Proposal for DRD8
Mechanics & Cooling of Future Vertex and Tracking Systems

October 31, 2024

Corrado Gargiulo, Andreas Werner Jung, Andreas Mussgiller, Paolo Petagna,
Burkhard Schmidt, Georg Viehhauser
(Provisional DRD8 Steering Committee)

Diego Alvarez Feito, Joao Batista Lopes, Oscar Augusto de Aguiar Francisco, Sushrut Kamarkar,
Adam Lowe, Fabrizio Palla, Bart Verlaat
(Provisional DRD8 Work Package Conveners)

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1 Introduction

Modern particle physics experiments comprise large arrays of active detection elements and their associated front-end electronics, often integrated within highly congested spaces. They are supported by lightweight mechanical structures, which must provide exceptional stability and positioning accuracy. These structures also support the detector services and play a crucial thermal management role, helping to extract the heat generated in the sensors and readout electronics to ensure optimal operating conditions. Both the mechanical and thermal performance requirements must be fulfilled with minimal material usage, particularly within vertex and tracking systems in front of the active volume of calorimeters. However, the demands associated with future experiments call for even lighter and more efficient structures to capitalise on the continuous advances in sensor technologies and front-end electronics. The adoption of new design approaches to develop innovative solutions that make extensive use of advanced materials and novel manufacturing techniques will be essential for our sector to meet the challenge.

Due to the extraordinary operational environment (e.g. high radiation, strong magnetic fields, limited accessibility) and the unique set of requirements for particle detectors (e.g. ultra-high stiffness, efficient heat transfer, low material budget, small production volumes), off-the-shelf solutions cannot meet the needs of future experiments. While certain aspects of our work may have commercial relevance and could benefit from joint efforts with industrial partners, progress in this field must be led by our community. This Detector Research and Development (DRD) proposal aims to establish a structured framework and define a clear roadmap to drive innovation in our field, which will be crucial for the success of the next generation of detector systems.

As stated in the Letter of Intent submitted to the DRD Committee in February 2024, the activities of DRD8 will focus on mechanical supports, cooling and detector integration, with particular emphasis on semiconductor trackers. The research initiatives in these areas will be aligned with the main integration themes identified in the 2021 ECFA Roadmap [1]. Without focusing on the active detection elements, the work of the DRD8 collaboration will be carried out in the context of new developments in solid-state sensor technologies and front-end electronics. Thus, building strong links with both DRD3 [2] and DRD7 [3] will be vital to define meaningful specifications, performance targets and deliverables for our research.

The DRD8 collaboration aims to strengthen and widen the small but dedicated international community built around the Forum on Tracking Detector Mechanics, which takes place yearly since 2012. Moreover, it will be open and actively seek cooperation with industrial partners for the benefit of the particle physics sector. Despite a deliberate focus on semiconductor trackers at first, research on other detector systems and infrastructure will be also pursued if the interest level of the participating institutions so justifies.

This document is structured as follows: Section 2 outlines the organisation and governance of the proposed DRD collaboration. Sections 3 to 6 describe the areas of technical development, which are divided into four distinct work packages. Section 7 provides a summary of the expected deliverables and resources, while Section 8 discusses the relationship with other DRD collaborations.

2 Organisation of the Collaboration

The DRD8 collaboration emerged from the Forum of Tracking Detector Mechanics, a meeting of the community held yearly since 2012. In December 2023 the future DRD8 scientific programme was developed further in a dedicated community meeting, soliciting input to this program. A list of institutes interested to participate in this DRD collaboration is given in Appendix A.

The scientific organisation and the governance of DRD8 are outlined in the following sections. It includes bodies typical for collaborations in high energy physics, but tailored to the needs of the relatively small community involved in our research topics. At this point in time this represents a proposal for the organisation. The final structure of DRD8 will be decided by the Collaboration Board once the collaboration has been approved.

2.1 Scientific Organisation

The scientific work in the collaboration is organised in R&D projects, each with a well-defined scope outlined for an initial duration of three years (36 months) after the official start of the collaboration. The projects are grouped into four development areas (organised as Work Packages, WP):

- Global system design and integration (WP 8.1)
- Low-mass mechanics and thermal management (WP 8.2)
- Detector cooling (WP 8.3)
- Design and qualification tools (WP 8.4)

The majority of contributors to DRD8 have been involved in R&D on Tracking Detectors for the upgrades of the four large LHC experiments. While some are still strongly involved in the completion of the Phase II upgrades of the ATLAS and CMS trackers, others are already participating in funded R&D for future detectors (ALICE 3, ePIC, Mu3e etc.), which pursue progress in many of the target fields of the DRD8 programme as listed above. Therefore, improving opportunities for networking, information exchange and access to equipment and/or facilities in the framework of the ongoing development projects will be one of the priorities for DRD8. However, no specific R&D projects are defined in this proposal for these rather well defined detectors.

The main focus of DRD8 will be the management of a limited set of R&D projects (two per WP). These R&D projects will target key overarching and generic aspects and opportunities within the DRD8 programme that show great potential for significant development leaps and are to some extent visionary, but have limited prospect of funding as part of a specific experiment, because their scope is too broad or speculative at this point. These will be pursued through international collaboration of several groups. Resources to implement these projects will be sought in a coordinated way through the collaborators from national funding agencies and large laboratories. The number of R&D projects is limited to be compatible with the number of groups within the community.

The collaboration will remain open to additional R&D projects, subject to management capacity, and intends to evolve in the long-term. New project proposals will be first reviewed and pre-selected by the respective Work Package conveners and subsequently passed to the Steering Committee for final selection and proposal to the Collaboration Board. Changes to running projects (in scope or participating institutes) will be handled in a similar way.

A third group of activities under the umbrella of DRD8 will be (new) research activities undertaken by (small collaborations of) member groups that will not be managed by the DRD8 organisation, but address research goals within the DRD8 portfolio. Such projects can be submitted for endorsement to the DRD8 Steering Committee, to strengthen their case when applying for funding. DRD8 will maintain a list of endorsed projects on the collaboration web site. DRD8 will also support these activities by networking and providing a platform for information exchange, and it will help these activities by organising reviews of these projects on request from the research group, the results of which can be shared with funding agencies.

Finally, DRD8 will also set up a repository for information obtained from research undertaken in all activities within the DRD8 framework. This will comprise reports, slides from talks, technical reports and proposals, but also databases of material data, and software for general use, together with its documentation.

2.2 Governance

The main governing bodies of the DRD8 collaboration are the Collaboration Board (CB), the Steering Committee (SC), and the Resources Board (RB). The scientific structure of the collaboration is represented by the Work Package Conveners. Work Package Conveners and Steering Committee constitute the Technical Committee. Collaboration membership is defined by contributions to one or several DRD8 projects. The structure of the DRD8 collaboration is illustrated in Fig. 1

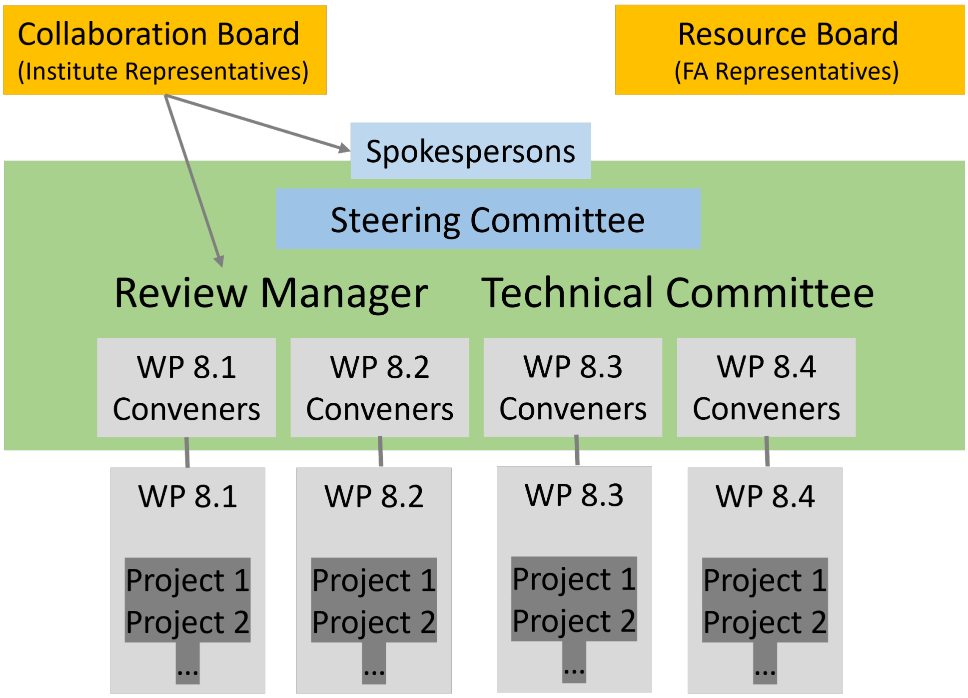

Figure 1: Structure of the DRD8 collaboration

- The **DRD8 collaborating institutes** are the project contributors. They are participating in one or more of the Work Packages corresponding to their project development area, as defined in the scientific structure of the collaboration. DRD8 encourages the participation of industrial partners as collaborators. The exact arrangements for the management of IP will be defined in detail in the MoU.

- The **Work Packages** are led by **Conveners** (two per Work Package) who manage the R&D projects within their WP. They also animate regular meetings where progress of the R&D projects is monitored and contributors to their WP are invited to present results and to exchange ideas for all activities within their WP. Conveners also organise and chair the WP sessions during the periodic DRD8 collaboration meetings, one of which will be scheduled in conjunction with the annual Forum on Tracking Detector Mechanics. The conveners aggregate also the material for the annual DRD8 progress report, and ensure that results and data of general interest are stored in the DRD8 repository.

The usual term for WP conveners is 3 years, after which their tenure is subject to renewal.

- The **Steering Committee** (SC) guides the collaboration and represents it to the outside world, in particular to the DRDC. The SC follows the progress and activities of the Work Packages. It updates the R&D vision of the Collaboration and calls regular DRD8 meetings to report publicly on the progress of the R&D effort. Each year, the SC issues the annual DRD8 progress report and presents it to the Collaboration Board. The SC nominates Work Package Conveners, to be approved by the Collaboration Board.

  The SC proposes a Chairperson and a Deputy from its members for approval by the Collaboration Board. Chairperson and Deputy jointly chair the committee and serve as the **Spokesperson** and **Deputy Spokesperson** of the collaboration, constituting the main representatives and contact points. The term of office is one year, and while extensions are possible, rotation among the members is desired.

  The SC consists of six to eight members. The term of membership in the SC is normally three years, renewable once. To ensure continuity as well as changes in membership, each year up to two members of the SC will be replaced. Candidates are expected to be identified by an ad-hoc search committee mandated by the Collaboration Board, and are elected and appointed by the Collaboration Board.

  Two places within the SC should be reserved to junior members of the community (at the equivalent level of a post-doc or below), both to ensure the representation of fresh viewpoints, and to raise young talents and familiarise them with high-level management of hardware particle physics projects.

  The composition of the SC should strive for the diversity beneficial to all particle physics projects.

- The Work Package Conveners and the Steering Committee collectively form the **Technical Committee** (TC), which tracks projects, organises internal reviews and monitors progress. It is the TC that issues recommendations to the projects and drafts the annual DRD8 progress report. The TC will also approve presentations and publications in the framework of DRD8. It is expected that concrete procedures will be worked out and documented in the initial phase of the collaboration.

- The **Collaboration Board** (CB) is the scientific and technical representation of the collaborating institutions. Each contributing institute sends one representative to the CB. The board meets at least once per year to discuss progress and vision. It approves the annual DRD8 progress report, the eventual proposals for new projects, work packages and contributors, appoints the Steering Committee members and endorses the Spokesperson, Deputy Spokesperson and the Work Package Conveners nominated by the Steering Committee. To provide oversight, members of the CB should, where possible, not be members of the Technical Committee.

  The Collaboration Board elects a chairperson from among its members, who will serve for a period of two years. A renewal is possible, but a rotation among institutes is desired.

- The Collaboration Board also appoints a **Review Manager** (RM) for DRD8. The task of the RM is to set up regular technical reviews of the DRD8 R&D projects (or parts of them) to provide critical input and to help the projects to achieve the milestones and deliverables in time. The RM will set up the review panel (with some participation of experts outside DRD8 encouraged) and its chair, define together with the WP conveners the remit for each review, and set the time and place of the review in coordination with all parties involved. After the review the RM will ensure that a written report of the findings of the panel is distributed to the parties involved and the Steering Committee, and filed in the DRD8 repository, together with other relevant information from the review. The RM can supply funding agencies with the review reports on request. The RM can be a member of the Steering Committee.

  On request by the involved parties, the RM will provide the same support for the review of other research activities within the framework of DRD8.

- The **Resources Board** (RB) represents the funding agencies supporting the projects in the collaboration. This representation can be through representatives of collaborating institutions, or delegated to a body acting on behalf of one or several institutions. The RB meets at least annually. It approves the annual DRD8 progress report and the eventual proposals for new projects and contributors.

2.3 Formation of the DRD8 Collaboration

As mentioned earlier, the DRD8 collaboration has emerged out of the Forum on Tracking Detectors Mechanics. In this process, DRD8 has been guided by an ad-hoc Steering Committee, which has evolved from the membership of the organising committee of the Forum of Tracking Detector Mechanics. This preliminary Steering Committee has appointed an original team of Work Package Conveners, who in turn have guided the proposal phase for the first set of projects of the collaboration.

Once DRD8 is approved, the transition to the regular governance structure described in section 2.2 will be managed in a smooth way. As a first step, the Collaboration Board will convene to elect its chair. The board members will then be asked for nominations of Steering Committee members, with the majority of current Steering Committee members expected to be willing to continue in their role for at least another year and being available as candidates. The Collaboration Board will then elect the members of the Steering Committee. Once in place, the Steering Committee will propose the Work Package Conveners, again with the expectation that the majority of those currently active in these roles will be willing to continue while being open to nominations, rotation and increased diversity wherever possible. From the second year on, the rolling renewal of the Steering Committee will enter into effect, subject to Collaboration Board approval.

2.4 Education and Training

One aspiration of the DRD collaborations is training of junior members of the community. DRD8 is too small and its research topics too narrow to justify stand-alone schools or similar. However, we will identify lecturers for lecture courses on relevant topics, and facilitate exchange of educational material among these lecturers. The lecturers will then participate in other schools to be organised within the DRD collaborations and outside (e.g. CERN summer school, ECFA summer school, EDIT).

3 Work Package 1: Global System Design and integration

This Work Package focuses on the design, integration, and monitoring of the next generation of detectors for particle physics experiments. The primary objectives involve researching and developing the global mechanics of future detectors, including their installation, service integration, life cycle, and interfaces with future colliders. Another key focus of the work package is the exploration of remotely operated robotic systems for the inspection, maintenance, and handling of these detectors within the experimental cavern. These goals are streamlined into two major programs named: (i) The vertex region of future collider experiments and (ii) Robots in the experimental caverns.
The first program is dedicated to designing and integrating the next generation of vertex detectors and beampipes, with an emphasis on moving closer to the interaction point and reducing the material budget while improving the mechanical stability. To meet these ambitious requirements, the project will explore the design, manufacturing and integration of innovative solutions such as ultra-thin beampipes, ultra-light silicon detectors with curved sensors, and a retractable vertex detector placed inside the beampipe.
The second program focuses on the development of robotic systems capable of operating in harsh environments for inspecting and maintaining particle detectors, as well as monitoring the cavern even during the beam run. To achieve these goals, different robotic platforms, both ground and aerial, such as legged robots and airships, are currently under development along with a mesh network to ensure an uninterrupted communication among the robots within the cavern.

3.1 Project 1.1: The Vertex Region of Future Particle Physics Experiments

Project Description

The unprecedented requirements for minimum material budget, mechanical stability, and proximity to the beamline necessitate the development of new design solutions for the beam pipes and vertex systems for future particle physics experiments. Furthermore, to achieve the largest luminosity, the e^+e^- colliders require to be put in collision with a very complex optics, where accelerator components are inside the experimental apparatus, posing integration issues with the innermost detector layers. Standard solutions currently available do not meet these specific requirements, making this research and development programme crucial for preparing the ambitious design of future beam pipe and detector mechanics.
Within this context, this project focuses on the development of the next generation mechanics for advanced layouts, including ultralight beam pipe, curved and tilted sensors, low radii vertex systems and retractable detectors for future High Energy Physics experiments.

- **Curved sensors**
  This subproject aims at developing new wafer-scale curved silicon pixel chips to surround the beam pipe and minimise on detector services, profiting of the experience developed at CERN for the ALICE Experiment. This concept has the potential to reduce the material budget of the concerned layers significantly and to bring the first hit point outside the beam pipe closer to the interaction point. First simulations of a light ($\frac{x}{X_0} = 0.1\%$) layout indicate significant benefits to the physics performance. Together with the design of the chip, an innovative air cooling system [4, 5] and mechanical support made of carbon foam [6, 7] will be further developed.

- **Thin beam pipe**
  At CERN, current beam pipes are made from beryllium and have, for example, a thickness of 0.8 mm with a minimum inner radius of 18.2 mm in ALICE. For Run-4 ALICE is aiming for a 16 mm inner radius and 0.5 mm wall thickness still made from beryllium, while the 10 mm radius beam pipe of the FCC-*ee* requires to be cooled with liquid paraffin flowing in a double layer of 0.35 mm thick beryllium walls. These are unprecedentedly thin pipes at the limit of the present

technologies to achieve wall impermeability. To push these limits even further, future R&D will focus on alternative beam pipe materials like alloys of beryllium and aluminium (Albemet), and carbon composites.

- **Retractable detectors**
  A collaboration with the CERN TE-VSC group has already started at CERN for the development of a retractable vertex detector, inside the beampipe [8]. Apertures, impedance and vacuum stability at the interaction points are key beam parameters both for the safe operation of the LHC machine and to obtain the best physics performance from the experiments. Going closer to the beam with the vertex detector petals has a direct impact on these parameters.

- **Integration of accelerator and vertex detectors**
  In order to achieve and exploit the high luminosity of the FCC-*ee* or the CEPC, the electrons and positron beams must be focused and put in collision with a complex optics, the elements of which are placed very close to the IR, within the detector volume. The assembly of the detector must cope with tight requirements to guarantee a high luminosity, and at the same time allow the operations and maintenance of detector elements difficult to access.

- **Low-mass hardware alignment systems for future tracking detectors**
  Achieving the ultimate performance of a tracking detector ultimately often depends on the quality of its alignment. Especially weak degrees of freedom, often linked to the direction through the sensor thickness, can be limiting factors. We propose to develop a solution to provide information that is complementary to that available through track-based alignment algorithms and that is low-mass and radiation-hard.

Performance Targets

To achieve the desired pointing resolution in future particle physics experiments, it is crucial to measure the first hit as close as possible to the interaction point while minimising the material in front of the first layer to reduce multiple scattering. One approach in the R&D effort involves reducing the diameter and thickness of the beam pipe, pushing technological boundaries, and surrounding it with curved silicon sensors. In parallel, to address the limitations imposed by beam operation and injection, which require a minimum beam pipe radius and constrain the position of the first layer, the concept of placing the first layers inside the beam pipe is considered, with the ability to retract the layers during injection.
The overall goal of this project is to explore the next generation mechanics for advanced layouts, investigating the design, manufacturing and system integration challenges of new components like a carbon beam pipe, a vertex detector located inside the beam pipe and tilted and curved silicon pixel chips.
The progress and test results will be tracked via public reports in the form of presentations, public notes and/or papers.

Milestones and Deliverables

Label	Topic	Month	Description
M1.1.1	Curved and tilted sensors	12	Demonstrate curved and tilted sensors bringing the first hit point closer to the interaction point.
D1.1.1	Carbon beam pipe	24	Deliver an ultra-thin vacuum beam pipe (carbon, beryllium, Albemet) for primary and secondary vacuum compatible with vacuum operational requirements.
M1.1.2	Retractable detectors	36	Develop a design for a retractable vertex detector with minimum material budget that could withstand the primary and secondary vacuum.
D1.1.2	Mock-up & integration	36	Delivery of a mock-up of the interaction region with integration of vertex detector and services.

Multi-disciplinary and transversal content

Global system design and integration are critical aspects to consider in view of the advanced layouts for the next generation vertex detector mechanics. There is potential collaborations with DRD7 and DRD3 which will be covered by communications via the respective liaisons and workshops (e.g. Forum on Tracking Detector Mechanics).

Contributors and areas of competence

Preliminary list of the institutes involved in WP1.1:

- CERN: Global carbon composite light-weight mechanics, tracker and vertex ultra-light mechanics and cooling, large surface curved silicon detectors, and retractable vertex inside the beampipe.
- IHEP/CAS:The Institute of High Energy Physics (IHEP), a Chinese Academy of Sciences research institute, is China's biggest laboratory for the study of particle physics. IHEP has been successfully constructed and operated Beijing Electron-Positron Collider and its upgrade project BEPCII, and BESI/II/III. We have built the beryllium beampipe for BESI/II/III and proposed the design for the CEPC.
- GSI Darmstadt: Access to a mechanical workshop for aluminium mould production and CF manufacturing with industrial partners. The intention is to prototype a fully-composite, thin-wall CFRP conical beam pipe for secondary vacuum applications for the CBM-FAIR experiment.
- INFN Pisa: Participation to several HEP tracking and vertex detectors (CDF, ALEPH, BaBar, Belle-II, CMS) with contributions to the design, fabrication, assembly and system integration tests. The laboratory is equipped with a large (500 m^2) clean room and a thermo-fluid-dynamic workshop.
- INFN Perugia: Numerical simulations and characterization of material properties.
- INFN Frascati: Thin and light beam pipes design and fabrication. Integration of accelerator and vertex detectors. The expertise comes from the DAFNE collider construction and is now continuing with a project on a full-scale FCC-*ee* MDI mockup. We will be interested to develop beryllium and carbon fibre beam pipes.
- Nikhef: Expertise in the design and quality control of ultra-high vacuum (UHV) systems, with capabilities in manufacturing UHV components and movable systems.

- IPHC Strasbourg: Vertex detector design and prototyping. Based on curved MAPS sensors, covering for integrations aspects: mechanics, services (power+data transmission) and cooling
- IFIC Valencia: Tracker and Vertex detectors design and construction. Integration of CMOS sensors with mechanical support, signal and power lines and cooling
- University of Geneva: Design of light carbon fibre structures, including optimization of detection modules in terms of material budget and thermal performances. These competencies have been applied for the ATLAS ITk currently under construction.
- University of Liverpool: Design and construction of HEP vertex and tracking detector systems, manufacture of composite structures
- University of Oxford: Design and construction of HEP vertex and tracking detector systems, manufacture of composite structures
- University of Bristol: Design and construction of HEP vertex and tracking detector systems
- University of Freiburg: Silicon detector development and construction and tracker alignment.

Estimate of resources

Table 1 gives a summary of the existing and required effort in terms of human resources and material budget for WP1 Project 1 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. In the case of CERN the resources are allocated through the R&D Programme on Experimental Technologies of the EP department, for which the objectives have been defined in [9]. Resources have been included in this project to the extent that they are aligned with the EP R&D Programme. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 1: Summary of available and required resources for WP1 Project 1.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
CERN	1.0	1.0	100	100
IHEP/CAS	0.5	1.0	50	100
GSI Darmtadt	0.2	0.4	0	10
INFN Pisa	0.5	1.0	50	90
INFN Perugia	0.5	0.5	0	30
INFN Frascati	0.5	1.0	100	500
Nikhef	0.5	1.0	20	50
IPHC Strasbourg	3.0	4.0	10	10
IFIC Valencia	0.5	1.0	300	300
University of Geneva	0.5	0.5	10	10
University of Liverpool	0.5	1.0	0	50
University of Oxford	0.5	1.0	0	100
University of Bristol	0	0.5	0	100
University of Freiburg	0.5	1.0	10	30
Total	**9.7**	**15.4**	**650**	**1530**

3.2 Project 1.2: Robots in the HEP Experimental Caverns

Project Description

The CERN underground particle detector areas consist of large semi-structured caverns housing the particle detector, with high magnetic fields and radiation levels present. The complex and delicate equipment in these sites requires frequent scheduled maintenance and inspections, currently carried out by human personnel. However, future particle accelerators and detectors will encompass areas with even higher radiation doses at levels that constitute a serious risk to human operators [10].
To allow maintenance under these conditions, this project focuses on the provision of robotic systems to future high energy physics experiments to inspect and monitor particle detectors even during the operation of beams. The employment of these robotic systems for autonomous and on-demand inspections and 3D environmental mappings will help to reduce accelerator down-time, for instance by preventing unnecessary beam dumps due to false alarms, by detecting anomalies at an early stage, and by constantly monitoring operation of the experiments, and will preserve personnel health [11].
In order to achieve a reliable and robust environmental monitoring, several mobile platforms, both ground and aerial, with specific payloads have been identified and will be developed in three different subprojects:

- **Legged ground robotic platforms**
  This subproject aims at developing legged ground robotic platforms for the autonomous and on-demand inspection with dedicated sensor suites, patrolling all the walkable areas. These robots are characterised by a high payload, allowing them to be equipped with a wide variety of sensors, and an enhanced mobility, which makes them suitable to operate inside cluttered environments with the presence of stairs and obstacles such as the detector cavern.

- **Robotic airships**
  This subproject aims at developing Lighter-than-Air Unmanned Aerial Vehicles (LtA UAV), such as blimps, to provide a 3D environmental mapping of the background magnetic field and radiation dose of the whole cavern volume by employing a custom lightweight payload. Blimps are characterised by a low battery consumption and they pose a low risk to surrounding detector equipment in case of failure [11, 12].

- **Mobile mesh network**
  This subproject investigates the use of a swarm of mini robots to visually inspect tight and cluttered confined spaces, aiming at spotting leaks and anomalies among the intricate detector services. In such a scenario, a mobile ad-hoc mesh network that guarantees an uninterrupted communication within the swarm has to be developed to ensure that information originating from the deepest robot inside the experiment can reach a robot outside, which provides a link to the main network.

In the future, this project will also aim at developing manipulation capabilities for the robotic systems for first intervention, and detector maintenance or removal, minimising personal exposure to harsh radiation environments.

Performance Targets

The overall goal of this project is to develop robotic systems able to operate within the harsh detector cavern environment and provide a comprehensive 3D environmental mapping as well as the ability to inspect the detector.
As for the legged robotic platform and the robotic airship the main deliverables are to develop robots able to operate in the high intensity cavern background magnetic field, and to perform autonomous inspection/mapping of the environment. The mobility and controllability of such robots have already been

successfully tested in a detector cavern without magnetic field, and tests have been carried out to investigate the magnetic disturbances on electromagnetic actuators, which are the components most likely to fail under these conditions. Future work will develop new shielding solutions, investigate potential different actuators, build a robust control system including a reliable model for the magnetic disturbance estimation, and develop a virtual environment to simulate the robotic systems before testing them in the cavern.
For the interconnected swarm of mini robots the main deliverable will be the successful inspection of a cavern with confined spaces, keeping a continuous and efficient data stream. A mobile ad-hoc mesh network has been already developed integrating the BATMAN protocol to ensure that the information is transferred to an external robot that is connected to the main network, via the shortest and least congested path in the swarm. Future work will develop a strategy to move the swarm within the confined space, minimising the connection losses, and providing automatic reconfiguration of the external robot in case the connection with the main network breaks down.

Milestones and Deliverables

Label	Topic	Month	Description
M1.2.1	Mobile mesh network in cavern	12	Demonstrate a robust ad-hoc mesh network ensuring an efficient data stream within a cavern confined space.
D1.2.1	Legged robots and robotic airships in magnetic field	24	Deliver robots able to counteract the background magnetic field disturbances.
D1.2.2	Legged robots and robotic airships in cavern	36	Deliver robots able to perform an autonomous inspection/monitoring of the detector cavern environment.
M1.2.2	Legged robots and robotic airships control system	36	Develop a robust control system including the magnetic disturbances.
M1.2.3	Mobile mesh network cavern inspection	36	Inspect a cavern with confined spaces with an uninterrupted data stream.

Multi-disciplinary and transversal content

The development and test of robotic systems able to operate in harsh environments are crucial activities for the inspection/monitoring of both current and future HEP experiments. There are potential collaborations with DRD3 for the radiation sensors with which the robot payloads must be equipped, and with DRD7 for the development of radiation-hardened electronics and data processing technologies. The advancements in this area will be communicated through the respective liaisons and workshops.

Contributors and areas of competence

Preliminary list of the institutes involved in WP1.2:

- CERN-EP-DT: Test and simulation of magnetic field disturbances on robotic systems, autonomous measurement of radiation levels, design and development of aerial robotic, development of mesh networks for multi-robot systems, development of indoor navigation systems and payload design.
- CERN-BE-MRO: Software development for robotics and robotic assistance for particle accelerators.
- IHEP/CAS: So far limited experience but strong interest in detailed studies of the Legged Ground Robotic Platforms.

- La Sapienza University of Rome: Guidance, navigation, and control systems for robotic airships.
- University of Arizona: Design and control of robotics systems.

Estimate of resources

Table 2 gives a summary of the existing and required effort in terms of human resources and material budget for WP1 Project 2 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. In the case of CERN the resources are allocated through the R&D Programme on Experimental Technologies of the EP department for which the objectives have been defined in [9]. Resources have been included in this project to the extent that they are aligned with the EP R&D Programme. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 2: Summary of existing and required resources for WP1 Project 2.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
CERN	2.0	2.0	100	100
IHEP/CAS	0.0	1.0	0	100
Roma I (La Sapienza)	0.5	0.5	10	10
The University of Arizona	0.5	0.5	10	10
Total	**3.0**	**4.0**	**120**	**220**

4 Work Package 2: Low-mass Mechanics and Thermal Management

This Work Package focuses on the advancement of low-mass mechanics and integrated thermal management for the next generation of vertex and tracking detectors for HEP experiments. We will achieve these objectives through the application of advanced materials and manufacturing techniques, and by challenging existing design paradigms. These activities will be helped by another key focus of this work package, which is the qualification of materials with a focus on their application in High Energy Physics. This will include selection of test standards, collation of data, inter-lab certification and development of a database through which the data can be accessed.

Section 4.1 outlines a project that will pursue novel approaches to tracking detector design. Emphasis is placed on reducing material mass significantly through the application of advanced materials, optimising structures around orthotropic material characteristics and revisiting conceptual detector geometries.

Section 4.2 describes activities towards developing a material database aimed at servicing the HEP community and those designing the next generation of particle physics detectors. Part of the work will revolve around inter-lab certifications, multiple test piece validation and identification of novel test practices, where existing standardised test practices may not exist.

4.1 Project 2.1: Advanced Mechanical Tracker Structures

Project Description

The goal of this project is to challenge particle physics tracking detector design paradigms with an unhindered and blue-sky approach making use of modern materials as well as design and manufacturing techniques. The traditional, standard approach of simplistic, planar geometries will be revisited. Working from fundamental design criteria that must be respected, this project will aim to investigate how detector structures can be improved when embracing advances in materials, manufacturing techniques, and subsequently the design and analysis that accompany this. Splitting design, analysis and testing tasks across the work package, this project will aim to holistically address the following potentially large improvements in tracking detector mechanics:

- **Orthotropic materials** and exploitation of optimised mechanical and thermal performance in each direction whilst minimising material budget;
- **Non-planar structures**, and **complex** (non-traditionally manufacturable) **geometries** utilising Advanced Digital Manufacturing (ADM) techniques such as Additive Manufacturing (AM), Hybrid Manufacturing and tow-steering;
- **Integration of services**, such as cooling channels, into mechanical structures to reduce overall material budget and increase mechanical performance;
- Development, where appropriate, of **tools** to help predict and optimise the performance of detector support structures featuring orthotropic materials, complex geometries and/or integrated services produced with advanced manufacturing techniques;
- **Non-Destructive Testing (NDT)** and other forms of **Quality Assurance/Quality Control (QA/QC)** that will guarantee quality of non-traditional, homogeneous or isotropic structures. Long term reliability testing processes will also be considered and implemented;
- Potential **tie-in with other DRDs** will be investigated to help inform the design work.

It is foreseen that all of the above sub-topics are likely complementary to one another, and as such should be seen as a broader, more general common topic of revisiting fundamental concepts of mechanical support structures.

Performance Targets

The overall goal of this project is to make fundamental advancements in the mechanical engineering that supports tracking detectors, allowing for a blue-sky approach. We therefore expect that the direction of the programme will follow emerging opportunities as the research and development work progresses.

In the application of **orthotropic, composite materials** we aim to significantly reduce radiative material of mechanical structures compared to traditional approaches. We will investigate structures exhibiting differing desired behaviours in multiple axes, composite structures involving complex co-cures, and thin coating techniques to optimise surface characteristics of the structures, and demonstrate the expected performance.

The investigation into the **utilisation of non-planar structures** will look at **advancements in manufacturing techniques** and how such techniques can deliver complex mechanical geometries which will improve detector performance, by increasing mechanical, thermal and radiative properties. Where possible, prototype demonstrators will be produced to verify the manufacturing and design concepts.

As the use of composite materials increases and the complexities of the laminates and co-cured structures evolves **integration of services and thermal management** into these structures will become an attractive approach to reducing material mass, sharing mechanical support across structures and improving reliability by reducing failure points. This approach is commonly used in motorsport and aerospace applications, and understanding how future detectors may benefit from this integration will be a key output.

As understanding of the material behaviour is advanced it will be important that **tools are developed** to aid design, analysis and manufacture to account for this more complex material behaviour, or to investigate performance parameters only of interest within HEP. The efficacy of these tools will be confirmed via, in part, the testing programme outlined in project 2.2.

The adoption of the new approaches outlined above for detector applications, where reliability is paramount, will require development of new **Non-Destructive Testing (NDT), Quality Assurance (QA) and Quality Control (QC)** techniques. The work on this area will focus on novel inspection techniques to understand the failure modes of the structures and identify potential manufacturing defects, using simplified prototypes to validate their effectiveness. Techniques that will allow monitoring and evaluation of long-term reliability will also be investigated - with potential to exploit cross-overs with project 1.2.

The potential detector performance benefits realised from all of the subtopics above will be documented within the yearly design reports, following standard levels of maturity within designs that can be seen in the **Milestones and Deliverables** section below. This is how the output of these sub-topics will be judged.

Milestones and Deliverables

Label	Topic	Month	Description
M2.1.1	Design specifications	6	Design specifications are needed to ensure that the pursued designs have relevance. They will be based on current generation detector specifications and informed estimates of requirements for future detectors.
M2.1.2	Pre-Concept Design Report	12	This pre-Conceptual Design Review (pre-CDR) report will evaluate and report advancements in the areas mentioned above. It will guide and steer the direction of work over the following 12 months.
M2.1.3	Concept Design Report	24	This CDR will evaluate and report advancements in the areas mentioned above at an elevated level of maturity. The collaboration will look to use standard definitions and gateways for CDRs to judge the feasibility and potential impact of the work.
D2.1.1	Production of simple prototypes for NDT Testing	24	Produce simplified prototypes of designs that have emerged during the course of the project. These simple prototypes will be used to evaluate NDT techniques and QA/QC.
M2.1.4	Critical Design Report (CrDR)	36	Produce a full critical design report of the work carried out within the project, evaluating the potential improvements in performance based on in-depth numerical simulations and prototypes. The report will outline the work and where areas of value have been identified.

Multi-disciplinary and transversal content

The overlap with other projects in DRD8 are multiple and manifold. It is therefore imperative that progress is reported at collaboration meetings and workshops. Furthermore, work in other DRDs, including DRD3, DRD4 and DRD7 will be be essential in the early phase of this project, to define a relevant set of specifications and subsequently heavily inform the appropriate direction of work being carried out.

Developments in this project will be of interest to the aerospace, automotive and defence industries, where lightweight structures, integrated thermal management solutions, complex geometries and harsh environments are also prime targets. Some of the advancements led by our community in these areas have attracted industrial interest. We will therefore ensure that relevant commercial advisory bodies are made aware of any significant advancements achieved.

Contributors and areas of competence

- CERN (EP-DT): Composite manufacturing, detector design, analysis, testing, assembly and operation expertise.
- DESY: Composite manufacturing lab (incl. autoclave, tape layer robot, pattern cutting). Material testing.
- GSI Darmstadt: Simulation of complex air cooling for low-mass tracking detectors, leveraging OpenFOAM for high-performance computing with access to the Virgo computing cluster at GSI.

- Nikhef: Facilities for testing and qualification of materials with extensive experience in advanced design for detector components.
- Purdue University: Composite and adhesive based material testing and Non-Destructive Testing (NDT), quality assurance and quality control
- University of Oxford: Design and manufacture of lightweight composite UHV structures and orthotropic mechanical structural analysis. Clean composite manufacture and expertise with tow-spread materials. Co-curing of structures and services.
- University of Liverpool: Composite design, analysis and manufacture.
- Bristol Composites Institute: Cooling integration in composite structures, novel over-braiding techniques.
- National Composites Centre UK: Development of advanced composite structures
- STFC RAL: Composites and materials testing, additive manufacturing facility, metrology, chemistry and safety.
- INFN Pisa : Design and build of vertex detectors for HEP, knowledge of detailed problematics of vertex detector integration.

Estimate of resources

Table 3 gives a summary of the existing and required effort in terms of human resources and material budget for WP2 Project 1 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. In the case of CERN the resources are allocated through the R&D program on Experimental Technologies of the EP department for which the objectives have been defined in [9]. The extent to which these resources will be applied to DRD8-specific activities will depend on the degree of alignment with the approved objectives and deliverables in the EP R&D Programme. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 3: Summary of available and required resources for WP2 Project 1.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
CERN	2.0	2.0	100	100
DESY	0.2	0.5	0	10
GSI Darmstadt	0.2	0.5	0	5
Nikhef	0.5	0.5	10	50
Purdue University	1.0	2.0	15	50
University of Oxford	1.0	2.0	50	100
University of Liverpool	0.7	1.7	0	45
Bristol Composites Institute	1.0	1.5	4	50
National Composites Centre	0.1	0.5	1	10
STFC-RAL	0.5	1.0	10	30
INFN PISA	0.5	0.8	0	50
Total	**7.7**	**13.0**	**190**	**500**

4.2 Project 2.2: Characterisation of Material Properties and Database Development

Project Description

Particle physics detectors are increasingly pushing the limits of materials due to higher integrated luminosities, resulting in radiation-induced degradation. Future detectors and accelerators will need stiffer, low-mass structures, integrating thermal and electrical services, in order to minimise the radiation length and the consequent impact of multiple scattering on measurement resolution. For the development of future detectors, such as those foreseen at the FCC, and other experiments worldwide, a centralised database with validated material data would be of high value to the HEP community. This will optimise the resources allocated to material testing, avoiding redundancies while making data available for thermo-mechanical simulations and informed detector designs.

Currently, detector and accelerator components are often designed based on ad hoc material testing and characterisations performed at different institutes. In some cases, material properties used in simulations are either guessed or sourced from a very limited literature.

The goal of this project is to create a collaborative community for material characterisation across countries and institutions. It is crucial to establish standardised procedures for testing and reporting material properties. Standardising material testing for thermal and mechanical properties requires establishing clear protocols and guidelines that ensure consistency, and reproducibility across different laboratories and institutions. This project will pursue a structured approach that will help to achieve standardisation.

Previous efforts in this domain have been set up for more specific needs and have served the community in the past, such as the design and construction of LHC (CERN Yellow Reports) and later in major HEP experiment upgrades programs (IMHOTEP[13], MaxRad[14]).

- **Material testing protocols -** HEP applications need different critical material properties based on the category of materials (e.g., adhesives, thermal interface materials (TIMs), polymers, composites). The goal of this project will be to identify ISO / ASTM standard test procedures for each material category, document step-by-step testing procedures including specimen preparation, testing equipment, environmental conditions, and measurement techniques that can be recreated across the laboratories using controlled environmental conditions. For radiation-dependent material properties, pre-irradiated material property measurement as well as irradiated material property for degradation model building shall be carried out using available irradiation facilities.

- **Documentation and database development -** The goal of this subproject is the development of a database, covering material characterisation data and offering a standardised documentation of testing campaigns across the participating laboratories. This will make use of existing database engines and will be based on available platforms to keep it accessible and user-friendly. The defined comprehensive reporting guidelines following ISO / ASTM standards will enable automated database entries using strong GUI and back-end database structures/protocols. The reporting guidelines as well as documentation of the test procedures, equipment calibration recommendations, and personnel training documentation thus generated will enable consistency and repeatability of test results for thermal, mechanical, optical, and other material properties.

Performance Targets

To achieve consistency and repeatability of material testing protocols it is crucial to perform round-robin baseline material characterisation tests with reference samples. Along with the test procedures and test results, the quality and form of data reporting is essential for providing consistent and usable information. Precision engineering of future detector mechanics requires diligent and detailed material models and cross-validated inputs for informing finite element design and simulations. The overall goal of this project is to identify standardised testing protocols that will help design the future HEP detector mechanics with precision engineering to implement irreducible mass mechanics with integrated services. The database to be delivered by this project will enable the use of validated material properties across collaborations, standardising the inputs to FEA as well as reducing material test costs and time.

Milestones and Deliverables

Label	Topic	Month	Description
M2.2.1	Identification of community needs	6	Definition of the community needs (e.g. material families to be considered in the database, properties to be measured/stored).
M2.2.2	Standardised test protocols & lab infrastructure archive	12	Deliver first calibrated material tests for two thermal and mechanical material samples with round-robin tests conducted across participating labs. Standardised reporting protocols and documentation agreed upon. List of available test facilities across participating institutes.
M2.2.3	Database GUI and back-end selection	24	Finalise the complete list of requirements from the database front- and back-end. Deliver first iteration of implemented database for collaboration review.
D2.2.1	Updated test protocol documentation	24	Implementation of non-standard test requirements within HEP and delivering agreed-upon calibrated test method for the same. Second round of TIM, adhesive and composite round robin test campaign.
D2.2.2	Database Beta Version release	30	Deliver beta version of the database for stress test within the collaboration.
D2.2.3	Public database release	36	Deliver final database and setup database maintenance structure.

Multi-disciplinary and transversal content

Material characterisation is needed across DRD collaborations. The material test requirements and material selection shall be covered with communication with liaisons, and this project shall be open to expanding the database as needed for electrical, simulation, and integration needs with DRD3, 4, and 7. The scope of this database can be expanded at a later stage with consultation with DRD conveners as needed.

Contributors and areas of competence

- CERN (EP-DT): Material irradiation, mechanical and thermal testing, composite manufacturing, additive manufacturing. Access to CERN EN-MME infrastructures for advanced material testing.
- DESY (Particle Physics Division): Thermal and mechanical testing. radiation length measurements at testbeam. Composite manufacturing and machine workshop.
- Purdue University (Composites Manufacturing and Simulation Center, Purdue Silicon Detector Labs): Thermal and mechanical testing. Micrographs and SEM/XRD/CT scanning. Composite Manufacturing and machine shop.
- University of Oxford (Mechanical Engineering Group): Radiation length calculations and testing campaigns. Vacuum testing of composite structures (including accumulation testing). Pull testing

and accelerated fatigue testing.

- Bristol Composites Institute: Manufacture of composites and carry out a variety of tests, as the need arises.
- INFN Perugia : CAD modelling and numerical simulation of mechanical systems, with particular emphasis on fluid dynamics and heat transfer aspects. Heavy involvement in the cooling studies for the new Phase-2 Tracker for the CMS experiment and also in the micro-cooling studies.
- Florida Institute of Technology: Thermal and Electrical Characterization of materials.
- Cornell University: Experience with thermally conductive interface materials for cooling of high-density active device. New materials will be selected/developed based on being radiation hard and of low radiation length, whilst providing high thermal performance.

Estimate of resources

Table 4 gives a summary of the existing and required effort in terms of human resources and material budget for WP2 Project 2 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 4: Summary of available and required resources for WP2 Project 2.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
CERN	1.0	1.0	30	30
DESY	0.5	1.0	10	20
University of Oxford	0.5	1.0	10	35
Bristol Composites Institute	0	1.0	10	30
INFN Perugia	0.5	0.5	0	30
Purdue University	1.0	1.5	15	35
Cornell Laboratory	1.0	1.5	20	40
Florida Institute of Technology	0.0	1.0	0	25
Total	**4.5**	**8.5**	**85**	**245**

5 Work Package 3: Detector Cooling

The focus of this Work Package is on the development of new cooling technologies for a more efficient and sustainable thermal management of future detectors. The focus is on two projects: the first explores the use of natural refrigerants to extend the field of operation towards colder evaporation than presently covered by CO_2 boiling flows; the second aims at the development of heat transport geometries based on microchannel cooling substrates, which will result in a much wider application of such highly efficient cooling devices.

5.1 Project 3.1: New Evaporative Cooling Fluids and Systems

Project Description

Current detectors require cooling temperatures in the range of +20°C down to -40°C. For warm applications the adopted solutions rely either on water, with risks associated to potential leaks often pushing to system designs operating at sub-atmospheric pressure, or using synthetic fluids like perfluorinated compounds (PFCs) or hydrofluoroolefins (HFOs), which have limited refrigerant performance and/or a very high environmental impact. The cold applications are the domain of the well developed cooling with evaporative CO_2, using the highly successful 2PACL (2-Phase Accumulator Controlled Loop) method, which is able to circulate saturated flow at a precisely controlled temperature between +20°C and -40°C through the detector.

This project will develop sustainable cooling solutions in both the warm and cold domain. Ultra-light weight and warm cooling is typically needed for lepton collider detectors, ultra-cold temperatures are typically needed for future hadron collider detectors.

- **Cold-operated detector -** Silicon detectors subject to high radiation levels require accurate and reliable thermal control under operation and when powered off. During operation, a large amount of heat needs to be absorbed by the cooling, keeping the temperature of the detector low enough to avoid thermal runaway. When the detector is off, active cooling is required to limit detrimental annealing in the silicon.

  In future experiments cooling temperatures in the range of -90°C / -50°C are likely needed. This is beyond the practical temperature range for CO_2, as CO_2 freezes at -56°C. Krypton (R784) has been identified as a new evaporative cooling fluid. Calculations have demonstrated that it works well in this lower temperature range, and its fluid properties make it a promising candidate.

  However, while CO_2 can be made liquid at room temperature by pressurisation, krypton can only be liquefied by cooling. This has a severe impact on the system architecture. In the 2PACL method the fluid is liquefied cooled down in the liquid state. This allows a controlled ramp-down of the temperature and thermal shocks are avoided. For krypton a transcritical cooldown in a compressor cycle is foreseen as a method to achieve controlled cooldown. This cycle is completely different from any other evaporative cooling system used at CERN and in industry.

  This project will demonstrate the viability of krypton as a cold detector cooling fluid, and develop a new krypton transcritical cooldown cycle with an internal ejector for detector circulation. Currently, exploratory early R&D is performed within a PhD project, which has demonstrated the feasibility of a krypton cooling cycle. One challenge of krypton is that it is a refrigerant with very different fluid properties than known refrigerants. Therefore, specific components need to be developed or modified from standard to be able to work for krypton. A follow-up PhD project is foreseen to work on the two major component upgrades, which are the compressor and the ejector. This PhD project is already half-funded by NTNU, with funding for the remainder still required.

- **Warm-operated detector -** Silicon detectors operating under mild radiation levels do not require to be constantly kept below 0°C and are usually characterised by low-power electronics. However, the power dissipated in the detector must still be removed, and solutions based on forced air flows might not be applicable in all layers of the detector. Liquid cooling might still be required for parts of the detector, but with raising awareness of the environmental impact of scientific research, the use of synthetic refrigerants is likely to be excluded. On the other hand, water is known to have excellent refrigerant properties, but it is electrically conductive and poses unacceptable risks in case of leaks.

  Supercritical carbon dioxide (sCO_2) is an electrically non-conductive fluid with much lower viscosity than water and allowing for higher heat transfer coefficients operating at high pressure and temperatures above 31.7°C. Its adoption as single-phase refrigerant for electronics operated in the range +35°C to +40°C would allow for lighter and smaller pipes - potentially including multi-microchannel devices - with a positive impact on the detector material budget.

  Again, exploratory R&D is currently being performed within a PhD project, which has lead to the completion of a new test bench for precision measurements on sCO_2 flows. The activity aims at shedding light on the open points left on the understanding of the thermal-fluidic properties of sCO_2 in view of an optimal design of cooling circuits for future detectors. Furthermore, by exploring in detail the properties of supercritical fluids, this activity will also provide useful information for the optimal design of the cold krypton-based system, which is largely operating in the supercritical state.

Performance Targets

- Exploration of a colder cooling domain using a natural refrigerant, krypton, in a novel cycle. Cooling of detector structures with high heat dissipation in the temperature domain between -90 °C and -50 °C.

- Exploration of a natural refrigerant with superior properties than water for highly demanding detectors operating in mild radiation fields (warm temperatures allowed).

Milestones and Deliverables

Label	Topic	Month	Description
M3.1.1	Krypton system demonstration	12	Development of a demonstration system proving the krypton cooling system concept
M3.1.2	Krypton component development	15	Development of components required for a krypton cooling system, like ejectors and (oil free) compressors
M3.1.3	sCO_2 properties	18	Publication on detailed properties of sCO_2 flows in small pipes
D3.1.1	Krypton system development	30	Development of a working prototype of a krypton cooling system
M3.1.4	Krypton cooling performance	36	Performance testing of evaporative Kr in detector cooling tubes
D3.1.2	sCO_2 system development	36	Development of a working prototype of an sCO_2 cooling system

Multi-disciplinary and transversal content

Inputs will be required from DRD3 and DRD7, which should help to define better the temperature requirements for future experiments. This communication will be done via the respective liaisons and workshops (e.g. Forum on Tracking Detector Mechanics). Krypton being a new refrigerant has very different properties than conventional refrigerants. Some industrial key components need adjustments in the design to be able to work with krypton in a reliable way. Partnerships with industry will be set up for this component development.

Contributors and areas of competence

- CERN (EP-DT): Vast expertise in detector cooling, in particular with CO_2 cooling systems; fluid property expertise
- NTNU (Norwegian University of Science and Technology): Natural refrigerants and system expertise
- DESY: CO_2 detector cooling systems and expertise
- Fachhochschule Offenburg: Thermal process engineering and system engineering expertise.
- University of Sheffield: Interconnections and system integration.
- Cornell Laboratory: CO_2 detector cooling systems and expertise
- Dorin (industrial partner): Krypton compressor development.

Estimate of resources

Table 5 gives a summary of the existing and required effort in terms of human resources and material budget for WP3 Project 1 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. In the case of CERN the resources are mainly available through the R&D program on Experimental Technologies of the EP department for which the objectives have been defined in [9]. Resources have been included in this project to the extent that they are aligned with the EP R&D Programme. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 5: Summary of available and required resources for WP3 Project 1.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
CERN	2.0	2.5	10	50
NTNU	0.5	1.0	10	100
DESY	0.0	0.2	0	10
FH Offenburg	0.2	0.2	0	0
University of Sheffield	0.2	0.2	0	10
Cornell Laboratory	0.1	0.4	5	10
DORIN	0	0	5	20
Total	**3.0**	**4.5**	**30**	**200**

5.2 Project 3.2: Microchannel Cooling Substrates

Project Description

Microchannel cooling plates are extremely efficient for removing heat due to the proximity of the coolant to the heat sources. In this project, several tasks are foreseen, covering different manufacturing techniques and materials:

- **Silicon microchannels via buried channels (T1) -** We propose technological developments along two lines: First, the development of a microchannel cooling technology fully compatible with (CMOS) sensors in the same substrate. We intend to develop a technology that can fabricate microchannels for cooling in the same substrate as the silicon sensors. Several intermediate stages are foreseen with different silicon sensor technologies, but the final aim will be to create a post-processing technology that can incorporate buried micro-channels in a commercially available CMOS technology. Secondly, we propose the development of ”active interposers” which hold the mechanical support and the buried micro-channels to provide local, high-efficient cooling to the detector system, together with interconnection capabilities to cover the electrical connection between the detector and front-end electronics with the back-end electronics and the rest of the system to provide re-distribution of the I/O signals (readout, control signals), plus power lines. In a first stage, the interconnection would be provided by a re-distribution metal layer (RDL) which can be composed of multi-metal layers. Later, more advanced interconnection technologies can be implemented in the interposers, like Through Silicon Vias (TSV).
- **Silicon Microchannel via thermocompression (T2) -** This task covers several developments: the setting up of a dedicated cooling test bench; the fabrication of cooling plates with micro-channels of various geometrical and surface form factors; the development of numerical 3D models - based on dedicated measurements - and their implementation in numerical simulation tools to optimise the micro-channel heat exchanger design; the development of a low-cost silicon cooling-plates fabrication process, mainly based on an innovative bonding technique: “the hyperbaric bonding”, which uses a thin layer of gold - similarly to thermo-compression - and is performed at room temperature inside a hyperbaric chamber; the development of cooling-plates interconnects to allow the fabrication of heat exchangers covering large areas.
- **LTCC/HTCC ceramics (T3) -** In this task, low-temperature co-firing ceramic (LTCC) and high-temperature co-firing ceramic (HTCC) will be explored as manufacturing process. It combines different ceramic layers to enclose the channels, and it offers the possibility, for instance, to integrate high conductivity materials in between those layers. Lines inside the cooling plate can be accessed via vias. The benchmark model is the LHCb VELO Upgrade 2 which has very challenging requirements (high power density, high pressure, and high vacuum operation). The project is currently ongoing and initial samples have already been produced.
- **3D metal printing (T4) -** The ability to print cooling/mechanical structures brings a higher level of design flexibility, fast turn-around processing time, and cost-effectiveness, especially in electronics-dense areas with limited space. In this scenario, metal 3D printing will be explored. The surface finishing and potential of the material budget improvement will be explored via post-processing techniques. This topic will also follow the requirements for the LHCb VELO Upgrade 2 (CO_2) as a benchmark, but this approach can also be used for different applications.

Performance Target

Explore the cooling parameter space of low material budget (down to $\leq 0.2\%\ X_0$) and low power dissipation ($\sim$10-100 mW/cm^2) and high power dissipation ($\gtrsim 2$ W/cm^2). The progress will be tracked via public reports through presentations, public notes and/or papers.

Milestones and Deliverables

Label	Topic	Task	Month	Description
D3.2.1	New round of 3D printing prototypes exploring different geometries	T4	9	
M3.2.1	Ceramics feasibility tests	T3	15	Public note or paper
M3.2.2	Prototypes bonded with thermo-compression or hyperbaric process characterisation	T2	18	
M3.2.3	3D printing	T4	24	Public note or paper
D3.2.2	Fluidic and thermal results from integrated system	T1	27	
M3.2.4	Bi-phase CO_2 thermo-fluidic models	T2	36	Bi-phase CO_2 Thermo-fluidic models development for microchannels/nuclear and annular flows. Heat exchanger characterisation and interconnections

Contributors and areas of competence

- University of Manchester: Experience in the assembly, testing, and quality control of silicon detectors in general and micro-channel cooling plates with CO_2 evaporative cooling. LHCb VELO Upgrade 1 module assembly.
- Institute of Microelectronics of Barcelona, Centro Nacional de Microelectrónica (IMB-CNM): Technology development, 3D integration, electronic testing.
- Instituto de Física Corpuscular (IFIC): Full system integration, cooling interconnection, mechanics, services.
- DESY: Fluidic and thermal tests, system development.
- Nikhef: Experienced in 3D-printed design, with dedicated R&D in ceramics and metal materials for detector cooling solutions.
- CPPM (Aix Marseille Univ, CNRS/IN2P3) - *French Collaboration*[1]: Experience in the assembly, testing, and validation of silicon detectors in general (ATLAS) and in the development of micro-channel cooling plates. Recently, the development of bonding processes at room temperature in collaboration with the micro-fabrication CNRS laboratory FEMTO-ST.
- Laboratoire d'Annecy de Physique des Particules (LAPP) - *French Collaboration*[1]: Experience in CO_2 microchannels heat exchanger studies, thermal and mechanical simulations, characterisation and measurement on bi-phase CO_2 cooling test bench.
- LEGI - *French Collaboration*[1]: Experience in numerical modelling to simulate the flow of bi-phase coolant inside micro-channels. Microchannel heat exchanger production (etching, anodic silicon/Pyrex bonding and connectors brazing)

[1] The institutes indicated by the term "French Collaboration" have expressed their interest in their funds being treated as a single project. Therefore, in the funds-related sections, they are treated as a single body: "French Collaboration".

- Laboratoire de physique nucléaire et des hautes énergies (LPNHE) - *French Collaboration*[1]: Experience in assembly, construction and characterization of silicon pixel modules, design of microchannel cooling plates and interconnections.
- CERN: Long experience in the design, production and testing of microchannel cooling plates with different technologies. Leader of the dedicated WP in the two EC-funded projects AIDA2020 and AIDAinnova. Dedicated test benches available, including to users, for measurements on both single-phase and boiling flows in micro-channel devices.
- MPG HLL, Semiconductor Laboratory of the Max Planck Society: Extensive experience in design, fabrication and testing of silicon sensors and detector systems for HEP, astrophysics and material science. In-house production of cutting edge 6" and 8" wafer scale radiation sensors and full assembly line for integration of detector systems. Backend-of-line includes post-processing capabilities of up to 8" wafers and fabrication of micro-mechanical structures for various applications. Contributions of the MPG HLL include all-silicon modules with integrated micro-channels as well as micro-channel cooled interposers with multi-metal wiring.
- University of Sheffield: Expertise on interconnections and system integration.
- INFN Genova - *Italian Consortium*[2]: Expertise for FEA simulations with ANSYS Fluent software for the ALICE ITS and NA62 microchannels in collaboration with CERN. It is actively collaborating with FBK for the construction of microchannels which it will be possible to dissipate up to 6 W/cm^2. It is also actively developing 3D metal printing techniques in AISI 316L with more flexible printing parameters within the INFN network.
- INFN Perugia - *Italian Consortium*[2]: Expertise in numerical modelling and simulations of the cooling devices. The group has also the possibility to build "in-house" small test setups in the laboratory, with the aim of measuring the real thermal performance of the prototype-devices, as well as the pressure loss inside the cooling circuit. The same can also be used to provide useful input for the validation of simulations.
- INFN Pisa - *Italian Consortium*[2]: Expertise in FEA simulations with ANSYS Fluent SW, design and fabrication of micro-channels in AIDA and AIDAINNOVA. Active collaboration with FBK for the design and fabrication of Silicon micro channels on several substrates.
- FBK - *Italian Consortium*[2]: The Bruno Kessler Foundation (FBK) brings decades of experience in the microfabrication of silicon-based microchannels, catering to a wide range of applications. With extensive expertise in both wet and dry etching processes, FBK is uniquely equipped to handle complex production requirements. The capabilities in anodic and direct bonding as well as integration further enhance the reliability of the microfabrication process, enabling them to seamlessly manage the entire production cycle—from silicon wafers to fully functional devices ready for installation.

[2]The institutes indicated by the term "Italian Consortium" have expressed their interest in their funds being treated as a single body. Therefore, in the funds-related sections, they are referenced as "Italian Consortium".

Estimate of resources

Table 6 gives a summary of the existing and required effort in terms of human resources and material budget for WP3 Project 2 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 6: Summary of available and required resources for WP3 Project 2.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
University of Manchester	1.0	1.5	30	90
French Collaboration	1.0	1.5	45	105
IMB-CNM, IFIC and DESY	1.5	4.5	150	630
CERN	0.2	0.2	10	10
Nikhef	0.5	0.5	15	50
MPG HLL	0.2	0.2	10	10
University of Sheffield	0.1	0.1	0	10
Italian Consortium	1.0	2.0	25	125
Total	**5.5**	**10.5**	**285**	**1030**

6 Work Package 4: Design and Qualification Tools

This Work Package is focused on exploring and testing new tools to improve how the particle physics community designs and builds detectors. Some of these tools go beyond the design phase and could impact other stages of a detector lifecycle (e.g. installation, repairs, decommissioning). Initially, five activities were identified: open-source software for high-performance computing, machine learning-driven topology optimisation, virtual reality-aided design, 3D modelling of complex geometries, and linking CAD tools with GEANT. These have now been streamlined into two main programs, namely: (i) Extended Reality (XR) development and (ii) connecting engineering design tools with physics simulation software. The XR program has a broad scope, with the potential to be used throughout the detector lifecycle. The focus on connecting engineering tools with physics simulations aims to enhance data-sharing between designers and physicists by producing simplified models, which can also be used in XR applications, another key focus of this work package.

6.1 Project 4.1: Extended Reality (XR) Development

Project Description

XR technologies bridge the gap between the physical and digital world. As such they are being adopted by leading industries and institutions and their positive impact in society is expected to grow in the coming years [15]. The growing adoption of XR technologies is driven by advancements in low-cost, off-the-shelf hardware and software [16].

This R&D project aims to integrate Extended Reality (XR) technologies—Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR)—within our community:

- **Augmented Reality (AR) -** Enhances the physical world by overlaying digital content onto real-world environments. AR applications can display in real-time for instance digital working instructions or safety instructions in physical equipment that is used in our experimental areas and laboratories.

- **Virtual Reality (VR) -** Provides a full immersion into a digital environment and can be used for virtual interventions in experimental and accelerator areas while these are not accessible.

- **Mixed Reality (MR) -** Allows to interact with both virtual and physical worlds simultaneously. MR technologies, such as Microsoft's HoloLens, allow for connecting remotely with colleagues, for instance located in a collaborating institute and working together in a physical experiment located in an experimental area [17].

XR technologies also support the creation of **digital twins**, virtual replicas of hardware and systems used in experiments and accelerators. These digital twins enable real-time monitoring and analysis of physical objects and can be accessed via VR for interaction before engaging with the real object. In MR applications, digital twins offer operation and maintenance instructions for detectors and can be shared with remotely connected team members.

This proposal seeks to advance the use of XR within the particle physics community, changing the way how we design, construct and interact with particle detectors. In some respect this R&D activity complements the work carried out in WP1 in robotics applications for detectors.

Project phases

Currently, the particle physics community has limited experience with Extended Reality (XR), despite some recent initiatives [18, 19]. This R&D program aims to bridge this gap by establishing a framework for effective collaboration among institutions to achieve XR adoption and integration within particle physics.

At this early stage, we have outlined two key development phases, which will be refined as we gain more knowledge and experience:

- Phase 1: Research on current XR technologies.
  - Conduct extensive research on the current state of XR technology. This includes identifying hardware (e.g., VR headsets, AR glasses) and software platforms required for implementing XR solutions.
  - Evaluate low-budget and off-the-shelf VR hardware for testing purposes, considering their compatibility with future scaling.
  - Training members of the WP on the technologies.
  - Identify institutions (e.g. universities and research institutions) with experience in XR to advise on strategy to follow on the implementation of the XR technologies.
  - Involve students to perform early-stage testing and evaluation.
- Phase 2: Implementation of XR technologies in an ongoing project in one of the CERN experimental areas during LS3, as a technology demonstration (covering one or more phases in the life cycle of a detector).
  - Experiment with XR technologies in small lab environments to assess their main features and limitations.
  - Develop digital content required for XR technologies to support technology demonstration based on an ongoing project in one of the CERN experimental areas.
  - Test XR technologies in both virtual and mixed reality environments to evaluate their effectiveness and usability.

Once Phases 1 and 2 are completed, the goal is to scale the acquired knowledge and technologies to larger projects and areas.

Performance Targets

The goal of this project is to lead, promote, and accelerate the adoption of XR technologies in the design, operation, and maintenance of particle detectors. The integration of such technologies has the potential to revolutionise how we interact with particle detectors, from the initial design phases to final decommissioning. It will also enhance safety and efficiency during interventions in experimental and radiation areas.

This project will identify early applications of existing commercial XR solutions that can benefit our field in the short term. By reducing prototyping time and costs through virtual models, we aim to streamline the design process, enabling faster iterations and cutting down on physical resources. Immersive XR technologies will also improve training by allowing engineers, physicists, and technicians to simulate complex assembly and maintenance tasks in safe virtual environments, without physical exposure. During interventions, operators will benefit from detailed, real-time information, enabling more efficient operations and potentially reducing detector downtime.

This foundational work will pave the way for more advanced and customised applications designed to meet the specific needs of future particle detectors, including potential integration with digital twin technologies for predictive maintenance and real-time system monitoring.

Milestones and Deliverables

Label	Topic	Month	Description
M4.1.1	Market survey report	12	A detailed market survey report identifying key technologies, software tools, and hardware for developing XR solutions, including a recommendation for the elements to purchase for the implementation of phase 2.
D4.1.1	Purchase of hardware and software	18	
M4.1.2	Application of XR technologies to detector projects	36	Application of XR technologies to detector projects to highlight their potential impact on activities such as training, design, installation, maintenance and decommissioning.
D4.1.2	Project reports	36	Provide detailed reports on the activities conducted and any software developed during the project.

Multi-disciplinary and transversal content

The adoption and development of XR solutions for detector applications present significant opportunities for both current and future high-energy physics (HEP) experiments. Close collaboration with existing experiments will be essential to tailor these technologies to the specific needs of congested experimental areas with limited access. In this context, there are clear overlaps and shared interests with the work of WP1, particularly in project 1.2. Additionally, we will actively pursue potential collaborations with the accelerator sector, as it faces similar challenges.

Contributors and areas of competence

List of contributions to WP4 Project 1 (Preliminary):

- CERN: Extensive expertise in design and integration of complex detector systems, as well as their installation in congested and hard-to-access experimental areas. Management of large and complex experimental areas, including the operation, maintenance and upgrade interventions in radiation areas. Operation of irradiation facilities.
- GSI Darmstadt: Expertise in managing large, radiation-restricted facilities with controlled access to experimental areas, as well as assembling large-scale detector systems with the support of software-guided workflows and quality assurance tools.
- University of Sheffield: Use of XR to estimate dose rates during access and maintenance of particle detectors close to the beam pipe.

Estimate of resources

Table 7 gives a summary of the existing and required effort in terms of human resources and material budget for WP4 Project 1 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. The total resources required for a successful completion of the proposed project are as well indicated.They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 7: Summary of available and required resources for WP4 Project 1.

Institute	Effort [FTE/year]		Material budget [kCHF]	
	available	**required**	**available**	**required**
CERN	0.2	1.5	0	60
GSI Darmstadt	0.1	0.1	0	10
University of Sheffield	0.1	0.1	0	10
Total	**0.4**	**1.7**	**0**	**80**

6.2 Project 4.2: Connection of Engineering Design Tools with Physics Simulation Software

Project Description

The objective of this R&D proposal is to establish a communication between CAD design tools, used for designing and integrating particle physics equipment, and physics simulation software. Currently, the workflow between designers and physicists is inefficient, relying on manual transfer of over-simplified geometry and material data through spreadsheets. This R&D program aims to automatise the transfer of simplified engineering models, including geometry and material metadata, from engineering design software to physics simulation tools (e.g., Geant4, FLUKA). This will simplify the workflow, improve data sharing between designers and physicists, and reducing the time it takes to understand of particle interactions with detector material.

Project phases

Designers of particle detectors create complex and detailed CAD models that are crucial for the design, manufacturing, and integration of these systems. These CAD models are not directly usable by physics simulation software. As a result, the detailed models must be manually rebuilt with significant simplifications before they can be used as input for the simulation software. This manual process is time-consuming, prone to errors, and slows down the optimisation of the detectors. This R&D activity aims to address these issues by developing tools to improve the exchange of information between engineering and physics software. The work will be organised into two phases:

- Phase 1: Define data exchange requirements by identifying the inputs and outputs of both engineering design and physics simulation software.
  - Collaborate with detector designers and physicists to understand the requirements of both groups.
  - Identify the input and output formats of CAD software (e.g. CATIA, SolidWorks) and physics simulation tools (e.g. Geant4, FLUKA) to establish a unified foundation for data exchange.
- Phase 2: Develop tools to generate essential geometry data and material metadata in the engineering design software, ensuring compatibility and seamless transfer with physics simulation software.
  - Generate a simplified CAD model with metadata that complies with the transfer protocol for integration into physics simulation software.
  - Develop a plug-in for the physics simulation software capable of importing and exporting file formats used by CAD software (e.g. STP or STEP).

In Phase 2 of the project, depending on the level of participation from the institutions and advancements made in CAD software technologies, the scope may include the automatic generation of simplified models derived from complex designs [20, 21, 22].

Performance Target

The primary objective of this R&D project is to streamline the workflow between CAD design tools and physics simulation software, enhancing the efficiency of the design process for particle detectors. By automatising the transfer of simplified geometry and material metadata, we aim to achieve a significant reduction in manual intervention, thereby reducing errors and shortening the overall design iterations. The tools will be designed for compatibility with multiple CAD packages.

Milestones and Deliverables

Label	Topic	Month	Description
M4.2.1	Specification of transfer system	12	Draft a functional and technical specification for a system that enables the transfer of geometric and material information between CAD models and physics simulation software.
M4.2.2	Simplified 3D models	36	Produce simplified 3D models of a tracker detector to be installed in the LS3 upgrades and transfer it to physics simulation software.
M4.2.3	Export from physics simulation software	36	Export from physics simulation software files readable by CAD software.

Multi-disciplinary and transversal content

This project aims to enhance collaboration and improve information exchange between engineering and physics simulation teams. It will provide a platform that encourages regular interaction between both communities, including joint workshops and brainstorming sessions to align goals and share expertise.

Contributors and areas of competence

List of contributions to WP4 Project 2 (Preliminary):

- CERN: Experience in CAD modelling and physics simulation software.
- IHEP/CAS: The Institute of High Energy Physics (IHEP), a Chinese Academy of Sciences (CAS) research institute, has significant experience in CAD modelling .
- University of Oxford: Work on physics simulation software and exporting of geometry from CAD.
- GSI Darmstadt: Expertise in CAD-to-ROOT conversion using the VecGeom library to streamline geometry modelling. Direct CAD-to-GDML conversion for modelling complex geometries in physics simulations, enabling tessellated solids compatible with CERN-ROOT and Geant4 for detector assembly.
- INFN-LNF Frascati: Experience in translation of CAD date into simulation software for FCC-ee.
- Purdue University: Existing experience and ongoing project for modelling of ultra-lightweight drift chamber concepts which require detailed GEANT simulations among other more engineering type of work. The group has extensive experience in transformer, deep learning and other forms of AI which we are leveraging against this challenge.

Estimate of resources

Table 8 gives a summary of the existing and required effort in terms of human resources and material budget for WP4 Project 2 during the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 8: Summary of available and required resources for WP4 Project 2.

Institute	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
CERN	0.2	1.0	0	0
IHEP	0.1	1.0	0	10
GSI Darmstadt	0.1	0.2	0	0
Oxford University	0.5	0.5	0	0
INFN-LNF Frascati	0.1	0.1	0	0
Purdue University	0.5	2.0	0	10
Total	**1.5**	**4.7**	**0**	**20**

7 Milestones, deliverables and resources

Table 9 summarises the proposed milestones and deliverables for DRD8, as mentioned in the previous sections.

Table 9: Summary of milestones and deliverables.

Month	Label	Topic
6	M2.1.1	Design specifications
	M2.2.1	Identification of community needs
9	D3.2.1	New round of 3D printing prototypes exploring different geometries
12	M1.1.1	Curved and tilted sensors
	M1.2.1	Mobile mesh network in cavern
	M2.1.2	Pre-Concept Design Report
	M2.2.2	Standardised test protocols & lab infrastructure archive
	M3.1.1	Krypton system demonstration
	M4.1.1	Market survey report
	M4.2.1	Specification of transfer system
15	M3.1.2	Krypton component development
	M3.2.1	Ceramics feasibility tests
18	M3.1.3	sCO_2 properties
	M3.2.2	Prototypes bonded with thermo-compression or hyperbaric process characterisation
	D4.1.1	Purchase of hardware and software
24	D1.1.1	Carbon beam pipe
	D1.2.1	Legged robots and robotic airships in magnetic field
	M2.1.3	Concept Design Report
	D2.1.1	Production of simple prototypes for NDT Testing
	M2.2.3	Database GUI and back-end selection
	D2.2.1	Updated test protocol documentation
	M3.2.3	3D printing
27	D3.2.2	Fluidic and thermal results from integrated system
30	D2.2.2	Database Beta Version release
	D3.1.1	Krypton system development
36	M1.1.2	Retractable detectors
	D1.1.2	Mock-up & integration
	D1.2.2	Legged robots and robotic airships in cavern
	M1.2.2	Legged robots and robotic airships control system
	M1.2.3	Mobile mesh network cavern inspection
	M2.1.4	Critical Design Report (CrDR)
	D2.2.3	Public database release
	M3.1.4	Krypton cooling performance
	D3.1.2	sCO_2 system development
	M3.2.4	Bi-phase CO_2 thermo-fluidic models
	M4.1.2	Application of XR technologies to detector projects
	D4.1.2	Project reports
	M4.2.2	Simplified 3D models
	M4.2.3	Export from physics simulation software

Table 10 gives a summary of the existing and required effort in terms of human resources and material budget for the next 3 years. Existing resources are usually funded through other projects that match the aims of DRD8. The total resources required for a successful completion of the proposed project are as well indicated. They are the sum of what is available and what will be requested. The latter are subject to awarding the resources by the respective Funding Agencies.

Table 10: Summary of existing and to be requested resources.

Project	**Effort [FTE/year]**		**Material budget [kCHF]**	
	available	**required**	**available**	**required**
Project 1.1	9.7	15.4	650	1530
Project 1.2	3.0	4.0	120	220
Project 2.1	7.7	13.0	190	500
Project 2.2	4.5	8.5	85	245
Project 3.1	3.0	4.5	30	200
Project 3.2	5.5	10.5	285	1030
Project 4.1	0.4	1.7	0	80
Project 4.2	1.5	4.7	0	20
Grand total	**35.3**	**62.3**	**1360**	**3825**

It is important to note that several of the collaborating institutes is still deeply involved in the Phase II upgrades of the ATLAS and CMS trackers. This limits the available resources in these institutes for DRD8 significantly.

Several institutes have state-of-the-art infrastructure which will be made available to carry out the proposed research programme. The infrastructure includes in particular facilities to drive composites manufacturing into the future with cutting-edge techniques for highly specialized structures.

8 Relations to other DRDs

The research activities in DRD8 cover non-active supporting aspects for future tracking systems, like support structures, service integration and thermal management. Consequently, requirements and specifications for the solutions to be developed in DRD8 will be heavily influenced by the needs and opportunities imposed by future sensor and readout technologies. These aspects will be covered within the overall DRD programme in the DRD3 and DRD7 efforts and thus close interaction with these efforts will be an important aspect of the DRD8 project.

To conclusively demonstrate the success of the DRD8 research programme verification of the solutions developed within DRD8 for tracking applications will require the construction of one or more demonstrator(s), which is (are) large enough and include(s) representative advanced sensors and electronics prototypes, and its (their) operation in a realistic environment. This enterprise can only be undertaken in close collaboration with DRD3 and DRD7, and will require an appropriate management platform across these collaborations. DRD8 contributions towards this demonstrator will initially be organised by the SC, but once the effort and the collaboration with DRD3 and DRD7 becomes more defined a dedicated management structure will be put in place.

The near-term tasks of the demonstrator effort will be the creation of this structure and the development of specifications for the(se) demonstrator(s). Without preempting this process we currently can conceive of two such demonstrators, one for an environment that allows low-power (LP) operation (as found in a future e^+e^- collider), and another for a future high-intensity (HI) tracker (for example in a future hadron collider). The former will allow for reduced services and gas cooling, while the latter will require thermal and service management that is compatible with large readout channel density and radiation damage. Both will require aggressive reduction of structural and service material.

Acknowledgements

We would like to thank Massimo Angeletti, Luca Bernardi and Nicola Pacifico from CERN, and Jan-Hendrik Arling from DESY for careful reading of this document and many valuable suggestions.

Appendix

A Participating institutes

Table 11 lists institutes that expressed an interest to contribute to the DRD8 R&D effort on Mechanics and Cooling for future Vertex and Tracking Systems, together with names of contacts and their email.

Table 11: List of Collaborating Institutes in DRD8.

Country/Organisation	Institute	Contact person	Email address
CERN	CERN	Burkhard Schmidt	Burkhard.Schmidt@cern.ch
China	IHEP	Haoyu Shi	shihy@ihep.ac.cn
France	CPPM Marseille	Eric Vigeolas	vigeolas@cppm.in2p3.fr
	IJCLab Orsay	Julien Bonis	bonis@ijclab.in2p3.fr
	LPNHE Paris	Giovanni Calderini	giovanni.calderini@lpnhe.in2p3.fr
	IPHC Strasbourg	Jerome Baudot	baudot@in2p3.fr
Germany	DESY	Andreas Mussgiller	andreas.mussgiller@cern.ch
	Freiburg University	Marco Gersabeck	Marco.Gersabeck@cern.ch
	GSI Darmstadt	Maksym Teklishyn	m.teklishyn@gsi.de
	Halbleiterlabor of the Max-Planck-Society	Laci Andricek	ladislav.andricek@cern.ch
	Fachhochschule Offenburg	Susanne Gleißle	susanne.gleissle@hs-offenburg.de
Italy	FBK Trento	Maurizio Boscardin	boscardi@fbk.eu
	INFN Ferrara	Stefano Gramigna	gramigna@fe.infn.it
	INFN LNF Frascati	Manuela Boscolo	Manuela.Boscolo@lnf.infn.it
	INFN Genova	Cecilia Rossi	Cecilia.Rossi@ge.infn.it
	INFN Perugia	Cristiano Turrioni	cristiano.turrioni@pg.infn.it
	INFN and University of Pisa	Fabrizio Palla	Fabrizio.Palla@cern.ch
	University of Rome La Sapienza	Fabio Curti	fcurti@arizona.edu
Netherlands	Nikhef	Freek Sanders	fsanders@nikhef.nl
Norway	NTNU Trondheim	Armin Hafner	Armin.hafner@ntnu.no
Spain	CNM Barcelona	Miguel Ullan	miguel.ullan@imb-cnm.csic.es
	IFIC Valencia	Marcel Vos	Marcel.Vos@cern.ch
Switzerland	University of Geneva	Franck Cadoux	franck.cadoux@unige.ch
United Kingdom	UKRI-STFC Rutherford Appleton Laboratory	Fergus Wilson	fergus.wilson@stfc.ac.uk
	University of Bristol	Joel Goldstein	Joel.Goldstein@bristol.ac.uk
	Bristol Composites Institute	Laura Rhian Pickard	laura.pickard@bristol.ac.uk
	National Composite Centre (NCC)	Matt Scott	Matt.Scott@nccuk.com
	University of Liverpool	Tim Jones	timjones@liverpool.ac.uk
	University of Manchester	Oscar Augusto de Aguiar	oscar.augusto@cern.ch
	University of Oxford	Georg Viehhauser	georg.viehhauser@physics.ox.ac.uk
	University of Sheffield	Paul Kemp-Russell	p.kemp-russell@sheffield.ac.uk
USA	Cornell University	Karl Smolenski	karl.smolenski@cornell.edu
	University of Arizona	Fabio Curti	fcurti@arizona.edu
	Fermilab	Petra Merkel	petra@fnal.gov
	Florida Institute of Technology	Souvik Das	sdas@fit.edu
	LBNL	Eric Anderssen	eric.anderssen@cern.ch
	Purdue University	Andy Jung	andreas.werner.jung@cern.ch
	SLAC	Marco Oriunno	oriunno@slac.stanford.edu

Most of the above institutes will participate to one or more of the Work Packages and Projects outlined in this proposal. Beyond them, the above list includes as well some institutes which expressed interest to be part of the DRD8 collaboration, but have not yet indicated to which Research Project they intend to participate. We expect clarification on this in the near future.

Table 12 lists commercial companies participating in DRD8.

Table 12: List of Collaborating Companies in DRD8.

Country	Company name	Contact person	Email address
Italy	Dorin	Giacomo Pisano	g.pisano@dorin.eu

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