sources. The actual cost implication will be provided by Sunday Jonah and sent to the Nuclear Physics Committee. In terms of running expenses, there will be available training of technician through seminars and workshop to be organised via the IAEA regional training courses. In terms of communication and outreach, there was a suggestion that the committee should develop pamphlets for distribution to other African countries who might be interested in setting up similar training facility in their institutions regionally within the country.

15.8.3 Unique Research Facilities at the SSC Laboratory in South Africa

Iyabo Usman (University of the Witwatersrand, South Africa) presented on the updates about the South African Isotope Facility (SAIF) project taking place at iThemba LABS. New IBA cyclotron has been brought to complement the SSC and dedicate to the medical isotope production at iThemba LABS, Cape Town South Africa. Also, on the nuclear education and training activities, SAINTS program have been implemented whereby several training activities for undergraduate and postgraduate students are been organised. This includes training workshops on radiation protection, accelerators, radiation biophysics, nuclear metrology, detectors and GEANT4 simulations. More information on future workshops will be announced through ASFAP for participation by students from other African countries.

15.8.4 Challenges

: One of the attendee pointed out about challenges in accessing Am-Be training facilities in the northern part of Nigeria, and suggested if regional facility of the same kind can be implemented due to a very large geographical area of the country. Sunday Jonah and Moji Usikalu will prepare a proposal for six regional centres in Nigeria, and encourages all other countries to emulate this strategy.

Another challenge is the funding to set-up this training facility in African countries. A suggestion about approaching IAEA funding through AFRA technical cooperation research as alternative source of funding can be implemented vi National Liaison Officers of each member states in Africa.

Finally, challenges of getting more members signing up for the ASFAP Nuclear Physics group was mentioned in the discussion. Conveners and committee members should develop a strategic way to get more researchers involved. This can be achieved through nominating country representatives into the ASFAP Nuclear Physics working group.

15.9 Electron Ion Collider (EIC) Nuclear Physics Research Contributions in Africa

The Electron Ion Collider (EIC) is a new and powerful accelerator being built by the Department of Energy (DoE)'s Brookhaven National Laboratory (BNL) in collaboration with Thomas Jefferson National Accelerator Facility in the United States [11, 12]. The EIC is the next quantum chromodynamic (QCD) frontier designed to understand the force that binds all matter in the Universe. QCD is a quantum-field theory described in terms of strong interactions between quarks with gluons as mediators. While significant advancements have been made in various regions worldwide, African nations have yet to harness the full potential of nuclear physics and the EIC. The community is vibrant, currently comprising an international community whose user group now stands at 1,400+ physicists in over 290 institutions. Of these institutions, ten (10) are from the African Continent namely: University Mohammed V in Rabat (Morocco), University Mohammed First in Oujda (Morocco), University Ibn-Tofail (Morocco), Egyptian Center for Theoretical Physics (Egypt), University Cheikh Anta Diop (Senegal), American University in Cairo (Egypt), University of M'sila (Algeria), University of Cape Town (South Africa), Faculty of Sciences of Monastir (Tunisia), and University of Zambia (Zambia). These African institutions are committed to the success of the science program for the EIC.

15.9.1 Prospects

The prospects of engaging in nuclear physics such as EIC-related research from Africa are promising. Increased collaboration with international research teams could position African scientists at the forefront of global discoveries in the field. Participation in large-scale experiments such as at the EIC and sPHENIX could foster a generation of African physicists who are well-versed in advanced nuclear research methodologies, influencing their countries' scientific agendas and policies [13]. Furthermore, understanding the properties of matter at fundamental levels can be highly beneficial in various applications, including materials science, medical technology, and energy production[14]. These prospects underscore the importance of establishing a vibrant nuclear physics research community in Africa.

15.10 Contribution to Knowledge through research and innovation

What is the percentages of nuclear physics research publications in international high impact journals such as Physical Review C, Physical Review Letters, Nuclear Physics A, Physical Review Accelerators and Beams, European Nuclear Physics Journal, Physical Review X, and Reviews of Modern Physics? According to APS, Published by APS Physical Review Journals,

- Since 1980, over 1,500 articles by authors in Africa have been published in the APS Physical Review Journals.
- Over 110 articles published Physical Review Journals in 2020 were from authors in Africa.

In general, some of the problems facing nuclear physics communities in Africa include:

- Lack of experimental setups in many African countries
- Problems of maintenance due to lack/absence of technical services
- Affordability to purchase new equipment
- Bureaucracy in laboratory governance and management
- No funds to support students (Master, Ph.D students) and postdocs
- Students are not trained during their Bachelor/Master to use the experimental setup
- Cannot easily access equipment in other institutions in the same country
- Acquisition of equipment is subject to time-consuming bureaucratic procedure
- Lack of high performance computing centres for theoretical projects
- Problems with internet connection to use HPC in other institutes
- Lack of affordable and powerful workstations
- Lack of commercial software licenses for nuclear physics simulations
- No training within schools and workshops
- Lack of suitable student exchange programs /projects among African countries
- Despite the potential benefits, numerous challenges remain for African researchers wishing to engage in EIC-related nuclear physics research.
- There is a shortage of skilled scientists and personnel who are trained in nuclear physics, specifically in areas related to the EIC.

Statistics on the use of radioisotopes, uranium mining, movement of nuclear waste from power plant to the repository waste disposal. Link to the future of the need for power sources to reduce climate change. Therefore, the future is nuclear fusion.

15.11 Recommendations

Based on the identified challenges and prospects, the following recommendations can be made to enhance the involvement of African researchers in nuclear physics related research:

- Increase Funding: Advocate for increased investment in nuclear physics research from both government and private sectors to ensure adequate resources for EIC related research studies.
- Strengthen Collaborations: Foster strong partnerships with international research organizations and institutions involved in EIC research for mutual benefit and knowledge exchange. Collaborations with established global institutions are essential to foster knowledge transfer and expertise development [15]. As the construction of the EIC progresses at Brookhaven National Laboratory in the USA, there are significant opportunities for African scientists to engage in international collaborations and contribute to the scientific knowledge base surrounding this innovative facility.
- Develop Infrastructure: Advocate for the establishment of regional-research facilities equipped for nuclear-physics research, including proton and ion-beam technology.
- Enhance Education and Training: Invest in educational programs and workshops that focus on advanced nuclear-physics topics, targeting students and early-career researchers.
- Promote Networking: Encourage the formation of regional-research networks to improve collaboration between institutions and promote collective-research efforts.
- Engage the Youth: Implement outreach initiatives aimed at inspiring high school students and undergraduates to consider careers in nuclear physics and related fields.
- Interdisciplinary approaches: Universities and research institutions in Africa must develop interdisciplinary approaches that combine nuclear physics with other scientific domains to maximize research outputs.
- Public engagement: Promoting public engagement and awareness surrounding the importance of nuclear physics research could also harness broader support for funding and collaboration [16].

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16

High Energy Physics Working Group

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16.1 Overview

High energy physics is unique in the sense that it encompasses a broad range of explorations, spearheaded by probing what happens at smallest length scale with the highest energy and most complex scientific experiment ever built. However stress-testing the well established Standard Model of Particle Physics or searching for beyond the Standard Model phenomenon at the Large Hadron Collider (LHC) and other experiments is only a part of the story. The field spans complex theoretical endeavours such as string theory, to the current hot topic of machine learning, which has possibly been used in this field the longest. While high energy physics by nature is global and collaborative, African researchers have been involved in all of the above, while making their mark in the worldwide endeavour. However, this chapter is more focused on experimental explorations and related phenomenological work, building on previous works along this direction [1].

16.2 LHC Physics

The particle physics programme at the LHC is based on four major experiments, ALICE, ATLAS, CMS and LHCb. It has to be noted that becoming part of any of the collaborations implies long term commitment from the funding agency, and by extension the national government. Considering that the economic and political situation in many African countries is far from stable, this presents a substantial challenge. So it is indeed remarkable that five countries, Egypt, Morocco, Nigeria, South Africa and Tunisia have varying levels of participation in ALICE, ATLAS, and CMS experiments, while Algeria was associated with ATLAS in a limited technical capacity. These groups are supported by phenomenologists working alongside experimentalists in Egypt, Morocco and South Africa.

The LHC started in 2009, first at a collision energy of 900 GeV, and then moving up to 7 TeV, concluding its Run 1 in 2013. The discovery of the long postulated Higgs boson [16, 17] was a highlight of this run, where the African groups contributed. After two years of maintenance and upgrade, it restarted in 2015 at a collision energy of 13 TeV, concluding the Run 2 in 2018. Another long pause allowed more upgrade to all the detectors and accelerator itself, and Run 3 started in 2022, with a slightly increased collision energy of 13.6 TeV. The Run 3 is supposed to go on till 2026. Then a long shutdown will allow for the preparation for high luminosity phase, known as HL-LHC. This includes installation of new key equipment on the accelerator side, and replacing critical detector and electronics components for the experiments. The start-up of the HL-LHC (Run 4 and Run 5) is now planned for June 2030 till 2041, including a short stop in 2034-35. As no new energy frontier experiment after that is still not decided, this is the data this and the next generation of particle physicists will see, trying to unravel critical mysteries like dark matter.

Morocco and South Africa participates in ATLAS experiment [2] as clusters, where a number of institutes from each country have a common voice in the collaboration matters. This allowed the groups to develop without having a critical mass of physicists in a particular university.

The Moroccan cluster started in 1996, and consists of:

1. Universite Hassan II (Casablanca)
2. Mohammed VI Polytechnic University
3. Université Cadi Ayyad (Marrakech)
4. University Mohammed V (Rabat)
5. Mohammed 1st University (Oujda)
6. Ibn-Tofail University (Kenitra)

The South African cluster started in 2010, and consists of:

1. iThemba Labs (iTL)
2. University of Cape Town (UCT)
3. University of Johannesburg (UJ)
4. University of South Africa (UNISA
5. University of Witwatersrand (Wits, with University of the Philippines Diliman as an associate institute)
6. University of Zululand (UniZulu, which is classified as a historical black university, exemplifying the inclusivity of the SA-CERN programme).

Ecole nationale Supérieure d'Informatique in Algiers is unfortunately not active any more, having started in 2019 and continued till 2023.

Moroccan and South African clusters collectively have about fifty authors now, and an ever expanding number of post-graduate students. The South African hardware activities span detector maintenance and upgrade. They include:

1. Silicon detector developments on both the SCT and ITk detector systems, including, data acquisition electronics development, evaporative cooling systems, material description in simulation, firmware and test quality control for readout cards, polymoderator design, procurement, and fabrication. CFD simulations for temperature and humidity distributions inside the detector ITk volume was also performed.
2. On Muon New Small Wheel, including, material description in simulation, manufacturing and assembly of components and installation tools as well as commissioning.
3. Assembly, quality checks and installation of the gap scintillator counters.
4. Phase-II upgrade of the Tile Calorimeter, 50% of the production of the Low Voltage Power Supplies (LVPS), 24% of the production of the Tile Preprocessor (PPr) and participation in TileCal November 2021 Test-beam.

Moroccan groups work on Transition Radiation Tracker, Liquid-Argon Calorimeter and High Granularity Timing Detector. Moroccan researchers playing a pivotal role in the construction, testing, and commissioning of the ATLAS Electromagnetic Calorimeter Presampler from 1998 to 2003. The groups also have actively engage in distributed data analysis through grid computing, by coordination of the ATLAS Distributed Analysis Support Team. UMP6 is poised to serve as a crucial Moroccan Tier-3 center supporting ATLAS research, with aspirations to evolve into an ATLAS Tier-2 center.

As the interests of the group members and group compositions change over time, any description of the physics analyses the groups currently involved in will be incomplete, but here is a snapshot for the South African institutes:

- Part of the Wits group has been invested in searching for new physics in final states with Higgs boson, with or without significant missing energy. Some of the final states probed or being probed recently include photons and multi-leptons, having previously contributed to exploring the WW decays of the Higgs boson.
- Another part of Wits group has contributed to measurements sensitive to internal structure of jets, and searching for new physics in novel final states, including boosted heavy neutrino signature resulting in a lepton inside a jet, semi-visible jets, and dark photons decaying to lepton jets.
- The UJ group has for a long term focussed on new physics showing up in four lepton final state, including decays of hypothetical dark Z boson or additional new scalars. The group also led the Run 2 BSM Higgs Physics Report from ATLAS.
- The UCT group has focussed on top physics, such as measurement of top mass utilising leptonic J/ψ decays, top quark coupling and charge asymmetry and also on new physics searches via the study of top electro-weak couplings in rare electroweak processes.

Similarly, a possibly incomplete snapshot of the Moroccan groups follows:

- The Kenitra group has been involved different di-Higgs as well as in charged Higgs searches.
- The Casablanca group is also involved in di-Higgs searches, mostly focussing on $bbll$ final state, but also have members contributing to hypothetical Z' to $\mu\mu$ search and search for new physics in events with leptons and missing energy.

- The Rabat group is mostly focussed on searches in final states with additional scalars or dark photons or charged Higgs bosons decaying to leptons with or without missing energy. They also look at rare light-by-light scattering events in lead-lead collisions.
- The Oujda group looks for signs for super-symmetry in electroweak-production processes, including signatures of displaced tracks.

This shows the diverse interest of both the countries in ATLAS. Some of the recent achievements will include a collaboration wide thesis-award winner, ATLAS PhD grant winner, featuring the first semi-visible jets search result in ATLAS briefing, and multiple leadership positions in different levels of the collaboration, including as a chair of tile calorimeter institutional board, memberships in collaboration board chair advisory group, appointment as a contact on Diversity and Inclusion, memberships in early career scientist board, and leaderships of different physics sub-groups. The collaboration week was successfully organised in in Marrakesh in 2013, showing the impact of the Moroccan cluster to ATLAS already then.

ALICE experiment [6] is more focussed on studying ultra-relativistic heavy-ion collisions in which extreme conditions of energy density and temperature occur, and a new state of matter, termed the quark-gluon plasma is formed. The groups based in iThemba Labs and in the University of Witwatersrand and Cape Town are active. They contribute to upgrade projects towards a common read out unit for the muon identifier, the Low-Voltage System for muon tracking, and online data processing for the Transition Radiation Detector. In terms p physics analyses, the groups work on W and Z boson tests of the Standard Model via the study of the cross-sections in lead-lead and proton-lead collisions.

A major focus have been student training. As South Africa is the leading country in Physics research in sub-Saharan Africa, students from all over the continent have worked on ATLAS and ALICE experiments over the years, some prominent examples being students from Nigeria, Zambia, Zimbabwe, Cameroon, Botswana, Madagascar, Lesotho, eSwatini. Some of these students have continued to excel overseas.

The South African community organised annual High Energy Particle Physics workshop, where students presented their work along with tutorials on selected topic. This has not restarted after the pandemic, but in 2024 January, a school on computing in High Energy Physics, termed Chacal hosted about forty students from across the continent and leading experts from all over the world for two weeks in Johannesburg. This was funded by French CNRS. The biannual Kruger conference on discovery physics, organised in the vicinity of the popular national park, has grown to be a major international meeting in the field. The Moroccan community organised the first African Conference on High Energy Physics in 2023. Additionally, the ever popular African School and Conference of Physics, always has strong component covering particle physics.

The South African effort is generously supported by the National Research Foundation and Department of Science and Industry under a common SA-CERN consortium. It also provides bursaries for postgraduate students and support for postdoctoral researchers, which is critical for the growth of the programme. The establishment of the Moroccan High Energy Physics Cluster (RUPHE) in 1996 epitomises the nation's commitment to advancing science, technology, and innovation. It serves as a hub of collaborating institutes in ATLAS. In September 2020, the Moroccan Foundation for Advanced Science, Innovation, and Research (MAScIR) achieved recognition as an Associated Technical Institute within the ATLAS experiment. The Moroccan Academic and Research Wide Area Network (MARWAN) stands as the national computer network dedicated to education, training, and research, supported by Minister of Higher Education, Research, and Innovation and the National Center for Scientific and Technical Research (CNRST).

The CMS [3] effort in the continent is led by Academy of Scientific Research and Technology (Cairo) and by Center for High Energy Physics (CHEP-FU), Fayoum University (Al Fayoum) in Egypt, and coordinated by the Egyptian Network of High Energy Physics (ENHEP). From the detector side, the groups are involved in the assembly and testing of gaseous muon detectors, including both GEM and RPC gas detectors. In addition to detector development, Egyptian researchers contribute to the physics performance of these sub-detectors, ensuring their proper functioning in particle detection. On the analysis side, the contributions span diHiggs production studies, probing Higgs boson decay to dimuon channels and searches for dark matter. Egyptian groups are is involved in the MATHUSLA experiment, which focuses on detecting long-lived particles beyond the Standard Model.

University of Benin in Nigeria is working on establishing a High-Performance Computing (HPC) as a technical part of CMS collaboration. Along with that, the group has contributed to the development and Operation of the CMS online system administration, Development and Operation of the CMS Online System Administration, unified web-page management, static code analysis, and deployment with GitLab-CI for the CMS Tier-0 sites.

Just like Morocco and South Africa, Egypt is also leveraging its active contribution in CMS to encourage the next generation of HEP researchers. Several universities, such as Zewail City of Science and Technology in Giza, have established programs specifically designed for this. These educational programs, together with research initiatives at other institutions, demonstrate Egypt's commitment to developing HEP expertise at the academic level and preparing students for advanced research in the field. Egypt has also significantly benefited from international training opportunities, such as the Erasmus Mundus program, and collaborations coordinated by the Academy of Scientific Research and Technology (ASRT) in Cairo. These partnerships, which involve funding agencies from different countries around the world, provide crucial support for capacity building, enabling students and young researchers to gain valuable experience and expand their knowledge through global collaborations.

The primary objective of the HPC initiative in Nigeria as well is to enhance Nigeria's and Africa's overall computational capacity.The center is expected to allocate 20% of its total capacity to functioning as a CMS computing center within the Worldwide LHC Computing Grid (WLCG), supporting high-energy physics research. The remaining 80% will be utilized for computational tasks in other critical research areas such as agriculture, healthcare, and climate change.

While the impact in the LHC physics programme by Africa-based collaborators is undeniable, it is worth mentioning the recent interest in machine learning aspects that came about. High energy physics in some ways has been the original test-bed of these algorithms, so this has made particle physics attractive to funding agencies and even for students pursuing a career beyond physics. In this context, the close connection with the African Institute for Mathematical Sciences, which is a pan-African institution (with centres in South Africa, Cameroon, Senegal, Ghana, Tanzania and Rwanda) offering a MSc degree in mathematical sciences must be mentioned. Even though they are not directly part of the CERN programme, ATLAS members have supervised projects, and ran courses focussed mostly on data science. The connection is further strengthened by their connection with Quantum Leap Africa (QLA), an organisation supporting students and researchers in the quantum science domain. Recently QLA has agreed to support a doctoral student working in ATLAS, exemplifying the increasing connection.

16.3 Neutrino Experiments

Groups from Morocco and Madagascar are involved in the state-of-the-art neutrino experiments. Having previously been part of the ANTARES experiment [8], three universities (Mohammed V, Cadi Ayyad, and Mohammed 1) are part of the KM3NeT1 Collaboration [9]. It is a research infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea with the main objectives being the discovery and subsequent observation of high- energy neutrino sources in the Universe and the determination of the mass hierarchy of neutrinos. The groups are actively participating in the production line of optical modules in a national site located in Rabat. Besides, the Moroccan team is also involved in the physics analysis of many topics, essentially related to search for magnetic monopoles, search for nuclearites, and study of the neutrino mass hierarchy.

As of November 2024, Madagascar is currently the only African country member of the Deep Underground Neutrino Collaboration or DUNE [13], having joined in 2016. Madagascar is represented by the Neutrino Experimental group of from the University of Antananarivo. The group unfortunately does not have any supports from the University or the Government yet of now but rely on alumna and collaborators from abroad. Three Universities in the US and two national labs have offered and continue to support the university research initiative. (The University of Pittsburgh, Stony Brook University, South Dakota School of Mines, Brookhaven National Laboratory via the African School of Physics and Fermilab). The Neutrino Experimental group of Madagascar have contributed in the Detector Conceptual design report to the System for on-Axis Neutrino Detector and in a project involved cold electronics specifically LArASIC lifetime study at cryogenic temperature.

The ongoing collaborative contributions of Madagascar along with Stony Brook University is a contribution on the ProtoDUNE data analysis and the FD3 simulation and reconstruction. A study of neutrino energy reconstruction using light in the GeV and MeV ranges. Madagascar has a vision to increase the numbers of experts in neutrino event generators in the country as well. One project among many that is worth special note is implementation new cross sections for hadron transport models in the GENIE Monte Carlo event generator, a tool widely used in neutrino experiments. The group have developed a theoretical code that calculates total and differential cross sections for interactions involving πN, ηN, $\kappa\lambda$, and $\kappa\sigma$ utilizing the DCC facility in ANL-Osaka. The impact in joining DUNE is a tremendous expansion of knowledge in term of experimental high energy physics which was non-existent in the island prior joining DUNE.

16.4 Future Experiments

The HL-LHC is expected to run for the next decade, but so far it is not clear what the next big collider facility will be. CERN is strongly advocating for the Future Circular Collider (FCC), starting with an electron–positron collider for precision measurements offering a 15-year research programme from the mid-2040s. Subsequently it will be upgraded to an hadron collider, aiming to reach collision energies of 100 TeV, colliding protons and also heavy-ions, and running until the end of the 21st century. A competing proposal is the Circular Electron Positron Collider (CEPC) in China, for probing the Higgs boson physics in great detail. Many colleagues are involved in feasibility study of different physics scenarios in these proposed colliders.

While neither of these have been approved, the Electron Ion Collider (EIC) [14] is being constructed at Brookhaven National Laboratory (BNL) in partnership with Jefferson Lab (JLab) in USA. The EIC will be a particle accelerator that collides electrons with protons and nuclei to produce snapshots of internal structure of those particles, like a CT scanner for atoms. The following African institutes have joined:

1. University Mohammed V (Rabat), Morocco
2. University Mohammed I (Oujda), Morocco
3. American University (Cairo), Egypt
4. Egyptian Centre for Theoretical Physics, Egypt

5. University Mohamed Boudiaf (M'sila), Algeria
6. University of Monastir (Monastir), Tunisia
7. University Cheikh (Anta Diop), Senegal
8. University of Cape Town (Cape Town), South Africa
9. University of Witwatersrand (Johannesburg), South Africa
10. University of Zambia (Lusaka), Zambia

The groups aim to contribute to EIC detector design, simulations and development of the experimental data-analysis software kit. They intend to contribute to the study of generalized parton distributions (GPDs), study of factorization, jet broadening and parton energy loss in electron-proton (ep) and electron-nucleus (eA) collisions, final state particle production mechanisms via spin asymmetries following initial state electron-proton (ep), electron-nuclei (eA) particle collisions. Additionally, the extension of comprehensiveness of high-dimensional phase space integration taking into account radiations from the initial and final states occurring in electron-ion collisions using Monte Carlo integration method is also foreseen.

16.5 Phenomenology

The searches and measurement at the experimental facilities are intricately connected to phenomenological explorations. This is exemplified by the fact that some of the so-called experimentalists have published such papers, and went on to pursue that direction in the experiments. Acknowledging this unique synergy, the South African CERN consortium includes theory as an integral part, which has massively contributed to the growth of the field in South Africa an beyond. The contributions span exploration of a wide range of beyond the Standard Model scenarios, at LHC to future colliders, focussing on LHC multilepton, diphoton, and top-quark excesses, models with extra dimensions, dark-QCD and other dark matter scenarios and use of machine learning. Additionally, more formal aspects of QCD are also explored, including jets in heavy ion collisions, and various aspects of the quark-gluon plasma. The efforts are led by University of Witwatersrand, Johannesburg and Cape Town.

The Moroccan and Egyptian groups similarly are involved in studies of super-symmetry (SUSY) phenomenology, Higgs physics, theoretical and EW precision constraints on scalar sectors in various extensions of the SM like models with massive gravitons, various extensions of 2HDM, dark photons, Laser-assisted particle decays, and astro-Particle Physics. The Moroccan effort is mostly concentrated in Cadi Ayyad University in Marrakech and Safi, Rabat University, Tanger University, Ibn Zohr University, Ibn Tofail University, Abdelmalek Essaadi University and CPM, Rabat, not in any particular order. The Egyptian effort is led by Zewail City of Science, Technology and Innovation, Ain Shams University, Cairo University, Alexandria University, Egyptian Center for Theoretical Physics, Cairo, and Assiut University, again not in any specific order. Various new physics scenarios such as heavy neutrino, semivisible dark photon, additional Higgs bosons, as well as aspects of QCD are studied.

The East African Institute for Fundamental Research (EAIFR), at the University of Rwanda has research interest in fundamental physics with a focus on collider physics, physics beyond the Standard Model, cosmic inflation, Dark Matter and Dark Energy. EAIFR has produced results on the impact of additional Higgs bosons on signal rates and study of possible deviations from the SM. The group from Madagascar, based in Institute of High-Energy Physics, is specialist of non perturbative methods in strong interactions. More precisely, they use QCD sum rules to predict hadron properties, such as masses and coupling constants.

16.6 Challenges Hindering the Growth of HEP in Africa

Growing particle physics in Africa faces numerous significant challenges that must be addressed to cultivate a thriving and sustainable research environment. Let's delve into some key considerations:

- Infrastructure and Funding: One of the foremost hurdles is the absence of adequate infrastructure and funding for particle physics research across many African countries. Constructing and maintaining particle accelerators, detectors, and other critical facilities demand substantial financial investment. The scarcity of funds inhibits the establishment of top-tier research centers and the acquisition of state-of-the-art equipment, thereby impeding the ability to compete globally.

- Education and Expertise: Nurturing a proficient workforce in particle physics necessitates a robust educational framework. Unfortunately, several African nations encounter difficulties in providing quality education in physics and related disciplines. Targeted programs are imperative to train scientists, engineers, and technicians equipped with the specialized knowledge essential for particle physics research. Moreover, attracting and retaining skilled researchers poses a challenge amidst global competition for talent.

- International Collaboration: Collaboration with international institutions is pivotal for the advancement of particle physics in Africa. However, navigating logistical, bureaucratic, and communication barriers can pose challenges in establishing and sustaining such partnerships. Fostering collaborations with established research institutions can grant access to expertise, resources, and collaborative prospects, thereby assisting African researchers in overcoming local constraints.

- Political Stability and Support: Political stability and governmental backing are indispensable for the enduring viability of particle physics endeavors. Political unrest and fluctuating climates can disrupt research endeavors, jeopardizing progress and investments. It is imperative to advocate for stable political environments and underscore the significance of particle physics research for the scientific and technological progression of the continent.

- Public Awareness and Engagement: Heightening awareness about the significance and potential impact of particle physics research is pivotal for garnering public support and securing funding. Educating both the public and policymakers about the contributions of particle physics to technological innovation, medical advancements, and our comprehension of the universe can foster a supportive atmosphere for research initiatives.

- Access to Data and Publications: Ensuring open access to data and research publications is critical for the growth of particle physics in Africa. Restricted access to scientific literature and data can impede researchers' progress and hinder the dissemination of knowledge. Initiatives promoting open science practices and facilitating information-sharing across borders are essential.

Addressing these challenges necessitates a multifaceted approach involving collaboration among governments, educational institutions, international organizations, and the scientific community. By surmounting these obstacles, Africa can make significant contributions to the global field of particle physics and reap the broader scientific and technological advancements stemming from such research efforts.

16.7 Prioritizing Future Imperatives: HEP in Africa

To foster particle physics in Africa effectively, it is imperative to conduct a thorough assessment of the key future requirements necessary to advance the field and nurture a flourishing scientific community across the continent.

- Infrastructure and Technological Advancements: Establishing robust infrastructure tailored to the unique demands of particle physics research is paramount. This entails developing and maintaining particle accelerators, detectors, and computational facilities. Adequate investment in infrastructure equips African scientists with the necessary tools to conduct cutting-edge experiments and make substantial contributions to global scientific endeavors.
- Shared Research Facilities: Encourage the establishment of shared research facilities that can be accessed by scientists from multiple African nations. This can include shared laboratories, data repositories, and computational resources, enhancing the infrastructure available for particle physics research.
- Establish Collaborative Research Networks: Create and support regional networks and consortia dedicated to particle physics research. These networks can facilitate collaboration, information exchange, and joint research projects among institutions and researchers across African countries.
- Cross-Border Collaborative Research Centers: Support the establishment of collaborative research centers that span multiple African countries. These centers can serve as hubs for joint research, fostering a culture of collaboration and providing a focal point for researchers to converge and exchange ideas.
- Promotion of International Collaboration: Facilitating robust collaboration with esteemed research institutions worldwide is indispensable for driving innovation and knowledge exchange in particle physics. By fostering strategic partnerships and participating in collaborative projects, African researchers can leverage resources, expertise, and cutting-edge technologies to advance scientific discovery on a global scale.
- Research Support and Funding: Sustained investment in research and development is crucial for nurturing a conducive research environment. Governments, funding agencies, and private sector entities must prioritize funding for particle physics research initiatives, enabling scientists to explore new frontiers and address fundamental questions in the field. Adequate research support fuels innovation, drives technological advancements, and positions Africa as a key player in the global scientific community.
- Capacity Building and Education: Investment in education and capacity-building initiatives is fundamental. Enhancing the quality of physics education across all levels, from primary to tertiary institutions, cultivates a pipeline of skilled researchers capable of tackling complex challenges in particle physics. Specialized training programs and collaborations with international institutions bolster expertise within the continent, fostering a dynamic scientific community.
- Exchange Programs and Fellowships: Implement exchange programs and fellowships that allow researchers, students, and faculty to spend time at institutions in other African countries. This cross-pollination of ideas and expertise can strengthen research capabilities and foster long-term collaborations.
- Open Access and Knowledge Dissemination: Ensuring open access to data, research findings, and scientific publications is vital for fostering collaboration, transparency, and knowledge dissemination within the scientific community. Efforts to promote open science practices and establish accessible

platforms for sharing information empower African researchers to leverage existing knowledge and contribute meaningfully to scientific advancements.

- Advocacy for Policy Reform: Advocating for policies that prioritize scientific research, innovation, and technological development is critical. Governments and policymakers must recognize the strategic importance of investing in scientific infrastructure, supporting research initiatives, and fostering a conducive regulatory framework. By advocating for policy reform, stakeholders can create an enabling environment that stimulates scientific inquiry, drives economic growth, and enhances global competitiveness.

In conclusion, addressing the high-priority future needs for HEP in Africa demands a collaborative and multifaceted approach. By investing in infrastructure, capacity building, international collaboration, research support, and advocacy for policy reform, Africa can harness its scientific potential, contribute to groundbreaking discoveries, and shape the future of particle physics on the global stage.

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17

Multidisciplinary Science at Underground Facilities

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Abstract

Establishing a deep underground physics laboratory to study, amongst others, double beta decay, geoneutrinos, reactor neutrinos and dark matter has been discussed for more than a decade within the austral African physicists' community. Such facilities can also be used for multisciplinary science that include biological science, geophysics, quantum computing and ultra-low radioactivity measurements. Most of the operating laboratories of this type are to be found in the northern hemisphere: Europe, USA, Russia, Canada and Japan, with none in Africa. PAUL, the Paarl Africa Underground Laboratory, is an initiative for establishing an international underground laboratory devoted to the development of competitive science in the austral region, specifically in South Africa. It has the advantage that the location, the Huguenot tunnel earmarked for hosting the laboratory, exists already and the geology and the environment of the site is appropriate for an experimental facility.

17.1 Preamble on an ASFAP underground science laboratory

During the ASFAP process, in December 2021, two authors of this chapter submitted a letter of interest [1] on the potentiality of setting up an underground laboratory (UL) in Africa. These laboratories (ULs) are located in mines and tunnels, and most of the operating laboratories are to be found in the northern hemisphere: Europe, USA, Russia, Canada and Japan. One UL is under commissioning in Ausralia, and two more are planned: ANDES at the Argentina-Chile border and INO in India. About one hundred experiments are running or are under construction in the ULs currently in operation and roughly 6000 researchers are involved.

Contact have been taken by the authors of the LoI to prospect whether there is motivation and potential engagement in Africa. An interest was expressed by physicists from South Africa and the first contacts and discussions were established by end of 2022. On Figure 17-1 The yellow star is the foreseen location of the future Africa underground lab facility, in the Western Cape Province of South Africa, under the 1300 m Du Toitskloof mountain [2].

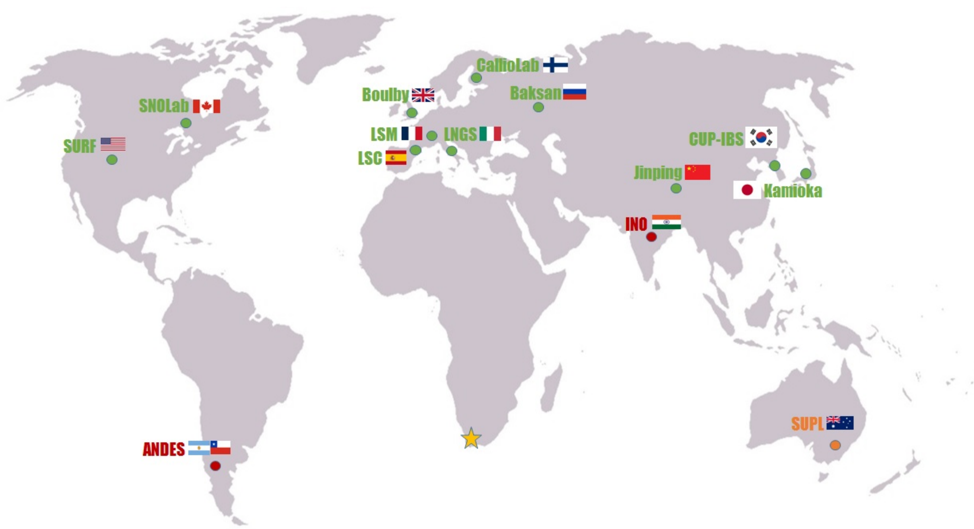

Figure 17-1: Map of the existing or planned underground laboratories. Green dots: the operating facilities. Orange dot: under commissioning SUPL facility in Australia . Red dots: ANDES at the Argentina-Chile border and INO in India. Yellow star: the future Paarl Africa underground lab facility, in the Western Cape Province of South Africa [2].

17.2 Frontier science motivation

Neutrinos and the search for dark matter have been big drivers in the field of experimental physics, sitting at the frontier between nuclear physics, particle physics, astroparticle physics and cosmology. These studies are only possible in underground laboratories where the experiments are shielded from cosmic rays by at least about 1,000 m of rock. These laboratories are located in mines and tunnels, and most of the operating laboratories are to be found in the northern hemisphere.

Underground laboratories provide the low-background radioactive environment necessary for astroparticle physics to explore extremely rare phenomena. The underground location naturally guarantees high suppression of muons and cosmic-ray particles produced in the atmosphere and, consequently, of cosmogenic by-products.

The foreseen location of the future Paarl Africa underground lab facility or PAUL is inside the Huguenot tunnel, Figure 17-2, which is conveniently located between the towns of Paarl and Worcerster in the Western Cape Province of South Africa. The facility will be under the 1300 m Du Toitskloof mountain with about 800 m of rock overburden for the Huguenot tunnel itself [3].

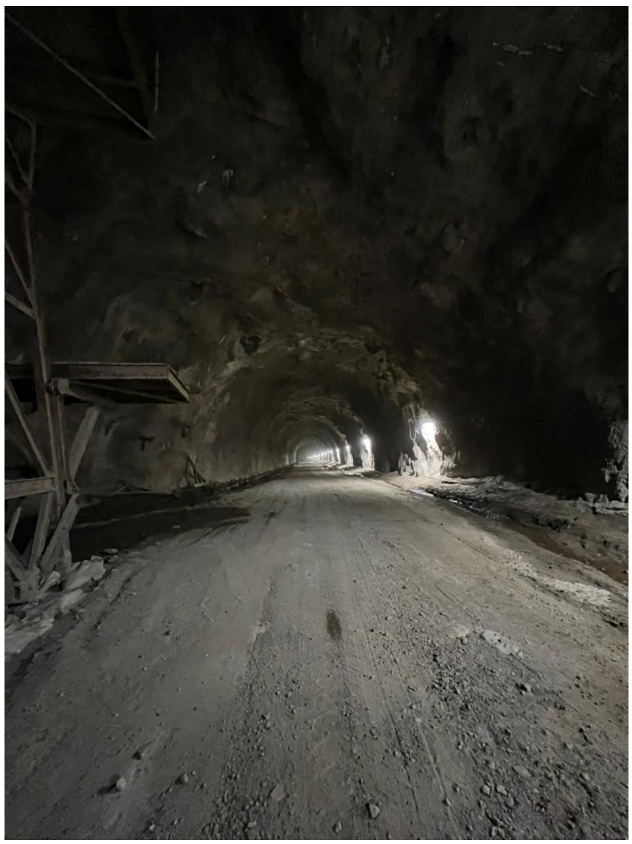

Figure 17-2: Inside the Huguenot Tunnel. Photo credit: courtesy JJ Van Zyl/Stellenbosch University.

At high dark matter masses, only detectors using noble liquids (Xenon and Argon) can reach the required sensitivity. While the underground site for those experiments is not yet defined, a novel underground site that does not surpass the existing ones in terms of depth can hardly be a good choice for them. At small dark matter masses, however, there are many new opportunities to which a novel underground laboratory can. Dark matter with mass below the proton (sub-GeV) typically lies in a dark sector, which does not interact directly with any of the Standard Model forces. Instead, new particles (such as dark photons, scalars, or pseudo-scalars) can mediate interactions between the dark matter and the ordinary matter. There is nowadays a plethora of experimental techniques that are trying to gain sensitivity to such small signals. In this case, the challenge is to develop detectors with very low energy thresholds and excellent control over detector backgrounds, rather than to build large detectors that are highly demanding in terms of occupied volumes in an underground laboratory. There are many other efforts and plans, and since the hunt for low-mass dark matter is relatively young, there is space for new experiments and new underground sites. The search for light dark matter particle is particularly attractive for these new technologies as significant advances can be achieved with kg-scale detector arrays.

17.3 Motivation for the specific location of the laboratory in the southern tip of Africa

One of the most interesting facts about having the possibility to perform an experiment of direct dark matter detection in an underground laboratory located in the Southern Hemisphere is to compare the eventual systematic errors or modulation with respect to the same detector in the Northern Hemisphere. It also opens different regions of parameter space when searching for daily modulations.

The other advantage to build such a facility in South Africa is to combine the direct detection with indirect dark matter detection from radio astronomy surveys that South Africa is leading. As is well known, South Africa has been leading the world-astronomy collaboration "Square Kilometre Array" (SKA) [4] mid-frequency arrays, and has already built 64-dishes precursor "MeerKAT" telescopes in 2018 [5]. The dark matter annihilation into standard model particles (e.g. $b\bar{b}, \tau^+\tau^-, \mu^+\mu^-$) can eventually cascade to electron-positron pairs, which can lose their energies by inverse Compton-scattering and synchrotron radiation. This cascade process can generate fluxes in X-rays and radio wavelength respectively, with detailed variation determined by the dark matter mass and the astrophysical environment. Both experiments have South Africa's deep participation and involvement. Therefore, the strong synergy between the astrophysical (indirect) probes and Paarl Africa Underground Laboratory (direct probe) can jointly measure and constrain dark matter effect, which may shed lights on new physics.

The need for very low radioactive material for dark matter and neutrino underground experiments gave birth to the study of new detectors able to measure extremely low radiation levels. These very sensitive detectors, able to detect levels of radiation a millionth of the natural radiation of the human body and they have to be located deep underground to be shielded from cosmic radiation. The industry has shown interest in these techniques to select pure materials with almost no radioactive content. Researchers involved in this project can contribute to many needs in South Africa for accurate measurements, such as the detection of the radioactive gas radon that has been identified as a major radiation hazard in South African underground mines. The scientific work can expand to research projects in multiple fields including biology (radiation interaction with cells, microbiology in extreme environments), geosciences, chemistry, mining technology, quantum computing etc.

In addition, the underground laboratory will provide a dynamic environment for advances in ultra-sensitive detectors and ultra-low radiation techniques and highly trained graduates ready to lead innovation in both the global search for rare events and cutting-edge technological development to benefit South Africa industry.

Discussions about an underground research facility in South Africa started in 2011. As one of the world's largest producers of gold, South Africa has a number of the world's deepest gold mines, including the recently closed TauTona Gold Mine with a depth of 3900 m, and Mponeng deeper still. In 1965 the Nobel Prize laureate Frederich Reines along with South African Physicist, Friedel Sellschop detected the first atmospheric neutrino events in the East Rand mine near Johannesburg, South Africa [6]. Initial focus by the South African nuclear physics community was on establishing an underground facility in one of South Africa's deep gold mines. The alternative is to develop such an underground laboratory inside the Huguenot tunnel, located between the towns of Paarl and Worcerster in the Western Cape Province [7].

The development of the Huguenot tunnel as an underground low-level radiation facility holds a number of strategic advantages. Such a facility is located approximately 25 km from Stellenbosch University and 40 km from the iThemba LABS. It offers a unique possibility to build up a scientific complex suitable for the detection of events under ultra-low radiation exposure, as required for dark matter and neutrino studies, as well as for other areas of research.

The laboratory will consist of a surface facility, located near the road freeway Huguenot tunnel, and potentially extensive underground spaces and various connecting tunnels. The experimental hall will be covered by about 800 m of rock, under the Du Toitskloof Mountains, protecting the experiments from cosmic rays. It will be easily accessible, with the ability to drive to it rather than using mine-shaft elevators, similarly to the LSM (Laboratoire Souterrain de Modane, France) [8], LSC (Laboratorio Subterráneo de Canfranc, Spain) [9] or LNGS (Laboratori Nazionali del Gran Sasso, Italy) [10] facilities.

17.4 Prospects for establishing the facility in Africa

In December 2023, South Africa's Department of Science and Innovation (DSI) gave mandate to the PAUL collabortion for independent scientific and engineering feasibility studies. The main objective is to explore the viability of an underground laboratory of about 10,000 m^3 inside the Huguenot Tunnel and to establish a scientific culture of international cooperation, between African countries, and with the international community.

The first symposium on Science at PAUL was held on January 2024 at Du Kloof [11]. This event has gathered an international community of underground laboratories and led to the official launch of the project [12, 13].

The tunnel provides quick and easy access to the local research communities. Research programs done at such a facility will also support postgraduate training programs at Stellenbosch University, the University of the Western Cape, the University of Cape Town and Cape Peninsula University of Technology. Furthermore, the research at the PAUL will support national and international research activities in astronomy, nuclear and particle physics, as well as many of the research topics already discussed.

More than that, the project will offer the chance to integrate with other worldwide facilities, laboratories and experiments and increase the potential of the region by increasing its academic activities, the formation of new human resources and the development of new basic research and technologies. This is a unique opportunity to build an excellent deep underground laboratory, the only one in Africa, with a strong impact on regional integration.

The collaboration has been built from the beginning together with high-level scientists from top-level underground laboratories. More importantly, the local leading universities, Stellenbosch University and the University of the Western Cape, not only attracted other South-African universities such as Wits, UNWA and UNISA but facilitated the participation of physicist from other African countries, such Botswana, Nigeria, Kenya and even North Africa. This was made possible thanks to the good relations South-African universities kept with their former African students. It is also well-reflected in the authorship of the founding article [2]. The actual collaboration includes thirteen African universities or research organizations.

17.5 Multidisciplinary Science at the underground laboratory

17.6 Status of the underground laboratory in Paarl, South Africa

The preliminary work to be followed during 2024 and 2025 is the design and study of PAUL facility including the excavation work. This is accomplished together with SMEC, the tunnel company for the civil engineering aspect and SANRAL, South African National Roads Agency, for the more strategic aspect of the work.

At the same time, the radiation measurement inside the tunnel are important to measure to be able to establish the specifications of PAUL facility. A muographer has been shiped frm France to Cape Town in December 2023 and the muon flux scan from inside the tunnel is planned for year 2024 and 2025 [14, 15]. In parallel to this, the aspect of gathering the community around the project and discussing the future science programme is on-going [16].

PAUL will be a top-level international laboratory and is supported by the international community. The founding event [11] where the international attendance was evident, not only from northern hemisphere but also the southern including African from Nigeria, Rwanda, Botswana etc. has granted not only support but also a budget for the feasibility study. In parallel, new collaborations are being established to build the physicists of tomorrow to operate PAUL. These collaborations include hosting African students at underground laboratories, Grand Sasso, Modane, Canfranc or SNOLAB [17], to participate to the actual experiments and their R&Ds, e.g. Damic-M [18] or Tesseract [19], to acquire the know-how, the skills and the technologies and to grow the community of African in science of ULs. Contacts have been made with the geophysics community at the Witwatersrand university where the experts are located. A new collaboration between austral universities is being set up. Other contacts and workshops have been planned in view of creating synergies between biophysicists to explore life science underground, similarly to what is done at Canfranc [20].

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18

Community Engagement

Marie Clementine Nibamureke, Jamal Mimouni, Chidnima Sike, Arame Boye Ndeye

18.1 Introduction

In 2015, countries adopted the UN 2030 Sustainable Development Goals as a universal call to end poverty. Poverty is considered one of the greatest challenges to sustainable development in Africa as approximately 80% of the people in extreme poverty are located in Sub-Saharan Africa. However, Africa has the potential to beat poverty as it has the youngest and fastest-growing population in addition to 60% of the world's arable lands and 30% of the world's minerals being located in Africa (Coulibaly and Golubski, 2020).

Factors contributing to poverty in Africa are closely related to Science and Technology education. These include among others inadequate infrastructures, inadequate resource management, inadequate or lacking long-term policies and strategies for education and human resource development, etc. Africa is lagging far behind in technology and its ability to compete at the international level is impeded by poor education systems (Heckman, 2004). Thus, adequate STEM science education is essential to unlock Africa's potential for sustainable development. We need to address the gaps in science and technology skills in Africa. One very important key in science education concerns improving the teaching and learning of Physics (Babalola and Folasade, 2022). Physics is considered as the basis of all applied sciences; its adequate education can help break the cycle of perpetual poverty in Africa for example by building sustainable clean energy systems and finding solutions to social and environmental problems such as water pollution and climate change.

The main problem with Physics education in Africa is that the enrolment in Physical Sciences is low in high school and university. To mitigate this, collaboration and communication between all stakeholders (local communities, the scientific community, policymakers, regional bodies and international partners) are needed (Sa'id et al. 2020). It is in this context that community engagement initiatives have emerged as a transformative approach to enhancing STEM education in Africa. These initiatives are driven by a deep understanding of the critical role education plays in shaping Africa's future by empowering its youth. Traditional class teaching and learning is vital but community engagement adds a layer of real-world experience and application to STEM concepts. This makes STEM subjects more tangible, accessible, and interesting for students (Sa'id et al. 2020).

In November 2020, the African Strategy for Fundamental and Applied Physics (ASFAP) initiative was launched by African Physicists (Pan-African and Diaspora) and was mandated by the African Physical Society (AfPS) with a mission to develop a strategy to increase Physics education and research capabilities in Africa and improve collaborations between all stakeholders to help Africa take its due place as a co-leader in the global scientific process. This report will explore the advantages of community engagement initiatives in Physics education in Africa, highlighting the thoughts, ideas, and recommendations from different meetings conducted by the ASFAP Community Engagement Working group members. By embracing these initiatives, African countries can forge a strong bond between educational institutions and their communities which will contribute towards scientific progress and sustainable development across the continent.

"Communities count, they are key to improving everything from education and economic development to health care and race relations" (Mattews, 2008)

18.2 Principles and Definitions

Before delving into the work of the ASFAP Community Engagement Working group, it is important to try to understand what community engagement is and why it is important for Physics education in Africa. We will also look at the principles of a successful community engagement initiative.

Definitions

Community engagement can be defined as "the process of working collaboratively with and through groups of people affiliated by geographic proximity, special interest, or similar situations to address issues affecting the well-being of those people" (Centers for Disease Control and Prevention, 1997). Thus, community engagement is a powerful vehicle for bringing about environmental and behavioral changes that will improve "the understanding and practice of Physics" by the physics community, its members and the public at large. Community engagement initiatives "involves partnerships and coalitions that help mobilize resources and influence systems,... and serve as catalysts for changing policies, programs, and practices" (Centers for Disease Control and Prevention, 1997).

Why does community engagement matter?

Community engagement initiatives matter as they increase the likelihood that projects or solutions will be widely accepted, they will create more effective solutions, help to improve people's knowledge and skills in problem-solving, empower and integrate people from different backgrounds, help create local networks of community members as well as opportunities for discussing community problems before they get out of control (Bassler et al. 2008).

Principles of a successful community engagement initiative

To be successful, each community engagement initiative should be guided by clear principles including the following:

1. Careful planning and Preparation (adequate and inclusive)
2. Inclusion and Demographic Diversity (people, voices, ideas, and information)
3. Collaboration and Shared Purpose (work together to advance the common good)
4. Openness and Learning (listen to each other, explore new ideas)
5. Transparency and Trust (clear and open process)
6. Impact and Action (ensure that each effort has the potential to make a difference)
7. Sustained Engagement and Participatory Culture (programs and institutions that support continuous quality engagement) (Matthews, 2008).

18.3 Relationship between Community Engagement and Capacity Building

Each community engagement initiative often involves capacity building of the concerned community. How are the two concepts related? The concepts of "community engagement and capacity building" are closely interconnected and reinforce each other in various ways. Let's see how they complement each other in various ways to develop sustainable education in a community.

- *Empowerment and Skill Development*: Community engagement initiatives often focus on empowering individuals within the community, including students, educators, and local residents. Through active participation in these initiatives, individuals can acquire new skills, knowledge, and competencies. Capacity building, on the other hand, aims to enhance the abilities and potential of individuals, organizations, or communities. By engaging with the community, capacity-building efforts become more effective as they are tailored to address the specific needs and aspirations of the people involved.
- *Collaboration and networking*: Both community engagement and capacity building foster collaboration and networking among various stakeholders. Community engagement initiatives often bring together educators, students, local leaders, non-profit organizations, and government agencies. These collaborations create a supportive ecosystem where capacity-building efforts can be shared, expanded, and sustained, leading to a more comprehensive and lasting impact (Beegle and Christiaensen, 2019).
- *Sustainability*: When individuals are involved in the decision-making process and take ownership of their educational and developmental goals, they are more likely to sustain the outcomes of capacity-building efforts. This sense of ownership and responsibility drives a culture of continuous learning and improvement within the community.
- *Knowledge transfer and sharing*: Community engagement provides a platform for the exchange of knowledge and experiences. Capacity-building initiatives can leverage this shared knowledge to design programs that are inclusive, culturally sensitive, and locally appropriate. In turn, capacity-building activities enhance the expertise and resources available within the community, contributing to its overall growth and development.
- *Developing community-driven solutions*: Community engagement allows for a bottom-up approach, where solutions are developed based on the specific needs and priorities of the community. Capacity-building efforts can then be tailored to address these unique challenges, making them more effective and sustainable in the long run.

In summary, community engagement and capacity building are intertwined in their efforts to empower individuals, promote collaborative learning, and foster sustainable development. By combining these two approaches, communities can harness their collective potential and drive positive change in various aspects of Physics education in Africa. Improved Physics education in Africa can significantly contribute to improved health care, agriculture, natural resources conservation, etc.

Thus, community engagement is an important topic to consider for any attempt to uplift Physics in Africa. As the ASFAP Community Engagement Working Group, we have considered various leads without exhausting them. It is also a topic at the intersection of various other subgroups like Education, Outreach, Young physicists, and women in physics. There is also a need to introduce ASFAP goals and scope of activities to the community members first. This can be done by the representatives of ASFAP in each county. By doing so, we shall be in a position to interact directly with society and get different feedback on common areas of interest. The ASFAP Community Engagement Working Group is made of four active members, and co-conveners from different countries (Rwanda, Algerie, Senegal, and Nigeria). We have met several times and we were able to identify seven potential areas of possible common action:

1. Physics communication and outreach.
2. Technology transfer; Internet connectivity/ internet start-up resources; Applications and industry.
3. E-lab and e-learning.
4. Business development and entrepreneurism
5. Public education and outreach; Diversity and inclusion and equity.
6. Government engagement and public policy.
7. Career pipelines and development; Retention; Capacity development.

18.4 Outreach Goals and community needs

We present below some actions worth engaging the community with which delineate the importance of using physics in solving societal problems.

1. *Physics and Environmental Pollution*:

   How can we use Physics to resolve the problem of environmental pollution? To raise awareness of the local community on subjects that matter to their everyday life. In the cases of plastic and pharmaceutical waste:

   - Recycling methods for plastics
   - Waste burning (e.g., incineration of pharmaceuticals wastes)
   - Pharmaceuticals return to pharmacists or clinics
   - Special collection programs for pharmaceutical waste (old and unused)
   - Education and Awareness campaigns on the safe disposal of pharmaceuticals and plastic waste (e.g., School visits; Radio Talks; Podcasts; website; etc.)

2. *Physics outreach and Education*:

   To create awareness and broaden the community's understanding of Physics

   - Survey on the views of Physics teachers in Africa;
   - Periodic Training of Physics teachers in Africa;
   - Virtual Physics laboratories: for those schools where there is no access to laboratories (+ internet access): classroom demonstrations for teachers and students;
   - Annual Physics community fairs: to show the local community how Physics can help them in everyday life and introduce children to the fun of Physics;
   - Organise campus visits for high school children to observe some fun Physics experiments;
   - Weekend and holidays science classes (for example the University of Johannesburg SOWETO Science Centre in South Africa).

3. *Astronomy at the service of physics*:

   The Cosmos is after all the largest laboratory in the World... by definition and it is a great stage to use various physics branches to illustrate its cognitive.

4. *Introduce the ASFAP initiative to local governments through the African Union (AU)*: There could have been a part in the blueprint engaging with various physicist bodies or governmental ones at the level of each country. This task needs strong connections and we did not attempt to engage with those important actors as it needs members in these various countries and regions that we did not have (Possibly taking India's engagement with it as a showcase).

18.5 Community Goals and Priorities

Among the submitted letters of intent (LOIs) we have noticed that some of them are related to our proposed topics. Most of them underline several community goals and priorities crucial for promoting scientific literacy, fostering interest in Physics, and building a strong foundation for scientific development. As goals and priorities vary across different regions and countries in Africa, some common ones are shown here:

1. *Accessible and Inclusive Education*: Making Physics education accessible to all students, regardless of their socioeconomic background, gender, or geographical location, is a key community goal. This includes providing resources, facilities, and opportunities for underprivileged communities to engage in Physics learning (Makarova, Aeschlimann and Herzog,2019).

2. *Local Relevance*: Emphasizing the relevance of Physics education to the local context and challenges is vital. Aligning the curriculum with real-world problems faced by African communities can motivate students and demonstrate the practical applications of Physics in their daily lives (Heckam, 2004; Sa'id et al. 2020).

3. *Teacher Training and Professional Development*: Prioritizing the training and professional development of Physics teachers is essential to ensure they have the necessary skills and knowledge to deliver quality education (Heckman, 2004). Thus, continuous support and capacity building for Physics educators in Africa can help improve teaching methodologies and inspire effective learning experiences for the students.

4. *Gender Equity and Inclusion*: Promoting gender equity and inclusion in Physics education in African countries is critical as women form a large percentage of the African population. Thus, encouraging girls and women to pursue Physics as a field of study and research can help bridge the gender gap in STEM (Science, Technology, Engineering, and Mathematics) fields and contribute to increased development in Africa (Jolly, 2009; Beegle, and Christiaensen, 2019).

5. *Practical Learning and Laboratories*: Establishing well-equipped Physics laboratories will allow students to engage in hands-on experiments and practical applications of theoretical concepts. Practical learning experiences enhance understanding and stimulate curiosity in the subject (Jolly, 2009).

6. *Collaboration with Local Industries*: Fostering partnerships between educational institutions and local industries can provide students with exposure to real-world applications of Physics principles. This collaboration can also lead to research opportunities and internships, preparing students for future careers in scientific fields.

7. *Public Awareness and Outreach activities*: Increasing public awareness of the importance of Physics education and its role in societal development is essential. Community engagement programs, public

lectures, and outreach events can help generate interest in Physics and inspire the next generation of scientists.

8. *Scholarships and Financial Support*: Providing scholarships and financial support for students pursuing Physics education can alleviate financial barriers and encourage talented individuals to pursue careers in scientific research and innovation.

9. *Research and Innovation*: Encouraging research and innovation in Physics within the African context can lead to solutions for local challenges (health care, agriculture, clean energy, etc) and contribute to global scientific advancements.

10. *Sustainable Development*: Integrating concepts of sustainable development and environmental awareness within Physics education can create environmentally responsible scientists who contribute to sustainable solutions for Africa's development.

11. *Stopping the Brain drain*: Creating interesting and satisfying jobs for African graduates and making sure that they do not immigrate to developed countries will help boost African development.

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19

Physics Education Working Group

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19.1 Abstract

The African Strategy for Fundamental and Applied Physics (ASFAP) initiative brought together physicists from Africa and beyond to address critical issues in physics education across the continent. Through a series of meetings held within the physics education group, Letters of Intent (LOIs) were submitted, highlighting key challenges such as inadequate infrastructure, outdated curricula, insufficient funding, and a lack of collaboration. These issues hinder the development of robust physics education and research capabilities across Africa. In response, several strategic proposals emerged from discussions and LOIs, including the use of microelectronics to enhance theoretical teaching, the establishment of regional physics experiment centers to foster practical learning and research, and the creation of a Pan-African science foundation to support sustainable funding and collaboration. This report synthesizes the insights from the LOIs and online workshops, outlining a roadmap for addressing the systemic challenges in physics education in Africa and advancing the field through collaborative efforts. The proposed initiatives aim to build stronger educational frameworks, increase access to resources, and promote innovation in teaching and research, ultimately contributing to the growth of physics education and scientific advancement on the continent.

19.2 Physics education goals

The African Strategy for Fundamental and Applied Physics (ASFAP) sets forth a vision to harness the transformative power of physics education to foster scientific progress, technological innovation, and sustainable development across the African continent. Physics is a fundamental discipline that drives advancements in various fields such as engineering, medicine, energy, and information technology, making it a key pillar for Africa's future growth. In alignment with this vision, ASFAP outlines the following core goals for physics education:

19.2.1 Cultivating Scientific and Technological Literacy

One of the primary goals of ASFAP is to promote widespread scientific literacy across Africa, empowering citizens to make informed decisions in an increasingly technology-driven world. Physics education must equip students with the ability to understand and engage with the scientific principles that underlie everyday phenomena, from energy generation to telecommunications. By fostering a solid foundation in physics, students will develop critical thinking skills that enable them to evaluate scientific and technological developments, contributing to a society that is more innovative and better prepared to tackle global challenges such as climate change, health crises, and resource management.

19.2.2 Developing 21st-Century Skills

Physics education must go beyond theoretical knowledge to nurture 21st-century skills that are essential for success in modern economies. These include problem-solving, analytical reasoning, creativity, collaboration, and digital literacy [1]. ASFAP envisions a physics education system that engages students in inquiry-based learning, hands-on experimentation, and interdisciplinary projects that encourage critical thinking and innovation. By embedding these skills into physics curricula, students will not only excel in science but also become adaptable and resilient individuals capable of addressing complex societal challenges and seizing new opportunities.

19.2.3 Enhancing Africa's Capacity for Innovation

A central goal of ASFAP is to build Africa's capacity for scientific and technological innovation. Physics education plays a crucial role in laying the groundwork for research and development in fields such as renewable energy, space exploration, and healthcare technologies [2]. Through a strong physics education, Africa can cultivate a generation of researchers, engineers, and technologists who will drive innovation and contribute to the continent's industrialization and economic diversification. This goal also involves establishing pathways from education to industry, ensuring that physics graduates have the skills and opportunities to engage in applied research and entrepreneurship.

19.2.4 Promoting Sustainable Development

ASFAP aligns physics education with Africa's broader goals for sustainable development, as outlined in the African Union's Agenda 2063 and the United Nations' Sustainable Development Goals (SDGs). Physics education must contribute to solving pressing environmental, energy, and health challenges. For instance, physics can offer solutions to Africa's energy needs by fostering expertise in renewable energy technologies such as solar, wind, and geothermal power [3]. Similarly, physics education can play a pivotal role in addressing issues related to water purification, sustainable agriculture, and medical technologies, thereby improving the quality of life for millions of Africans [4].

19.2.5 Addressing the STEM Gender Gap

ASFAP emphasizes the importance of gender equity in physics education. Women remain underrepresented in science, technology, engineering, and mathematics (STEM) fields, particularly in physics [5]. To address this, ASFAP seeks to create inclusive learning environments that encourage female students to pursue physics and other STEM careers. This includes developing mentorship programs, offering scholarships, and promoting role models who inspire girls to engage with physics from an early age. By fostering a more diverse and inclusive STEM community, Africa can tap into the full potential of its population to drive scientific and technological advancements.

19.2.6 Supporting Teacher Training and Professional Development

Recognizing the critical role of educators in achieving these goals, ASFAP prioritizes the professional development of physics teachers. Well-trained, motivated teachers are essential for delivering high-quality physics education [6]. The strategy aims to enhance teacher preparation programs, provide ongoing professional development, and create networks for physics educators across Africa. This support will enable teachers to adopt innovative pedagogical approaches, integrate technology into their teaching, and create engaging, inquiry-based learning environments. By investing in teachers, ASFAP ensures that physics education remains dynamic and responsive to both local and global developments.

19.2.7 Fostering International Collaboration and Knowledge Exchange

ASFAP recognizes the value of international collaboration in strengthening Africa's physics education and research capabilities. The strategy encourages partnerships between African institutions and global scientific communities to facilitate knowledge exchange, joint research projects, and access to cutting-edge technologies. This collaboration will not only enrich the learning experience for African students but also position African physicists as active contributors to the global scientific community. Additionally, ASFAP seeks to establish centers of excellence in physics education and research across the continent, creating hubs for innovation and leadership in fundamental and applied physics.

19.2.8 Bridging the Gap Between Education and Industry

ASFAP aims to bridge the gap between physics education and industry needs, ensuring that graduates are prepared for the workforce and can contribute to Africa's economic growth. This requires aligning physics curricula with the skills demanded by emerging industries such as telecommunications, energy, and aerospace. By fostering partnerships between educational institutions and the private sector, ASFAP seeks to create pathways for students to transition from education into careers that apply their physics knowledge in practical, impactful ways. This alignment will also drive the creation of new industries, contributing to job creation and economic resilience.

19.2.9 Leveraging Technology for Inclusive Education

ASFAP envisions a physics education system that leverages technology to ensure inclusivity and equitable access to learning resources. Many African schools, particularly in rural areas, face challenges related to infrastructure and resource shortages [7]. By incorporating digital learning tools such as virtual laboratories, simulations, and online platforms, ASFAP aims to democratize access to high-quality physics education. These tools can provide students with interactive, immersive learning experiences, even in the absence of physical laboratory facilities. Moreover, digital tools can help overcome geographical barriers, allowing students from across the continent to access the same high-quality education and connect with global learning networks [8].

Physics as a Catalyst for Africa's Future The African Strategy for Fundamental and Applied Physics envisions physics education as a catalyst for Africa's scientific, technological, and economic future. By cultivating scientific literacy, promoting innovation, and addressing societal challenges through sustainable development, physics education will play a transformative role in achieving the continent's long-term goals. ASFAP calls for a concerted effort to reform physics education, address structural challenges, and ensure that every African student can engage with and excel in the subject. With the right investments in education, infrastructure, and international partnerships, Africa is poised to become a global leader in fundamental and applied physics, driving innovation and progress for generations to come.

19.3 Learning Approach and Challenges for Physics Education

Physics education across Africa holds the potential to significantly contribute to scientific innovation, technological advancement, and socioeconomic development. However, achieving this potential requires a comprehensive and contextually relevant approach to teaching and learning, combined with strategies to address the unique challenges faced by educators and learners on the continent. The African Strategy for Fundamental and Applied Physics (ASFAP) aims to provide a roadmap for strengthening physics education by aligning pedagogical methods with the realities and aspirations of African societies.

Contextualized and Culturally Relevant Pedagogy: One of the key pillars of the ASFAP is the development of a learning approach that resonates with the African context. Physics education must move beyond the rote memorization of abstract concepts to one that incorporates real-life applications drawn from local environments and cultures [9]. This involves integrating indigenous knowledge systems and using culturally relevant examples, such as African innovations in engineering, agriculture, and energy, to make learning more relatable and meaningful. Contextualized learning empowers students to see the relevance of physics in solving everyday problems, from water purification to renewable energy solutions [9].

Inquiry-Based Learning and Hands-On Experiments: A fundamental goal of ASFAP is to emphasize active learning approaches, such as inquiry-based learning (IBL), where students engage in experimentation, exploration, and discovery. This method fosters curiosity and critical thinking, allowing students to develop problem-solving skills by conducting hands-on experiments and working collaboratively [10]. Physics, being an experimental science, benefits from a learning approach that encourages students to pose questions, test hypotheses, and refine their understanding through practical experience. Inquiry-based methods also foster a deeper conceptual understanding and retention of knowledge [11].

Leveraging Technology for Physics Education: The integration of technology into physics education is essential to modernize learning and bridge resource gaps. E-learning platforms, virtual laboratories, and simulation tools such as PhET and GeoGebra can help students visualize complex concepts, even in resource-limited settings [12]. Technology not only enhances the learning experience but also enables educators to reach students in remote areas who may lack access to fully equipped laboratories [13]. ASFAP supports the expansion of digital tools to complement traditional teaching methods, ensuring that learners across the continent have access to high-quality education.

Collaboration and Professional Development for Educators: To implement effective physics education, ASFAP emphasizes continuous professional development for teachers. Educators need support in adopting innovative teaching strategies, incorporating research-based practices, and mastering emerging technologies [14]. Collaborative networks that connect African teachers with global counterparts are crucial for sharing best practices and resources. Initiatives such as cohort-based professional development and teacher exchange programs can help build capacity and ensure that educators are well-equipped to deliver high-quality instruction.

19.3.1 Challenges

While the goals of the African Strategy for Fundamental and Applied Physics are ambitious, several challenges must be addressed to realize the transformative potential of physics education.

Resource Constraints and Infrastructure Deficits: One of the most significant challenges is the lack of adequate resources and infrastructure. Many schools in Africa face shortages of textbooks, laboratory equipment, and basic teaching aids [15]. Physics, being an experiment-driven subject, requires hands-on learning, but many schools are unable to provide students with access to functioning laboratories. This lack of resources impedes students' ability to engage with the subject matter deeply and hinders the development of critical scientific skills.

Teacher Shortages and Capacity Building: Africa experiences a shortage of qualified physics teachers, particularly in rural and underserved areas. This teacher shortage exacerbates the difficulty in delivering effective physics education. Many teachers lack the necessary background in physics or sufficient training in modern pedagogical approaches [16]. Continuous professional development is needed to bridge these gaps, but resource constraints and heavy teaching workloads often limit opportunities for teacher growth.

Gender Disparities in STEM Education: The underrepresentation of girls and women in physics remains a pressing challenge across Africa. Cultural biases, societal expectations, and gender stereotypes discourage many female students from pursuing careers in STEM fields, particularly physics [17]. ASFAP recognizes the need to create more inclusive and supportive learning environments that encourage gender equity in physics education. Addressing this challenge requires targeted interventions such as mentorship programs, scholarships, and awareness campaigns that inspire young women to pursue physics and other STEM disciplines.

Curriculum Rigidities and Examination Pressures: The current curricula in many African countries are often rigid, with an overemphasis on content memorization rather than conceptual understanding and critical thinking [18]. This approach can stifle creativity and discourage students from developing a deeper interest in physics. Additionally, the pressure to perform well in high-stakes exams often forces teachers to "teach to the test," focusing on examination preparation rather than fostering genuine inquiry and exploration [19]. ASFAP advocates for a curriculum reform that emphasizes conceptual learning, real-world applications, and creativity over rote memorization.

Language Barriers and Cognitive Load: Many African students study physics in a language that is not their first language, which can significantly increase cognitive load and hinder their comprehension of complex

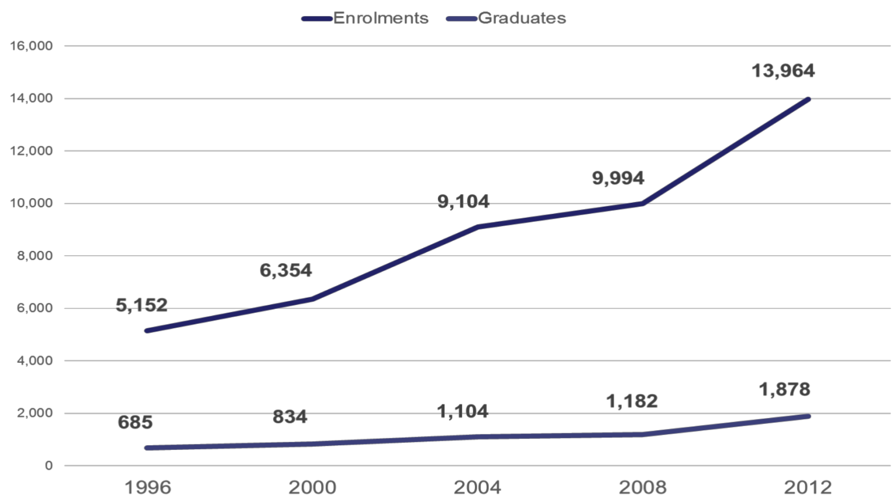

Figure 19-1: PhD enrolments and graduates in South Africa: 1996–2012 [41].

physics concepts [20]. This language barrier often results in a shallow understanding of physics, as students focus more on language comprehension than on engaging with the scientific content. Implementing bilingual or multilingual teaching strategies, including code-switching where appropriate, can help students grasp key concepts while gradually developing their language proficiency [21].

Inequitable Access to Technology: While technology has the potential to revolutionize physics education, unequal access to digital tools and resources remains a challenge. Internet connectivity, access to computers, and reliable electricity are often limited in rural and underserved areas [8]. This digital divide must be addressed through policies that prioritize infrastructure development and the provision of affordable, accessible technology for all students.

Figure 19-1 presents a longitudinal analysis of PhD enrolments and graduates in South Africa from 1996 to 2012, as reported by the Department of Higher Education and Training (DHET) in 2013 [41]. The data indicates a steady increase in PhD enrollments over the 16-year period, highlighting a growing demand for advanced academic qualifications. This growth is likely a result of national policies aimed at expanding post-graduate education and research capacity to address skills shortages and drive innovation in the knowledge economy.

Figure 19-1 reveals two distinct trends: one related to PhD enrollments and the other to PhD graduates. The increase in enrollments suggests that more individuals are pursuing doctoral degrees, reflecting a broader recognition of the importance of doctoral-level education for both personal and professional development. However, the gap between enrolments and graduates is also evident, underscoring the challenges students face in completing their PhD programmes.

A key observation is the gradual but slower increase in PhD graduates compared to enrollments. This discrepancy may be attributed to several factors, including the time-intensive nature of doctoral studies, financial constraints, academic preparedness, and the availability of adequate supervisory capacity. The latter issue has been identified as a significant barrier in South Africa, where a shortage of qualified supervisors has impeded timely PhD completions.

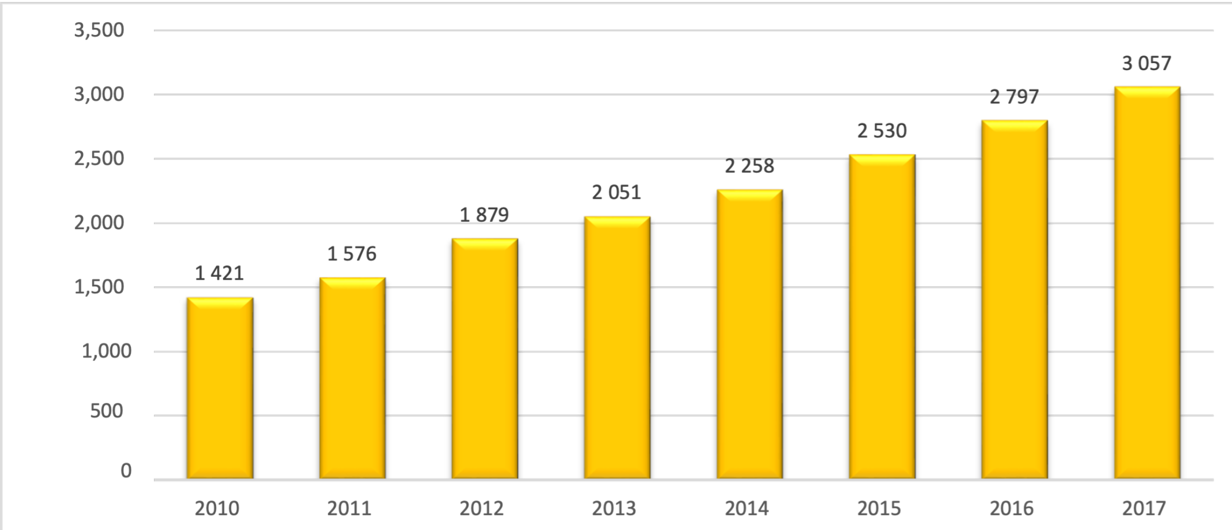

Figure 19-2: Number of doctoral degree graduates in South African universities, 2010–2017 [42].

The data further suggests that while the growth in enrollments signals progress in addressing the country's need for highly skilled researchers, the system still faces obstacles in ensuring that a higher proportion of enrolled PhD candidates complete their studies. Addressing these barriers is critical to achieving the national target of producing more PhD graduates, which is essential for South Africa's research output and its global academic standing.

In summary, Figure 19-1 highlights both the opportunities and challenges in the South African higher education system concerning PhD education. While significant strides have been made in increasing enrolments, further efforts are required to improve throughput rates and enhance the overall success of PhD programmes in the country.

Figure 19-2 presents the number of doctoral degree graduates from South African universities between 2010 and 2017, as reported in the Statistics on Post-School Education and Training in South Africa [42]. The data illustrates a consistent upward trend in doctoral graduates over this eight-year period, reflecting positive progress in the country's efforts to enhance its research capacity and produce more highly qualified scholars.

From 2010 to 2017, the number of PhD graduates increased significantly, with universities producing more doctoral candidates each year. This rise can be attributed to various national initiatives, such as the Department of Higher Education and Training's (DHET) drive to increase research output and capacity, as well as targeted funding programs aimed at supporting postgraduate students. The government has placed a strong emphasis on doctoral education as part of its broader strategy to strengthen South Africa's global competitiveness in research, innovation, and the knowledge economy.

Despite this positive trajectory, the number of doctoral graduates remains modest when compared to international standards. This suggests that while there has been notable growth, challenges remain in achieving the desired scale of doctoral production. These challenges may include limitations in supervisory capacity, high dropout rates, and the financial burden on students, which could hinder their ability to complete their degrees.

The increase in PhD graduates over time can also be linked to efforts by universities to improve their research output and reputation. As many institutions seek to climb global university rankings, the production of

PhD graduates has become a key performance indicator. Additionally, policies encouraging the enrolment of underrepresented groups in postgraduate studies, including women and Black South Africans, have contributed to diversifying the profile of doctoral graduates.

However, the data also highlights the uneven distribution of PhD graduates across different universities. While some institutions have significantly boosted their doctoral outputs, others continue to struggle, reflecting disparities in resources, research infrastructure, and academic support. Addressing these disparities will be crucial for South Africa to meet its long-term goals for higher education transformation and equity.

In summary, Figure 19-2 demonstrates encouraging progress in the production of doctoral graduates in South Africa between 2010 and 2017. Although the numbers reflect a growing pool of highly skilled researchers, further efforts are required to ensure that all universities can contribute to this national priority, and that the growth in PhD graduates continues to align with the country's broader socio-economic development goals.

A Collective Vision The African Strategy for Fundamental and Applied Physics envisions a future where every African student has access to high-quality physics education that equips them with the knowledge and skills to contribute to their societies. Overcoming the challenges in physics education requires a collaborative approach, bringing together governments, educational institutions, non-governmental organizations, and international partners. Investments in teacher training, infrastructure, curriculum reform, and gender equity are essential to transforming physics education across the continent. By addressing these challenges head-on and implementing innovative learning approaches, Africa can cultivate a new generation of physicists, engineers, and problem solvers who will drive the continent's scientific and technological progress. Physics education, when aligned with African realities and opportunities, has the potential to unlock transformative solutions for energy, health, agriculture, and sustainable development, positioning Africa as a global leader in science and innovation.

19.4 Physics Education on an International Level

In the global context, physics education serves as a critical foundation for technological advancement, scientific inquiry, and economic development. Internationally, it plays a significant role in addressing pressing global challenges, from energy sustainability and climate change to healthcare innovations and space exploration. For the African continent, aligning with global physics education trends and participating in international collaboration is pivotal in realizing the goals of ASFAP. By engaging with the international physics education community, Africa can both contribute to and benefit from the collective progress of global science, ensuring that African students, educators, and researchers have the tools and opportunities to thrive in a competitive, interconnected world.

Figure 3 presents a comparative analysis of the number of doctoral degree graduates across various countries in 2015, based on data from the UNESCO Institute for Statistics [43]. This figure offers insight into the global landscape of PhD production, highlighting significant differences in the output of highly trained researchers among nations.

The data reveals those countries with advanced research infrastructures and well-established higher education systems, such as the United States, China, and Germany, lead in the production of PhD graduates. These nations consistently invest heavily in research and development (R&D), with strong governmental support and robust institutional frameworks that facilitate high levels of postgraduate education. The high number of doctoral graduates in these countries reflects their capacity to generate knowledge and drive innovation on a global scale.

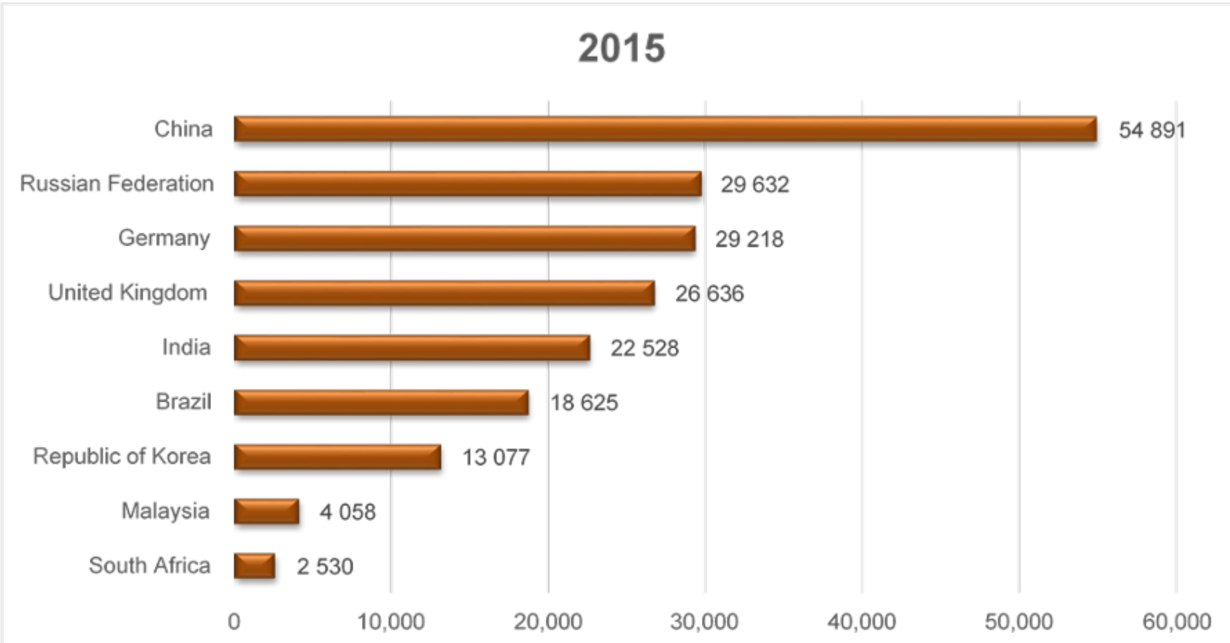

Figure 19-3: Number of doctoral degree graduates by country, 2015 [43].

In contrast, many developing countries, including South Africa, produce significantly fewer PhD graduates. South Africa's position in the figure, though modest compared to larger economies, reflects its growing commitment to enhancing research capacity and doctoral education. However, the gap between South Africa and leading nations points to persistent challenges, such as limited funding, insufficient supervision capacity, and infrastructural constraints, which impede the country's ability to scale up doctoral production to the levels seen in more developed countries.

It is also notable that emerging economies like China and India are rapidly increasing their PhD outputs, driven by targeted national strategies aimed at boosting innovation and research to support economic development. For instance, China's exponential rise in doctoral graduates reflects its strategic focus on becoming a global leader in science, technology, and innovation. This trend underscores the critical role of national policies and investment in higher education and research to drive PhD production.

European countries such as the United Kingdom and Germany are also prominently featured in the figure, reflecting their longstanding tradition of academic excellence and their role as global hubs for research. These countries benefit from well-funded higher education systems, high levels of international collaboration, and strong research outputs, which contribute to their ability to produce many doctoral graduates annually.

In summary, Figure 19-3 highlights the stark disparities in PhD production between developed and developing countries in 2015. While leading economies continue to dominate the global doctoral landscape, countries like South Africa show signs of progress, though challenges remain in scaling up doctoral education to meet global standards. The data emphasizes the importance of sustained investment in higher education, research infrastructure, and supervisory capacity to close the gap between nations and fully leverage the potential of doctoral education for societal and economic development.

19.4.1 Leveraging Global Best Practices in Physics Education

Physics education at the international level has evolved significantly with advancements in pedagogy, technology, and research methodologies. The global physics education community emphasizes inquiry-based learning, active engagement, and the integration of technology to make physics more accessible and relevant to students. ASFAP aims to adopt and localize these global best practices to ensure that African students receive a world-class physics education. By aligning curricula with international standards and incorporating emerging trends such as computational thinking, robotics, and interdisciplinary learning, Africa can prepare its students to compete on the global stage and engage in cutting-edge scientific endeavors.

19.4.2 Fostering International Collaboration and Research Partnerships

International collaboration is essential for the advancement of physics education and research. ASFAP emphasizes the importance of building global networks that link African institutions with leading research centers, universities, and international organizations in physics education. These partnerships will enable knowledge exchange, joint research projects, and access to cutting-edge laboratory facilities and technologies. Furthermore, collaborative efforts can support the development of African centers of excellence in physics education and research, attracting global talent and positioning Africa as a key player in the international scientific community. Participation in global initiatives such as the International Centre for Theoretical Physics (ICTP) and the European Organization for Nuclear Research (CERN) will also provide African students and researchers with invaluable opportunities to contribute to and learn from international scientific advancements.

19.4.3 Addressing Global Challenges through Physics Education

Physics is at the heart of many global challenges, including energy sustainability, environmental protection, and public health. On an international level, physics education prepares students to tackle these challenges by equipping them with the necessary scientific knowledge, problem-solving skills, and innovative thinking. For Africa, participation in international efforts to address these issues is essential. ASFAP envisions a physics education system that not only responds to local needs but also contributes to global scientific solutions. For instance, African physicists and researchers can engage in international collaborations on renewable energy projects, space research, and medical physics initiatives, helping to address both African and global challenges. This cross-border collaboration will enhance the visibility of African contributions to science and foster a global community of learners and researchers working toward common goals.

Figure 19-4 presents data on the share of academic staff holding PhDs in South African universities between 2010 and 2017, as reported by the DHET HEMIS database [42]. Over this period, the figure shows a clear upward trend, reflecting a growing emphasis on the professional development of academic personnel and a broader national push to enhance the qualifications of university staff.

In 2010, a relatively small percentage of academic staff in South African universities held PhD qualifications. However, from 2010 to 2017, this share increased steadily, highlighting the sector's focus on improving academic quality and research output. The rise in PhD-qualified staff is in line with national priorities, particularly the Department of Higher Education and Training's initiatives to strengthen research capacity, improve postgraduate supervision, and enhance the quality of higher education.

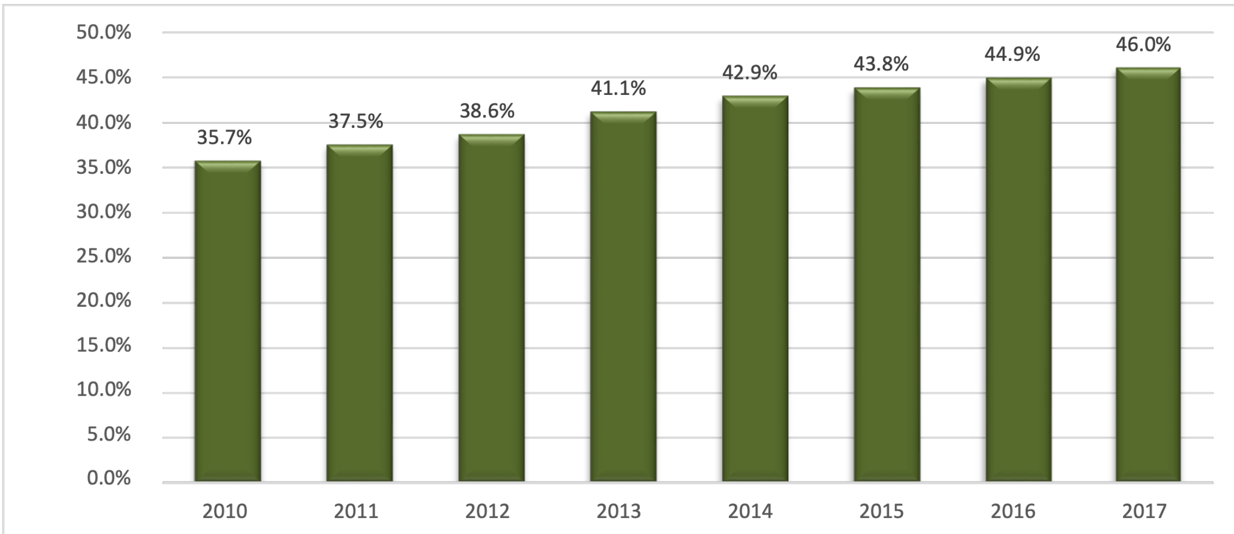

Figure 19-4: Share of academic staff with a PhD in South African universities, 2010–2017 [42].

Several factors have driven this positive trend. One key factor is the government's push to professionalize the academic workforce. DHET has implemented various funding programs, such as research grants and incentives for PhD completion, to support academic staff in obtaining doctoral qualifications. Additionally, universities themselves have recognized the need to boost the number of PhD-qualified staff to meet institutional goals for research output, rankings, and global competitiveness. As a result, many institutions have prioritized hiring academics with PhDs and supporting existing staff in their doctoral studies.

This increase in PhD-qualified staff is particularly important for postgraduate education. As more staff members hold doctoral qualifications, universities are better equipped to provide high-quality supervision to postgraduate students, which is crucial for improving completion rates and the production of master's and doctoral graduates. It also strengthens the research culture within universities, leading to greater contributions to knowledge generation and innovation.

Despite these gains, the data shows that South Africa still faces challenges in meeting international benchmarks for the share of academic staff with PhDs. While the upward trend is encouraging, the overall percentage of PhD-qualified staff remains lower than that seen in leading research-intensive institutions globally. This suggests that additional efforts are needed to accelerate the pace of transformation and reach international standards.

Furthermore, there are notable disparities across institutions. Historically advantaged universities tend to have a higher proportion of PhD-qualified academic staff, while historically disadvantaged institutions often lag due to resource constraints, lower research funding, and challenges in attracting highly qualified personnel. Addressing these inequities will be critical for ensuring that all universities can benefit from a more qualified academic workforce and for promoting equity in higher education.

In summary, Figure 5 illustrates the steady progress in increasing the share of academic staff with PhDs in South African universities from 2010 to 2017. While this trend is a positive indicator of efforts to enhance academic qualifications and research capacity, further work is needed to address disparities between institutions and to raise the overall percentage of PhD-qualified staff to meet international standards.

Expanding opportunities for academic development and supporting equitable growth across all universities will be essential for sustaining this progress.

19.4.4 Promoting Mobility and Knowledge Exchange

International mobility for students, educators, and researchers is a key component of global physics education. ASFAP prioritizes the mobility of African physics students and scholars, enabling them to study, teach, and conduct research abroad, while also attracting international talent to African institutions. This two-way flow of knowledge will ensure that African students and researchers are exposed to diverse perspectives, cutting-edge technologies, and innovative teaching practices. Programs such as international exchange scholarships, joint PhD programs, and visiting professorships will play a crucial role in fostering this knowledge exchange. By building these international connections, Africa will enhance its physics education ecosystem, benefiting from the expertise and resources of the global community.

19.4.5 Aligning with Global Standards in Physics Education

To ensure that African students and researchers can compete on the global stage, ASFAP aims to align African physics education systems with international standards in both curriculum design and research output. This alignment involves updating curricula to reflect the latest scientific discoveries and integrating emerging fields such as quantum computing, nanotechnology, and data science. It also includes adopting global best practices in assessment, accreditation, and certification. By doing so, African students will be able to seamlessly transition into global scientific and academic communities, ensuring that their education is recognized and valued worldwide. Additionally, ensuring compatibility with international standards will enable African institutions to collaborate more effectively with global partners and attract international funding for research and development projects.

19.4.6 Enhancing Digital Learning and Open Science Initiatives

The digital transformation of education has had a profound impact on global physics education, with online platforms, virtual laboratories, and open educational resources (OERs) becoming integral components of learning. ASFAP seeks to leverage digital technologies to democratize access to physics education across Africa and to connect with global learning platforms. By embracing digital learning tools, African students can participate in online courses offered by leading global universities, engage in virtual experiments, and collaborate with peers worldwide. Additionally, the strategy promotes open science initiatives, encouraging the sharing of research findings, data, and educational resources across borders. These initiatives will provide African students and researchers with access to global knowledge pools, accelerating scientific discovery and innovation.

19.4.7 Supporting Teacher Development through Global Professional Networks

The quality of physics education depends on the expertise and dedication of teachers. ASFAP recognizes the importance of supporting the professional development of physics educators by connecting them with global networks and professional organizations. International collaboration provides African teachers with opportunities to attend international conferences, participate in workshops, and engage in online communities that focus on innovative teaching practices and educational research. By being part of these networks, African physics educators will stay at the forefront of global pedagogical trends and bring innovative practices into their classrooms. This continuous development will not only enhance the quality of physics education in Africa but also create a generation of educators who are active contributors to the global education community.

19.4.8 Encouraging International Recognition of African Contributions to Physics

African physicists have made significant contributions to global scientific knowledge, yet these contributions are often underrecognized [22]. ASFAP seeks to elevate the visibility of African contributions to physics by encouraging more African researchers to publish in international journals, participate in global conferences, and collaborate on high-impact projects. By showcasing Africa's scientific achievements on the global stage, ASFAP aims to challenge stereotypes about African science and establish Africa as a key contributor to the advancement of physics. This increased visibility will also attract international collaborations, investments in African research institutions, and opportunities for African students to engage in prestigious global projects.

19.4.9 Facilitating Global Engagement in Space and High-Energy Physics

Emerging fields such as space science and high-energy physics offer exciting opportunities for African participation in global research efforts. ASFAP envisions the development of programs and partnerships that will enable African students and researchers to engage with international space agencies and high-energy physics projects, such as those at CERN. Africa's growing interest in space science, exemplified by the development of the African Space Agency, aligns with the global push to explore space as the next frontier for scientific discovery. By fostering partnerships in these fields, African physicists can contribute to cutting-edge research that has global implications while also gaining access to advanced technologies and scientific infrastructure.

Figure 19-5 depicts the number of doctoral degree graduates per million of South Africa's population each year between 2010 and 2017, based on data from the Department of Higher Education and Training [42]. This metric provides a per capita perspective on PhD production, allowing for a clearer understanding of the country's capacity to produce highly qualified researchers relative to its population size.

The figure shows a gradual increase in the number of doctoral graduates per million people over the observed period. This rise reflects ongoing efforts by South Africa to build a more robust research and development sector, recognizing that doctoral education is critical for advancing innovation, economic growth, and addressing complex societal challenges. The steady growth highlights a national commitment to expanding postgraduate education, which aligns with government policies aimed at improving research output and fostering a knowledge-driven economy.

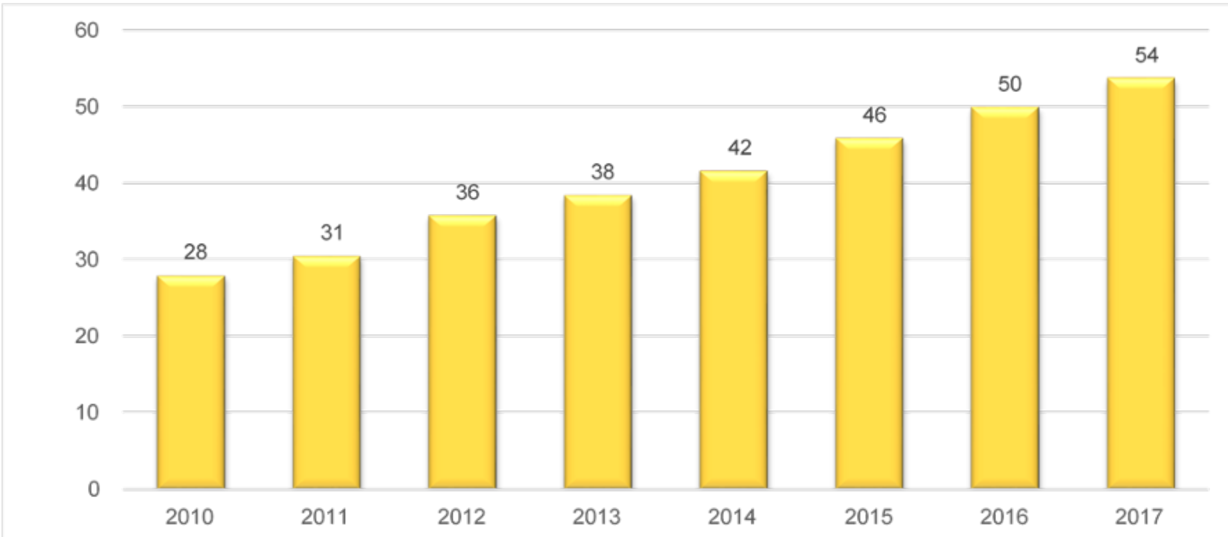

Figure 19-5: Number of doctoral degree graduates per million of population per year, 2010–2017 [42].

Despite this positive trend, the number of doctoral graduates per capita in South Africa remains relatively low when compared to global benchmarks, especially in comparison to developed countries with advanced research ecosystems. This suggests that while South Africa is making progress, the country still has substantial ground to cover to achieve parity with global leaders in doctoral production. Factors such as limited funding, supervision capacity, and challenges in student retention continue to constrain the potential for large-scale PhD output.

However, while the figure shows progress in increasing doctoral graduates relative to the population, there are still structural challenges that need to be addressed. For instance, South Africa faces disparities in PhD production across its universities and academic disciplines. Certain institutions and fields, particularly in the natural sciences and engineering, are more successful in producing PhDs than others. This uneven distribution limits the overall capacity of the country to leverage doctoral education for widespread socio-economic development.

In summary, Figure 19-5 highlights South Africa's strides in boosting the number of doctoral graduates per million of the population between 2010 and 2017. Although the data shows a positive trajectory, the country must address existing challenges, such as enhancing supervision, increasing funding, and ensuring equitable PhD production across all institutions and fields. Achieving these goals will be essential for South Africa to fully realize the benefits of doctoral education on a national and global scale.

19.4.10 Addressing the Global STEM Gender Gap

Globally, women remain underrepresented in STEM fields, including physics [23]. ASFAP aligns with international efforts to address this gender gap by creating policies and programs that encourage more women to pursue careers in physics and related fields. International collaborations can provide mentorship, scholarships, and networking opportunities for African women in physics, helping to break down barriers and inspire future generations. By drawing on global best practices and success stories from other regions, Africa can develop a more inclusive and equitable physics education system that supports gender diversity in STEM at both the national and international levels.

Africa as a Global Contributor to Physics Education The African Strategy for Fundamental and Applied Physics envisions a future where Africa is an active participant in the global physics community, contributing to and benefiting from international advancements in science and education. By aligning physics education with international standards, fostering collaboration, and encouraging the mobility of students and researchers, ASFAP seeks to position Africa as a key player in the global scientific arena. Through these efforts, African students, educators, and researchers will not only gain access to the world's best educational resources and technologies but also contribute to solving global challenges through the power of physics.

19.5 Major Challenges Facing Public Schools

Public schools across Africa face significant challenges that hinder the delivery of quality physics education [24]. For the African Strategy for Fundamental and Applied Physics (ASFAP) to be successful, these obstacles must be addressed to ensure that students receive the foundation needed to thrive in both fundamental and applied physics. Some of the major challenges include:

19.5.1 Lack of Qualified Physics Teachers

One of the most pressing issues facing public schools is the shortage of qualified physics teachers. Many teachers in African public schools either lack formal qualifications in physics or are not adequately trained to teach the subject [25]. This shortage is exacerbated by the fact that physics is often viewed as a difficult subject, deterring both teachers and students. Without properly trained educators, students struggle to grasp foundational physics concepts, limiting their ability to pursue further studies in the subject. The ASFAP needs to prioritize teacher training programs and continuous professional development to ensure that teachers are equipped to deliver high-quality physics instruction.

19.5.2 Inadequate Infrastructure and Laboratory Facilities

Public schools in many African countries suffer from inadequate infrastructure, particularly when it comes to laboratories and science equipment. Physics, as a subject, requires practical, hands-on learning experiences that are often difficult to provide without well-equipped laboratories. Many schools lack basic laboratory equipment such as electrical circuits, measuring instruments, and experimental setups [26]. This prevents students from engaging in practical experiments, which are crucial for understanding physics concepts and developing scientific thinking. Addressing this challenge requires significant investment in school infrastructure to create environments where students can experiment and apply theoretical knowledge.

19.5.3 Overcrowded Classrooms

Overcrowding is a widespread issue in many African public schools, where student-to-teacher ratios are often extremely high [27]. In such settings, it is challenging for teachers to provide individualized attention or manage the class effectively, especially in subjects like physics that require complex explanations and experimentation. Overcrowded classrooms lead to lower student engagement, poor academic performance, and a lack of in-depth understanding of physics concepts [28]. To counteract this, the ASFAP must advocate for policies that reduce classroom sizes and ensure a more conducive learning environment for both students and teachers.

19.5.4 Inconsistent Curriculum and Assessment Standards

Many African countries face challenges related to the lack of consistency in curriculum design and assessment standards in physics education. In some public schools, the curriculum may not be aligned with international standards, leading to a disparity in the level of physics knowledge imparted to students [29]. Inconsistent assessments further exacerbate this issue, with students in different regions being tested on varying levels of content difficulty. This inconsistency hinders the development of a cohesive physics education framework across the continent. The ASFAP must promote the development of a standardized, yet contextually relevant, curriculum that ensures all students receive a comprehensive and rigorous education in physics.

19.5.5 Limited Access to Educational Technology

While educational technology plays an increasingly important role in modern physics education, many public schools in Africa lack access to digital tools and resources. In developed countries, students can engage with virtual labs, simulations, and digital learning platforms that make physics more accessible and engaging. In contrast, many African public schools lack the infrastructure to support such technologies, including reliable internet access and electricity [30]. This technological divide limits students' exposure to modern physics applications and global advancements. ASFAP should prioritize digital inclusion by advocating for investment in educational technologies, ensuring that all students have access to the tools necessary for 21st-century learning.

19.5.6 Language Barriers and Code-Switching

In many African countries, students are taught in a language that is not their first language, particularly in the sciences. This language barrier complicates the learning of complex physics concepts and leads to code-switching—where teachers and students alternate between languages to facilitate understanding [31]. However, this practice can cause confusion and hinder the development of a strong foundation in scientific terminology and conceptual thinking. Addressing language barriers through the development of localized teaching resources and improved language training for teachers is critical for enhancing physics education outcomes in public schools.

19.5.7 Socio-Economic Disparities

Many public schools serve students from low-income households, where poverty significantly affects students' ability to engage fully with their education. Limited access to resources such as textbooks, learning materials, and even transportation to school creates barriers to consistent attendance and academic performance [32]. Additionally, students from disadvantaged backgrounds may need to prioritize economic survival over education, leading to high dropout rates and lower academic achievement. For the ASFAP to succeed, it must address the socio-economic challenges that impact students' access to quality education, particularly in physics, which often requires additional resources for effective learning.

19.5.8 Gender Disparities in Physics Education

Across Africa, gender disparities remain a significant challenge in physics education. Physics is often perceived as a male-dominated subject, leading to lower participation rates among girls. Cultural stereotypes, societal expectations, and a lack of female role models in science contribute to this gender gap [33]. As a result, girls are often underrepresented in physics classes, and those who do participate may face additional challenges in receiving support or encouragement. The ASFAP should promote gender-inclusive policies and initiatives that encourage more girls to engage with physics from an early age, providing mentorship programs and creating awareness to break down gender biases.

19.5.9 Inadequate Funding for Public Schools

Public schools in many African countries suffer from chronic underfunding, which affects all aspects of the education system [34]. Limited budgets mean that schools cannot invest in critical resources such as laboratory equipment, teacher training, and student support services. Moreover, underfunding impacts the salaries of teachers, leading to low morale and a lack of motivation to improve teaching practices. For the ASFAP to achieve its goals, there must be a concerted effort to increase investment in public education systems, ensuring that schools have the resources necessary to deliver high-quality physics education.

19.5.10 Lack of Emphasis on Physics at the Primary and Secondary Levels

Physics is often introduced too late in students' academic careers, with many students only encountering the subject in secondary school. This late introduction contributes to students viewing physics as abstract and difficult, as they may not have a solid foundation in basic scientific principles. Moreover, the lack of exposure to physics at the primary school level reduces students' interest and confidence in pursuing the subject further [35]. ASFAP should advocate for the early introduction of physics concepts in primary education to build students' interest and capability in the subject from a young age, laying the groundwork for more advanced studies in secondary and higher education.

Tackling Challenges for a Stronger Physics Education Ecosystem For the African Strategy for Fundamental and Applied Physics to succeed, addressing the challenges facing public schools is critical. By focusing on improving teacher training, enhancing infrastructure, standardizing curricula, and addressing socio-economic and gender disparities, ASFAP can help build a stronger, more resilient physics education system. Overcoming these obstacles will ensure that African students are better prepared to contribute to the continent's scientific and technological progress, ultimately positioning Africa as a key player in the global scientific community.

19.6 Physics Laboratories in High Schools

Physics laboratories play a crucial role in secondary education, serving as the foundation for experiential learning and the application of theoretical concepts. For the African Strategy for Fundamental and Applied Physics (ASFAP) to realize its goals of advancing both fundamental and applied physics across the continent, enhancing the availability and functionality of high school physics laboratories is essential. Well-equipped and effectively managed laboratories can significantly improve students' understanding of physics and inspire interest in pursuing further studies in the subject.

19.6.1 Importance of Laboratories in Physics Education

Physics is an inherently practical subject, where students learn through experimentation and observation. Laboratories allow students to directly interact with physical phenomena, helping them grasp concepts like motion, electricity, magnetism, and optics [36]. Through hands-on experiments, students can see the real-world application of abstract theories, deepening their understanding and retention of scientific principles. In addition, laboratory work fosters critical thinking, problem-solving, and analytical skills, which are essential for success in physics and other STEM fields [37]. The ASFAP must recognize the central role of laboratories in cultivating scientific literacy and encouraging innovation among students. Without access to these practical learning experiences, students may struggle to develop the foundational knowledge and skills necessary for success in higher-level physics courses or careers in science and technology.

19.6.2 Current Challenges Facing High School Physics Laboratories in Africa

Many public high schools across Africa face significant challenges in providing adequate laboratory facilities for physics education. Some of the key issues include:

Limited or Outdated Equipment: Many schools lack basic physics equipment such as oscilloscopes, voltmeters, ammeters, or simple pendulum setups. Even where equipment exists, it is often outdated or in disrepair due to a lack of maintenance funds. This scarcity limits the range of experiments students can perform, hindering their ability to explore physics concepts thoroughly.

Inadequate Funding: The underfunding of public schools across Africa is a major obstacle to the establishment and maintenance of functional physics laboratories. Schools often lack the financial resources to purchase necessary equipment, chemicals, and safety gear, or to build and maintain proper laboratory spaces.

Teacher Training: Many physics teachers in Africa, particularly in rural areas, are not adequately trained in conducting laboratory experiments. They may feel unprepared to manage practical sessions, which limits the frequency and quality of hands-on learning experiences for students.

Unequal Access: Schools in urban areas may have access to better resources than those in rural areas, creating disparities in the quality of physics education. Rural schools lack the infrastructure, including electricity and water, needed to run laboratories, making it difficult to provide any form of practical learning.

19.6.3 Recommendations for Improving Physics Laboratories in High Schools

Increased Investment in Laboratory Infrastructure: Governments and stakeholders need to prioritize investment in the construction and refurbishment of physics laboratories in public high schools. This includes providing modern equipment and ensuring that laboratories are safe, functional, and accessible to all students. A dedicated budget for the maintenance and periodic upgrading of laboratory facilities should be a part of national and regional education strategies.

Provision of Mobile Laboratories: For schools in remote or rural areas where building permanent laboratories may not be feasible in the short term, mobile laboratories can be an effective solution. These traveling labs, equipped with essential physics tools and materials, can bring practical physics education to underserved regions. Mobile laboratories ensure that students in all regions have access to the same quality of education, bridging the urban-rural divide. Teacher Training and Professional Development: Teacher training programs must emphasize laboratory management and practical instruction. Continuous professional development should be offered to physics teachers to help them stay up to date with modern experimental techniques, safety protocols, and best practices for engaging students in hands-on learning. This will not only improve the quality of laboratory sessions but also boost teachers' confidence in using laboratory resources effectively.

Innovative Teaching Aids and Virtual Labs: Where traditional laboratories are not available, the use of virtual labs and low-cost teaching aids can offer alternative solutions. Virtual labs allow students to perform simulations of experiments through computers, providing an interactive and immersive learning experience. Similarly, low-cost, locally sourced materials can be used to create physics experiment setups that mimic standard laboratory equipment. ASFAP can support the development and dissemination of such innovative tools to ensure that even underfunded schools can provide meaningful practical experiences.

Community and Private Sector Involvement: Engaging the private sector and community organizations in the provision of physics laboratories can complement government efforts. Partnerships with businesses, non-governmental organizations (NGOs), and international donors can help fund laboratory construction, equipment procurement, and teacher training initiatives. These collaborations could also promote the development of internship or mentorship programs, linking high school students with professionals in physics-related fields.

Standardization of Laboratory Facilities: Establishing minimum standards for high school physics laboratories across Africa is crucial to ensure consistency in the quality of education. ASFAP should work with national governments to develop a standardized framework that specifies the basic equipment, safety requirements, and infrastructure needed for a functional physics laboratory. This will ensure that all students, regardless of location, have access to laboratories that meet these standards.

19.6.4 The Role of Laboratories in Promoting Careers in Physics

Well-equipped and properly utilized physics laboratories can inspire students to pursue careers in science, technology, engineering, and mathematics (STEM). Early exposure to practical physics experiments can spark curiosity, foster creativity, and provide a deeper appreciation for the subject [38]. By making physics more engaging and accessible, laboratories help demystify the subject, encouraging more students to consider physics as a viable and exciting career path. To meet the long-term objectives of the ASFAP, it is critical to cultivate a generation of students who are not only competent in physics but also passionate about its potential applications in fields such as energy, telecommunications, healthcare, and space science. Functional high school laboratories can play a pivotal role in this mission by providing students with a robust foundation in experimental science and critical thinking.

Building a Strong Physics Education Ecosystem Through Laboratories For the African Strategy for Fundamental and Applied Physics to be successful, high school laboratories must become a priority. By addressing the existing challenges and implementing practical, sustainable solutions, ASFAP can ensure that African students receive the hands-on, practical experience necessary to excel in physics. This approach will not only improve academic outcomes but also help build a stronger physics education ecosystem, fostering innovation and scientific advancement across the continent. The investment in high school laboratories today will lay the groundwork for Africa's future leaders in science and technology, empowering them to contribute to global knowledge and development.

19.7 Promotion of Active Learning

Active learning is a pedagogical approach that encourages students to take an active role in their own learning, fostering deeper understanding and engagement with the subject matter [39]. For the African Strategy for Fundamental and Applied Physics (ASFAP), promoting active learning in physics education is crucial to enhancing the quality of teaching and learning across the continent. Active learning methodologies can transform passive, lecture-based teaching into a dynamic process where students interact with physics concepts, collaborate with peers, and apply their knowledge to solve real-world problems.

19.7.1 The Role of Active Learning in Physics Education

Physics is inherently complex, with abstract theories and principles that can be difficult to grasp through traditional lecture methods alone. Active learning, which includes strategies such as peer instruction, problem-based learning, interactive simulations, and inquiry-based experiments, engages students in the learning process, making them participants rather than passive receivers of information [40].

Active learning supports the development of critical thinking, problem-solving, and collaboration skills, which are essential for success in physics. For ASFAP, embedding active learning strategies into physics education can lead to:

Deeper Conceptual Understanding: By actively engaging with material, students better internalize and comprehend difficult physics concepts. They can see how theories apply in practical settings and develop a stronger foundation for future studies in both fundamental and applied physics.

Increased Student Engagement: Active learning methods make physics more interesting and relevant. Rather than merely memorizing formulas, students actively explore the principles of motion, energy, and matter through discussions, experiments, and simulations. This can lead to increased interest in physics, higher motivation, and improved academic performance.

Collaboration and Communication Skills: Many active learning strategies encourage group work and peer interaction, helping students develop teamwork and communication skills. These skills are vital in real-world scientific and engineering environments where collaboration is key to success.

19.7.2 Challenges to Implementing Active Learning in Africa

Despite the clear benefits of active learning, many public schools across Africa face challenges that hinder its widespread implementation in physics education. Some of the primary barriers include:

Large Class Sizes: Many African public schools have overcrowded classrooms, making it difficult to implement active learning techniques that require interaction, discussion, and group work.

Limited Resources: Active learning often requires resources such as laboratory equipment, technology (for simulations), and teaching aids. Many schools, especially in rural areas, lack access to these resources, making it challenging to incorporate hands-on, student-centered learning experiences.

Teacher Preparedness: Successful active learning depends on well-trained teachers who are confident in facilitating student discussions, guiding experiments, and using technology in the classroom. However, many teachers have not received sufficient training in active learning methods and may be more comfortable with traditional lecture-based approaches.

Cultural and Educational Norms: In some educational systems, there is still a strong focus on rote learning and memorization. Shifting towards an active learning paradigm requires a cultural change in how teaching and learning are viewed, particularly in high-stakes subjects like physics, where examinations often drive instructional approaches.

19.7.3 Strategies for Promoting Active Learning in African Physics Classrooms

To promote active learning in alignment with the African Strategy for Fundamental and Applied Physics, several key strategies should be implemented to overcome existing challenges and encourage the adoption of active learning methodologies:

Professional Development for Teachers: Teachers are central to the success of active learning. Providing ongoing professional development and training on active learning techniques is critical. This could include workshops on problem-based learning, interactive simulations, flipped classroom approaches, and the effective use of technology. Teachers need practical strategies for managing large classrooms while fostering an active, student-centered learning environment.

Incorporating Low-Cost, Hands-On Learning Tools: In resource-limited environments, innovative and low-cost teaching aids can be utilized to bring active learning into the classroom. For example, simple materials like string, weights, and stopwatches can be used to demonstrate physics concepts like motion and force. By embracing creativity in teaching aids, teachers can provide hands-on learning opportunities even when formal laboratory equipment is unavailable.

Leveraging Technology and Virtual Labs: In schools that have access to technology, the use of interactive simulations and virtual labs can be a powerful tool for active learning. These technologies allow students to visualize complex physics concepts and experiment with variables in a virtual environment, promoting engagement and understanding. ASFAP can support the development and dissemination of these technologies across African schools, particularly in under-resourced areas.

Problem-Based and Inquiry-Based Learning: These active learning methods involve students working on real-world problems or conducting their own experiments to explore physics concepts. Teachers can present physics problems relevant to local contexts (such as energy, telecommunications, or transportation) and guide students through the process of investigating solutions. This approach helps students see the relevance of physics to their everyday lives and future careers while building critical thinking and problem-solving skills.

Peer Instruction and Collaborative Learning: Involving students in peer teaching is a cost-effective and impactful strategy. Techniques like Think-Pair-Share, where students think individually about a question, discuss their ideas with a partner, and then share with the larger class, can be easily implemented in most classrooms. This encourages active participation and deeper understanding as students explain concepts to their peers and engage in collaborative problem-solving.

19.7.4 Active Learning and Gender Inclusivity

Promoting active learning can also address issues of gender inclusivity in physics education. Traditional lecture-based instruction can sometimes create environments where girls feel less confident or less likely to participate. Active learning strategies that focus on collaboration, discussion, and hands-on experiments create more inclusive classrooms where all students, regardless of gender, can engage fully with the material. Encouraging girls to take active roles in physics learning through group work and problem-solving can help break down gender stereotypes and inspire more young women to pursue physics-related careers.

19.7.5 Institutional and Policy Support for Active Learning

For active learning to thrive in African schools, institutional and policy support is necessary. Ministries of education, school administrators, and curriculum developers need to:

Revise Curricula: Active learning approaches should be integrated into national physics curricula, shifting away from a focus on rote memorization towards deeper understanding and practical applications. This requires a rethinking of both the content and the methods of teaching physics.

Support Classroom Innovation: Schools and teachers should be encouraged to experiment with innovative teaching methods, and there should be mechanisms for sharing best practices and successful active learning strategies across the education system.

Assessment Reform: Traditional assessments, which often prioritize memorization over conceptual understanding, may discourage active learning. Revising assessment systems to include evaluations of students' problem-solving abilities, practical skills, and conceptual understanding can support the adoption of active learning methods in the classroom.

Active Learning as a Catalyst for Physics Education in Africa The African Strategy for Fundamental and Applied Physics can significantly advance its goals by promoting active learning in physics education. Active learning not only improves students' understanding of complex physics concepts but also helps them develop the skills needed for innovation, scientific inquiry, and technological advancement. By addressing challenges such as large class sizes, resource limitations, and teacher training, ASFAP can foster an educational environment where students are actively engaged, inspired, and equipped to become the next generation of physicists, engineers, and innovators across the continent. Through strategic investment and policy support, active learning can become the cornerstone of a transformative physics education system in Africa.

Active Learning: Steps that can foster growth Large-scale changes will greatly help to improve the physics learning environment in Africa. At the same time, African institutions and educators can take steps in the relatively near term that can stimulate the growth of active learning in physics. The first of these is for physics research institutions to partner with teachers for both professional development in physics and creation of useful materials and activities. This should not be top-down but rather a sharing of expertise: physicists offering knowledge and mentorship with teachers offering their knowledge of the classroom environment, teaching techniques, and how students learn or fail to do so. While these partnerships can be fruitful, networking them across countries, regions, or the whole continent can enable these groups to pool experiences to increase their effectiveness. In-person workshops and even one-on-one partnerships are very effective; they can be enhanced from local region to local region by means of online collaboration. Models of such collaborations which can be modified and adapted for the African context are Netzwerk Teilchenwelt [44] in Germany and QuarkNet [45] in the United States. Such groups can emphasize affordable, doable solutions for high school from simple, effective, and inexpensive laboratory equipment to online access of both simulations and data from actual experiments, including those at the cutting edge. African institutions have recently joined International Masterclasses [46] in increasing numbers, giving high school and university students opportunities to engage with data from experiments at CERN and other forefront laboratories; as this data is from physics research, there are no answers "in the back of the book" and students, consulting with tutors, must make their own judgments and construct results. This sort of activity can be spread by means of an African network or networks to engage more students and their teachers, who gain expertise by preparing and helping the students. [47] University students can participate as masterclass students or tutors, both of which enhance their physics education. As research grows in Africa, it should be possible to create masterclasses based on African research, such as current research at iThemba Labs or new opportunities at the proposed African Light Source. At the same time, it is possible at the university or laboratory level to create opportunities for high school and undergraduate - or even graduate - students to experiment with inexpensive, do-it-yourself equipment such as the Cosmic Watch [48] small cosmic ray detector or simple cloud chambers. Thus, opportunities to promote active learning at all levels but especially in high school exist now and can be embraced by the physics community from research physicists and their students to high school teachers and their students.

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20

Women in Physics Working Group

Marie Chantal Cyulinyana, Iroka Chidinma Joy

Dephney Mathebula

"It's important to recognize that intelligence is malleable and can be enhanced through a growth mindset. This involves embracing challenges, learning from criticism, viewing effort as a journey toward mastery, persisting in the face of obstacles, and finding inspiration in the achievements of others.", **Dr Cyulinyana**.

20.1 Introduction and motivation

The status of women scientists in research has evolved over the years, but challenges and disparities still exist in many parts of the world. It's important to note that the experiences of women scientists can vary widely depending on factors such as geographic location, cultural context, and specific fields of research.

Overall, women account for a minority of the world's researchers. Despite the growing demand for cross-nationally-comparable statistics on women in science, national data and their use in policy making often remain limited. This fact sheet presents global and regional profiles, pinpointing where women thrive in this sector and where they are under-represented. Researchers are professionals engaged in the conception or creation of new knowledge. They conduct research and improve or develop concepts, theories, models, techniques instrumentation, software or operational methods, in the framework of R and D projects [1].

The persistent under representation of women in traditionally male-dominated fields remains a challenge, and despite diverse efforts to eliminate it, breaking the "glass ceiling" for women in the field of science proves particularly difficult. While strides have been taken toward achieving gender parity in higher education, the disparity is more pronounced in scientific disciplines. UNESCO's 2021 [3] estimate revealed that globally, 45-55% of students at the master's and bachelor's levels are women. However, in science-related areas like engineering and computer science, the proportion of female graduates is significantly lower. This gap widens as one ascends the academic career ladder. Presently, women constitute 30% of the world's researchers and a mere 12% of members in national science academies, with even smaller percentages in low-income nations. This trend is also evident in high-tech sectors such as artificial intelligence (AI). According to a Strathmore University study, women make up 29%of the workforce and only 10 % of leadership positions in the AI industry across the African continent [5].

This issue extends beyond a mere concern about representation and is not exclusive to women alone—it is a challenge that impacts all members of society. Those engaged in science, technology, engineering, and mathematics (STEM) bear significant responsibility in devising innovative and enduring solutions to the intricate problems facing our world [2],[4]. Without the contributions of women scientists and the distinct perspectives they offer, scientific possibilities will be constrained, limiting our collective capacity to tackle a range of challenges, spanning from diseases and food insecurity to climate change.

In general, the challenge becomes particularly pronounced when applied to the field of physics, as gender bias and stereotypes persist. Physics lags behind in addressing these issues, necessitating greater efforts to encourage the younger generation both males and females to pursue the subject and shape their future careers around it [6], [7] and [8].

20.2 Goals, challenges and Solutions

20.2.1 Goals

The main goal of a Women in Physics working group in the African context is to promote gender inclusively, empower women in physics, and address barriers, aiming to increase representation, provide support, and foster a collaborative and supportive community for women pursuing physics careers in Africa.

20.2.2 Challenges and Disparities

Women in physics in Africa, like in many other parts of the world, face various challenges that can impact their participation, advancement, and retention in the field. While experiences may vary, some common challenges include:

Underrepresentation: Women are often underrepresented in physics in Africa, both in academic institutions and research settings. This underrepresentation can lead to a lack of visibility and fewer role models for aspiring female physicists.

Gender Bias: Gender biases may exist in hiring, promotion, and funding processes. Preconceived notions about gender roles can affect how women are perceived in the workplace, potentially hindering their career progression.

Sociocultural Factors: Cultural and societal norms may discourage or limit women's pursuit of careers in physics. Stereotypes about gender roles and expectations may influence career choices and opportunities.

Access to Education: Limited access to quality education, especially in rural areas, can disproportionately affect girls and women, limiting their entry into physics and related fields.

Work-Life Balance: The demanding nature of physics research, with long hours and intense workloads, can create challenges for women, especially those balancing family responsibilities. This may contribute to difficulties in maintaining a healthy work-life balance.

Lack of Support Networks: The absence of strong support networks, mentorship programs, and female role models in physics can make it more challenging for women to navigate the academic and professional landscape.

Harassment and Discrimination: Instances of harassment and discrimination, whether subtle or overt, can create hostile work environments, leading to a lack of job satisfaction and hindering career advancement.

Limited Resources: Inadequate resources, including funding for research projects and access to modern laboratories and equipment, can hinder the ability of women physicists to conduct cutting-edge research.

Networking Challenges: Building professional networks is crucial for career advancement, but women in physics in Africa may face challenges in networking opportunities, which can impact collaboration and visibility in the field.

Policy and Institutional Barriers: Institutional policies and practices that are not gender-inclusive may create barriers for women in physics. Lack of family-friendly policies and support for maternity leave can particularly affect women in their career trajectories. Efforts to address these challenges include promoting diversity and inclusion, implementing supportive policies, fostering mentorship programs, and raising awareness about the importance of gender equality in physics. Collaborative initiatives at the institutional, national, and international levels are essential to creating an environment where women in physics in Africa can thrive and contribute fully to the scientific community

Imposter Syndrome Women in STEM fields, particularly in Physics, might encounter imposter syndrome, a phenomenon where they question their capabilities and sense a lack of belonging, even in the face of their achievements and qualifications. This psychological hurdle has the potential to impact self-confidence and impede career advancement.

20.2.3 Progress, Achievements, Solutions

Promoting Gender Inclusivity: Advocate for gender inclusivity and equal opportunities within the field of physics in Africa. Work towards dismantling gender biases and stereotypes that may hinder women's participation in physics.

Empowering Women in Physics: Provide support, mentorship, and resources to women pursuing careers in physics. This could involve establishing mentorship programs, organizing workshops, and creating networking opportunities.

Increasing Representation: Strive to increase the representation of women in physics at all levels, including academia, research institutions, and industry. Encourage women to take on leadership roles and contribute to decision-making processes within the physics community.

Educational Outreach: Engage in educational outreach programs to inspire and encourage young girls to pursue physics. This may involve collaborations with schools, organizing science fairs, and conducting awareness campaigns to showcase the contributions of women in physics.

Addressing Barriers: Identify and address specific barriers that women face in pursuing physics careers in the African context. This could involve advocating for supportive policies, addressing cultural norms, and ensuring that women have access to educational and professional opportunities.

Networking and Collaboration: Foster collaboration and networking among women physicists in Africa. Create platforms for sharing experiences, knowledge, and resources to build a supportive community.

Research and Data Collection: Conduct research on the status of women in physics in Africa, collecting data on representation, challenges, and success stories. This information can be valuable in informing policies and initiatives aimed at improving gender equity.

Partnerships with Institutions: Collaborate with academic institutions, research organizations, and industry partners to create a more inclusive environment for women in physics. This may involve working with institutions to develop and implement policies that support gender diversity.

Advocacy for Policy Changes: Advocate for policy changes at the national and institutional levels to address gender disparities in physics. This could involve lobbying for equal opportunities, fair recruitment processes, and family-friendly policies.

Celebrating Achievements: Recognize and celebrate the achievements of women in physics in Africa. Highlighting success stories can serve as inspiration and motivation for others, helping to create a positive and supportive community for women in the field.

20.3 Conclusion

It is of utmost importance to enhance the involvement of women in physics and address gender disparities in the field to shape a promising future for women in physics. This involves implementing various strategies, such as establishing alliances with other working groups within ASFAP to collaboratively devise inclusive measures for the physics community. We at ASFAP Women in Physics working group (WPWG) strongly support the collection of data through regular surveys to accurately assess the number and status of women in physics across Africa. It is essential to include the voices of men in this endeavor to foster a collective and united approach. Additionally, at the educational level, efforts should be made to make physics an appealing course that attracts the interest and enthusiasm of everyone.

Women in Physics are continually shattering barriers and surmounting daily challenges. Their impactful contributions to fields traditionally dominated by men showcase their resilience and expertise. Although there remains progress to achieve gender parity in Physics, numerous avenues exist to bolster and champion women in this field. Encouraging young girls, championing equal pay and representation, and fostering mutual support can collectively cultivate a more inclusive and diverse Physics community.

The Women in Physics Working Group (WPWG) is dedicated to making a significant contribution to society by actively mentoring young physicists in Africa. Furthermore, the group is committed to fostering research collaborations with underrepresented women physicists on a global scale. In its efforts to advance higher education and support local scientific research projects in Africa, the WPWG is eager to collaborate with policymakers globally, as well as engage with the private sector and business enterprises.

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21

Young Physicists Working Group

Benard Mulilo, Mounia Laassiri, Diallo Boye

Education and scientific research lead to social, economic, and political development of any country. Developed societies like the Group of Seven (G7) countries have not only heavily invested in education, but also in scientific research in their respective countries. Similarly, for African countries to develop socially, economically, and politically, they should follow suit by massively investing in education and local scientific research.

21.1 Introduction and motivation

In 2009, the United Nations Population Fund announced that the population of Africa had reached the one-billion mark and doubled in size in 27 years [1]. Regardless of the size and large pool of the human resource that the continent is endowed with, most African countries continue struggling economically. Based on the World Bank estimates [2], the proportion of Africans living on less than US$ 1.90 per day fell from 56% in 1990 to 43% in 2012. This indicates an improvement of 13% in the living standards of the people in Africa though according to the World Bank Report [2], there were still more poor people in Africa in 2012 than in 1990 estimated to be more than 330 million up from about 280 million due to the rapid population growth [1] that the continent has been undergoing over the years. Furthermore, despite poverty being a major problem in Africa [2], the continent also experiences deadly diseases such as the Acquired-immunodeficiency syndrome (AIDS) caused by the Human-immunodeficiency virus (HIV) believed to have originated from Africa [4, 3]; Ebola-virus disease [5] whose fatality rate is around 50% with case fatality rates ranging from 25% to 90% in past outbreaks [5], and the recent outbreak of the COVID-19 pandemic [6], which has impacted negatively on Africa and the rest of the world. The continent also faces challenges in science and technology [7] with many African countries technologically dependent on other continents in engineering, education, agricultural products, health services, among others. African countries also face inadequate research-output capability or interest with Africa noted to generate only less than 1% of the world's research output [8] despite its increasing population [1]. Due to all these challenges and other factors, the continent has seen young, talented, skilled, and educated Africans leaving the continent in search for better opportunities overseas, a trend referred to as brain drain [9]. To address these challenges, African countries can draw inspiration from developed societies, particularly the Group of Seven (G7) nations [10], renowned for their massive investments in higher education, science, and technology. The establishment of the Young Physicists Forum (YPF) [12] in 2021, under the African Strategy on Fundamental and Applied Physics (ASFAP) [11] amid the COVID-19 pandemic [6], was meant to identify the major challenges that young physicists face and solutions thereof in order to positively contribute to the educational and local-scientific research on the continent, and thus, build capacity for Africa.

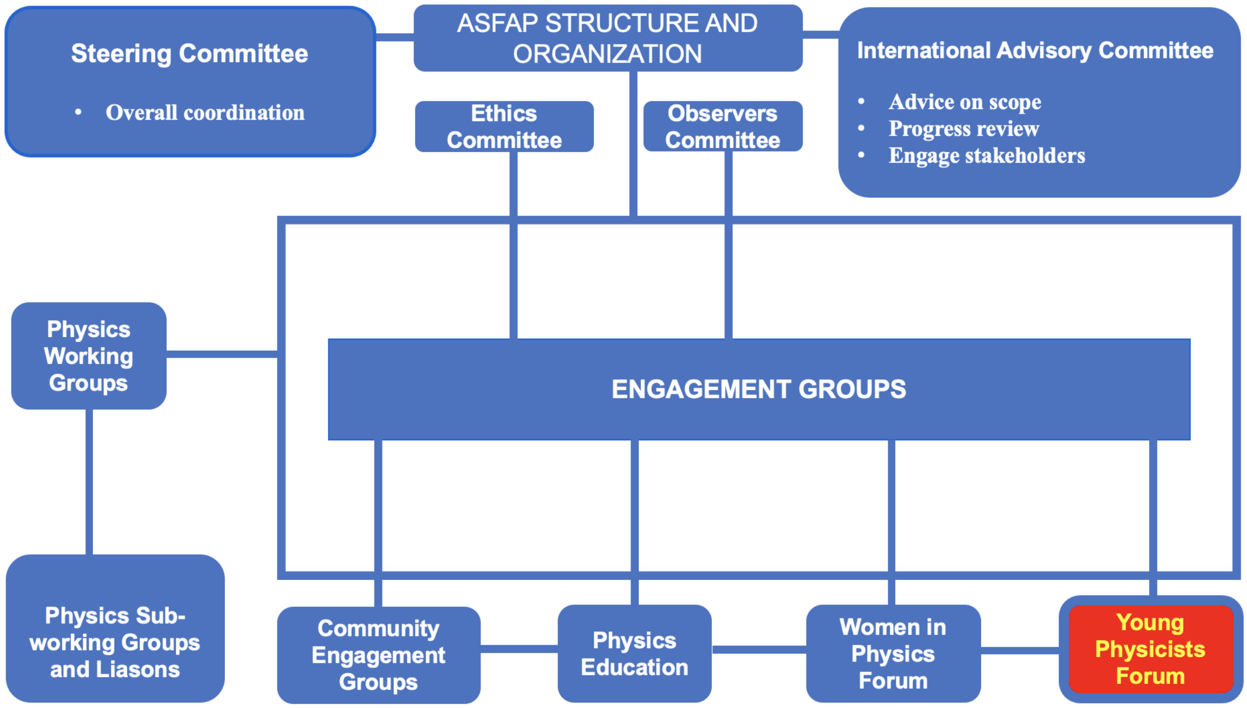


Figure 21-1: Structure and organization of the African Strategy on Fundamental and Applied Physics.

The Young Physicists Forum [12] is one of the engagement and physics working groups (PWG) under the African Strategy on Fundamental and Applied Physics (ASFAP) [11]. The forum is driven by three, young, and vibrant physicists who are co-conveners of the group all in possession of a doctor of philosophy in physics [12]. The co-conveners' mandate is, among other things, to ensure that the group remains sharply focused on its aims and objectives. The forum has a total of 110 active members [12], most of whom are in possession of either a master of science degree or doctor of philosophy in physics. There is, however, no discrimination regarding the highest level of education YPF members [12] should meet and, therefore, all interested individuals within and outside the African continent are eligible to join the forum [12] as long as they sign up [12] and get approved by the steering committee of ASFAP [11]. The group also encourages undergraduate students in various science disciplines, particularly physics, from various African universities to join the YPF [12] and enjoy the mentoring/scholarship benefits that YPF members share within the group, and thus increase their chance of embarking on postgraduate studies either within Africa or overseas. The Young Physicists Forum [12] reports to the steering committee of ASFAP [11] in a well organized structure as shown in Figure 21-1.

21.2 Goals, challenges, and solutions

The aims and objectives of the YPF [12] are, among others, to collect ideas, opinions, and experiences on education, physics outlook, careers, workplace environment, and scientific research in Africa. Furthermore, the forum is mandated to clearly identify and raise awareness of the educational challenges and science career opportunities for young physicists in Africa and advocate for change by informing policymakers for action. Last, but not the least, the forum also aims to collect preliminary data for future research.

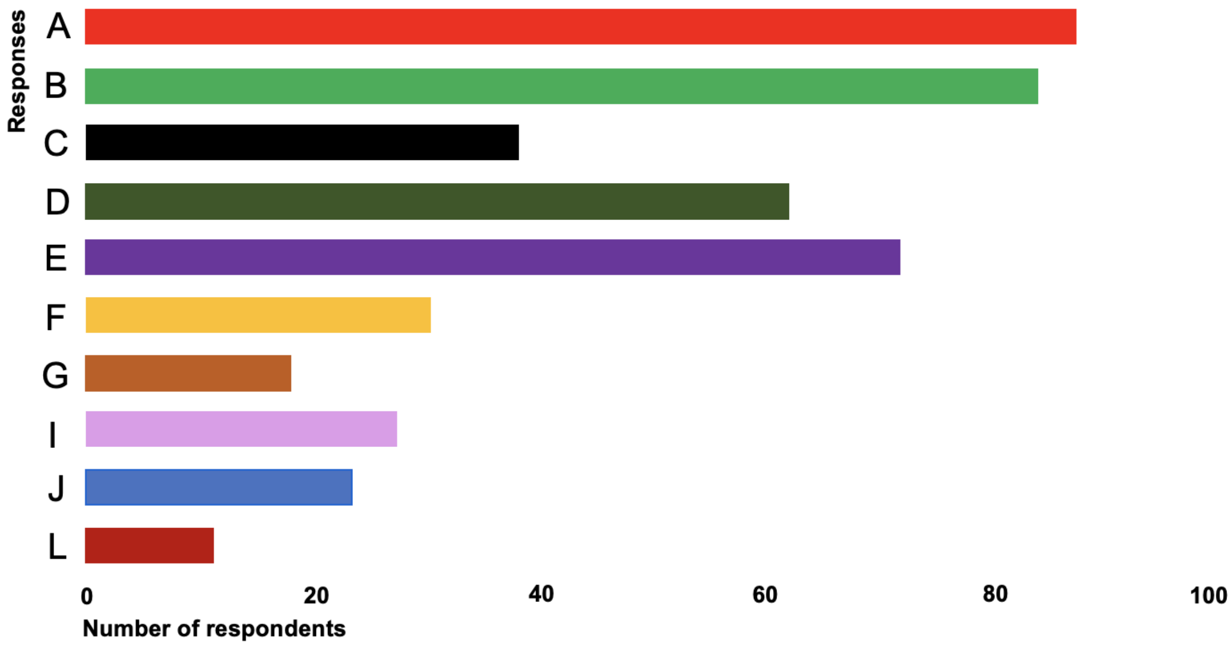


Figure 21-2: Challenges faced by respondents pursuing their highest level of education in African universities.

Since the group's inception in 2021, the Young Physicists Forum [12] has made tremendous progress in meeting its mandate (i.e., its aims and objectives) with the main modes of information dissemination being through scheduled meetings within the group and regular co-conveners' meetings, which are usually held on Wednesday at 5:00 PM, Coordinated Universal Time (UTC). The forum also formulated a survey [15] to solicit for a wider community input of ideas. In addition, the group virtually held a successful workshop with stakeholders within and outside ASFAP [11] on 26^{th} January, 2022 tagged *ASFAP: YPF-Challenges and Opportunities* [13]. The YPF [12] also actively participated in the second edition of the African Conference on Fundamental and Applied Physics tagged *ACP2021* [17] and contributed three talks under different themes mainly focused on the status and progress the forum has so far made in line with the aims and objectives of the group.

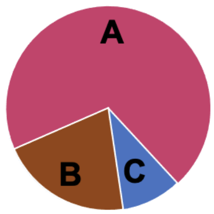
To solicit for a wider community input, the Young Physicists Forum [12] opened a survey [15] to sample African respondents within and overseas, main of whom are alumni of the African School of Physics (ASP) [16]. The survey [15] was aimed at gathering information on the education background, research performance, collaboration opportunities, career development, and workplace environment of the respondents. Survey results [15] show that 79.56%, of the respondents pursued their highest level of education within Africa while 20.44% of the respondents attained their highest level of education outside the continent of Africa. The survey [15] has further revealed that of the respondents who attained their highest level of education within Africa normalized to 100%, only 39.42% were satisfied. Factors leading to the educational dissatisfaction rate by respondents are plotted in Figure 21-2 and outlined in Table 21-1. From Figure 21-2 and Table 21-1, it is evident that good quality education and research in Africa still remain a huge challenge. Other major obstacles of an African educational system include the lack of mentors, skills training, libraries, job insecurity, and to a lesser extent political instability such as wars, among others. Since education, science, and technology are ingredients that contribute massively to a good life and development of global economies, there is need to solicit for remedies that counter the education and research challenges that many African countries have been grappling with for years.

Table 21-1: Educational challenges faced by respondents pursuing higher education in African institutions

Responses	Challenges	Rate (%)
A	Lack of research funding	20.35
B	Lack of research equipment	19.26
C	Lack of mentoring support	7.88
D	Lack of mobility opportunities	13.57
E	Lack of proper skills training	15.75
F	Lack of access to libraries	6.35
G	Limitation of academic freedom	3.50
H	Imbalance between work and family demands	5.91
I	Job insecurity	4.81
J	Political instability and wars	2.63

According to the survey [15] conducted by the Young Physicists Forum [12], prominent solutions to educational challenges include raising awareness to African policymakers and private enterprises on the need to fund research through provision of grants, which universities in Africa should utilize to buy experimental equipment and conduct research. African governments should also invest in building higher learning institutions that are well equipped with research facilities such as modern laboratories where academic staff and their students could establish the link between theory and experimental work. This would then help reduce over-dependence on foreign research facilities and contribute to meaningful and reliable collaboration with other institutions and research facilities overseas. Public and private universities should work together and help improve the internet network in universities and research facilities across Africa as a good and stable internet connectivity undoubtedly enhances scientific research output and helps improve the quality of learning.

Other measures that may help counter educational challenges in Africa include revision of the school and university curricula by reducing over-dependence on theoretical work [15], building scientific research facilities, and securing laboratory equipment to encourage research skills and knowledge acquisition through experimental work among African students. Furthermore, the lack of mentors in science disciplines like physics in African universities could be resolved by motivating professors to embark on scientific research projects and closely working with their students [15] once research grants are available to them from governments and private enterprises. Academic staff should also spend more advisory time with their students and try and establish the link between theoretical and experimental work together [15]. Additionally, academic staff should offer more structured feedback to students and also establish research collaborations within and outside the continent so as to expose their students scientifically [15]. Occupational and career guidance should also be provided to students by their advisors in order to motivate them regarding their future endeavours in academia within Africa [15]. A career with occupational development is another huge challenge being faced by young physicists in Africa [15]. According to the population sampled in the survey [15], it is found that roughly 85.82% of the respondents are in the field of academia where they are teaching and conducting research in national universities and laboratories while those in non-academia fields accounted to about 12.06%, and approximately 2.13% preferred not to reveal their occupation as shown in the pie chart in Figure 21-3 by A, B, and C, respectively. Those in academia identified themselves as bachelors, masters, and doctoral students including postdocs, engineers, technicians, physicists as well as faculty members.



- A: Academia, i.e., teaching or conducting research in universities or national laboratories (85.82%)
- B: Non-academia (12.06%)
- C: Preferred not to answer (2.13%)

Occupation and precent representation of sample									
Current position	Bachelors students	Masters students	PhD students	Postdocs	Engineers	Technicians	Faculty	Physicists	other
Percent (%)	3.55	10.64	44.68	8.51	0.71	0.71	14.18	9.93	7.09

Figure 21-3: Occupation and percent representation of respondents according to the survey conducted by YPF.

Results of the survey [15] have further revealed that securing an academia position within African universities and national research facilities poses a major challenge and is, at the same time, a huge sacrifice owing to the fact that the workplace environment is mostly not conducive due to lack of experimental facilities, among other challenges, more so in the last two years with the breakout of the COVID-19 pandemic [6]. Based on the results of the survey [15], the Young Physicists Forum [12] has learnt that the combined effect of the nature of an academia workplace environment in Africa and the impact of the COVID-19 [6] has led to a reduction of academic interactions between academic staff and students according to 19.35% of the respondents. Other effects include the reduction of experimental activities (14.52% of the respondents) and research funding according to 12.50% of the respondents. The nature of the workplace environment with the impact of the COVID-19 pandemic [6] has also led to fewer advisor-student interactions according to 13.91% of the respondents while other effects include physical and mental health problems as well as financial hardships as described in Figure 21-4. The poor currency-exchange rates of African currencies against major world currencies such as the United States Dollars ($), Euro (€), and the British Pound (£), among others, is another major challenge [15] of being in the academia field in Africa as this significantly and negatively impacts scientific collaboration work between Africa and other continents as far as international research visits and conferences by students and academic staff are concerned.

The lack of good will and minimal interest in education, science, and technology in Africa [7] have led to a huge challenge over the years where the world has witnessed a large number of skilled manpower leaving Africa for other continents in search of a more conducive workplace environment and an attractive income to support their families, a trend known as brain drain [9]. The survey [15] conducted by the YPF [12] has revealed some instances of brain drain [15, 9] that have been taking place in Africa over the years. These include young and skilled African students studying abroad on scholarships opting to stay and working overseas after completion of their studies [15]. Researchers and postdocs also feel more comfortable working overseas than in African universities where they are either not welcomed or because of the nature of an African academic-workplace environment and meagre salaries [15]. The lack of academic freedom (i.e., students having no choice of what to study due to financial reasons), inadequate funding, and absence of research equipment disfavor Africa as a good destination for good quality education and research work [15]. Political instability such as wars in some countries in Africa drive away academically qualified personnel to other countries outside the continent where they settle down and continue to contribute to science and technology there than in their African

	Nature of workplace and COVID-19 impact	(%)
A	Reduction of research funding	12.50
B	Reduction of experimental activities	14.52
C	Reduction of academic interactions	19.35
D	Less productivity of online classes	8.87
E	Less advisor and student interaction	13.91
F	Physical healthy problems	7.26
G	Mental healthy problems	9.48
H	Financial hardship	13.10
I	None	0.40
J	Not applicable	0.60

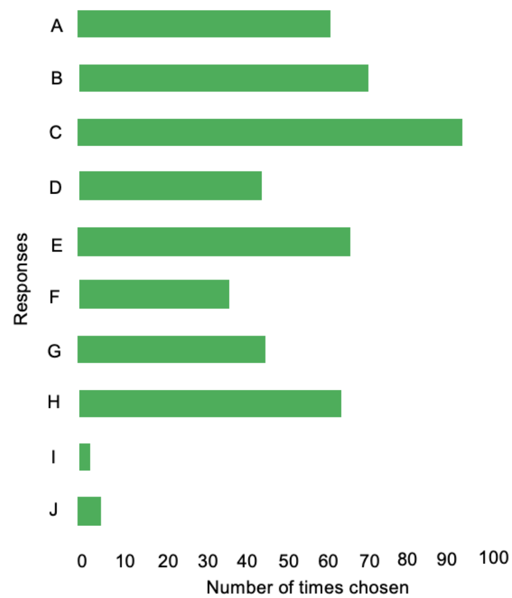


Figure 21-4: Impact of the nature of the workplace and COVID-19 pandemic on research institutions in Africa.

Table 21-2: Measures that may help counter brain drain according to the survey conducted by the YPF

1	Create a school of excellence within Africa for Africans who have obtained their baccalaureate with honors in order to encourage African academic excellence and experience.
2	Policymakers on the continent should partner with private enterprises and work together to improve the research-workplace environment and conditions of service such as salaries to match foreign-based counterparts in academia.
3	Create national research laboratories and more academic positions in African universities and provide research grants to enable academic staff members to embark on a meaningful scientific research experience within the continent.
4	Policymakers should stabilize African currencies to compete favorably with other major world currencies such that the salaries skilled academic staff are earning in Africa are favourably comparable to salaries fellow counterparts earn abroad.
5	Enhance and connect African academic infrastructures with the rest of the world; promote scientific collaborations with international universities, research institutions, and laboratories and allow creative young Africans to present new scientific research projects.
6	Massive investment in African university education is required that will result in an increase in well paying jobs. A marketing campaign should be setup to encourage the youth to stay and work in their respective countries in Africa.

countries of origin [15]. In spite of all these brain-drain challenges [15, 9], the hope for Africa in education, science, and technology [7] is still alive. Through the survey [15], the YPF [12] have compiled measures to counter the effects of brain drain [9] and hence help keep alive the hope for African countries to develop their education and build capacity for Africa. These interventions are summarized and listed in Table 21-2.

21.3 Outlook

During the ASFAP process, the Young Physicists Forum has been representing young African physicists within the ASFAP community. However, no overarching group exists to provide broad representation for young African physicists outside or beyond ASFAP. Therefore, YPF conveners are taking steps to ensure the continuity of a field-wide young African physicists representative group within Africa. In this section, the main ideas emerging from community feedback, steps taken to form a long-term organization in accordance with that feedback, and possible next steps in evolving YPF to become an organization that can serve the entire YPF community for the long term in Africa are outlined.

21.3.1 YPF at ASFAP Town Hall Meeting

The ASFAP Community Town Hall meeting took place from July 12 to 15, 2021. It was held online to discuss the scope and focus of the working groups [18]. The YPF co-conveners served as representatives of the YPF. The key points from the community feedback included establishing a representative group for the YPF community to lead initiatives beyond the ASFAP process, maintaining the goals of representation in the ASFAP and ASFAP—YPF surveys, and enhancing efforts on other key long-term initiatives. The community feedback formed around two arms of the organization:

1. **ASFAP— YPF Coordination** to coordinate with ASFAP— Physics working groups and help get young African physicist members involved in the ASFAP process.
2. **ASFAP— YPF Core Initiatives** to assess and initiate ASFAP-YPF critical issues independently. The community feedback formed around three key initiatives that will extend beyond the ASFAP process as follows:
    - **Surveys** to collect ideas, opinions and experiences on careers, physics outlook, workplace culture, and scientific research on the African continent.
    - **Enrichment** to deal with professional development and building cohesion within the YPF community.
    - **Long-term organization** to define the long-term structure of the young African physicists organization after the ASFAP process.

21.3.2 Mission and Goals of the Long-Term Representation

The YPF aims to provide long term young-physicists representation to all members of the fundamental and applied physics community in Africa. Toward this mission, the YPF has a goal of fostering a welcoming, inclusive, collaborative, and multidisciplinary community. Initiatives that benefit young-physicist members of the fundamental and applied physics community within the continent will benefit the community at large. The creation of an inclusive space that promotes equity, respect, and representation across the discipline is of the utmost importance. The YPF community has expressed the necessity of continuing and extending the organization and community established during the ASFAP process. The organizational structure and community established by the YPF during the ASFAP strategy will serve as a starting point for this long-term organization. Based on community feedback, the YPF plans to continue and adapt the *long-term organization's* key initiatives beyond the ASFAP process and solicit for new key initiatives. The YPF has, therefore, put forward the above goals to ensure that its mission not only continues beyond the ASFAP process, but also empowers members of the YPF community to function effectively.

21.4 Recommendations

The recommendations in this section were prepared by the YPF community and are a supplement to the survey recommendations in Sec. 21.2. They include recommendations from contributed white papers and community feedback obtained throughout the ASFAP process.

Recommendation 1: Raise Awareness and Secure Research Funding - African policymakers and private enterprises should be made aware of the importance of funding research in education in Africa. The provision of grants could enable universities to purchase experimental equipment and conduct research thereby reducing reliance on foreign facilities and fostering collaboration with overseas institutions.

Recommendation 2: Invest in Higher Learning Institutions - African governments should invest in building well-equipped higher learning institutions with modern research facilities. This includes establishing modern laboratories where students and academic staff can bridge the gap between theory and practical experimentation.

Recommendation 3: Improve Internet Connectivity in Higher Learning Institutions - Reliable internet access greatly enhances scientific research output and improves the overall quality of teaching and learning. The collaboration between public and private sectors is, therefore, essential in ensuring that internet connectivity across African universities and research facilities is enhanced.

Recommendation 4: Revise Science Curricula and Expand Research Facilities - Reduce overemphasis on theoretical work by revising school and university curricula. Investing in scientific research facilities and securing laboratory equipment can encourage hands-on research among African students, fostering valuable skills and knowledge acquisition.

Recommendation 5: Promote Science Research Projects and Mentorship Programs - Encourage academic staff members to engage in scientific research projects and mentor students closely. The availability of research grants from governments and private enterprises can facilitate this process. Establishing a strong link between theoretical and experimental work is crucial for student development.

Recommendation 6: Provide Structured Feedback and Foster Collaboration - Academic staff members should offer structured feedback to students and facilitate research collaborations within and outside the continent. Exposure to diverse scientific environments enhances students' scientific understanding and skills.

Recommendation 7: Offer Occupational and Career Guidance - Faculty staff should provide students with guidance on future academic and career paths within Africa, motivating them to pursue their endeavors in academia. This guidance plays a crucial role in shaping the future of African students in the global scientific community.

Recommendation 8: Retain Skilled Humanpower within Africa and Minimize Brain Drain - Policymakers should provide a conducive work-place environment that is fairly comparable to workplaces in other scientifically advanced continents. This will greatly help in minimizing the brain-drain syndrome in Africa. Attracting skilled manpower will entail high-quality service delivery within the continent.

21.5 Conclusion

The African continent is endowed with abundant natural resources ranging from huge arable land through oil, natural gas, minerals to floras and faunas. It is amazingly puzzling to note that the continent holds a large proportion of the world's natural resources, both renewable and non-renewable and yet, to a large extent, Africa still remains undeveloped with higher poverty levels [2] than other continents. To restrain or minimize these challenges, Africa should heavily invest in higher education and promote local scientific research [15, 7]. Advanced scientific research carried out within Africa would, for example, help find solutions to diseases such as HIV/AIDS [3, 4] that have been ravaging the continent over the years; produce vaccines of its own to cure pandemics such as COVID-19 [6] without having to entirely depend on or solely wait for developed societies [10] to share portions of their vaccines; process its abundant natural resources from raw materials to finished products, and reduce over-dependence on developed countries for finished goods and services [7]. This would, in turn, build an even better relationship between Africa and the rest of the world as far as business is concerned. Since higher education is one of the keys to social, economic, and political independence of any country, it goes without saying that, higher education should be prioritized across Africa. Policymakers should ensure that the educated-human resource is enticed to work within Africa by offering an attractive workplace environment and good conditions of service. These measures would help minimize the brain-drain [15, 9] phenomenon. The YPF [12] is entirely open and solely devoted to identifying the challenges that young physicists face in developing their careers in Africa and finding solutions as well as career opportunities available for young physicists on the continent so as to revamp education and build capacity for Africa. The YPF is also entirely committed to mentor young physicists in Africa and to help promote research collaborations with other young physicists globally [15]. To broaden its impact, the YPF plans to evolve beyond the ASFAP process by leveraging the community it has built to create a permanent structure that offers new opportunities and support to its members. This expanded YPF aims to partner with policymakers, the private sector, and business enterprises globally to advance higher education and local scientific research projects in Africa. The YPF will work closely with various African governments to unite skilled young physicists, find solutions in fundamental and applied physics, and conduct significant research across sectors such as clean energy, medicine, agriculture, transport, and communication. The overarching goal is to improve the quality of life and service delivery across Africa.

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