MuCol

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List of participants

Participant No. *		Participant organisation name	Short Name	Country
1 (Coordinator)	Beneficiary	Organisation Européenne pour la Recherche Nucléaire	CERN	IEIO
2	Beneficiary	Deutsches Elektronen-Synchrotron	DESY	DE
3	Beneficiary	Technische Universität Darmstadt	TUDa	DE
4	Beneficiary	Universität Rostock	UROS	DE
5	Beneficiary	Commissariat à l'énergie atomique et aux énergies alternatives	CEA	FR
6	Beneficiary	Istituto Nazionale di Fisica Nucleare	INFN	IT
7	Beneficiary	Università degli studi di Milano	UMIL	IT
8	Beneficiary	Università degli Studi di Padova	UNIPD	IT
9	Beneficiary	Universiteit Twente	UTWENTE	NL
10	Beneficiary	Laboratório de Instrumetação e Física Experimental de Partículas	LIP	PT
11	Beneficiary	European Spallation Source ERIC	ESS	SE
12	Beneficiary	Uppsala Universtet	UU	SE
13	Beneficiary	Imperial College of Science Technology and Medicine	Imperial	UK
14	Beneficiary	United Kingdom Research and Innovation	UKRI	UK
15	Beneficiary	University of Warwick	UWAR	UK
16	Beneficiary	University of Lancaster	ULA	UK
17	Beneficiary	University of Southampton	SOTON	UK
18	Beneficiary	University of Sussex	UOS	UK
19	Associate	Paul Scherrer Institute	PSI	CH
20	Associate	Université de Geneve	UNIGE	CH
21	Associate	Sun Yat-sen University	SYU	CN
22	Associate	Karlsruher Institut Für Technologie	KIT	DE
23	Associate	Centre National de la Recherche Scientifique	CNRS	FR
24	Associate	Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	ENEA	IT
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27	Associate	University of Strathclyde	Strathclyde	UK
28	Associate	University of Huddersfield	HUD	UK
29	Associate	Royal Holloway and Bedford New College	RHLU	UK
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31	Associate	Iowa State University	ISU	US
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Abstract

Two facility concepts have emerged in the past years as pathways to the future of particle physics at the energy frontier in Europe: FCC-hh, a 100 TeV circular hadron collider and CLIC, a 3 TeV linear lepton (i.e. electron-positron) collider. They are improved versions of projects realised in the past. The expected cost and power consumption are 24 GCHF and 580 MW for FCC-hh and 18 GCHF and 590 MW for CLIC.

The recent European Accelerator R&D Roadmap (https://arxiv.org/abs/2201.07895) includes a 10 or more TeV Muon Collider (MuC). This novel interest is based on two considerations:

- The recognition of the physics potential of a lepton collider with a centre-of-mass energy of 10 TeV or more.
- The recent advances in technology that make the realisation of a muon collider plausible.

The Muon collider promises to expand the lepton collider energy reach. Muons are much heavier than electrons. The resulting, much reduced, synchrotron radiation allows acceleration and collision of the beam in rings, even at multi-TeV energies. This results in compact dimensions and promises high efficiency and limited cost. The tunnel length of a 10 TeV muon collider is expected to be in the worst case similar to the 3 TeV CLIC and about half that of the FCC-hh. Because muons are point-like particles, in contrast to the composite hadrons, MuC would have a comparable physics case to a 100 TeV hadron collider.

Past work has demonstrated several key muon collider technologies and concepts, and gives confidence that the concept is viable. Component designs have been developed that can cool the initially diffuse beam and accelerate it to multi-TeV energy on a time scale compatible with the muon lifetime. Relevant technologies, e.g. superconducting magnets, have recently progressed.

While the muon collider promises high benefits it also poses a significant risk. No muon collider has yet been built. The facility is based on advanced concepts and technologies. The Roadmap identifies remaining key challenges that require to be addressed by the next ESPPU so that the High Energy Physics community may make informed choices.

MuCol will address the core of these key challenges. It will develop the baseline design and assess the physics performance based on realistic performance goals for the collider components. The identification of the cost and power consumption drivers will enable determination of the cost and power consumption scale. This will allow the next European Strategy for Particle Physics Update (ESPPU) process to seriously consider also Muon Colliders for the selection of the next large collider to be built in Europe.

1. Excellence

1.1. Objectives and ambition

The MuCol study will produce a coherent description of a novel particle accelerator complex that will collide muons of opposite charge at the energy frontier. The study will target a centre of mass energy (E_{CM}) of 10 TeV with 3 TeV envisaged as a first stage.

The main outcome of MuCol will be a report documenting the facility design that will demonstrate:

- **the physics case of the muon collider is sound and detector systems can yield sufficient resolution and rejection of backgrounds;**
- **there are no principle technological issues that will prevent the achievement of a satisfactory performance from the accelerator side or from the detectors side;**

- **that the muon collider provides a highly sustainable energy frontier facility as compared to other equivalent colliders; and**
- **that exploiting synergies with other scientific and industrial R&D projects, it can provide a valuable platform to provide Europe a leading edge not only in terms of discovery potential, but also for the development of associated technologies.**

The final report will include a thorough assessment of benefits and risks of the accelerator and detector complex, including an evaluation of the scientific, industrial and societal return beyond high-energy physics, the cost scale and sustainability of the complex and the impact arising from an implementation on the CERN site.

Muons, like electrons, are point-like particles (leptons) so that their nominal center-of-mass collision energy E_{CM} is entirely available to produce high-energy reactions. By contrast, the relevant energy for proton colliders, which are hadrons, is the center of mass energy of the collisions between the partons that constitute the protons. The partonic collision energy is distributed statistically, and represents hence only a fraction of the proton collider nominal energy. A muon collider with a given nominal energy and luminosity is thus more effective than a proton collider with comparable energy and luminosity. Figure 1 shows the center of mass energy, $\sqrt{s_p}$ that a proton collider must have to be considered *equivalent* to a muon collider of a center of mass energy $\sqrt{s_\mu}$. The *equivalence* definition is a not trivial and depends on the physics channel, and it is related to the production cross section of the particles under study. A detailed discussion can be found in [https://doi.org/10.48550/arXiv.2203.07261]. As a reference, a 100 TeV center of mass proton collider, representative of the design efforts for a hadron-hadron Future Circular Collider (FCC-hh) at CERN, is shown to be *equivalent* to a muon collider with E_{CM} in the range of 7 to 14 TeV.

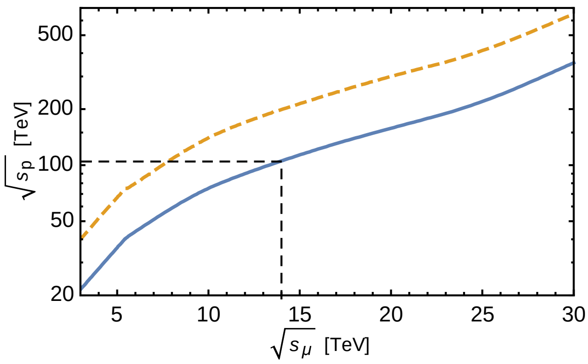

Fig. 1. The center of mass energy at which the proton collider cross-section equals that of a muon collider. The dashed line assumes comparable Feynman amplitudes for the muon and the proton production processes. A factor of ten enhancement could possibly be considered as the continuous line due to QCD production.

The above considerations clearly point to the competitive advantage of lepton colliders at the energy frontier. Still accelerating leptons to such high energy poses very significant challenges. Specifically, the energy reach of circular electron and positron colliders is limited due to the energy loss by synchrotron radiation. The highest energy circular e^+e^- collider under design at CERN, the FCC-ee, will be limited to a maximum collision energy of 365 GeV for a circumference of about 90 km, i.e. much below the range of E_{CM} discussed here.

Linear e^+e^- colliders are an alternative configuration, as they do not suffer from synchrotron radiation, but they are inherently less efficient than circular colliders since the particles collide only once, and the collision energy is proportional to the length of the collider. Therefore, higher energies require longer and longer colliders. As an example, the Compact Linear Collider (CLIC) studied at CERN, would have a total length of nearly 50 km to achieve a collision energy of 3 TeV, with an estimated power consumption of 590 MW, while the estimated consumption for a 3 TeV Muon Collider is of the order of 250 MW (although this last number needs to be confirmed by more detailed studies).

Synchrotron radiation is strongly reduced in heavy particles, such as hadrons, which is why proton circular colliders are the preferred and most efficient option to reach high E_{CM}. In this case the main limitation comes from the maximum magnetic field in the dipoles to keep an affordable collider circumference. As an example, FCC-hh, with a total circumference of about 90 km, requires magnetic fields up to 16 T to get a collision energy of 100 TeV, which is at the limit of the technology of superconducting dipoles and is a cost driver.

Muons are heavy leptons, with a mass that is 207 times that of electrons, and synchrotron radiation in a circular accelerator is largely suppressed. They are hence ideal candidate particles for acceleration and collision in circular accelerators. A muon collider, if proven feasible, would outperform by far any electron-positron collider. The reason why this has not been realized already is that muons decay spontaneously with a lifetime of 2.2 μs at rest. This exceedingly short time is expanded in the laboratory frame by relativistic time dilation, but still the time available for production, acceleration and collision of muons is orders of magnitude shorter than the typical acceleration and collision times of high-energy physics collider facilities built so far. Specific technologies have therefore to be developed to ensure a satisfactory performance for the entire complex.

Indeed while the necessary technologies for electron-positron and proton-proton colliders are either readily available or within proven reach, a comprehensive and self-consistent study of Muon Colliders is not available. The US Muon Accelerator Program (MAP) has studied the concepts at the basis of a muon collider facility, producing a preliminary design of machines at different center of mass energies up to 6 TeV [M-H. Wang *et al* 2016 *JINST* **11** P09003]. While the MAP study was seminal to our proposal, it focused only on selected areas of the whole accelerator complex, missing an integrated view of the whole facility. Also, the study identified several technological issues that, a decade later, we believe can be tackled and overcome.

MuCol will address the design of the Muon Collider facility using a holistic approach, from muon generation to collision, including the study of the interaction regions and the background to the experimental detectors, and will explore the associated technologies.

Physics Motivations

Interest in the potential of a muon collider was greatly revived in the past years, as demonstrated by a large number of theoretical and phenomenological papers culminated in the "Muon Smasher Guide" (Al Ali, Hind et al - arXiv:2103.14043, accepted for publication)

The current proposal of a muon collider at 10 TeV center of mass energy foresees a first stage at 3 TeV, both of which provide compelling physics opportunities. The physics potential at 3 TeV is similar to the potential of CLIC at its highest energy, with the bonus of the unique possibilities offered by collisions of muons instead of electrons. As discussed in [https://doi.org/10.48550/arXiv.2203.07261], muon and anti-muon collision at the TeV energy scale offer a tremendous opportunity in the search for new physics. Indeed, both the *g-2* and *b-physics* observed anomalies with respect to the Standard Model (SM) predictions involve muon coupling. This supports the importance of investing now in a muon collider feasibility study.

The second stage, a muon collider with a centre-of-mass energy of 10 TeV or more, would open entirely new opportunities for the exploration of fundamental physics. The "Muon Smasher's Guide" [https://doi.org/10.48550/arXiv.2103.14043] analyses physics potential in all the high energy physics sectors and illustrates how the muon collider can be complementary to other experiments that are probing for new physics like the study of electric dipole moments and gravitational waves. MuCol will show whether a high energy option can be envisaged, and within a practical technology reach.

The detector design for a 3 TeV collider could be similar to the one of CLIC, with significant modifications of the inner (tracker) region needed to cope with the background distribution induced by the muon beams decays. The detector optimization and the final performance is one of the objectives of MuCol. A detector for physics studies at center of mass energy of 10 TeV or higher has never been designed. MuCol offers the unique possibility to study the beam-induced background by varying the accelerator interaction region and to produce an efficient background shielding, thus producing the best experimental conditions. Moreover, and most important, a novel detector design for a muon collider will quantify the challenges and foster opportunities to explore new experimental concepts for high energy physics, integrating sub-detectors R&D with innovative event reconstruction algorithms.

Accelerator Physics and Technology Motivations

As we indicated earlier, a muon collider will have to resolve the difficulty inherent with the very short lifetime of muons, of the order of 2.2 μsec in the particle reference frame, requiring all processes of muon generation and acceleration to be significantly faster that what is normally done with hadrons or electrons.

The second major challenge of a muon collider is the emission of neutrinos by natural decay of muons. Neutrinos penetrate the earth at long distance and therefore showering arising from neutrino interactions may appear on the surface, even for a collider constructed underground, e.g. 200 m as presently considered at CERN. The proposed techniques to reduce the flux to a negligible level need to be studied to ensure that the effect remains at a level consistent with existing facilities. This is required in order to prove the feasibility of construction at CERN or in any European country, and ensure the required public acceptance.

To address the two issues above we will use as a starting point the conceptual layout of the chain of accelerators elaborated by the Muon Accelerator Program (MAP) that has coordinated US efforts on muon collider R&D [JINST Special Issue]. The layout proposed by MAP is shown in fig. 2, and described briefly below.

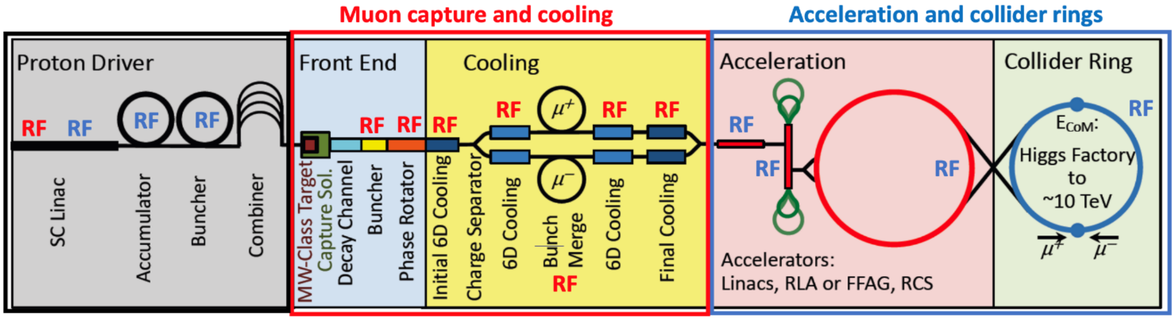

Fig. 2: Layout of the Muon Collider complex as elaborated by the MAP

The proton complex produces a short, high intensity proton pulse that hits a target and produces pions. The decay channel guides the pions and collects the muons produced by their decay into a buncher and phase rotator system to form a muon beam. A high muon beam brightness is mandatory to deliver the largest number of particle collisions. This implies that a large proton beam power is driven onto the pion production target to make the largest possible number of pions and, following decay of the pions, muons. The muon collider design foresees a state-of-the-art proton complex, capable of delivering around 2 MW of proton beam power at around 5 GeV. This beam power is slightly beyond existing pulsed proton driver facilities but crucially, the muon collider requires protons to be delivered at the target in an extremely short pulse, around 1 ns long, so that the resultant muon beam is also very short and can be subsequently captured in a suitable RF system. Compression of the proton bunch in such a short pulse will require an advanced arrangement of RF cavities. The overall efficacy of such a system is constrained by the self-repulsion of the protons due to space charge.

The following step is to reduce the volume of the resultant muons in position-momentum space, a process called *beam cooling*. This process is shown schematically in Fig. 1.3.

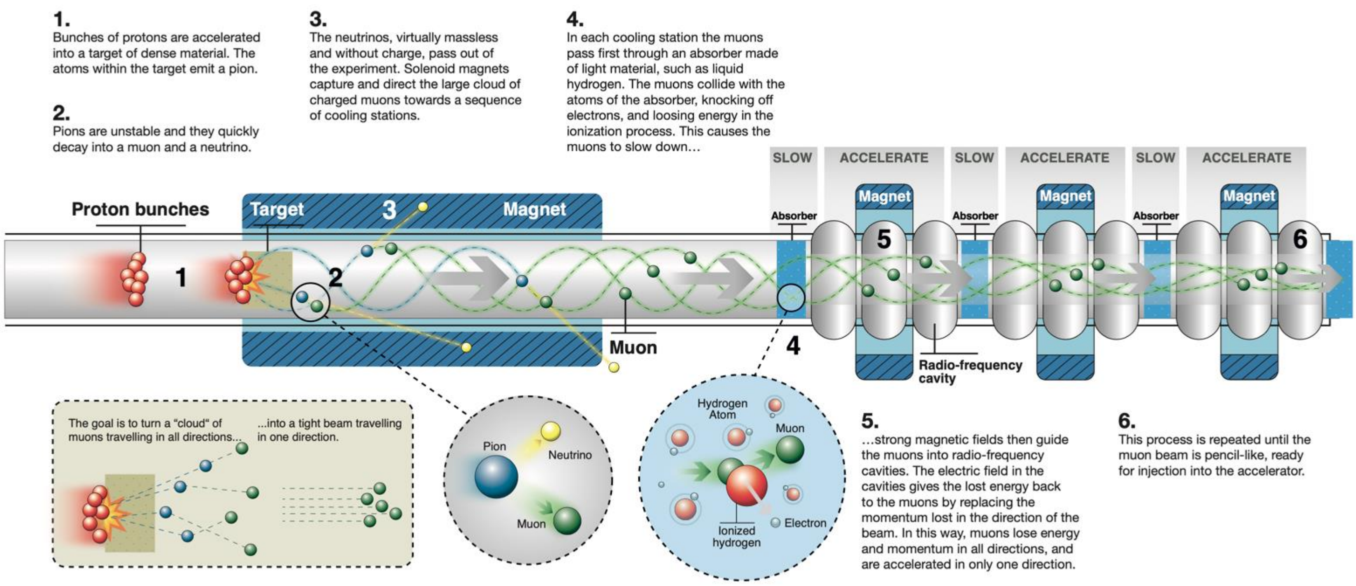

Fig. 3: Principle of the Muon Ionisation Cooling

A pair of approximately kilometre-long muon cooling linacs are proposed to reduce the six-dimensional volume of the positively- and negatively-charged muon beams by five orders of magnitude. Within each linac, muons are continuously decelerated and re-accelerated to provide the muon cooling. Muon ionisation cooling requires very tight focusing and high-gradient RF cavities to reach the lowest emittance. The whole lattice must be extremely compact to properly contain the beam. A design for such a lattice was shown by MAP to almost reach the required performance. Since the end of MAP, advances have been made in RF and magnet technology that suggest that the lattice design can be improved. On the other hand further work must be performed to understand constraints arising from engineering and integration challenges, such as the need to maintain a thermal barrier between cryogenic magnets and room temperature RF cavities.

A sequence of a linac and two recirculating linacs receive the cooled muon beams and accelerate them to 60 GeV. One or more rings then accelerate the beams to the final energy of 1.5 TeV (E_{CM} of 3 TeV) or 5 TeV (E_{CM} of 10 TeV).

As the beam is accelerated, the lifetime in the lab frame increases due to relativistic time dilation so later stage accelerators have proportionally more time for the acceleration process, making fast-pulsed synchrotrons a possible option. Fixed-field alternating-gradient accelerators (FFAs) are an interesting alternative that avoids pulsing the magnets of a synchrotron. Finally the two single bunch beams of opposite charge are injected at full energy into the collider ring to produce collisions at two interaction points.

The MAP study laid out the basic concept and examined the feasibility of some of the key components. Still, several important elements were not studied, including:

- **Muon source** – The individual elements of the muon source were studied separately, but an integrated system design and optimization was not performed. In addition, MAP studies considered gallium, graphite and mercury as options for the production target material. These studies should be pursued further, alternatives proposed and assessed to understand the expected performance and technical limitations of the system. Some of the options, such as mercury targets, are not compliant with European regulations and will not be studied in MuCol.
- **Muon cooling** – Cooling studies assumed limits in solenoid and RF fields that appear to be too conservative in the light of the recent progress in superconducting magnet RF technology. For instance in 2021 a solenoid based on HTS technology has reached 32 T. The MAP missed the target luminosity by a factor two due to technology limitations which constrained the expected performance of the cooling elements. MuCol will revise estimates based on the present state of the art.
- **High collision energy E_{CM}** – The highest collision energy studied by MAP was 6 TeV, and technical limitations such as beam-induced backgrounds or neutrino dose have not been studied in detail at higher energies.
- **Radiological impact** – The radiological impact on the environment should be studied at both 3 TeV and 10 TeV. The 3 TeV stage, based on MAP studies, is not expected to exceed public exposure limits. By contrast, at 10 TeV or more the situation should be studied to confirm its compatibility with legal requirements, or, if required, techniques devised to reduce or mitigate the impact .
- **Technology impact** – Beyond the interest of the HEP community for the physics case of a muon collider, the technologies that are crucial to its success are directly related to advances in other fields of scientific and societal applications. As an example, developed in detail later (impact), the HTS superconducting solenoids for a muon collider resemble very closely ultra-high-field NMR magnets (life science application), magnets for high-field science (solid-state, material and life science applications), and magnets for fusion (energy applications). Research on technology relevant to a muon collider can hence be conducive to significant advances in other fields.

Sustainability Motivations

Another important motivation for MuCol is the possibility that the next collider might have a size only slightly larger than the present LHC, both in terms of land use and of energy consumption. This stems directly from the fact that muons can be accelerated to high energy in a circular collider, because of their sizeable mass, and that the center of mass energy is fully available to produce clean events. The first consequence of these two properties is that a muon collider has the smallest footprint with respect to alternatives with comparable physics reach. The largest circular muon collider, for E_{CM} of 10 TeV, will have a diameter of approximately 10 km, to be compared with about 30 km diameter for the FCC and 50 km linear length for the 3 TeV CLIC. The second implication of the above properties is that the electricity consumption is expected to be significantly lower than alternatives. Moreover, several machines in the layout will be pulsed, with a low power consumption. For this reason MuCol will also simulate and design powering systems to demonstrate that these potential advantages can be capitalised in a low consumption complex, resulting in a concrete advantage with respect to comparable alternatives. MuCol will aim at estimating with more precision the energy consumption based on defined technological choices, and provide paths for optimization, for instance with studies on Energy Storage Systems that may accumulate energy during the pulse of the machines of the complex and give it back when necessary, thus reducing dramatically the energy pulled from the network. Energy performance over the operating lifetime will be established as one of the main design criteria.

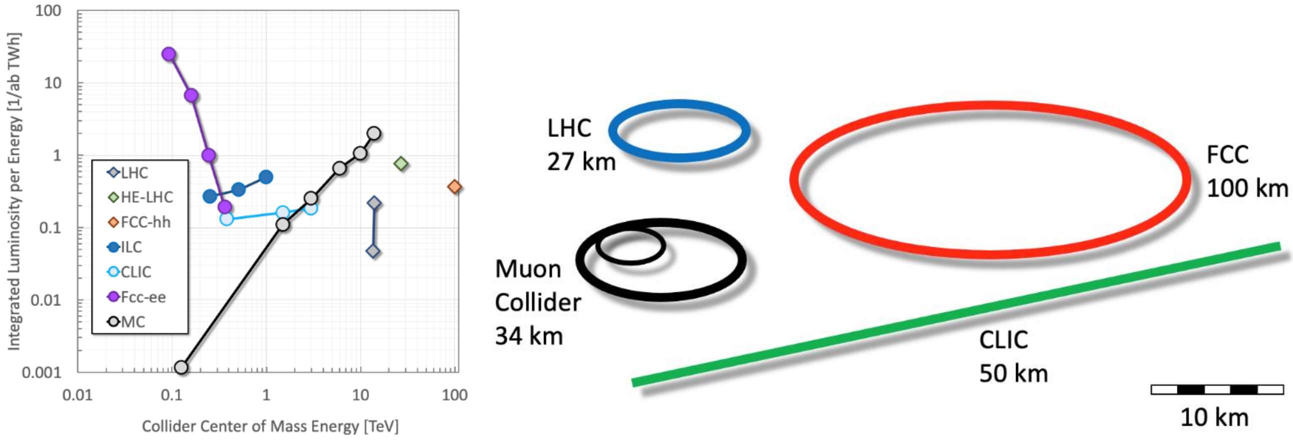

Fig. 4 left: Integrated luminosity of several collider options per TWh of energy consumption, as a function of Center of Mass collision energy. Fig. 4 right: comparison of footprint of the muon collider complex, FCC and CLIC. The LHC is shown for comparison

A muon Collider on the CERN site embeds intrinsically the “do not significantly harm” principle as the installations to be built are only slightly larger (20%) than the existing installations used for the LHC programme. It is therefore natural to expect that most of the existing technical infrastructure can be re-used for the project and only a very limited amount of additional installations will need to be added.

Moreover, 70% of CERN’s energy consumption is already produced with sources within the EU taxonomy and CERN plans to be ISO 50001 certified by the end of 2022. This will imply establishing clear resource optimisation and key performance indicators to monitor and optimise the use of resources in general and of electrical power in particular. A Muon Collider facility at CERN will therefore profit of all the measures put in place in the next years to become a fully sustainable Facility.

Synergies

MuCol will explore synergies with other fields of science that may provide further motivations for its construction. Due to its modularity and staging possibility, the muon collider may serve as an ideal platform to associate other facilities such as advanced Neutrino Factories and radioactive beam facilities downstream of the production target. As an example, the present conceptual design of the facility could unfold towards a possible implementation of nuStorm [DOI 10.17181/CERN.FQTB.O8QN]. Target technology challenges are shared with the progress sought in other fields of physics, e.g. neutrino factories, radioactive ion beams and nuclear and neutron physics, as well as for energy applications, e.g. studies of compatibility between liquid metals and metallic containment vessels.

A number of technologies to be developed for a muon collider are directly relevant to other fields of science and societal applications. Progress in high field solenoids bears potential for significant advancement in medical applications, material science and energy applications. Energy optimisation techniques, which are mandatory for a muon collider and included in MuCol, find natural application in any other project requiring large, pulsed power sources, and may profit from or benefit research on energy storage systems (e.g. supercapacitors and batteries).

MuCol plans to identify these prospected synergies, build collaboration links on the subjects identified, and exploit them to leverage the impact of the study.

Financial Plan

MuCol will provide an analysis of the main cost drivers in order to identify R&D topics on which it may be useful to invest to reduce the total cost, and an estimate of the order of magnitude of the cost of the Facility. A complete financial plan however is not in the scope of MuCol, and will be developed and will be developed at the request of CERN Council during the next R&D phase. A good basis for such a financial plan will be the experience on construction of the LHC, that is comparable in size, except for the need to eventually drill two new tunnels for the accelerator and collider ring. The possibility to re-use the LHC tunnel will be explored and will depend on the availability of high field magnets, and on the impact of neutrino flux at the surface. The LHC has been built using CERN’s normal operation budget with a modest amount of in-kind contributions from other regions. A muon Collider at CERN might have to rely on a somewhat higher level of in-kind contribution. This amount however could remain within 20 to 40% of the total, which, resorting to the experience of ESS, is within reach if the next ESPPU provides a clear choice foe European States to invest into it. The remaining 60% to 80% is comparable to the effort done for the construction of the LHC.

1.1.6 Technology Readiness level

MuCol does not address the construction of a single technology or a product, but rather to advance the understanding of how to design such a complex facility, integrating a number of disciplines and technologies. It is therefore difficult, if not inappropriate, to express the progress expected in terms of a unique TRL number. Overall, we can say that we intend to move from a level of Basic principles Observed and Reported, to Proof-of-Concpet validated analytically.

1.2 Methodology

MuCol will be structured as a project, resorting to previous successful experiences in the accelerator community, such as the EuroCirCol and the HI-LUMI projects. For the sake of conciseness, we will not detail here the responsibilities and the roles of each partner, as they are quite standard and similar to other projects. The Governance including the precise definition of all roles in the project, in-kind resources provided by each Institute, publication policies etc… have been discussed among the participants and will be detailed, before the start of the project, in a Consortium Agreement Document that all participants will be required to sign. This kind of organization of the consortium (including a Study leader and a Technical coordinator, an advisory Committee, a Governing Board and a management committee) is quite common in the communities of particle accelerators and particle physics. A sketch of the organization is shown in fig. 1.4.

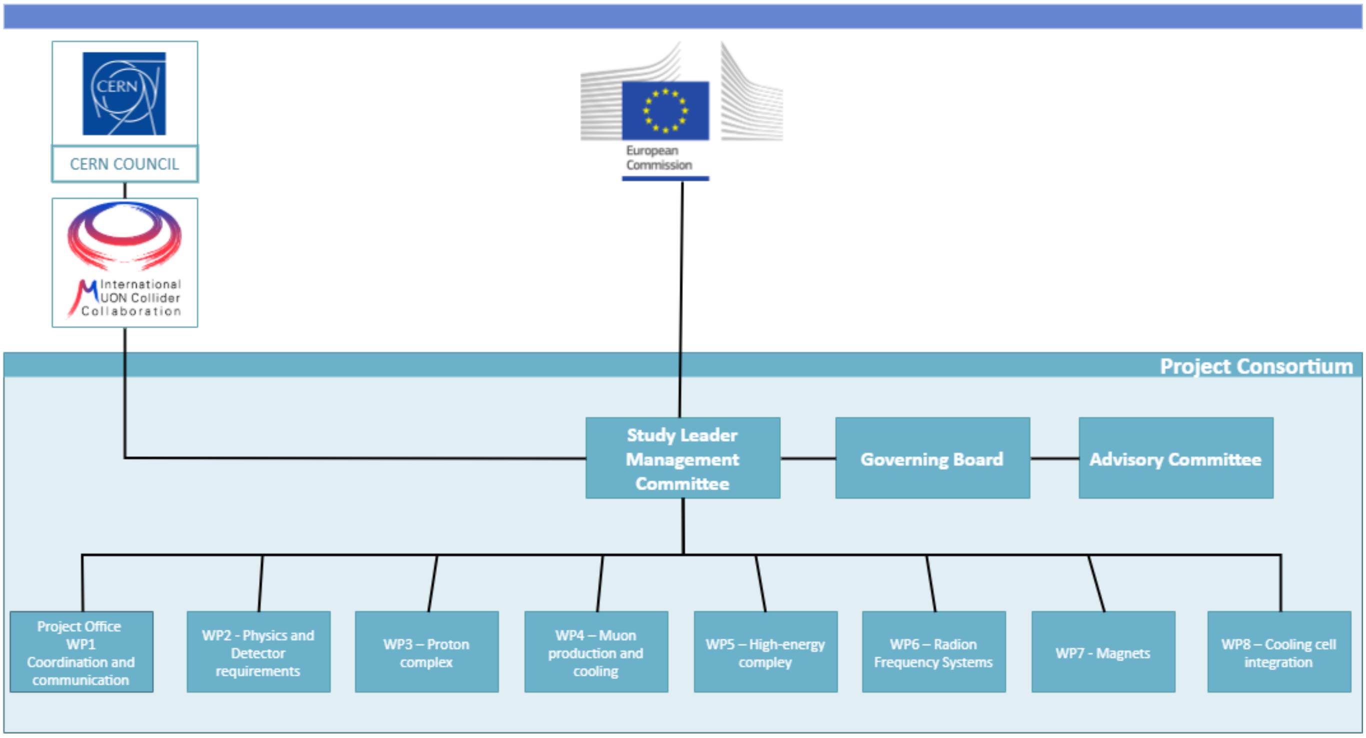

Fig. 5: Organisation of MuCol

The activities are grouped in work-packages, with the first one dedicated to coordination and communication activities, that have an important role in such a large consortium and with the variety of activities to be developed. Scientific and Technical activities in each work package have been specifically selected to address the challenges that are most critical to the feasibility of a muon collider, based on the analysis performed within the scope of the European Accelerator R&D Roadmap exercise [https://arxiv.org/abs/2201.07895], endorsed by CERN Council on behalf of its member States. This document clearly defines prioritised R&D scenarios. The medium term goal (five years, by the next ESPPU) is to provide the elements required by the European particle physics community, the CERN Council as well as other funding agencies to make informed choices on the future direction of HEP. The MuCol study inscribes itself perfectly and seamlessly in this process, and shall make key contributions to the implementation of the R&D in the Roadmap by delivering a Muon Collider Assessment Report (D1.3 of WP1).

The MuCol study described in this proposal will also be an integral part of the effort of the International Muon Collider Collaboration, hosted at CERN. MuCol is key to encourage and support participation of European Institutes to the collaborative efforts, allowing them to take responsibility for key parts of the collider design. This empowering process will build critical know-how at all participating parties, it will give them impact on the decisions within the scope of the International Muon Collider Collaboration, as well as the next ESPPU process. Finally, also of paramount importance, MuCol will prepare the future of all participating institutes by forming them in a solid community, ready for the design and construction of a future collider.

In the following we will clarify the scientific and technical measures, the methods as well as the organisation that we will adopt to achieve the objectives and unfold the potential mentioned in the previous paragraph.

Overall approach and structure

Core challenges and Interdisciplinarity

We list below the key challenges for the muon collider identified and prioritized in the European Accelerator R&D Roadmap. They have been retained as high-priority in the R&D Roadmap process, as they may limit the performance or drive the cost, power consumption and risk. MuCol will address the core challenges, identified explicitly below:

- The **production of a high-charge, high-quality muon beam**, which is required to achieve the desired luminosity. Optimisation of the cooling process and close integration of the technical components are required to reach the performance goal, while maintaining low power consumption and cost. The performance of the source also impacts the design of the high-energy part of the collider complex. Particular challenges addressed in MuCol are:
  - The *production of high-charge proton beams*, combining a very large number of protons into the short pulses required for the muon production.
  - The *effect of proton beam impact* on the pion production target and the *effect of hadronic showers on the surrounding solenoid*, as a consequence of the production of high charge muon beams.
  - The achievement of small final beam emittance in the muon beam ionisation cooling system.
- The **collider ring and the acceleration system** that follows the muon cooling can limit the energy reach. These systems have never been studied for 10 TeV or higher energy. The collider ring design impacts the neutrino flux and the background to the detectors. Particular challenges addressed in MuCol are:
  - The *cost and power effective muon beams acceleration*, in particular in the RCSs.
  - The *design of the collider ring*, and in particular the focusing of the beam in the collision point to obtain high luminosity.
  - The *impact of muon beam decay and loss* on the facility, in particular for the collider ring.
  - Intensity dependent *collective effects* of the beam can create bottlenecks in the design of the complex that need to be mitigated and could potentially lead to important cost increase or performance loss.
- The **Machine Detector Interface** (MDI) might limit the physics reach due to beam-induced background, and the detector and machine need to be simultaneously optimised. These issues will be addressed integrally in MuCol.
- **The environmental impact**. The foreseen methods to reduce the impacts of the **neutrino flux** to negligible levels have to be verified. Other aspects that will be studied in MuCol are the overall collider footprint and required power, mandatory information towards a **sustainable science** case. Other site dependent studies, such the geology of the site, will not be addressed by MuCol, but will be conducted by CERN within the framework of the International Collaboration.

MuCol will finally put the accent on the availability of the core technologies, and the required R&D that will enable meeting the challenges. The magnet and RF technologies are the most important drivers of performance, cost and power consumption. Their tight integration in the muon cooling cell is unprecedented and needs dedicated studies.

Workpackages

To address the core challenges, MuCol has to draw from a wide spectrum of different competences and closely integrate them. The work is organised in seven technical workpackages to cover the physics requirements (WP2), the accelerator chain (WP3, WP4, WP5) and the most critical technologies (WP6, WP7, WP8):

- **WP2: Physics and Detector Requirements** provides the link to the physics and detector studies. It will make available a database with Beam-Induced Background (BIB) to the physics community and maintain a simplified model of the detector for physics studies. Based on feedback from the physics community, it will provide feedback and guidance to the accelerator design.
- **WP3: The Proton Complex** will address the key challenge of the accumulation of the protons in very high-

charge bunches, by addressing in details the proton complex design, and will provide the basic parameters of the complex and the characteristics of the beam impacting on the production target.

- **WP4: The Muon Production and Cooling** will address the production of the muons by the proton beam hitting a target and the subsequent cooling, including some of the specific technologies, such as for the production target and the absorbers that reduce the beam phase space volume.
- **WP5: The High-energy Complex** will study the acceleration and collision complex of the muons.
- **WP6: Radio Frequency Systems** will address the Radio Frequency (RF) systems of the muon cooling ensuring coherence in frequency choice and synchronization among the various stages. It will contribute to sustainability studies by studying high efficiency RF Power sources.
- **WP7: Magnet Systems** will establish a complete inventory of the necessary magnets to optimize and standardise the design, and address the most critical ones. In particular it will focus on the solenoids of the muon production and cooling, which are specific to the muon collider, and the fast-ramping magnet system, which have ambitious requirements on power flow and power efficiency and limits the energy reach of the collider.
- **WP8: Cooling Cell Integration** will address the design of the muon cooling cell, which is a unique and novel design and which faces integration challenges.

These workpackages will closely interact to face the core challenges of the muon collider concept. In particular all WPleaders, and as required task leaders, will be invited regularly to participate in a Management Committee to exchange information and specifications, will have to report on the advancement of the work and will receive clear actions to implement. We show below a schematic representation of the grouping of the technical workpackages, their inter-relation, while the overall coordination will be provided by **WP1: Coordination and Communication**.

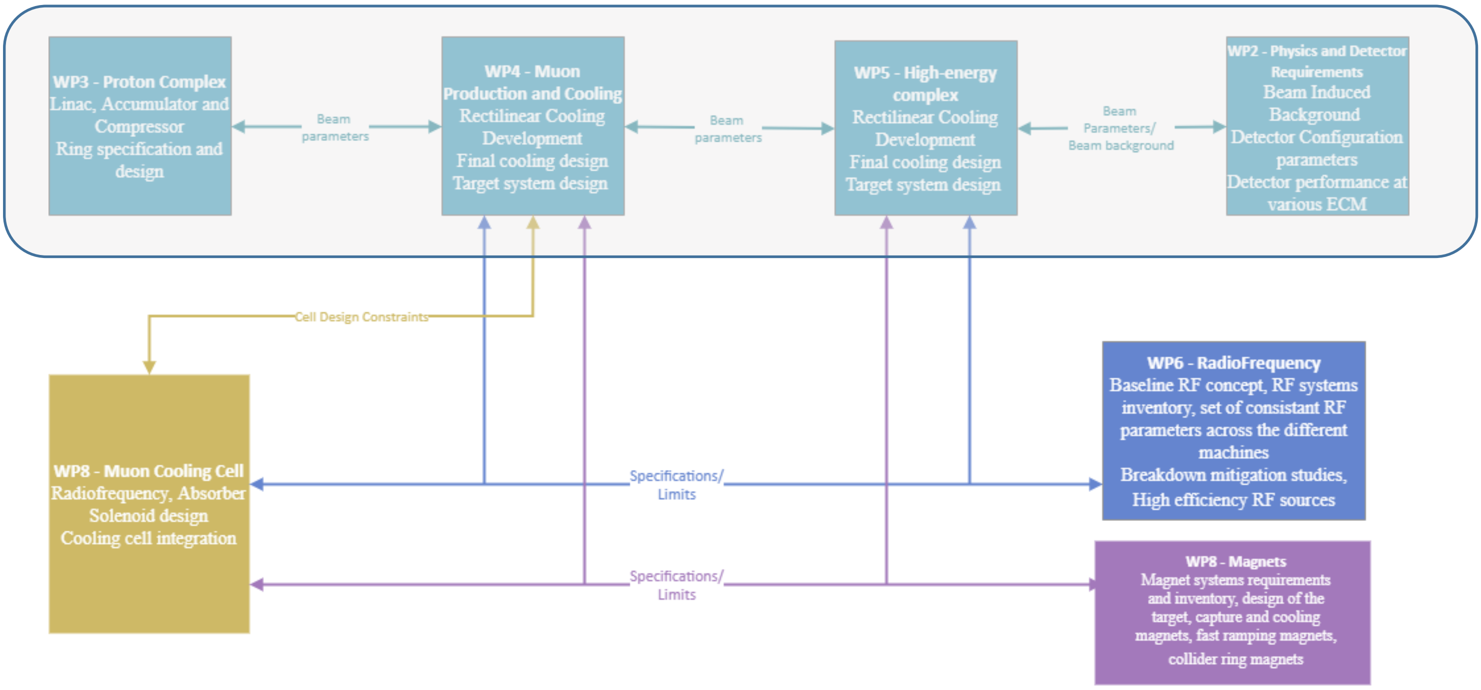

Fig. 6: Simplified diagram of interactions among WorkPackages

Below we detail the Responsibility Assignment Matrix of the project, showing how the single core challenges will be addressed jointly by the workpackages. The close integration is an important element of novelty introduced by MuCol in the study of feasibility of a muon collider. We show in Fig. 7 how the workpackages address the core challenges, and through which challenge they will be required to interact and integrate results.

In the following paragraphs we provide a more detailed description of the challenges and the methodology to address them.

High-charge Proton Beam Production

The proton complex has to deliver a high-power beam consisting of a few short pulses (O(1ns)) per second in order to produce a sufficiently large number of muons. The compression of the large number of protons (O(10^{15}))

into the short pulses is unprecedented. WP3 will develop a design for the combination and evaluate the limit arising from the repelling force between the protons. This has direct impact on the muon production, taken as input for the work of WP4.

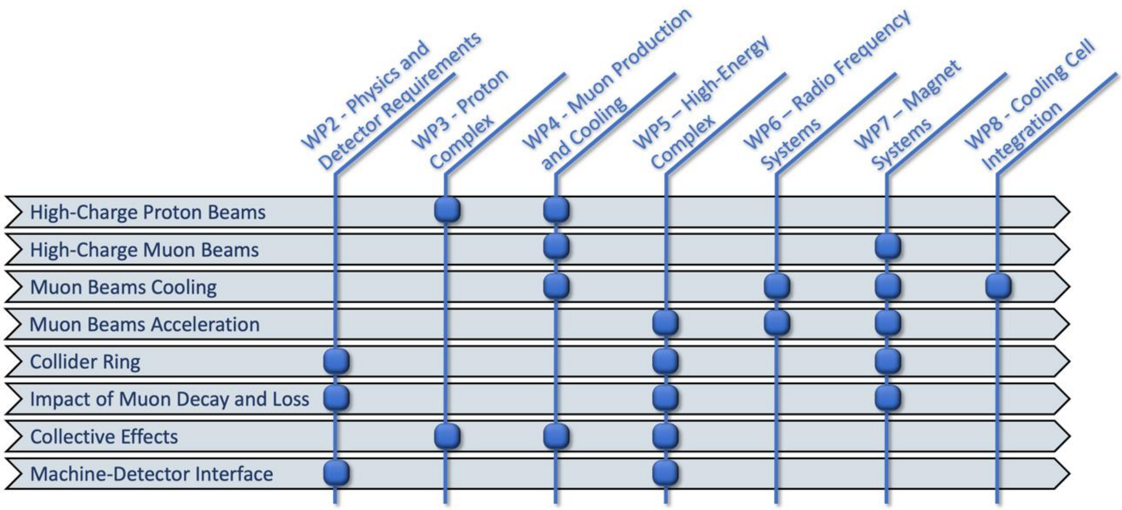

Fig. 7: Responsibility Assignment Matrix

High-charge Muon Beam Production

The proton beam will be sent into a target where it produces pions, which decay into muons. These are then compressed into a bunch. The proton target is beyond the state of the art, with an anticipated power of 2 MW. The beam consists of 5 pulses of about one ns and 400 kJ each and will induce shock waves in the target, lead to strong heating and, in the long run, induce radiation damage. WP4 will assess the performance of different target technology options, including graphite and fluidised tungsten, and determine the most promising solutions. The target is embedded in a high-field hybrid resistive and superconducting solenoid to efficiently collect the produced pions. The proton beam produces hadronic showers in the target that irradiate the solenoid. This is mitigated, in the MAP approach, by using a large aperture superconducting solenoid (O(1 m) radius) that allows to place nuclear shielding inside. The combination of high field and large aperture results in mechanical stresses that limit the performance of the superconductor. The second performance limit is the considerable amount of radiation leaking through the shield, and deposited in the coil, affecting radiation sensitive components (e.g. resins) as well as the cryogenic power and operation costs. WP4 and WP7 will evaluate the radiation, shielding and magnet design, and develop an overall configuration that balances the different requirements. Both existing (LTS) and emerging (HTS) magnet technology will be considered in this evaluation, possibly taking advantage from the energy efficiency associated with an operation temperature higher than liquid helium. Concerning the target, Studies will benefit of the recent studies in the HiRadMat facility at CERN where different materials are exposed to intense pulsed beams of protons at 400 GeV to benchmark dynamic and hydrodynamic codes for the simulation of energy deposition and instantaneous heating generating shock waves in the materials.

Muon Beam Ionisation Cooling

Even with a high muon flux, the beam must be tightly focused at the interaction point in the collider. To reach the desired luminosity, the volume of the beam in position and momentum space, known as beam emittance, must be reduced by five orders of magnitude. Ionisation cooling is the technique proposed to reduce the muon beam emittance. This consists in continuously decelerate and re-accelerate the muons in a linac consisting of tightly integrated superconducting solenoids, normal-conducting RF systems, absorbers and other components. The initial parts of the system are optimised to transport the initially large, diffuse beam, while the final parts of the system are optimised for small emittance yielding a high brightness, extremely short pulse of muons. The ionisation cooling is a novel concept and unique to muons. No previous experience with cooling an intense beam of muons exist. To prove that the concept delivers the required emittance, WP4 will explore performance and study limits of compact lattices, containing high-gradient RF cavities, studied in detail by WP6, and tightly focusing high field solenoids, studied in WP7. The integration of RF, Magnets and absorbers will be studied and modelled in WP8. A design for such a lattice was shown by MAP to almost reach the required performance (about a factor 2 was missing). Since the end of MAP, advances have been made in RF and magnet technology that suggest that the lattice design can be significantly improved. Specifically, WP6 will investigate the compatibility of the required high gradients and high magnetic fields, and mitigation measures to improve RF performance, such has cryogenically cooled resistive cavities. On the side of WP7, the recent successes in HTS magnet technology applied to user facilities and commercial NMR systems have greatly enlarged the landscape. WP7 will provide a realistic evaluation of performance limits and perspectives to go beyond the state of the art to feed the cooling lattice optimization. WP8 will consider the fully engineered integration of a complete cooling cell, providing crucial feedback on the single technology workpackages on matter such as required structures, access for services such as vacuum, powering and cooling, the necessity of thermal barriers, clearances for assembly and operation. These inputs will be the technology basis of the overall assessment and optimization of the rectilinear muon cooling system, done within WP4.

Cost and Power-effective Muon Beam Acceleration

After cooling, the muons have to be rapidly accelerated to full energy before they are injected into the collider ring to limit the fraction of the beam that is lost. The lion share of this acceleration is performed in the RCSs, which have a critical impact on the cost, performance and power consumption of the complex and are a main limitation of the energy reach. The design of the RCSs requires close integration of the optics design and the two technology components, the accelerating RF systems and the fast-ramping magnet system, as they impact each other. WP5, WP6 and WP7 will closely collaborate to design the RCS.

The currently proposed RCS design consists of cells that combine a sequence of fast-ramping normal-conductive magnets and static superconducting magnets. The superconducting magnets bend the beam to the inside of the ring. The fast-raping magnets are used to adjust the bending force of the cell to the increasing beam energy. When the beam is injected they are powered to bend the beam to the outside canceling most of the bending force of the superconducting magnets. While the beam energy is increasing by acceleration these magnets are ramped down and then up with the opposite magnetic field to increase the bending force of the cells. This system halves the amount of fast-ramping magnets required but lead to a challenging optics design to mitigate the impact of the path length and position changes during the ramp. WP5 will design the optics and devise the solutions to compensate the orbit changes. It will identify the ratio between injection and extraction energy that can be achieved in each ring.

The fast-ramping dipoles in these rings store a large magnetic energy, which needs to be rapidly extracted and re-injected several times per second. The total peak power flow into and from the fast-ramping dipoles is of the order of tens of GW and the average power of the order of GW; it is critical to minimise the losses associated with this power flow and to recover the magnetic energy almost completely to avoid excessive power use. WP7 will develop efficient magnet and power converter concepts to achieve this goal.

Each muon beam pulse consists of one short high-charge bunch to obtain high luminosity. When it passes through the RF cavities in the acceleration complex it extracts a significant fraction of the energy in the cavity and induces important parasitic fields, so-called wakefields. Both effects have to be mitigated to ensure the preservation of the beam quality that is essential for the luminosity. WP5 and WP6 will address this together.

Collider Ring

WP5 will be responsible to create a consistent optics for the 10 TeV collider. Compared to the MAP study at 3 TeV, the higher beam energy makes the ring significantly more challenging. This is especially true for the focusing system at the collision point, which may actually limit the energy reach of the collider. A concept for the interaction region is required to establish the validity of the 10 TeV design, including the interface to the experiments and measures to reduce background, in collaboration with WP2, as well as limits for magnet performance, with WP7. Neutrino flux from muons decay is one of the major issues identified for a muon collider. WP5 will devise configuration to minimize the effects, including an evaluation of energy and radiation dose, which affects the required shielding and aperture of the collider magnets. Based on the results of WP5, WP7 will consider magnet configurations compatible with the aperture request (e.g. stress-managed) and heat removal (e.g. open midplane).

Impact of Muon Beam Decay and Loss

During the acceleration and in particular in the collider ring muons decay into two neutrinos and an electron or positron, depending on the charge of the muon. The electrons and positrons carry on average one third of the muon energy and will be lost inside of the ring. This is particularly critical in the collider ring since one lets the muons circulate until the largest part has decayed. The superconducting magnets of the ring have to be shielded from the losses, which requires larger aperture; this in turn limits the magnetic field due to stress. In addition, the removal of the heat through a cryogenic plant is one of largest power consumers of the collider. Workpackages 5 and 7 will address this challenge and iterate on the design to find the optimum solution. The shielding must fulfill different purposes, like preventing beam-induced quenches, reducing the thermal load to the cryogenic system, and avoiding magnet failures due to the cumulative dose in insulators and atomic displacements in superconductors.

The work will use simulation tools that are well established in the community (e.g. BDSIM, MADx, FLUKA, GEANT4 etc…). It is anticipated that extensions to those tools will be necessary in some cases. Where applicable, new models will be made available to the community through the mechanisms of the Open Access policy of CERN. Input files for simulations will be stored in public repositories such as the CERN Github.

Collective Effects

Collective effects can create important bottlenecks along the collider, in particular in view of the very large bunch charge, that is about one order of magnitude above the one planned for HL-LHC. Particular concerns are the impedance effects arising from the wall around the beam and from the accelerating cavities, that need to be simulated and the performance of mitigation methods needs to be assessed. Important parameters for the facility such as the aperture of the beam pipe and the choice of cavity frequency and design will be impacted by those results. The beam pipe size will feed back into the aperture of the magnets. This has an important impact on the magnetic energy in the fast-ramping magnets and drive the cost and power consumption of these systems. It also drives the aperture of the collider ring magnets, combined with the shielding needs, and thus the stress in these magnets, their main challenge. We will assess collective effects as part of the machine workpackages (WP3 3, WP4 4 and WP5)

Machine-detector Interface

A multi-TeV Muon Collider needs to deliver high instantaneous luminosity to be able to exploit the diverse physics potential opportunities. To reach this goal high intense muon beams, with about $2x10^{12}$ muons per bunch, are necessary. A fraction of the muons continually decay, each producing two neutrinos and a high-energy electron or positron. The latter will be lost at the aperture of the beam guiding magnets and produce showers of secondaries and tertiaries. At the Interaction Point (IP), where the two muon bunches collide, these showers produce Beam-Induced Background (BIB). The flux of these particles is very high, at 10 TeV about 50,000 muons per meter decay per beam passage. Hence the background can strongly affect the detector performance and needs to be efficiently mitigated. The current solution, initially proposed by MAP, consists of two tungsten cone-shaped shielding (nozzles) around the beampipe, with the origin in proximity of the interaction point, to be accurately designed and optimized for each specific beam energy. In addition a robust detector with high granularity and good time resolution will be designed to cut in the time and direction of the tracks to further suppress the background.

Figure 8 illustrates the current design of the IR at $\sqrt{S} = 1.5$ TeV with the nozzles (green conical shape) entering the detector represented here by a cylindrical black box.

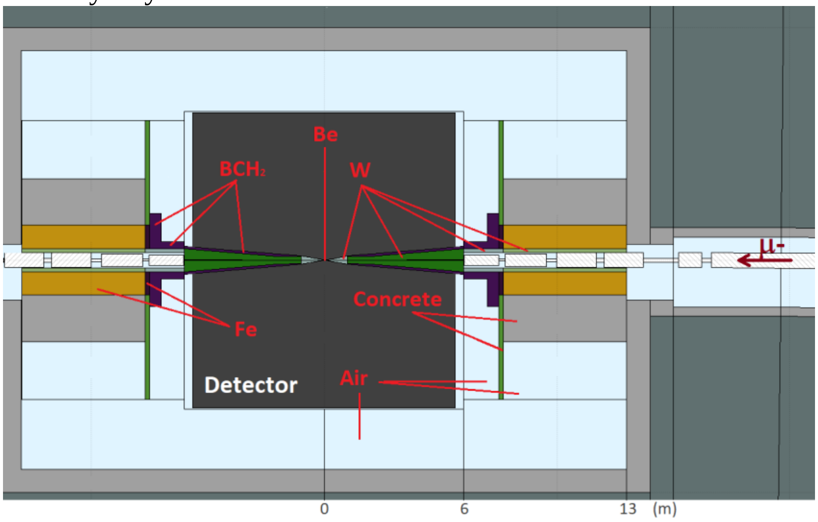

*Figure 8: Interaction region layout with the the passive elements labels. In green the two nozzles connected to the beam-pipe. Figure from JINST **16** P11009, 2021*

Workpackage 2 will assess whether the physics potential of a Muon Collider at 10 TeV center-of-mass energy can be realised with a proper detector design. As a starting point and also as a basis to understand the scaling with energy, it will study the 3 TeV configuration for which initial IR designs exist.

WP2 will provide performance specifications for detectors at 3 TeV and 10 TeV center-of-mass energies and determine its performance by assessing its sensitivity to major physics processes beyond the Standard Model and precision Standard Model measurements.

The activities will be developed in three tasks, focusing on different aspects. The effects of the beam-induced background - one of the main challenges in detector design - will be studied comparing different configurations of the interaction region (IR) and shielding around it. The studies will proceed in close collaboration with WP5, (high energy complex)), which will provide time-dependent distributions of beam-induced background particles entering the detector envelope. These distributions will then be propagated into the detector components and studied in detail. Feedback will be given to WP5, where experts will modify the IR configuration to optimise the beam-induced background level and the shielding volume. The process will continue iteratively until an effective compromise is found. The final data will be made available by using an appropriate format and location depending on the size..

At the same time, new algorithms for event reconstruction in each sub-detector will be developed by exploiting 5D event reconstruction - including 3D position, time and energy information - in order to mitigate the effect of the irreducible beam-induced background. Events produced by the primary muon interactions will be overlaid with the machine background to have a realistic description of the detector performance. State of the art machine learning algorithms will be used as base for the algorithms leveraging on the large experience the group has developed on the LHC experiments. Finally, the detector and algorithms performance will be determined by measuring the reach on the most challenging physics cases. Standard Model precision measurements and New Physics searches with discovery potential will be evaluated. The results will be used to define a simplified detector performance model in the form of a DELPHES card or/and similarly, which will be made publicly available on the project web site and continuously updated as new studies will be available. This format allows a wider community to study the impact of the detector on the physics performance in a simplified and slightly approximated fashion, without having to resort to full detector simulations taking into account also the effect of the beam-induced background.

The beam-induced background generation will be performed with a dedicated software package (FLUKA). The detector simulation and event reconstruction will be done by exploiting the ILCSoft package which is based on GEANT. The software used to simulate detector response and the reconstruction algorithms will be publicly available on the CERN github.

Core technologies

Significant progress in the muon collider will be possible only by advancing accelerator technology well beyond state of the art. MuCol puts a strong emphasis on this, dedicating three workpackages to RF (WP6), magnets (WP7) and the ionisation cooling cell (WP8).

The main challenges for the **RF system** that are addressed in WP6 are the effect of a large background magnetic field, efficient high-power klystrons, and effective energy transfer to the beam. The RF system of the muon ionisation cooling is integrated into the strong magnetic field of the solenoids that surrounds the absorbers and guide the beam. The magnetic field strongly increases the tendency to RF breakdown, which limits the cavity electric field. This is due to the effect of magnetic field on the electrons emitted at one location on the cavity surface, which may be focussed in their trajectory and cause local damage at the cavity surface. Two approaches have been tested to mitigate this effect: using beryllium instead of copper, less prone to damage, and filling the cavity with high pressure gas, limiting the energy gain of the electrons. WP6 will develop theoretical models to improve our capability to predict the effect and devise an experimental strategy to verify the theory. The normal-conducting cavities of the muon cooling system need to be filled with short high-power RF power pulses to avoid excessive power losses in the walls. This requires cost effective and efficient high-power klystrons. WP6 will develop the concept of these klystrons to minimise the cost and establish realistic performance targets. The RF system in the RCS is an important factor for the design of the ring and for the cost and power consumption of the facility. Currently, superconducting cavities are the baseline to accelerate the beam. Just before the beam arrives, they are filled with energy to establish the accelerating gradient. During each of the repeated passages the beam will extract a fraction of the energy, which is refilled by the next passage. Once the beam has been accelerated, the energy in the cavity will be dumped. For efficient operation one has to maximise the fraction of the energy in the cavity that is extracted by the beam compared to the energy that is required to establish the field, while maintaining the beam quality. In addition, the beam generates unwanted fields that can lead to instabilities.

The **magnets** required for a muon collider, within the scope of WP7, span a very broad range of technologies, from ultra-high field superconducting solenoids to very fast resistive pulsed dipoles and quadrupoles. They are grouped in WP7 by complex. The target and cooling area magnets are solenoids, where we will profit from advances in HTS technology. We will study HTS based options priming a reduction in size and power consumption, and an increase in field performance. A HTS target solenoid could produce the desired field requiring less shield and operating at temperature higher than liquid helium, i.e. improved energy efficiency. For the final cooling, where the objective is maximum bore field, we will consider magnet designs either based on cables, or using the novel partial-insulation technique, so to extend the present reach of HTS solenoids from 32 T (user facility), beyond 45.5 T (present highest field reached in an HTS winding), aiming at the 60 T target required to reach the emittance specification. Accelerator magnets will be designed as an integrated effort with energy storage and power management, striving for a true system optimum. The goal is to achieve the highest practical field performance and ramp quality at minimum stored magnetic energy, so to reduce the overall energy storage and power flow. HTS windings will be studied as an alternative, mainly to see whether it could be possible to increase the field swing, thus at the same time reducing the accelerator dimension and stored energy, and increasing the useful lifetime of the muons. Finally, the collider magnets will profit from synergy with the recently initiated EU High Field Magnet R&D Program (HFM), and the on-going US Magnet Development Program (US-MDP). HFM and US-MDP are considering stress management concepts for Nb3Sn magnets, as well as HTS dipole magnets for accelerators. MuCol WP7 will profit from these developments, focusing on specific designs and features, based on LTS and HTS, meeting the muon collider specifications. Of particular importance for the collider magnets will be energy deposition and radiation dose. WP6 will seek and design geometry and material alternatives that could minimize the heat load (e.g. open midplane) and maximise lifetime (e.g. rad-hard insulation).

The **ionization cooling cells**, which are the object of WP8, are unique to the muon collider and have never been designed. They pose specific challenges not only for the components but also for the integration. The cells have to be compact to minimise the length and the muon decay rate. They have to tightly integrate superconducting solenoids with normal-conducting RF, absorbers, beam instrumentation and auxiliary system, such as vacuum and cryogenics. The MAP study did not produce a detailed cooling cell design that is required to identify and mitigate limitations arising from the integration. WP8 will develop a full design of a representative cooling cell. It will investigate the state of the art for the components, select the most promising technologies for each component, and then cooperate to build a full 3D technical model of a cell. Phenomena such as increased breakdown in RF cavities, radiation load to superconducting solenoids, extreme energy deposition in absorber materials and vacuum windows will be taken into account to mitigate the risk that they may limit the performance of such a system. The participants will study the available literature on the subject, and provide new simulations and a full 3D mechanical model designed using CATIA or Inventor to confirm the feasibility. Reduced scale plastic models will be produced by additive manufacturing to double check the mechanical integration

Implementation Scenarios

The cost and power drivers of the facility will be identified and the cost and power scale be determined. We will assess whether a muon collider could be implemented at CERN considering environmental and geological factors. A scenario with a staged implementation will be considered with particular emphasis on minimising the time between the end of HL-LHC and the first stage. The required R&D path toward the construction of the collider will be laid out.

Gender dimension

MuCol will not involve any research linked to the gender dimension. The promotion of gender balance is a constant preoccupation of the High Energy physics community and will be promoted as well in this project, both from the point of view of hiring of students and in the different management and scientific bodies.

Concretely, a ***Gender Advisor*** will be appointed among the participants to enforce gender equality. She/He will regularly report to the Collaboration Board and will be available to the Participating Institutes of MuCol and to all the staff members and the students for suggestions and confidential contacts. The Gender Advisor will remain in contact with social services of the participating Institutes, in particular at CERN, to address eventual issues arising in the project. The presence of family services inside the main hosting laboratories (housing, kindergarten, summer camps for children, recreation services) will provide all personnel with the same opportunities for travelling, will reduce the impact of family duties on careers and will improve the work/life balance. On the Communication and Outreach side, particular attention will be dedicated to events aiming to attract young women to STEM careers.

Open Science and Data Management

MuCol brings together a diverse range of institutions and researchers who will produce research products of different complexity, sizes, formats serving different research communities and of course the public. Participating researchers are already practicing Open Science in their daily routine building on decades of Open Science experience in High-Energy Physics. CERN, a global leader in Open Science, is coordinating the consortium and, by autumn 2022, will publish its institutional Open Science policy (OSP). This will gather the already published Open Access and Open Data policies, and will have paragraphs related to Open Source Software, Open Hardware, Research Integrity and Reproducibility, Citizen Science and Research Assessment - as well as Training and Outreach. Once published, the CERN's OSP, that collects also input from other European institution, will become the de-facto standard for Open Science in the field of High Energy and Accelerator Physics.

MuCol will build by M6 its Data Management Plan on CERN OSP and taking into account the diversity of the different participating Institutes, uniting the Muon Collider community to further its Open Science practices with the goal to maximize the impact of its research/project outputs.

As part of the proposal a thorough identification of expected outputs is already considered, e.g. data and public reports will be released with the appropriate open science and FAIR practices for those.

2. Impact

MuCol will assess whether the muon collider is a viable option by the next ESPPU. So far, all the approaches to a future ESFRI in particle physics were based on the improvement of previously employed concepts: linear and circular electron-positron colliders as well as circular hadron colliders. The muon collider is a novel concept, such an infrastructure has never been realised up to date. It promises a path to lepton collision energies well beyond other particles accelerator and combines the precision of a lepton collider with a discovery potential associated with future hadron colliders. Hence it presents a disruption option where the presently high risk is balanced by the high benefit for the field.

This project lays the groundwork for a new ESFRI infrastructure proposal on a multi-TeV muon collider facility.

MuCol will develop concepts of the key collider systems that are based on realistic performance targets for the technologies and allow estimation of the physics capabilities through simulation studies. It will advance the understanding of the whole infrastructure, including the muon collider complex and the detector operations with the new accelerator well beyond the present state of the art. MuCol will reach a status where the facility is expected to deliver the desired physics outcome, the most important-challenges have been identified, and either solutions are proposed, or the necessary R&D is defined. The main **requirements and potential barriers** are centered around the fact MuCol requires the availability of a solid team of experts to address challenges in beam physics, in accelerator engineering and in detector design, not only to build on past experience, but also to guide young researchers towards the solution of complex problems of accelerator and detector physics.

Through its activities, MuCol will have significant impact on three of the outcomes defined in the scope of this call.

- **The future of a new ESFRI Infrastructure** – The study will establish a path to mitigate critical risks in the muon collider facility and support a robust assessment of cost, risk and performance, enabling it to be proposed as the next ESFRI infrastructure in particle physics at the energy frontier. In particular an initial stage with a centre-of-mass energy around 3 TeV could be constructed after the planned end of HL-LHC operations in the 2040s. The results of the MuCol study will be the foundation for an informed decision.

- **Aligning the scientific landscape** –The 2020 ESPPU identified several potential facilities for further R&D, including various options for electron positron colliders and a future very large proton-proton collider, however a decision on the construction of the future facility is expected to take place at the next exercise in 2026-2027. If the muon collider were shown to be a viable route for particle physics, MuCol would dramatically change the decision landscape.

- **A strong technology drive** – The MuCol study will identify and evaluate challenges that go clearly beyond the state of the art in most of the domains of accelerator physics and technology and detectors development. Several of these challenges are shared with other research areas like medicine, material science, life sciences, and energy. The richness of these connections makes MuCol particularly attractive, especially because a direct impact on the ability to tackle scientific and societal challenges can be expected already on the scale of the technology R&D, rather than on the longer time scale of facility construction and operation.

In the next section we describe how we address the above outcomes.

2.1 Project's pathways towards impact *[e.g. 4 pages]*

The future of a new ESFRI Infrastructure

MuCol will deliver a preliminary assessment report at the start of the next ESPPU process, foreseen in 2026, and contribute to the final report for the executive strategy decisions, to be endorsed by CERN Council in 2027.

The ambition of MuCol is to develop the concept to a level that allows the physicists' community and the funding agencies to make informed decisions. To be confident that the significant challenges of the muon collider can be successfully addressed with a well-defined R&D program . that one can commit to this path toward the next facility

The project is the framework for a well-founded decision-making process with two key elements. Every work package of MuCol is explicitly addressing topics that could not be studied or that have not been studied in detail by previous projects (such as MAP), aiming either at realistic and pragmatic solutions, or identifying the R&D

programme necessary to confirm the hypothesis behind design solutions that go beyond the state of the art. This is witnessed by the workplan, milestones and deliverables identified, strongly linking the WPactivities. The second key element is the integrated approach that we have defined for MuCol, aiming at a coherent and self-consistent baseline design of the whole facility, from physics case to the technology relevant to its construction.

Aligning the landscape

The solid support from the physics community that we are witnessing through the participation of several major institutions active in High Energy physics to MuCol, since its inception, is the path towards a successful completion of the project. Thanks to this wide support, the muon collider has been introduced already in 2020 in the ESPPU, and was identified as a promising alternative to other colliders. MuCol is now part of the ongoing coordinated accelerator R&D in Europe, and it received a strong community support in the Snowmass process in the US.

The analysis of the options for a next collider machine is a complex process, and it involves the world-wide high energy physics community. The result depends on a balance among (i) physics case, (ii) technology readiness, (iii) sustainable science and (iv) societal return. MuCol is the first project being able to quantify on a sound basis each of the four items above, which will be crucial for striking the proper balance in the decision.

The muon collider will be the game changer in the panorama if, as the studies done until now demonstrate, it will prove to be feasible. In the unlikely case the outcome of MuCol should find that a muon collider is not advantageous on a practical scale of time and investment, such result would nonetheless bring crucial elements in a future decision of a next collider, clearing scenarios and options, and thus would help aligning the high energy physics community.

The muon collider could represent the perfect choice for the next accelerator at CERN, giving to Europe the leadership on the energy frontier physics, in case the decision of building an electron-positron collider to be built in China or Japan to study the Higgs properties is taken.

In case no electron-positron collider will be built due to the international scenario, the first phase of the muon collider at low energy (around 3 TeV center-of-mass energy) may be considered as the better alternative. The legacy brought by MuCol will help in keeping the European leadership in the high energy physics research with accelerators.

A strong technology drive

A crucial element of impact for MuCol is the technology fall-out that we expect from the design study. Even if the size of the project will not allow the construction of prototypes or beam facilities that may validate concepts and finalize technologies, the proposed design and limited experimental effort have a definite potential to induce significant responses. We list below the main elements of novelty that could have measurable impact.

The work on the **Proton Complex** (WP3) will provide scenarios to achieve a single, very intense and stable pulse of protons that hits the production target. Although the techniques to achieve this goal are known, beam instabilities at the required intensity remain a challenge. This work has impact and synergies with proton sources for spallation sources for material research and life sciences.

The beam target which is part of the muon production (WP4) is a specific technology item whose challenges and results will be shared with other fields of science, e.g. spallation neutron sources, as well as energy, e.g. liquid metals moderators for fission and breeders for fusion.

Finally, in the domain of **Magnets** (WP7) the proposed conceptual design and R&D bears multiple implications to other fields of science, industrial and societal applications. The superconducting outsert of the target solenoid is in the range of field and geometry relevant for full-body MRI for neuroscience, or solenoid magnets for thermonuclear fusion. In addition, the work proposed here will consider large current HTS cables as an option to wind such solenoid, which bears direct connection and potential impact for the on-going research on compact tokamaks [MIT/CFS]. The ultra-high field solenoids required in the final cooling stage are conceptually similar, but well beyond the performance of present magnets for high-field science [4-6], as well as solenoids for NMR spectroscopy [7]. The challenges to be mastered for a fast-ramped acceleration stage are relevant to the development of rapid cycled synchrotrons for the generation of intense proton beams, for accelerator-driven reactors and transmutation systems [8] and material science, synchrotron for particle therapy applications, as well as nuclear physics. Finally, energy and power management for the fast ramped magnets in the accelerator complex share challenges with energy storage, power conversion and pulse forming networks for high-field pulsed magnets user facilities. In short, conceptual development in any of the magnet systems of a muon collider will bring advances in the above adjacent fields, by providing concepts and design solutions fostering significant progress.

The scale of the impact of MuCol is the largest. The entire worldwide community of Particle Physics will be impacted as only one Facility of this kind will be built in the world.

The significance of the impact is also of the highest relevance on only for the European community, but also for the other regions (US, Asia). If the next European Strategy recommends the Muon Collider as the next Collide on which European States should invest, also the other Regions (US, Asia) will participate, and update their strategy accordingly.

2.2 Measures to maximise impact - Dissemination, exploitation and communication

Scientific dissemination and communication activities will be the main instruments through which the community will build the knowledge basis and foster the approval of a muon collider project in Europe. The main goal will be a plan to inform and engage the wide community over time. MuCol will provide a strong driver within the wider scope of the International Muon Collider Collaboration. This action will generate the required momentum towards the next ESPPU, whose process relies heavily on a bottom-up scientific community approach to reach a consensus on the submitted plans. The same community will play a major role in the **exploitation** of results, and in particular when national groups will lobby at political level to receive support from the national and international funding agencies (e.g. single laboratories and research institutes, scientific councils, ministries, etc…) to endorse the ESPPU.

We also recognize that communication to the general public will be essential throughout the study. The approval of a large project such as a muon collider will have to rely on a solid public acceptance, in recognition of the investment of a significant budget for a scientific project, its return, but also the practical consequences of its construction and exploitation. Moreover we are convinced that it is important to leverage on the synergies identified, not only in terms of science, but also putting the accent on the societal implications such as advance of HTS technology for applications to medicine and energy production.

The plan devised is based on three main pillars:

- **Dissemination and communication of a sound and convincing physics programme** – The first requirement for a successful approval of a muon collider project is that the community of High Energy Physics (HEP) in Europe and beyond must be convinced, based on credible simulation studies and extrapolations, that the physics programme of the Muon Collider is competitive with the alternatives and achievable in a reasonable time frame. Besides scientific publications on the physics case, planned as a result of WP2, the MuCol community plans to participate and present to the major conferences in the field (ICHEP, IPAC) in order to engage an increasingly wider community around the muon collider study. Community meetings, in the form of yearly workshops, are planned during MuCol as an opportunity to communicate and discuss progress and plans., with dedicated funds allocated. The physics case will be also presented to the CERN Scientific Policy Committee, to build political support, and finally the project will take a leading role during the ESPPU process to lead the discussion on muon colliders, providing a convincing proposal document and representation at strategy meetings. **The goal is to achieve recognition in the final document of the ESPPU, with a high level of priority among R&D projects in Europe**.
- **A credible and consistent description of the facility**, from the proton source to the collision regions of the entire accelerator chain, including the devised solutions and a perspective development plan. The goal is to convince that the conceptual design parameters are appropriate to build the facility and run a strong scientific programme in a period of about five to ten years at each energy stage (3 TeV and 10 TeV). A fundamental part of the description shall point to uncertainties and critical issues that are left unresolved, by showing that they are understood, and establishing a credible R&D programme to address them. The MuCol design study, including the facility description and development plan will be internally reviewed at each step and phase by an independent advisory committee of experts in accelerator physics and technology to be established at the beginning of the project. In order to make sure that the design is sound and realistic, recommendations from the advisory committee will be considered in the MuCol reports. The majority of milestones and deliverables in the proposed workplan have scope and content suitable for publication in scientific journals. This will provide a wide scope peer review, and visibility for the work performed within the MuCol design study. In particular, we plan the final report of MuCol to appear as a special issue of a scientific journal to be identified in the course of year 2 of the project. As for the physics case, the achievements of each work package will be presented in general conferences, such as the IPAC series, as well as the yearly workshops planned within the scope of MuCol. Finally, participation and presentation at specialists conferences (e.g. MT, ASC) is planned, to get targeted feedback of the community of accelerator and technology experts.
- **Establish contact with synergic projects and activities** – As we have detailed above, MuCol has strong connection to on-going or perspective developments in other fields of science, medicine, energy and societal applications. We plan to reinforce them by reaching-out to those companion fields, bring the attention to the

case, present progress, and discuss practical terms of collaboration. The work planned within the scope of WP1 involves an analysis of the scientific and technology potential of MuCol beyond the muon collider, and support to participation to conferences and workshops in associated fields such as magnet technology and applied superconductivity, high-field magnet science, radio-frequency, nuclear energy. Once the analysis of WP1 complete, we plan to call for topical workshops within the scope of selected work packages (e.g. Target and cooling, WP4, or Magnets, WP7) joined with participants from other communities. The expected result will be to expose the technology challenges and advances, profiting from a wider knowledge basis, gaining further support from companion communities, and eventually conduct common studies on specific subjects by leveraging on shared interest.

To ensure that the plan is implemented effectively, we will nominate a Dissemination and Communication Officer, chosen among the partners of MuCol and working within the scope of WP1. The Officer will follow the dissemination and communication plan based on the following concrete scientific actions, which are foreseen in the MuCol budget to allow travel to conferences and workshops where the physics case and accelerator design may be presented:

- Participation and presentation to international conferences in particle and accelerator physics (ICHEP, IPAC);
- Organization of yearly community meeting for the whole study, expected duration of one week, with parallel sessions dedicated to each work package;
- Participation to international conferences and workshops in companion fields of science and technology (MT, ASC, SRF);
- Organization of a topical workshops on cross-cutting and companion fields of science and societal applications (i.e. high-field magnet science and NMR applications, energy and power management), promoting joint workshop with the EU project I-FAST on technology R&D, enhancing the industry’s engagement
- Scientific publications from each work package in international, peer reviewed journals, associated with milestone and delivery reports;
- Publication of a special issue on MuCol, in an international journal of relevance in the field.

The scientific community, as well as the general public, will be informed through a dedicate project website, managed by a responsible for communication within MuCol, in charge of preparing posts on social media. This activity will be in collaboration with the outreach services of CERN and other institutions. On top of scientific publications, a communication strategy will be established by the communication officer, to properly advert on the results through social media.

Finally since the next accelerator project will still be a global endeavor, even beyond the LHC, we have invited institutions form outside Europe to be associate members or collaborating institutes, and count on impacting decisional processes outside Europe. The contribution of MuCol to the Snowmass Strategy process in the US is important for the European community in order to remain at the forefront of the development of muon colliders. Should a decision to build a muon collider be taken by other regions (US or Asia), European Institutes will be considered as strategic partners to collaborate on the project. At the same time, should European countries decide to build it at CERN or another site in Europe, communities from other regions may obtain resources to participate to a EU project. Non-European colleagues will help with determining communication means and tools towards communities and at political level as appropriate to their specific processes.

Research data management and management of other research outputs:

The consortium will produce predominantly textual reports for internal and external consumption, as well as presentations in standard formats. As part of WP2, simulated data, the beam-induced background in the detector at different center-of-mas energies, will be produced. Additional simulated data will be used and produced in the consortium as part of WP3, WP4, WP5. The expected size of these datasets is in the range of few terabytes and they will be made available as open data at CERN. WP6, WP7 and WP8 will produce Engineering simulations and mechanical drawings that will be stored in Engineering databases with open access to the muon collider community, and to general public when relevant.

The MuCol research and data outputs will follow the FAIR principles:

Findability of research outputs: public reports will be published via established document repositories, such as the CDS, arXiv, Zenodo and other institutional repositories of consortium partners if needed. Both CDS and Zenodo use persistent identifiers (DOIs) to identify the reports and are considered trusted repositories. Whenever possible, the research outputs will be linked e.g. to an article, further documentation, auxiliary measurements/datasets etc.

Accessibility of research outputs: public reports and presentations will be made available through the repositories and the web sites. Detailed data and documents access provisions will be discussed as part of the Open Science Principles in the Data Management Plan.

Interoperability of research outputs: the repositories currently identified for publishing the research outputs, use standardized metadata schemas (e.g. Datacite Metadata Standard) that enable easy discovery. Whenever possible and applicable, community standards will be used, e.g. to submit data to the HEPData repository.

Reusability of research outputs: the consortium will preserve its assets at CERN, by using the standard and trusted storage facilities and software tools already developed for the LHC machine and experiments. To further the reusability of research outputs, the consortium will aim at linking its research outputs to provide more context to the individual assets, e.g. datasets on HEPdata and articles are linked, software components are linked to datasets or articles as well.

2.3 Summary

KEY ELEMENT OF THE IMPACT SECTION

SPECIFIC NEEDS	EXPECTED RESULTS	D & E & C MEASURES
What are the specific needs that triggered this project?	*What do you expect to generate by the end of the project?*	*What dissemination, exploitation and communication measures will you apply to the results?*
• A comprehensive assessment of the feasibility, benefits, risks, cost and sustainability of a muon collider, requested by the last ESPPU (2020). The assessment will provide the next ESPPU (2026-27) with crucial elements for an informed decision towards the next ESFRI infrastructure for European and worldwide particle physics. • A thorough evaluation of the technical challenges of a muon collider, identified within the Accelerator R&D Roadmap (2022) recently endorsed by CERN Council. Solutions beyond the state-of-the-art are clearly required, and a detailed resource loaded R&D plan towards the muon collider has to be submitted to the next ESPPU.	• A coherent description of the muon collider, a novel particle accelerator complex at the energy frontier, summarized in an assessment report that will be delivered to the next ESPPU for decision on the further steps. • The definition of a core R&D plan, necessary to access the technologies that are critical to a muon collider, and tightly connected to research of relevance for industrial and societal applications (e.g. HTS solenoids for NMR spectroscopy and high magnetic field science). Realizing the potential for a dramatic change in the landscape of high energy physics, allowing down-selection among the present collider options, and providing clear guidance to the community-driven strategy process even in case that the evaluation of feasibility of a muon collider reveals issues beyond present technology reach. • The confirmation that a Muon Collider can be built as a sustainable facility. • Sharing expertise among the participant laboratories and universities, training of young researchers and students, and forming the core team that will take the conceptual design of the facility forwards.	• The assessment and consolidated reports will be disseminated to the science community as part of the European strategy processes and through scientific publication. • Major results will be presented at international conferences. • Workshops will be organised to promote community participation, with sessions devoted to establishing connections and collaborations with companion programs, institutions and industry. • The International Muon Collider Collaboration has direct oversight from major national funding agencies and CERN management, enabling the results to be disseminated to the funding organisations. • Communication to the public will be achieved through the collaboration's website, social media, professional networks, and in liaison with other Accelerator EU programems such as IFAST, and committees like TIARA. CERN's and other Institutes' communication departments will be involved.

TARGET GROUPS	OUTCOMES	IMPACTS
Who will use or further up-take the results of the project? Who will benefit from the results of the project?	*What change do you expect to see after successful dissemination and exploitation of project results to the target group(s)?*	*What are the expected wider scientific, economic and societal effects of the project contributing to the expected impacts outlined in the respective destination in the work programme?*
• The high energy physics and Accelerator physics communities. The key aim of the project is to impact the conclusions of the next Update to the European Strategy for Particle Physics, which is a community-led strategy process. • Decision-making and advisory bodies such as CERN Scientific Policy Committee, CERN Council, the Laboratories Directors Group and the European and International Committees on Future Accelerators will be informed directly. • Technology developments in beam targets, RF and magnet technologies will benefit the accelerator community in general, and will have direct impact on other communities such as high magnetic field science, NMR spectroscopy and MRI, fusion power. • Synergies with other fields of science will impact the communities of Spallation Neutron Sources and Neutrino Physics.	• We expect the high energy physics community to invest in the muon collider, to progress beyond the study proposed here, ultimately leading to construction and exploitation. • To convince CERN member States through CERN Council to recommend a Muon Collider at CERN as the next collider to become an ESFRI • Build a solid and cognizable community in Europe so that EU Institutes can keep a leading role in a muon collider construction project. • Broaden the collaboration scope, enlarging participation to the International Muon Collider Collaboration, and engaging other communities whose expertise and activities are relevant to muon collider technologies .	• The detailed science case, including the understanding of technical risks, will enable the European high-energy physics community to align on a future ESFRI infrastructure at the next European strategy update. Reaching consensus and clarity, also thanks to the outcome of MuCol, will be important to maintain the EU leading role in this field. • MuCol shall point to a way to explore the energy frontier of particle physics in a more sustainable way, with a facility that uses lower power and reduced footprint when compared to other options. We expect savings by approximately a factor two vs. alternatives with equivalent physics reach. • The technologies that will be explored in the scope of MuCol, and in particular ultra-high field HTS magnets, could be directly conducive to significant progress in NMR spectroscopy and high magnetic field material and life science beyond 40 T.

3. Quality and efficiency of the implementation

3.1 Work plan and resources

The Workplan of MuCol is organised in view of providing input on the next Upgrade of the European Strategy for Particle Physics that will occur in years 2026/2027. In this respect the most important milestones are the general reports to be published at the end of 2025 and at the end of the project, the first to be submitted as kick-off information at the start of the ESPPU process, the second will document all the latest studies and will be published before the final decisions.

The first 12 months will be used to set-up the project structure, hire students (most of the budget will be used for postdocs and PhD students), and start the initial training. At the same time expert researchers will explore the available literature and results from MAP and other previous muon accelerator programmes in order to select the most promising configurations/solutions to be studied further. A tentative scenario will be selected at the end by M12, implying that technologies, layouts and tools to be used for detailed studies will be selected.

From month 12 (or earlier in some cases) to month 36 we will conduct a collaborative and iterative process that will involve detailed design of the accelerators, of some of the most critical components, and we will animate an intense exchange among different workpackages that will allow cross-fertilisation of ideas, and will highlight the need of further re-optimisation. During this period a preliminary scenario will be published by M24 and presented in major conferences in the different field in order to receive feedback also from a wider community. Adjacent fields will also be investigated and informed in order to build long lasting collaborations where synergies look promising.

At the end of month 36 we will issue the first general report that will be used as input to the ESPPU (Muon Collider assessment report). The last year will be used to finalise the studies and publish all the results not yet published and to participate to events relevant to the ESPPU process. A final report in the form of an update of the Muon Collider assessment report will be published.

MuCol will be instrumental to train a new generation of young researchers to Muon Collider specificities. Having such a reserve of young motivated researchers, will be a necessary condition to start the next phase of R&D on the muon Collider. This is the reason why we reserved almost 90% of the budget requested to EU for hiring students and young researchers. The infrastructure necessary for the studies (e.g. computing facilities, workshops for any prototyping activities, facilities for tests, some travel budget etc…), will be mostly provided in kind by the participating Institutes. In total we plan to hire about 30 among PhD students and post-doc fellows either on EU funds or on the Institutes funds. All participating Institutes, whether beneficiaries or Associated, will provide in kind the expert researchers to train and guide the students. In total about 1000 PM will be made available by the Institutes, while about 500 PM will be funded by MuCol EU funds for a total of ~1500 PM for the whole MuCol project.

Table 3.1a: List of work packages

WPNo	Work Package Title	Lead Part. No	Lead Part. Short Name	Person-Months	Start Month	End month
1	Coordination and Communication	1	CERN	0	1	48
2	Physics and Detector Requirements	12	UniPD	84	1	48
3	Proton Complex	15	ESS	35	1	48
4	Muon Production & cooling	18	UKRI	72.1	1	48
5	High Energy Complex	2	CEA	36	1	48
6	RF	10	INFN	106	1	48
7	Magnets	1	CERN	129	1	48
8	Cooling cell Integration	11	UMIL	68	1	48
				530.1		

Table 3.1b.1: WP1 - Workpackage description

Work package number	**1**	**Lead beneficiary**				**CERN**			
Work package title	**Coordination and Communication**								
Participant number	**1**								
Short name of participant	**CERN**								
Person months per participant:	**0**								
Start month	**1**			**End month**	**48**				

Objectives

WP1 will provide the resources to coordinate both the administrative and scientific tasks of MuCol. CERN will ensure most of the resources for scientific, technical and administrative coordination, and all participants will be involved in the decision making process through the collaboration board. The other Institutes will also contribute to dissemination activities and will provide candidates for relevant roles transversal to all the WorkPackages such as the Gender Advisor and the Communication and Dissemination Officer. The objectives of WP1 are:

- Comply with requirements from EU rules for the project (financial reporting, notification of the achievement of milestones and deliverables etc…)
- Organisation of Collaboration meetings and workshops, harmonization of events across the workpackages
- Editing of common reports, ensuring the respect of deadlines for deliverables and Milestones
- Scientific coordination of the work
- Technical coordination
- Coordination of Communication and Dissemination activities.
- Monitoring of gender dimension issues

Description of work

CERN will coordinate WP1 and provide the Study Leader and the Technical Coordinator, who will propose a Deputy from the collaboration for appointment by the Governing Board. All Institutes, both Beneficiaries and Associates, will contribute to this workpackage with participation to the relevant committies and Boards, with transversal roles and Communication and Dissemination. The associated resources are accounted for wither in each workpackage, associated to coordination activities, or are coming from own resources of each Institute, not claimed and accounted for to EU.

Task 1.1 Study Coordination (**CERN**)

This task will ensure the implementation of the workprogramme, the coordination of scientific aspects across workpackages, and the integration of the effort within the international collaboration established at CERN.

Task 1.2 Technical Coordination (**CERN**)

CERN will ensure the timely delivery of milestones and deliverables. It will prepare the periodic and final reports as well as follow the use of resources. CERN will also establish an infrastructure to store the relevant project data, in particular parameters, specifications and layouts and make them available to all partners and the IMCC. The technical Coordinator will also coordinate the establishment and follow-up of the Data Management Plan.

Task 1.3 Quality Management (CERN)

The Advisory Committee is the main tool to ensure the quality of the results of MuCol, and this task will be responsible to organize meetings, submit requests and diffuse recommendations. In addition, it will set-up an internal peer-review process for the publications of results.

Task 1.4 Communication and Dissemination(CERN, INFN)

CERN and INFN will ensure the communication of scientific results to relevant communities and scientific committees, as well as funding agencies. Also, it will organize and streamline the dissemination to general public.

It will be led by the Communication and Dissemination Officer.

Task 1.5 Implementation Scenarios (CERN)

CERN will identify the main cost and power consumption drivers to determine the cost and power-consumption scales of the collider. It will assess the impact on the environment and the constraints for an implementation at CERN.

Deliverables (brief description and month of delivery)

D1.1 Data-management plan - M5
D1.2 Preliminary ESPPU report - M36 – report about the studies of the chosen Scenario
D1.3 Consolidated ESPPU report - M48 – report about the final iteration of the Scenario

Table 3.1b.2: WP2 - Workpackage description

Work package number	**2**	**Lead beneficiary**				**UNIPD**			
Work package title	**Physics and Detector Performance Requirements**								
Participant number	**8**	**1**	**6**	**5**	**2**	**18**	**10**		
Short name of participant	**UniPD**	**CERN**	**INFN**	**CEA**	**DESY**	**UOS**	**LIP**		
Person months per participant:	**24**	**0**	**12**	**12**	**12**	**12**	**12**		
Start month	**1**			**End month**	**48**				

Objectives

WP2 will study the beam-induced background effects on the detector with different interaction region design to define its optimal configuration which will include the shielding. Event reconstruction algorithms will be developed to exploit 5D information in order to additionally mitigate the beam-induced background effects, in particular the irreducible part. The last objective is the detector performance evaluation by using the most relevant SM measurements and New Physics reaches.

Description of work

WP2 will be Coordinated by **UNIPD**, with the participation of **INFN, CEA, DESY, UOS, LIP, CERN, ISU, SYU, UNIPV.**

Task 2.1 Design of detector configurations at √s=3 TeV and √s=10 TeV with the optimised interaction regions (**UNIPD**,INFN, Sussex, ISU)

This task will study the beam-induced background effects on the detector components produced with different interaction region configurations. Feedbacks will be given to WP5, high energy complex , where the IR is designed to optimise background fluxes and the shielding configuration. This will be done in an iterative way until an optimised IR is defined and the relative detector configuration proposed.

Task 2.2 Design and implementation of event reconstruction algorithms in 5D at √s=3 TeV and √s=10 TeV (**DESY**,CERN,LIP, UNIPV, CEA)

This task will focus on developing reconstruction algorithms exploiting 3D position, energy, and timing measurements to mitigate beam-induced background and perform tracking and calorimetry clustering. Leveraging on the developments made for future colliders, this task will explore machine learning solutions and parallel computing, both for real-time event processing and for offline analysis, taking into account the specific challenges of a muon collider (e.g., particle tracking in the forward region).

Task 2.3 Evaluate detector performance at different collision energies by using major physics processes (**INFN**,DESY,CN,UNIPV, Sussex, UNIPD, CEA)

This task will explore the detector performance of a muon collider operating at different collision energies. Exploiting an optimal design of the interaction region (Task1) and advances in event reconstruction (Task2), the detector performance will be determined by evaluating the reach of major physics processes for Standard

Model measurements, and for searches for physics beyond the Standard Model.

Deliverables (brief description and month of delivery)

D2.1: Publication of open access beam-induced background files and related detector performance- M36
D2.2 Publication of the detector performance at different collision energies for given physics processes as contribution to the European Strategy process – M48

Table 3.1b.3: WP3 - Workpackage description

Work package number	**3**	**Lead beneficiary**				**ESS**	
Work package title	**Proton Complex**						
Participant number	**11**	**12**	**1**				
Short name of participant	**ESS**	**UU**	**CERN**				
Person months per participant:	**33**	**2**	**0**				
Start month	**1**			**End month**	**48**		

Objectives

This work package aims to define the most promising scheme for the linac, accumulator and compressor rings and prepare a comprehensive summary of the current technology and possible R&D topics of importance for the proton complex. A self-consistent parameter set will be developed to determine the input beam conditions for the muon complex, based on known technological limitations.

Description of work

ESS will coordinate the Workpackage, and will provide the overall coordination of the activity and the communication of its results. It will monitor work progress and inform the project management and work package participants **(UU** and **CERN)**, monitor the WP budget and use of resources and prepare internal and deliverable reports.

Task 3.1 – High power linac (CERN)

The goal of this task is to collect the parameters that can be used for a future design of a high-power H- Linac to be used as the driver of the proton complex. This collection will be based on inputs from ESS and the SPL/LINAC4 designs and may include: source type, preliminary acceleration layout, beam dynamics and stability considerations and chopping schemes. Consideration will be given of the need for additional acceleration after the linac in order to reach the required beam power. The parameters will be used to provide input on final beam parameters for task 3.2. CERN will be leader of this task bringing its experience in the design of the CERN LINAC4 and SPL and H- sources. ESS will bring expertise in high power hadron linac design.

Task 3.2 – Compressor ring design (ESS)

The goal of this task is to provide a self-consistent collection of parameters to be used in the design of a future compressor ring. The ring will create the high intensity short bunches that will be delivered to the target for muon production. With the input of WP4 (target and cooling) and task 3.1, a set of beam parameters will be defined. A preliminary design of the rings will be developed including accumulation and compression strategy, preliminary lattice and injection and extraction considerations. Further R&D needs will be outlined and eventually beam measurements at CERN or other facilities might be proposed. Preliminary study of intensity-based effects such as space charge, single-bunch and impedance effects will be carried out for the compressor ring. ESS will lead this task and bring expertise in lattice design and beam dynamics. UU will bring expertise in lattice design and RF. CERN will provide further lattice design expertise. ESS will hire a postdoc for this task and share the supervision with UU.

Deliverables (brief description and month of delivery)
D3.1 Final report on parameters and initial study for the Proton Complex - M45

Table 3.1B.4: WP4- Workpackage description

Work package number	**4**		**Lead beneficiary**		**UKRI**		
Work package title	**Muon Production and Cooling**						
Participant number	**14**	**13**	**21**	**1**			
Short name of participant	**UKRI**	**Imperial**	**UWAR**	**CERN**			
Person months per participant:	**28.8**	**22.5**	**21**	**0**			
Start month	**1**			**End month**	**48**		

Objectives
The muon cooling work package aims to establish a baseline for the muon target and cooling system in the light of known technological limits and identify areas where further R&D is required to deliver a satisfactory system conceptual design.

Description of work

The target and ionisation cooling work package will develop the muon source from the proton target through to the beginning of the acceleration system. A principle challenge for the muon collider is to deliver a beam having suitable luminosity so that the probability of a collision at the detector is significant. This WPwill study the specific issues generated by the impact of a high brightness proton beam ona solid, liquid or fluidised powder target. It will then advance the understanding of the Ionisation cooling technique, whose principle has been recently demonstrated by the Muon Ionisation Cooling Experiment (MICE) collaboration, and design a configuration capable of delivering a muon beam compressed into a minimum phase-speace volume, such as to satisfy the requirements in terms of luminosity production at the experiements. WP4 will explore the technologies necessary to cool the beam in collaboration with WP6, WP7 and WP8, and will provide specificatins and input to WP3 and WP5. This WP will be led by **UKRI**, that will bring in its experience gained within the MICE collaboration. Other participants are Imperial, **UWAR, CERN, INFN, UMIL, ENEA**.

Task 4.1 Cooling system development (UKRI)

The cooling system uses a system of magnets, RF cavities and energy absorbing materials, to compress the beam both transverse and parallel to the direction of travel of the muon beam. This key system has to deliver a compression in the phase-space volume occupied by the beam by five orders of magnitude. A preliminary design for such a cooling system was developed within the MAP, assuming solenoids limited to 13 T and RF cavities limited to 30 MV/m. Subsequent experimental work demonstrated RF cavities having fields up to 50 MV/m, while exposed to significant magnetic fields. In collaboration with WP6 and WP7, the lattice optimisation will be extended to include these new parameter sets. The lattices will be made more realistic, with appropriate consideration of space for alignment equipment, beam instrumentation and due consideration of requirements for the magnet and RF system, also in liaison with WP6 and 7. The lattices will be assessed for integration into a cooling test, in close collaboration with WP8. Appropriate interfaces with the surrounding accelerator subsystems will be considered.

Task 4.2 Target system development (CERN)

In order to reach high luminosity, a high muon beam current must be delivered into the cooling system. This is achieved by impacting high energy protons onto a target, where pions are created and collected in a high field solenoid or a magnetic horn system. The pions decay to muons and are then delivered into the cooling systems.

The proton beam proposed would be one of the highest power proton beams delivered. The proton beam pulse is proposed to be extremely short so that the resultant pion beam is also as short as possible. This would make the instantaneous proton power orders of magnitude higher than the state of the art.

In this work package the impact of such a beam on the target systems and supporting infrastructure will be investigated. The pion yield will be assessed. The impact of the beam on target lifetime will be considered and mitigating strategies such as novel target concepts will be assessed. The heat load on the surrounding magnets will be studied and, in close collaboration with the Magnets WP7, the required shielding and associated magnet aperture requirements for the capture of pions will be studied.

Task 4.3 Code development (Imperial)

The BDSIM code has been developed in Europe in order to enable simulation of accelerator equipment in the presence of beam intersecting devices. BDSIM has been used to study several major proposed accelerator facilities including FCC-hh, CLIC and the ILC. BDSIM provides a unique combination of accelerator-style mapping techniques and particle physics-style tracking based on the Geant4 physics library. Previous simulations of ionisation cooling have been performed using G4Beamline, developed in the US. However G4Beamline has not been updated for more than 2 years despite a number of issues in the code. Imperial College, London will develop BDSIM in close collaboration with the BDSIM project leaders at Royal Holloway University of London so that it is fully integrated and capable of delivering simulations of the full cooling system.

Deliverables (brief description and month of delivery)

D4.1: Development of BDSIM to model cooling systems – M24

D4.2: Preliminary Report on key Muon Source subsystems - M33

D4.3: Consolidated Report on the Muon Source – M45

Table 3.1b: WP5- Workpackage description

Work package number	**5**	**Lead beneficiary**			**CEA**
Work package title	**High energy Complex**				
Participant number	**5**	**1**	**6**		
Short name of participant	**CEA**	**CERN**	**INFN**		
Person months per participant:	**24**	**0**	**12**		
Start month	**1**		**End month**	**48**	

Objectives

WP5 will perform a design of the pulsed synchrotrons of the acceleration complex and will explore an alternative based on fixed-field alternating gradients. Another objective is the design of the collider to get the target luminosity in the interaction region taking into account the limitations due to collective effects, the machine detector interface and the background to experiment. WP5 will optimize the shielding design of the interaction region and magnets to handle the radiation due to muon decay and other beam losses.

Description of work

CEA will provide the overall coordination of the activity and of the communication of its results. It will monitor work progress and inform the project management and work package participants, monitor the WPbudget and use of resources and prepare internal and deliverable reports. Other Participants are **INFN, CERN, HUD, RHLU, BNL.**

Task 5.1 Collider design (CERN). This task focuses on study of the feasibility and optimization of the muon collider. The main goal is to develop a credible design concept of the muon collider with a cost estimate. It will develop a consistent lattice for a 3 TeV and 10 TeV com collider. Particular challenges are chromatic effects due to the small beta* and large momentum spread and their correction, control of linear and non-linear momentum compaction to keep small bunch length, acceptable beam induced background levels, control of the neutrino radiation issue, beam operation with moving beam lines and, possibly, non-linear effects.

Task 5.2 Pulsed synchrotron and FFA design (CEA). This task addresses the feasibility and optimization of the muon acceleration complex with upgrade path based on reasonable assumptions on technology development. This task will address two technical solutions: pulsed synchrotrons and FFA. This task will describe the beamline in a parameter table, provide a full set of lattices and have start-2-end tracking to validate luminosity performance, bunch compression and emittance preservation during the acceleration process. CEA will lead this task and perform the design study of the accelerator complex based on pulsed synchrotrons whereas STFC will focus on FFA. CERN will contribute to the longitudinal dynamics studies and bring expertise in synchrotrons.

Task 5.3 Beam dynamics (CERN). This task focuses on the transverse collective effects all along the muon accelerator chain and in particular, the ones linked to impedances. This task will study impedance effects to check that the very quick acceleration phase is feasible when high-intensity effects taken into account. The detailed proposed work plan is: i) Compute and store the resistive-wall impedance and wakefield. ii) Perform simulations of transverse beam stability assuming with a single bunch and scan the relevant parameters to set limits on the performance reach. iii) Choose the RF cavity impedance models and extend the previous parameters scan. v) Re-do the same analysis with the 2 counter-rotating bunches. vi) Propose possible mitigation measures and study in particular if pulsed synchrotrons need sextupoles.

Task 5.4 MDI design and background to experiment (CERN). This task will develop a conceptual interaction region design, which integrates a detector shielding together with the detector envelope and the final focus system and incorporates requirements from other activities. It will quantify particle fluxes for different source terms and study the time dependence with respect to the bunch passage: i) muon decay, ii) incoherent electron-positron pair production at the IP, and iii) beam halo losses. This task will optimize the shielding design with respect to different contributions and explore other possible background mitigation techniques on the machine side. It will assess the need of a halo-removal system for background reduction. It will provide estimates of the long-term radiation damage in the detector. CERN will lead this task. INFN and STFC will bring their expertise in machine-detector interface.

Task 5.5 Radiation studies for the accelerators (CERN). This task will address the simulation and mitigation of radiation-related effects including the neutrino hazard. This task will quantify the heat load distribution and long-term radiation damage in superconducting magnets due to muon decay and beam halo losses. It will develop a shielding design for arc magnets, in order to: i) avoid quenches, ii) sustain the thermal load, and iii) prevent magnet failures. This task will quantify the radiation environment in the tunnel and caverns and assess the need of machine protection systems including a beam extraction system and input for a beam loss monitoring system. This task will assess the effect of the lattice design on the neutrino distribution, and perform optimizations. It will refine the dose kernel for assessing the surface dose arising from neutrino-induced particle showers.

Deliverables (brief description and month of delivery)

D5.1: Final report on the collider ring design - M44

D5.2: Final report on the design of the high energy acceleration complex - M44

Table 3.1b: WP6 - Work package description

Work package number	**6**	**Lead beneficiary**				**CEA**	
Work package title	**RF considerations for a high energy muon collider**						
Participant number	**5**	**16**	**4**	**6**	**1**		
Short name of participant	**CEA**	**ULA**	**UROS**	**INFN**	**CERN**		
Person months per participant:	**22**	**36**	**12**	**36**	**0**		
Start month	**1**			**End month**	**48**		

Objectives

The objective of this work package is to assess crucial feasibility issues and technological challenges of the RF systems. The study will concentrate on the two most challenging sections, the Muon Cooling Complex (MCC), and the muon acceleration stage of the High Energy Complex (HEC), for which a baseline concept of most critical RF components will be outlined.

Description of work

This workpackage will be led by **CEA**, supported in some tasks by **INFN** that will provide the deputy WP leader. Apart from the coordination of the work inside the WP, CEA and INFN will ensure proper integration of the work of this work package with the studies done in WP4, WP5 and WP8. Other Participants to this WP are **UROS, CERN, ULA, Strathclyde.**

Task 6.1 Baseline concept of the RF system for acceleration to the High Energy Complex (HEC) (UROS)

This task, **led by the University of Rostock**, aims to provide a preliminary design concept for the SRF cavities for acceleration in the Rapid Cycling Synchrotrons (RCS) of the HEC of the muon collider. For the acceleration stage of the HEC, the short muon lifetime requires the highest possible acceleration rate to reach energy gains on the order of 10 GeV per turn. This is foreseen to be provided with very high voltage SRF cavities. A suitable cavity technology, including the accelerating cavity type and shape, the cavity material, and the main RF frequency, will be determined for this system. Strong transient beam loading effects, as well as strong wake field effects due to the very high intensity of the muon bunches will also have to be addressed in the cavity optimisation. In cooperation with WP5, a full set of parameters for the RF cavities that address longitudinal beam dynamics and stability will be established (R/Q, Vmax, …) for the fundamental mode and HOMs' suppression. This will provide input specifications for the design concept of the RCSs cavities.

Task 6.2 Baseline concept of the RF system for the Muon Cooling Complex (MCC) (CEA and INFN LASA)

The focus of this task, **led in conjunction by CEA and INFN LASA**, is to lay out a conceptual design of the RF systems for the MCC, based on a consistent set of parameters for all RF cavities and associated systems to be integrated into the cooling cells of the MCC obtained from inputs given by WP4 and WP8. For the muon cooling section, one challenge already pointed out in the preliminary MAP study, is to achieve gradients of at least 30 MV/m in RF cavities that will be placed in magnetic fields of 13 T, and explore whether it is possible to push these values at the light of the latest developments in RF and magnet technology. At first, specifications for the design of all RF cavities will be collected (frequency, gradient, length, B-field, aperture). Then, based on the guidance given by WP4, full set of parameters for the cavities will be calculated, serving as a base for their conceptual design and integration in the cooling cells. The impact of beam loading on the muon energy spread will also be assessed at this stage and appropriate mitigating actions will be recommended.

Task 6.3 Break down mitigation studies for cavities of the muon cooling cells (CEA)

The goal of this task, **led by CEA**, is to study and enhance the present comprehension of the intrinsic concepts that influence the break down rate of RF cavities submitted to strong magnetic fields. We plan to extend existing theoretical studies, and with additional inputs from previous experimental studies at CERN for CLIC and FermiLab for MAP, as well as from additional tests performed in the scope of this task, realistic solutions to mitigate the breakdown and provide guidance for the design and the fabrication of high gradient RF cavities that stand strong magnetic fields in the MCC will be proposed.

Task 6.5 Baseline concept of high efficiency and high-power RF sources for the muon collider (ULA)

The aim of this task, **led by University of Lancaster**, is to provide a baseline concept for the RF sources needed for the muon collider that will require higher RF power than is currently possible with commercially available sources. Recent studies at CERN and Lancaster have shown that using novel two-stage klystrons can significantly increase their efficiency and thus reduce their power consumption. At first, the requirements in terms of frequencies, peak power and efficiency for all RF sources that provide RF to the muon collider cavities will be collected. Then, conceptual studies to improve by design the intrinsic energy efficiency of the most power-demanding RF sources in order to ensure sustainability over the long term will be presented.

Deliverables (brief description and month of delivery)

6.1: Final report on baseline concept of high efficiency and high-power RF sources for the muon collider - M42

6.2: Final report on baseline concepts of the RF systems for the Muon Cooling and High Energy Complexes, including break-down mitigation studies for MCC cavities - M45

Table 3.1b.7: WP7 - Work package description

Work package number	**7**		**Lead beneficiary**		**CERN**		
Work package title	**Muon Collider Magnetic Systems**						
Participant number	**1**	**5**	**6**	**17**	**3**	**9**	**7**
Short name of participant	**CERN**	**CEA**	**INFN**	**SOTON**	**TUDa**	**UTWENTE**	**UMIL**
Person months per participant:	**0**	**18**	**32**	**42**	**15**	**14**	**8**
Start month	**1**			**End month**	**48**		

Objectives

The objective of this work package is to address feasibility and technology limits of the magnet and powering systems, assess technology readiness and R&D timeline. The leading topics are: (i) the value of the maximum field and free bore of the solenoids for the target, capture and cooling complex, (ii) the concept and feasibility of the fast accelerator chain, and (iii) design options for the magnets of the collider complex. We address the above topics through a combination of conceptual design work, targeted tests and specific characterization measurements. We also plan to exploit synergies with on-going developments in other fields (high magnetic field science, NMR, fusion) and programs (EU High-Field Magnets R&D, US-MDP).

Description of work

WP7 will be coordinated by **CERN**. Other participants are **CEA, INFN, SOTON, TUDa, UTWENTE, UMIL, PSI, UNIGE, KIT, CNRS, UNIBO**.

Task 7.1 Technical Coordination and Integration (Leader Institution: CERN)

We will establish within this task a *magnet catalogue*, including a set of target specifications, baseline concepts and technology options, and identification of leading drivers for the power consumption and cost. The catalogue will include the results from the other three tasks in this work package, and will complete it for the whole collider complex. This task also provides the interface for magnet energy deposition and radiation studies, magnet cooling studies, as well as safety and environmental aspects of the magnet system. CERN (Task Leader) will provide the resources and technical support, in collaboration with CEA, polling actively the demands from accelerator physics (WP2, WP3, WP4, WP5, WP8), and interfacing to the other aspects of the study, including the contribution to power and cost model.

Task 7.2 Target, Capture and Cooling Magnets (Leader Institution: INFN)

This task covers the conceptual design work required to establish performance limits, assess feasibility, and identify outstanding R&D for the target, capture and final cooling solenoids, in close collaboration with the activities on beam capture and cooling, target and absorber design (WP4), and RF (WP6). Specific focus will be put on (i) the target solenoid, which requires high field (20 T) in a large bore (150 mm), subjected to substantial energy deposition (100 kW) and radiation, and (ii) the final cooling solenoid, where the required field (40 T minimum to 60 T target) in a small bore (50 mm) is well beyond the present state of the art. The task will maintain a close interface with the engineering design and integration of the solenoid for the test module (WP8). The task provides coordination for a limited Technology Performance Limits (TPL) experimental activity devoted to establishing material and technology limits, towards the identification of priority R&D. The work will be performed by INFN (Task Leader), CEA, CERN, CNRS, KIT, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP.

Task 7.3 Fast Cycled Accelerators (Leader Institution: CERN)

The aim of this task is to propose concepts and evaluate realistic performance targets for the fast-ramping accelerators, in close collaboration with beam physics (WP5) and RF (WP6). The main challenge is the management of the large energy stored in the magnet system (of the order of 100 MJ), the power flow required for ramping (in excess of 50 GW reactive power), and the quality of the fast field ramp (0.5 ms for the shortest cycle time). This task includes the integrated development and optimization of concepts for the power storage, conversion and distribution in normal-conducting fast ramping magnets. The focus will be on the present baseline scheme, i.e. a Hybrid Cycled Synchrotron (HCS) consisting of a combination of DC dipoles (superconducting, up to 16 T) and AC dipoles (resistive, bipolar, ± 2 T). Alternative schemes will be considered at the level of conceptual study, and in particular HTS fast ramped magnets, to see whether performance can be improved and consumption reduced. The work will be performed by CERN (Task Leader), CNRS (within the Laboratoire National des Champs Magnétiques Intenses), TUDa, UNIBO and TWENTE, in collaboration with Kyoto University (HTS RCS) that will collaborate externally without formally joining the Consortium.

Task 4. Collider Ring Magnets (Leader Institution: INFN)

This task aims at assessing realistic performance targets for the large bore (range of 150 mm) collider magnets, in close collaboration with beam optics (WP5), machine-detector interface, and energy deposition studies (WP2). The design activity will be focused on the combined functions dipoles in the arc, 10 to 16 T, which are a good sample of the magnet challenges. The study will consider LTS and HTS materials, adopting a *stress management* mechanical system, which is an innovative approach for accelerator magnets. We finally plan to address the effects of the expected heat and radiation load, up to 0.5 kW/m linear power density in the coils, considering aspects such as thermal stability, heat removal and radiation-induced damage. The work will be performed by INFN (Task Leader) and UNIMI in collaboration with KEK, PSI and US-MDP.

Deliverables (brief description and month of delivery)

The deliverables of this task are the following:

D7.1: Preliminary report on muon collider magnets, containing a first conceptual baseline and technology selection for magnets and powering system, preliminary power and cost estimates - M33

D7.2: Final report on muon collider complex magnets: magnet catalogue, technology selection for baseline and alternatives, consolidated footprint, power and cost estimates, R&D plan - M45

Table 3.1b.8: WP8 - Workpackage description

Work package number	**8**	**Lead beneficiary**			**UMIL**	
Work package title	**Cooling Cell Integration**					
Participant number	**7**	**1**	**6**	**13**	**14**	
Short name of participant	**UMIL**	**CERN**	**INFN**	**Imperial**	**UKRI**	
Person months per participant:	**38**	**0**	**18**	**12**	**0**	
Start month	**1**			**End month**	**48**	

Objectives

The first objective of this workpackage is to select the technologies that are more suitable for a construction of a cooling cell that will demonstrate the feasibility of the concept including:

- **absorbers** that will decrease the emittance in both the longitudinal and transvers plane
- **Superconducting solenoids**, to limit the transverse blow-up of the beam**.**
- **RadioFrequency Cavities**, that will accelerate the beam providing back longitudinal momentum

The second objective is to design each component of the cooling cell and integrate them in a single assembly to demonstrate that there is no showstopper for such systems.

Description of work

This Workpackage will be led by **UMIL**, that will ensure that the individual designs of each component are performed taking into account the integration within a single mechanical assembly. To this purpose, UMIL will ensure the publication of clear functional specifications and will animate regular meeting among the different Institutes and across the various tasks. UMIL will also coordinate the preparation of reports and communication in general, and liaise with the rest of the project, in particular WP1, WP4, WP6 and WP7. Other participants are **CERN, INFN, Imperial, UKRI.**

Task 8.1: Absorbers and Windows: Coordinated by **CERN**, with studies on possible absorbers to be used in a cooling cells. Studies on windows will be necessary for the case of a liquid absorber, and in case that the RF task concludes that a high-pressure gas-filled cavity has to be used. This task will liaise with WP4.

Task 8.2: Solenoids: Coordinated by **UMIL**, will as well resort to the experience of past projects and will propose, with the support of **INFN-LASA** a solenoid configuration compatible with all constraints. UMIL will design the solenoids to be integrated in the cell and liaise with the relevant task of WP7.

Task 8.3: RadioFrequency, coordinated by **INFN-LASA**. This workpackage will critically review the experience built by the muon collider community mainly through projects in the US over the last 20 years (Muon factory, Neutrino factory, MAP) and the experience of the MICE experiment. INFN LASA will design a cavity for the cooling cell liaising directly with WP6.

Task 8.4: Cooling cell performance: coordinated by **UKRI**, has the goal of selecting the type of cooling cell that represents better the difficulties of integration. This task will specify the main parameters for each component and will ensure that the overall cooling efficiency is preserved during the detailed design of the cell. This task will liaise with WP4

Task 8.5: Integration: Coordinated by **UMIL**, will make sure that the design of every single component in the other tasks is performed having in mind the integration in an assembly and will provide at the end a full 3D model of the cooling cell including all services (fluids, electrical connections etc…). All other participants to the Workpackage will contribute to this task, In particular CERN will make sure the 3D model respects the CERN quality manual in order to allow a future integration on a test facility on the CERN site.

Deliverables (brief description and month of delivery)

D8.1: Presentation of cooling cell conceptual design at the Annual Meeting – M15

D8.2 : Final report on cooling cell design - M42

Table 3.1c: List of Deliverables

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
1.1	Data-management plan	1	CERN	O	P	5
1.2	Preliminary ESPPU report	1	CERN	R	P	36
1.3	Consolidated ESPPU report	1	CERN	R	P	48
2.1	Beam-induced background and detector configuration	2	UniPD	D	PU	30
2.2	Detector performance by using physics processes	2	DESY	R	PU	36
3.1	Final report on parameters and initial	3	ESS	R	PU	45

	study for the Proton Complex					
4.1	Development of BDSIM simulation	4	UKRI	O	PU	24
4.2	Preliminary Report on key subsystems for ESPPU input	4	UKRI	R	PU	33
4.3	Consolidated Report on key subsystems	4	UKRI	R	PU	45
5.1	Report on the collider ring design	5	CERN	R	PU	44
5.2	Report on the design of high energy acceleration complex	5	CEA	R	PU	44
6.1	Report on design of high power and high efficiency RF power sources	6	CEA	R	PU	42
6.2	Report on RF for MCC and HEC	6	ULA	R	PU	45
7.1	Preliminary report on muon collider magnets	7	CERN	R	PU	33
7.2	Consolidated report on muon collider magnets	7	CERN	R	PU	45
8.1	Presentation of cooling cell conceptual design	8	UMIL	O	PU	15
8.2	Final report on cooling cell design	8	UMIL	R	PU	42

Table 3.1d: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
M1.1	Web Site Available	1	2	Website online
M1.2	Kick-off meeting	1	3	Indico site
M1.3	Data-management plan	1	6	DMP published
M1.4	Annual meeting 1, 2, 3	1	15, 27, 39	Indico site
M2.1	Training on detector design and physics performance tools	2	6	Training material
M2.2	Workshop on MDI and IR design	2, 5	12	Indico site
M2.3	Release of simplified detector performance model (DELPHES card or/and similar format)	2	18	Model published on the website
M2.4	Workshop on detector design and physics performance with a public lecture on Muon Collider	2	24	Indico site with presentations
M2.5	Publication of report of detector performance with major physics process at several CoM energies	2	48	Peer reviewed paper
M3.1	Update for the proton complex parameters and review with WP4	3/4	12	Table of parameters approved by SL
M3.2	Preliminary report on the linac and accumulator work	3	36	Report published
M4.1	Baseline Demonstrator Cooling cell design	4	12	Specification report published
M4.2	Initial Assessment of Target radiation load on magnet systems	4	12	Report published
M5.1	Mini-Workshop with pulsed magnets	5	12	Indico site
M5.2	Preliminary design of the interaction region	5	18	Optics files
M5.3	Preliminary design of the collider	5	18	Optics files
M5.4	Preliminary design of the pulsed synchrotrons	5	18	Optics files

M5.5	Preliminary design of the FFA	5	24	Optics files
M5.6	Impedance budget in the collider and pulsed synchrotron	5	24	Dataset
M6.1	Preliminary report on breakdown mitigation for cavities for muon cooling cells	6	24	Report published
M6.2	Preliminary report on RF acceleration for rapid cycling cyclotrons of HEC	6	36	Report published
M6.3	Preliminary set of parameters for cavities for muon cooling complex	6	36	Report published
M6.4	Preliminary assessment of specifications for RF power sources for muon collider	6	24	Report published
M7.1	Report on solenoids and TPL experiments	7, 4, 8	12	Report
M7.3	Report on RCS and HCS configurations	7, 5	24	Report
M7.4	Workshop on ultra-high-field solenoids	7	30	Indico Site
M7.5	Report on HTS fast-cycled magnets	7	32	Report
M7.6	Report on solenoid conceptual design	7, 8	36	Report
M7.7	Report on high-field collider magnet design	7, 2, 5	36	Report
M7.8	Workshop on high-field collider magnets	7	42	Indico Site
M7.9	Report on footprint, power and cost model	7, 1	44	Report
M7.10	Report on R&D and impact	7, 1	44	Report
M8.1	Selection of Technology: RadioFrequency	8	12	Report
M8.2	Selection of Technology: Solenoid	8	12	Report
M8.3	Selection of Technology: Absorber/window	8	12	Report
M8.4	Cooling cell Design Intermediate Report	8	24	Report
M8.5	Cooling cell design 3D model achieved	8	36	3D model completed

Table 3.1e: Critical risks for implementation

Description of risk (indicate level of (i) likelihood, and (ii) severity: Low/Medium/High)	Work package(s) involved	Proposed risk-mitigation measures
Hiring difficulty (medium, high)	All	To exploit hiring strategies (websites, Professional networks, socials etc…) of all the participating Institutes to enlarge as much as possible the platform of publication of open positions.
Unilateral withdrawal of a Partner (low, medium)	WP1	The Consortium has a wide coverage of every necessary competence. Withdrawal for any reason of one of the partners will be mitigated with the reassignment of resources to another partner having the necessary competences. The decision will be taken at the Governing Board level.
Significant delay on deliverables (low, medium).	all	Progress will be regularly monitored via the Management Board and achievement of Milestones and Deliverables. Appropriate measures, if necessary will be addressed by the Governing Board
Failure to achieve performance goals with realistic target performance	WP1	Rebalance parameters to relax the requirements on the section that does not fulfil the specifications.

specifications (medium, high)		Identify R&D necessary to improve performance for final report. Adjust performance goals, if unavoidable
Additional challenges are identified that require unforeseen efforts (low, medium)	WP1	Discussion at the Governing board level. Participants will make additional resources available or reprioritisation of efforts
Delay in the availability of 10 TeV centre-of-mass energy IR lattice (low, high)	WP2	Study a procedure to scale the 3 TeV centre-of-mass results to high energy with much less accuracy
Lack of computing resources to fully simulate the beam-induced background for all the IR configurations (low, medium)	WP2	Discussion at the Governing Board. Members (including associates) will be requested to contribute with more computing resources
Different WPs advance in scenarios which are incompatible with studies performed in other WPs (low,high)	all	All WPshall regularly present their progress in the Management Committee. The Study Leader and the Technical Coordinator will address incoherences. Scientific and Technical WPs will be regularly asked to update the Parameter table to ensure coherency.
In the course of the study we find that a certain parameter required by the target (WP4) cannot be achieved (Medium, high)	WP3/WP4	the two WPs will have regular common meetings. Tradeoffs on performances may be requested. The management committee will be informed,
Complexity or cost of Technology Performance Limits (TPL) experiments beyond the scope of the work planned	WP7	Resort to basic electro-mechanical characterization measurements to identify design limits, postponing full TPL experiments to the R&D phase
Selected components of the cooling cell do not fit within the specified space (medium, high)	WP8	Additional iteration on components design, and cooling cell architecture. Organisation of a dedicated workshop open to international experts. If unavoidable, relax the specifications and check the impact on downstream sections of the complex.

Table 3.1f: Summary of staff effort

The cells in green show participation of the Institution based on own funds that will not be claimed to EU, but that will be committed to the Consortium for monitoring by each institute in signing the Collaboration agreement if MuCol is selected for funding. The total value of the project is estimated to about 10 MCHF, with the following share: 30% EU (claimed funds), 30% CERN, 40% all other Institutes. In particular all Institutes will ensure funds to provide PhD and PostDoc contracts in line with at least the minimal legal duration (typically 3 years for PhD students, 2 years for PostDocs). CERN will invest PMs in all the Technical WPs, and will ensure availability of Senior Scientists for Scientific, Technical and Administrative Coordination as required by the project. The table shows visually that for every WPthere is sufficient availability of partners that can work on each topic and eventually compensate the sudden withdrawal of one of the partners.

	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	Total Person-Months per Participant
CERN	x	x	x	x	x	x	x	x	0
DESY	x	12							12
TUDa	x						15		15
UROS	x					12			12
CEA	x	12			24	22	18		76
INFN	x	12		x	12	36	32	18	110
UMIL	x			x			8	38	46
UNIPD	x	24							24
UT-WENTE	x						14		14
LIP	x	12							12
ESS	x		33						33
UU	x		2						2
Imperial	x			22.5				12	34.5
UKRI	x			28.6				x	28.6
UWAR	x			21					21
ULA	x					36			36
SOTON	x						42		42
UOS	x	12							12
PSI	x						x		
UNIGE	x						x		
SYU	x	x							
KIT	x						x		
CNRS	x						x		
ENEA	x			x					
UNIBO	x						x		
UNIPV	x	x							
Strath-clyde	x					x			
HUD	x				x				
RHLU	x				x				
UOXF	x				x				
ISU	x	x							
BNL	x				x				
Total PM	0	84	35	72.1	36	106	129	68	**530.1**

Table 3.1g: ‘Subcontracting costs’ items

No partner has foreseen Subcontracting

Table 3.1h: ‘Purchase costs’ items (travel and subsistence, equipment and other goods, works and services)

Participant Number/Short Name 1/CERN		
	Cost (€)	**Justification**
Travel and subsistence	40000	Participation to projects meetings and events., visit to partners
Equipment		
Other goods, works and services	128000	Administrative support to CERN (128000). Consumables, software licenses for other labs (36000).
Remaining purchase costs (<15% of pers. Costs)		
Total	168000	

Participant Number/Short Name 8/UNIPD		
	Cost (€)	**Justification**
Travel and subsistence	20000	Participation to projects meetings and events., and to invite experts
Equipment		
Other goods, works and services		
Remaining purchase costs (<15% of pers. Costs)		
Total	20000	

Participant Number/Short Name 12/UU		
	Cost (€)	**Justification**
Travel and subsistence	5000	Participation to projects meetings and events.
Equipment		
Other goods, works and services		
Remaining purchase costs (<15% of pers. Costs)		
Total	5000	

Table 3.1i: ‘Other costs categories’ items (e.g. internally invoiced goods and services)

No partner has foreseen any other cost categories

Table 3.1j: ‘In-kind contributions’ provided by third parties

No In-kind contribution is foreseen at this stage.

3.2 Capacity of participants and consortium as a whole

The consortium comprises 32 Institutes out of which 18 are Beneficiaries and 14 Associates. The idea to setup a European Project to perform a design study of a Muon Collider has raised a lot of interest in several scientific communities, and the Consortium that has been setup has already reached the goal of enlarging the scope of the Muon Collider Collaboration to new Institutes and different fields of science. The Consortium will comprise in fact Laboratories and Universities from the following fields:

- High Energy Physics
- Accelerator Physics
- Spallation Neutron Sources
- Fission/fusion nuclear technologies
- High Field Magnets for medical applications and material studies

CERN will coordinate the project, in line with its mandate to coordinate at European level the efforts of R&D in accelerator physics and Technology. The goal of CERN's coordination will be to ensure coherence with the goals of the European R&D roadmap, in order to ensure that MuCol will deliver results that will critically impact the next ESPPU. CERN will also participate with in-kind resources in almost all the workpackages, and will serve as a host for the consortium for general meetings and events. CERN has a long experience in managing complex studies of Accelerator physics and technology, and has developed over the years tools for collaborative work that will be put at the disposal of the consortium.

The Consortium will comprise a balanced mix of Laboratories, some of them with specific competencies such as ENEA for liquid metal loops, and LNCMI for high field solenoids. Other laboratories have a vast experience and spectrum of competences in Accelerator physics and technology (e.g. INFN, CEA, UKRI, ESS). Finally the Consortium is complemented with Universities, that will provide the link to academia, will bridge the gap towards young generation of researchers, providing opportunities for direct dissemination through public lectures and seminars, and providing high level scientific support to the studies in MuCol, but also a platform to hire the reuiqred PhD students and PostDocs.

This large consortium will provide opportunities for discussion and exchange of know-how among experts, ensuring that all results will be peer-reviewed already internally because of the nature of the consortium itself. The contiguity with the larger International Muon collaboration, comprising also other universities and laboratories, and in particular institutes from US and Japan, will ensure that the progress and the results of MuCol will be of the highest quality standards.

Every institute has promised resources to MuCol and those resources will be committed through a Consortium agreement to be signed by every participant, to secure a sufficient level of Person Months to achieve the goals of Mucol and supervise the young researchers. Every workpackage is covered by more than one institution, this structure will ensure also a low level of risk since every Institute will be ready to take over more responsibilities in the unlikely case that one of the institutions will have to withdraw from MuCol.

Annex:

1) Letter of support of JM Perez and E Nappi, respectively Coordinator and Chairperson of the TIARA Consortium
2) Letter of Support of Dr M.J. Lamont, Director for Accelerators and Technology of CERN

TIARA Recommendations for the MulCol proposal to the INFRA-2022-DEV-01 call

April 7, 2022

Introduction to TIARA

The Test Infrastructures and Accelerator Research Area (TIARA) Consortium was established (formally since 2015) to optimize and enhance the outcome of the Research and Technical Development in the field of Accelerator Science and Technology (ASc&T) in Europe. The purpose of this consortium is to exchange expertise and to facilitate and support the setting-up of joint R&D programmes and education and training activities in the field of Accelerator Science and Technology in Europe. This support is horizontal to diverse scientific-technical sectors, research infrastructures and technological facilities, from basic to applied applications.

To that extent, TIARA exchanges information to enable the implementation of activities with the goal of developing and strengthening state-of-the-art research, competitiveness and innovation in a sustainable way on ASc&T in Europe. Its activities include the following:

- Provision of scientific-technical guidance and advice for cooperative R&D toward future Accelerator Science and Technology;
- Promotion and facilitation of cooperation concerning accelerator R&D activities for the benefit of the accelerator developers and the accelerator-user communities, so as to contribute to the development of innovation and the state of the art;
- Provision of support to the scientific communities for accessing equipment, facilities and accelerator systems at accelerator R&D facilities at a European level;
- Promotion of innovation through collaboration with industry, facilitating its integration on R&D activities and its participation on the roadmaps in the ASc&T field;
- Facilitate the upgrading of existing accelerator R&D facilities and the development of new accelerator R&D infrastructures by the Parties;
- Facilitation of applications by the Parties for grants or external funding from the European Commission and other International Organizations;
- Taking actions and supporting the dissemination of the knowledge and expertise on ASc&T, promoting conferences, education, training courses, seminars, workshops, focus groups, study tours, proposal preparation, project reviewing, surveys, among others.

In particular, TIARA coordinates and oversees the preparation of a coherent set of bids in response to the calls set up within the Framework programmes established by the European Commission (EC).

TIARA encompasses a long-term history of activity on coordination of proposals for research, development, innovation, access to infrastructures, dissemination and outreach projects. In short figures:

- A program of more than 17 years in accelerator R&D
- More than 22 projects supported, summing up a total cost above 333M€ (EC contribution 123M€).

- More than 100 partners (laboratories, Universities and industry).
- More than 21 countries involved in the projects supported.
- Supported some of the projects of highest relevance at European level in the last 10 years: LINAC4, XFEL, ESS, HL-LHC, FAIR, ARIES, IFAST, among others.

About the MuCol proposal

On January 2022, it was opened the topic HORIZON-INFRA-2022-DEV-01-01 *Developing the European research infrastructures landscape, maintaining global leadership (2022)*. The TIARA Council has been informed since September 2021 about the proposal MuCol, that will be submitted to this call.

We have reviewed this proposal and discussed it in two of our Council meetings meetings, paying specific attention to the adequateness of it for the European Strategy in the field addressed, the scientific relevance of the work proposed, the expertise of the participant institutes, the coherence of the proposed program and the implications of the expected results to the European and world programs on the field of particle accelerators.

Under these terms, TIARA has followed up with interest, provided support to the preparation of this proposal and strongly support its submission.

TIARA comments on the proposal

Aim

The objective of MuCol is to provide a study to demonstrate that a Muon Collider complex in Europe is feasible, at 3 TeV center of mass energy (E_{CM}) in a first phase, and ramping up above 10 TeV for the next configuration, developing a coherent concept of the entire accelerator complex.

Coherence with the European Strategy

The European community of Particle Physics deploys its strategy within the European Strategy for Particle Physics Update (ESPPU). The latest edition of the ESPPU encourages efforts of R&D for future colliders in several directions and the development of a roadmap for R&D on several promising technologies, among which those allowing the collision of bright muon beams. In response to the ESPPU recommendation, a number of research institutions within the ERA launched in 2020 a motivation to explore the feasibility of muon colliders within an International Muon Collider Study.

The proposal MulCol is fully integrated into the overall effort from the International Collaboration, providing an effective platform to allow European institutes to take the responsibility of parts of the study and develop know-how essential to maintain Europe at the forefront of the High Energy Physics.

Partners

The partners of this proposal complete a balanced representation of the key actors in Europe on the related technologies (CERN, CEA, INFN, KIT, DESY, ESS, STFC, among others), supported by external associated institutes. We confirm that the partners provide the needed expertise and know how to complete the proposed study.

Excellence

The project is based on the conceptual layout of the chain of accelerator components elaborated by the Muon Accelerator Program that coordinated efforts in the US on Muon Collider R&D. Under this base, the proposal will advance on limitations and technical constrains identified, namely: beam-induced *backgrounds at higher energies, the integration of systems and optimization, improving cooling studies based on state-of-the-art magnet and RF technologies, among others.*

This proposal pays specific attention to environmental aspects such as the review of target materials, under the premises of DNSH rules, or the radiological impact expected both at 3TeV and 10 TeV operation schemes.

Synergies

Due to its modularity, the Muon Collider may serve as platform to associate other facilities such as Neutrino Factories and radioactive beam facilities downstream the production target.

Some technologies to be developed in this study are synergic to identified key development lines such as High Field Solenoids (of common interest to basic sciences, medical applications, or energy). Energy optimization techniques find evident commonalities in other applications requiring large, pulsed power sources, and may profit or benefit of research on storage systems.

Interdisciplinarity

The project will provide a platform to discuss with expert of disciplines from particle physics, accelerator physics, accelerator operation or energy optimization, among others.

Dissemination

The communication strategy of the project will be done in close coordination of framework programs activities in the field of Accelerator Science and Technology, such as IFAST, and coordinated within the AS&T community via setting out communication program with TIARA and other bodies.

European leadership

We highlight that MuCol can impact on decisional processes outside Europe, such as the Snowmass process in US. This proposal will be a relevant support for the European community to remain at the forefront of the development of muon colliders, so that if the decision to build a muon collider is taken by other regions (US or Asia), European institutes can be considered as strategic partners to collaborate on that project, while if it is finally decided to be built at Europe, it will be set out the ground for communities from other regions to participate at our project.

TIARA recommendation

In conclusion, TIARA strongly supports the MuCol proposal as a realistic approach towards a design of a new muon collider accelerator complex at 3 TeV center of mass energy, and ramping up to 10 TeV. The outcome of the project will consolidate a solid step within the European Particle Physics Strategy towards the feasibility of a Muon Collider complex in Europe. Based on a clear physics case and on a thorough assessment of the accelerator complex, this project will push Europe to a leading position on the world initiatives on this topic.

Signed: José Manuel Pérez.
TIARA Coordinator.

Signed: Eugenio Nappi.
TIARA Chairman.

Annex 1

Information concerning TIARA can be obtained from http://www.eu-tiara.org

TIARA consortium is composed by the following institutions:

- CEA (FR), represented by Pierre Vedrine
- CERN (International Organization, CH), represented by Mike Lamont
- CNRS (FR), represented by A. Lucotte
- CIEMAT (ES), represented by Jose M. Perez
- DESY (DE), represented by Wim Leemans
- GSI (DE), represented by Peter Spiller
- INFN (IT), represented by Eugenio Nappi
- PSI (CH), represented by Leonid Rivkin
- RTU, on behalf of the Baltic Consortium[1], represented by Tom Torims
- STFC (UK), represented by Jim Clarke
- UU (SE), on behalf of the Nordic Consortium[2], represented by Tord Ekelof
- IFJ-PAN (PO), represented by Tadeusz Lesiak

TIARA meetings

The committee examined the Design Study proposal during its meetings of

- November 3, 2021 in Frascati, IT
- March 29, 2022 at CERN, CH

TIARA internal referees for this project:

- Jose M. Perez (CIEMAT)
- M. Vretenar (CERN)
- Roy Aleksan (CEA)

[1] The Nordic Consortium represents institutions of Denmark, Finland, Norway and Sweden.
[2] The Baltic Consortium represents institutions of Lithuania, Latvia and Estonia.

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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Geneva, April 15, 2022

Dear Sir or Madam,

As CERN's Director for Accelerators and Technology, I am writing in support of the MuCol project proposal being submitted in response to the HORIZON-INFRA-2022-DEV-01 call. The goal of MuCol is to provide a coherent concept for an infrastructure for the production and collision of high energy and high luminosity muon beams.

The 2020 Update of the European Strategy for Particle Physics (ESPP) stipulated that a to be established accelerator R&D roadmap should contain: *"…an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e+e– colliders, and potentially within a more compact circular tunnel than for a hadron collider"*. A conceptual design study for a muon collider shall be available in time for the next ESPP update foreseen for 2027.

Other options for a future European flagship collider include the Future Circular Collider (FCC) and the Compact Linear Collider (CLIC). The former is in the feasibility study phase, the latter is at a well-developed conceptual design stage. Both would be major enterprises with significant budgetary and geographical footprints. The muon collider concept has a well-motivated physics case and is pursued in parallel because it represents an innovative approach with a potentially smaller footprint than those of FCC and CLIC.

In 2020, following the ESPP update, CERN agreed to host an international muon collider study with wide-ranging participation from across the ERA. The accelerator R&D roadmap sanctioned by the ESPP was duly published at the end of 2021 and included a detailed breakdown of the way forward for "Bright muons beams and Muon Colliders". The study team has made good progress in parallel.

In short, the muon collider initiative is endorsed by the ESPP, has a long history of concept development, and a strong physics case, and widely supported by European institutes. The MuCol proposal is well structured with an engaged and committed community, there are strong technology synergies with other fields, and demanding technological innovation is required. The project gives Europe the chance to take a leading role in what could be a game changer for the field and develops what could be a potentially important component of the future RI landscape. Footprint considerations from a sustainability perspective are favourable in comparison with the other options.

I am happy to give my whole-hearted support to the proposal.

Yours sincerely

M. J. Lamont (Dr.)
Director for Accelerators and Technology