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

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1 Introduction

Particle physics experiments combine a large number of active detection elements with their associated front-end electronics in congested space. To support the excellent capabilities of the active sensor elements, the mechanical linking of these elements, and the provision of services, including heat removal from the front-end electronics, must satisfy extreme demands, in particular in maintaining mechanical and thermal stability with ultra-low material in tracking systems and in front of the active volume of calorimeters. To achieve a performance that matches the advances in active detector technologies novel materials and design and fabrication techniques are required.

Even though some aspects of our proposal are of direct relevance for commercial implementation, the key features of our applications, such as high structural stiffness, low mechanical loads, but with extremely low-material, and low production volumes entail that no commercial solutions for our requirements exist, and progress in this field must be driven by our community. This DRD proposal aims to create a framework and set out a roadmap to achieve progress in this field, which will be critically important for future particle detector systems.

The research proposed for DRD8 does not include work on any active detection technologies, but comprises elements that provide vital supportive functions in detector systems, namely mechanical supports and cooling. The auxiliary role of our activities implies that they can only be meaningfully pursued in the context of and to specifications defined by the supported active detection technologies and its readout electronics. With the current focus on mechanics and cooling for semiconductor trackers our set of DRD8 deliverables will be closely linked to the activities of DRD3 and DRD7. The way how we plan to achieve this will be outlined in section 8.

At this point, our planned activities are primarily aimed at tracking systems, in particular those using semiconductor sensors, as this DRD collaboration has grown out of the yearly Forum on Tracking Detector Mechanics. However, it can include work on similar topics for other detector technologies and infrastructure if groups interested in these will join.

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, solicitating input to this program.

The scientific organisation and the governance of DRD8 are outlined in the following subsections. 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 of 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 defined for an initial duration of three years. 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. The first task for DRD8 will therefore be to improve opportunities for networking, information exchange and sharing of equipment and/or facilities for these existing and funded activities.

The second group of activities for DRD8 will comprise a limited set of R&D projects (about two per WP) that will be managed within the DRD8 framework. 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 by the number of groups within the community, within DRD8 and outside.

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 also support these activities by networking and providing a platform for information exchange.

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), with the chairperson and deputy chairperson of the Steering Committee as the main representatives of the collaboration, and the Resources Board (RB). The scientific structure of the collaboration is represented by the Work Package Conveners. Work Package Conveners and Steering Committee come together in the Technical Committee. Collaboration membership is defined by contributions to one or several DRD8 projects.

- The **DRD8 collaborators** 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.
- 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 organize 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** 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 PDRA 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**, which tracks projects, organizes 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 oversee 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** 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, Co-Spokesperson and the Work Package Conveners nominated by the Steering Committee.

  To provide oversight, members of the CB should 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. The RM does not need to take part in the review. 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 group.

  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** 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 organizing 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 slate 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 be convened 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.

3 WG 1: Global/System Design and integration

3.1 Project/Task: Detector Integration in the Interaction Region

<table>
<tr><td>Project Name</td><td>Project/Task: MDI Integration (1.1)</td></tr>
<tr><td>Project Description</td><td>Study the integration of the detector elements close to the interaction region (IR) for future high luminosity electron-positron colliders. The main goal is to explore the mechanical assembly, maintenance and operation of the vertex, luminosity and calorimeter detectors. The project will explore the FCC-ee interaction region as benchmark, and build a demonstrator of the innermost IR; its duration is 2+ years.</td></tr>
<tr><td>Innova-tive/strategic vision</td><td>In order to achieve and exploit the high luminosity of the FCC-ee, the electrons and positron beams must be focused and put in collision with a complex optics, whose elements 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. The integration of such region is at least a factor 3 more complicated than the one of SuperKEKB.</td></tr>
<tr><td>Performance Target</td><td>Explore the technical feasibility to assembly and integrate the detector elements around the central beam pipe, and allow access operations while removing the cryostat containng the final focus quadrupoles. The progress will be tracked via public reports through presentations, public notes and/or papers.</td></tr>
<tr><td>Milestones and Deliverables</td><td><table>
<tr><td>Label</td><td>M</td><td>Target</td></tr>
<tr><td>D1*</td><td>12</td><td>Assembly (Demonstrator) of the interaction region beam pipe with the Vertex and Luminosity detectors</td></tr>
<tr><td>M1*</td><td>18</td><td>Feasibility tests public note or paper</td></tr>
<tr><td>D2*</td><td>24</td><td>Cooling tests (Demonstrator) and cooling performance</td></tr>
<tr><td>M2*</td><td>27</td><td>Final public note or paper</td></tr>
</table></td></tr>
<tr><td>Multi-disciplinary, cross-WG content</td><td>Communication with DRD7 and DRD3 via liaisons and workshops (e. g.: Forum on tracking mechanics).</td></tr>
<tr><td>Contributors</td><td>CH: CERN
IT: INFN LNF, Perugia, Pisa</td></tr>
<tr><td>Available resources</td><td>X FTE/yr (First year), YY /yr (First year)</td></tr>
<tr><td>Resource request</td><td>ZZ/yr (on 2024-2025), wwk/yr (on 2024-2025)</td></tr>
</table>

Project Description

In order to achieve and exploit the high luminosity of the FCC-ee, the electrons and positron beams must be focused and put in collision with a complex optics, whose elements are placed very close to the Interaction Region, within the detector volume. The distance of the face of the final quadrupole from the Interaction Point (IP) (ℓ^*) is of 2.2 m. The crab-waist collision scheme requires a small horizontal beam size and a large crossing angle at the IP, set to 30 mrad, which results with the beams entering/exiting with separate beam pipes at about 1.2 m from the IP. The 2 cm diameter Beryllium beam pipe must dissipate about 0.5 W/cm^2, and its thickness required to be less than 0.5% of a radiation length. The vertex detector must be cooled by air, keeping a stability of better than 1 μm. The Luminosity detector must be kept in place with 50 μm accuracy over 2.5 m and the forward hermeticity of the calorimeter must cope with the needs of a cryogenic Final Focus Quadrupoles system. The detector elements close to the IP, the Vertex Detector and the Luminosity Calorimeter must be carefully integrated in this congested area, and allow easy access in case of maintenace, removing the final focus elements, which are about 10 meters long.

Performance Target

The goal of this project is to design the interaction region of the FCC-ee. It will consist in demonstrating the technical feasibility to realize a low material budget beam pipe, capable to be integrated with a light weight vertex detector, and minimising the material budget in front of the luminosity calorimeter, taking care of the services needed to power, readout and cool both the machine elements and the detectors. It will demonstrate the possibility of the integration of the final focus quadrupoles,Particular emphasis will be devoted to the assembly procedure, the insertion in the detector, allowing maintenance operations and alignment.

The main deliverables are the feasibility study of the integation of the IR and a mock up of the innermost IR, with the beam pipe, vertex detector and luminosity calorimeter.

Milestones and Deliverables

Label	Month	Description
M1	3	Design of the interaction region
M2	5	Vertex Cooling definition
M3	6	
D1	9	Interaction region mock-up assembly
D2*	15	
M4*	27	Final public note or paper

*Major or main deliverable or milestone

Multi-disciplinary, transversal content

Designing, manufacturing and assembly ....

There is a clear overlap with DRD7 and DRD3 which will be covered by communications via the respective *liasons* and workshops (e.g.: Forum on tracking mechanics).

Contributors and areas of competence

- **CERN**: Experience in the

Available resources, existing funding and frameworks

Table 13 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial three-year project duration. The values are given as averaged annual amounts.

Estimate of to be requested resources

Table 14 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds

Table 1: Available resources and areas of contribution.

Institute	Framework	Areas of Contribution
CERNr	XXX	YYY
	FTE/yr	**Annual Funding** [EUR]
Total available	1.0 (2024)	30k (on 2025-2026)

to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement/cofunding from the DRD8 will help to enable those initiatives in the medium/long-term.

Table 2: Resources to be requested. One should consider that requests will be answered in the year following submission.

Institute	Framework	Request submission year
CERN	TBC	2025
	FTE/yr	**Annual Funding** [kEUR]
To be requested	0.5 (2025-2026)	30k (2025-2026)

3.2 Project/Task: The Vertex region of future HEP experiments

<table>
<tr><td>Project Name</td><td>Project/Task: The Vertex region of future HEP experiments (WG 1.2)</td></tr>
<tr><td>Project Description</td><td>This project aims to design and integrate the next generation of Vertex detectors and beampipe, with the goal of moving closer to the interaction point and significantly reducing the material budget. To meet the ambitious requirements of these future vertex detectors, the project will explore the design, manufacturing, and system integration of innovative components such as an ultra-thin carbon beampipe, ultra-light silicon detectors with curved sensor surfaces, and the insertion of the first detection layers inside the beampipe.</td></tr>
<tr><td>Innovative/strategic vision</td><td>To achieve the desired pointing resolution in future HEP experiments, it is crucial to measure the first hit as close as possible to the interaction point while minimizing 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 beampipe, 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 beampipe radius and constrain the position of the first layer, the concept of placing the first layers inside the beampipe is considered, with the ability to retract the layers during injection.</td></tr>
<tr><td>Performance Target</td><td>Different experiment will profit of the next generation of beam pipe, retractable vertex and new bent sensors. The progress will be tracked via public reports in the form of presentations, public notes and/or papers.</td></tr>
<tr><td>Milestones and Deliverables</td><td><table>
<tr><th>Label</th><th>M</th><th>Target</th></tr>
<tr><td>D1</td><td>24</td><td>Deliver of a thin wall beam pipe demonstrator.</td></tr>
<tr><td>D2</td><td>36</td><td>Deliver of a retractable detector located inside the beam pipe.</td></tr>
<tr><td>D3</td><td>12</td><td>Deliver of a curved and tilted silicon sensor.</td></tr>
</table></td></tr>
<tr><td>Multi-disciplinary, cross-WG content</td><td>WG chips, WPG vacuum TE-VSC, Machine Detector interface (MDI) grop, DRD7</td></tr>
<tr><td>Contributors</td><td>CERN, INFN Pisa, Nikhef
List of contributions to WG8.1 (Preliminary)
• France - IPHC Strasbourg – (FTE 1.5) - baudot@in2p3.fr
• Germany - DESY - (FTE 0.5)- andreas.mussgiller@cern.ch
• Italy – INFN Pisa - (FTE 0.2)- Fabrizio.Palla@cern.ch
• Spain – IFIC Valencia – (FTE 0.2)- Marcel.Vos@cern.ch
• Switzerland- CERN – (FTE 1) – Burkhard.Schmidt@cern.ch
• Switzerland - Univ. of Geneva – (FTE 0.25) – franck.cadoux@unige.ch
• United Kingdom - Nat. Comp. Centre – (FTE 0.25) - Matt.Scott@nccuk.com
• United Kingdom - Univ. of Liverpool – (FTE 0.4) - timjones@liverpool.ac.uk
• USA – Purdue University – (FTE 1) - andreas.werner.jung@cern.ch</td></tr>
<tr><td>Available resources</td><td>Grand Total FTE 5.3</td></tr>
<tr><td>Resource request</td><td></td></tr>
</table>

Project Description

The unprecedented requirements for minimum material budget, mechanical stability, and proximity to the beamline necessitate the development of new design solutions for future HEP experiments. Standard solutions currently available do not meet these specific requirements, making this research and development program crucial for preparing the ambitious design of future detector mechanics.
Within this context, this project focuses on the development of the next generation Mechanics for advanced layouts, including ultralight beampipe, curved and tilted sensors, low radii vertex systems and retractable detectors for future High Energy Physics Experiments.

- **Curved Sensors**
  This subproject aims at developing the new wafer-scale curved silicon pixel chips to surround the bampipe 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 the following potential benefits to the physics performance. Together with the design of the chip, an innovative air cooling system and mechanical support made of carbon foam will be further developed.

- **Thin Beam Pipe**
  Beampipe in present detector have a thickness of 0.8 mm and a minimum inner radius of 18.2 mm in ALICE with beryllium as material. For RUN4 ALICE is aiming to a 16 mm inner radius and 0.5 mm wall thickness still in Beryllium. This is an unprecedented thin pipe at the limit of the present technologies to achieve wall impermeability. To push even further these limits future R&D will focus on different material like alloy of Beryllium and aluminium (Albemet), and carbon composite.

- **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. 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.

Performance Target

To achieve the desired pointing resolution in future HEP experiments, it is crucial to measure the first hit as close as possible to the interaction point while minimizing 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 beampipe, 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 beampipe radius and constrain the position of the first layer, the concept of placing the first layers inside the beampipe 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
D1	Carbon Beam Pipe	24	Deliver an ultrathin vacuum beampipe (carbon, beryllium, albemet) for primary and secondary vacuum compatible with vacuum operational requirements.
D2	Retractable detectors	36	Develop a retractable vertex with minimum material budget that could withstand the primary and secondary vacuum.
D3	Curved and titled sensors	12	Deliver curved and titled sensor bringing the first hit point closer to the interaction point.

Reports, papers and presentations will be delivered when either a milestone is reached or when a test is carried out.

Multi-disciplinary, transversal content

Global system design and integration are critical aspect to consider in view of the advanced layouts for the next generation Mechanics. There is a clear overlap with DRD7 and DRD3 which will be covered by communications via the respective liaisons and workshops (e.g.: Forum on tracking mechanics).

Contributors and areas of competence

- CERN
- INFN Pisa
- Nikhef

List of contributions to WG8.1 (Preliminary):

- France - IPHC Strasbourg – (FTE 1.5) - baudot@in2p3.fr
- Germany - DESY - (FTE 0.5)- andreas.mussgiller@cern.ch
- Italy – INFN Pisa - (FTE 0.2)- Fabrizio.Palla@cern.ch
- Spain – IFIC Valencia – (FTE 0.2)- Marcel.Vos@cern.ch
- Switzerland- CERN – (FTE 1) – Burkhard.Schmidt@cern.ch
- Switzerland - Univ. of Geneva – (FTE 0.25) – franck.cadoux@unige.ch
- United Kingdom - Nat. Comp. Centre – (FTE 0.25) - Matt.Scott@nccuk.com
- United Kingdom - Univ. of Liverpool – (FTE 0.4) - timjones@liverpool.ac.uk
- Usa – Purdue University – (FTE 1) - andreas.werner.jung@cern.ch

Available resources, existing funding and frameworks

Table 3 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial three-year project duration. The values are given as averaged annual amounts.

Table 3: Available resources and areas of contribution.

Institute	Framework	Areas of Contribution
CERN	XXX	YYY
	FTE/yr	**Annual Funding** [EUR]
Total available	4.0 (2024)	(on 2025-2026)

Estimate of to be requested resources

Table 4 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement from the DRD8 will help to enable those initiatives in the medium/long-term.

Table 4: Resources to be requested. One should consider that requests will be answered in the year following submission.

Institute	Framework	Request submission year
CERN	TBC	2025
	FTE/yr	**Annual Funding** [kEUR]
To be requested	(2025-2026)	(2025-2026)

3.3 Project/Task: Robots for Experimental cavern monitoring

<table>
<tr><td>Project Name</td><td>Project/Task: Robotics for Detectors (WG 1.3)</td></tr>
<tr><td>Project Description</td><td>Development of robotic systems for future high energy physics experiments to inspect particle detector as well as monitor the cavern environment even during the beam run.</td></tr>
<tr><td>Innovative/strategic vision</td><td>Development of legged ground robotic platforms for the autonomous and on-demand inspection with dedicated sensor suites, patrolling all the walkable areas. Development of robotic airships, such as blimps, to guarantee a comprehensive 3D environmental mapping (magnetic field and radiation dose) of the whole cavern volume. Development of a mobile mesh network to ensure an uninterrupted and efficient data stream during the confined spaces inspection by employing a swarm of interconnected mini robots.</td></tr>
<tr><td>Performance Target</td><td>As for legged and aerial robots the main target will be the ability to operate within the cavern background magnetic field and then perform the first autonomous inspection/monitoring. Whereas the mesh network robustness has to be enhanced and proven in a detector cavern confined space. Experiments would be able to profit from these robotic systems, reducing the accelerator down time, detecting anomalies at an early stage, and monitoring the experiment right functioning. The progress will be tracked via public reports in the form of presentations, public notes and/or papers.</td></tr>
<tr><td>Milestones and Deliverables</td><td><table>
<tr><td>Label</td><td>M</td><td>Target</td></tr>
<tr><td>D1</td><td>12</td><td>Deliver a robust ad-hoc mesh network ensuring an efficient data stream within a cavern confined space.</td></tr>
<tr><td>D2</td><td>24</td><td>Deliver robots able to counteract the cavern background magnetic field disturbances.</td></tr>
<tr><td>D3</td><td>36</td><td>Deliver robots able to perform an autonomous inspection/monitoring of the detector cavern environment.</td></tr>
</table></td></tr>
<tr><td>Multi-disciplinary, cross-WG content</td><td>DRD7 (WG 7.4, WG 7.5), DRD3 (WG 3.1, WG 3.2)</td></tr>
<tr><td>Contributors</td><td>CERN-EP-DT, CERN-BE-MRO</td></tr>
<tr><td>Available resources</td><td>3 FTE/yr (First year), 3 FTE/yr (Second year)</td></tr>
<tr><td>Resource request</td><td></td></tr>
</table>

Project Description

The CERN underground particle detector areas consist of large semi-structured caverns housing the particle detector which are characterized by high magnetic fields and radiation levels. The complex and delicate equipment in these sites is subject to frequent scheduled maintenance and inspections, now carried out by human personnel. However, future particle accelerators and detectors will be characterized by the presence of high radiation dose areas that could be a threat to human operators.
Within this context, this project focuses on the integration of robotic systems in future high energy physics experiments to inspect and monitor particle detectors even during the beam run. The employment of these robotic system for autonomous and on-demand inspections and 3D environmental mappings would contribute to reducing the accelerator down time, for instance avoiding unnecessary beam

dampings due to false alarms, detecting anomalies at an early stage, constantly monitoring the experiments right functioning, and preserving the personnel health.
In order to achieve a reliable and robust environmental monitoring, several mobile platforms, both ground and aerial, with specific payloads have been identified and are currently being developed under 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 characterized 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 Airship**
  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 characterized by a low battery consumption and they are a harmless solution for the surrounding detectors equipment in case of failure, thus potential collisions.

- **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 the external one, which is linked to the main network.

Performance Target

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 counteract the magnetic disturbances, or rather to operate in the high intensity cavern background magnetic field, and to perform the first autonomous inspection/mapping of the environment. The mobility and controllability of these robots have already been successfully tested in a detector cavern with no magnetic field and several tests have been carried out to investigate the magnetic disturbances on electromagnetic actuators, which are the most prone components to experience these effects. Future work to achieve these milestones is to implement 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.
Concerning the interconnected swarm of mini robots, the main deliverable is to successfully inspect a cavern confined space 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 the external robot, which is connected to the main network, through the shortest and less congested path in the swarm. Future work to achieve this milestone is to develop a strategy to move the swarm within the confined space, minimizing the connection losses, and an automatic reconfiguration of the external robot in case the connection with the main network breaks down. 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
D1	Mobile Mesh Network	12	Deliver a robust ad-hoc mesh network ensuring an efficient data stream within a cavern confined space.
D2	Legged robots and robotic airships	24	Deliver robots able to counteract the background magnetic field disturbances.
D3	Legged robots and robotic airships	36	Deliver robots able to perform an autonomous inspection/monitoring of the detector cavern environment.
D4	Legged robots and robotic airships	36	Develop a robust control system including the magnetic disturbances.
D5	Mobile Mesh Network	36	Inspect a cavern confined space with an uninterrupted data stream.

Reports, papers and presentations will be delivered when either a milestone is reached or when a test is carried out.

Multi-disciplinary, 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 is an overlap with DRD7 and DRD3 which will be covered by communications via the respective liasons and workshops (e.g.: Forum on tracking mechanics).

Contributors and areas of competence

- CERN-EP-DT: Development, construction and operation of particle detectors for CERN experiments.
- CERN-BE-MRO: Software development for robotics and robotic assistance for particle accelerators.

Available resources, existing funding and frameworks

Table 5 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial three-year project duration. The values are given as averaged annual amounts.

Table 5: Available resources and areas of contribution.

Institute	**Framework**	**Areas of Contribution**
CERN	XXX	YYY
	FTE/yr	**Annual Funding** [EUR]
Total available	3.0 (2024)	(on 2025-2026)

Table 6: Resources to be requested. One should consider that requests will be answered in the year following submission.

Institute	Framework	Request submission year
CERN	TBC	2025
	FTE/yr	**Annual Funding** [kEUR]
To be requested	(2025-2026)	(2025-2026)

Estimate of to be requested resources

Table 6 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement from the DRD8 will help to enable those initiatives in the medium/long-term.

4 WG 2: Low Mass Mechanics and thermal management

4.1 Introduction/Context

4.2 Project/Task: Three-Dimensional Support Structures for Future Tracking Systems - University of Oxford

Develop methods to design and construct three-dimensional structures with optimized routing of structural and thermally conductive fibrous elements. These elements can be composites (carbon fibre or other), or thin metal elements created by additive manufacturing.

4.3 Project/Task: Long, Low Mass Staves for Future Tracker - University of Oxford

Ultra low mass CF staves with integral cooling gas, power and data transmission flexes, optimized for future MAPS detector based tracking systems targeting lengths ¿=1.2m, radiation length of x0¡0.1, modular flex based sub ladders to reduce risks of production, co cured background services.

4.4 Project/Task: XHV Tight Composite Structures - University of Oxford

Using novel coating and post-cure processes the Mechanical Engineering Group (MEG) at the Department of Physics, Oxford, have created simple XHV compatible composite structures (beam pipes and chambers). These range from non-structural 20um thick RF shields, all the way up to fully structural beam pipes. This tasks proposes the advancement of these systems and additional effort into integration of more complex components. One area of particular interest is achieving an XHV compatible seal between a composite structure and a co-cured metallic (or otherwise) insert. A seal between cylindrical composite pipes and CF flange inserts has already been achieved, but extending this to more complex (non-cylindrical/non-conical) geometry with an alternating pressure difference would be of particular interest for application with particle physics detectors. The first iteration of the design will target XHV compatibility and an alternating pressure difference of 10mbar. The main deliverables from this tasks would include the design development of such an interface and seal as well as the practical testing to prove it's function. Full design including orthotropic FEA of the structure and drape analysis will be carried out at Oxford as well as manufacture (laminating, coating, cure and post-cure treatments). Testing is proposed to happen at either the Vacuum Solutions Group at AsTEC, Daresbury Labs or CERN. Milestones;

- Final Design
- Proof of Concept Prototype
- Outgas Testing Complete
- Leak Testing Complete
- DeltaP Deformation Test
- DeltaP Destructive Test

Deliverables;

- Proof of Concept Demonstrator
- Design and Analysis Data

4.5 Project/Task: Ultra-Thin Composite RF Shields for Vertex Locators - University of Oxford

The design and testing of an upgraded RF shield for the current generation of LHCb VELO, as well as a fully exploited upgrade during LS3 are under way at MEG, Oxford Physics. This will deliver a sub-100um and sub-50um RF shield solution to the VELO, capable of protecting the modules from the 40 mHz beam signal.

Milestones;

- Final Design
- Proof of Concept Prototype
- Outgass Testing Complete
- Leak Testing Complete
- DeltaP Deformation Test
- DeltaP Destructive Test
- Stretched Wire RF Testing
- Conceptual Design of a Fully Exploited LS3 Design

Deliverables;

- Proof of Concept Demonstrator
- Design and Analysis Data

4.6 Project/Task: Radiation Length Characterisation of Composite Materials - University of Oxford

The Mechanical Engineering Group at University of Oxford, Department of Physics, plan to carry out extensive radiation length testing of a wide range of composite materials. This is done with a view to characterise the constituent parts of the composite material and create a piece of software that can create a plot of radiation length during the design process. This will be a powerful tool in reducing the actual radiation length of a produced component as it will allow designs to predict the effect of overlap joints, butt joints, darts, resin rich and dry areas during the design of components and tooling. Furthermore it will bolster understanding of the effect of the constituent parts of a composite material on radiation length and allow discussion of resin systems, fiber types, placements, weaves and densities to have a much more quantifies grounding.

Milestones;

- Radiation Length Testing of Varying Fiber Types;
- Radiation Length Testing of Varying Resin Systems;
- Radiation Length Testing of Varying Resin Volumes;
- Radiation Length Testing of Varying Fiber Weaves (UD, Plain, 2x2t, 5h, 8h);

Deliverables;

- Written Up Results from Radiation Length Testing;
- A Plug-In Script for Dassault CATIA CPD to Plot Radiation Length Based on Ply Schematic;

4.7 Project/Task: Carbon Over Braid Reinforced Microvascular Channels, Truss Structures with Integrated Cooling - National Composites Centre/University of Bristol

PhD co-supervised with CERN on plates with fuzzy carbon overbraid reinforced microvascular channels, truss structures with integrated cooling and connections between the two.

4.8 Project/Task: Carbon Over Braid for Curved Structures - National Composites Centre/University of Bristol

4th year undergraduate project to start in October on overbraids for curved geometries.

4.9 Project/Task: Composites with Integrated Cooling - National Composites Centre/University of Bristol

Composites with integrated cooling for an industrial application, including microvascular channels (industrial PhD project)

4.10 Project/Task: Development of Bio-Inspired Composite Materials - National Composites Centre/University of Bristol

NextCOMP focuses on improving compressive performance. Tailored fibre placement at NCC, allows manufacturing of organic type shapes.

4.11 Project/Task: Development of Flat Optical Fibre Sensors - National Composites Centre/University of Bristol

Flat optical fibre sensors- FOSSIC project with Southampton (Flexible-photonic Optical Strain Sensing In Composites).

4.12 Project/Task: Development of Manufacturing Simulation and Design Tools - National Composites Centre/University of Bristol

Development of Manufacturing Simulation and Design Tools - could tie in well with the work in Oxford on advancing drape analysis and radiation length analysis.

4.13 Project/Task : Experimental Qualification and Numerical Simulation of the Thermal Properties of Novel Materials - INFN Perugia

As a supporting project, or aligned with a tangential project, INFN Perugia propose offering their expertise and infrastructure to support experimental qualification and numerical simulation of the thermal properties of novel materials and structures being used within DRD8.WP2. Ongoing activities at INFN Perugia which compliment WP2 include;

- CFD simulations for evaluating thermal performance of the CMS modules for ph-2 upgrade;
- Thermal testing on CMS modules and cables for ph-2 upgrade;
- CFD simulations for fluid flows in micro-channels;
- CFD and FEA simulations for future air-cooled detectors, including experimental validation;

This includes access to the following instruments;

- Guarded Hot Plate;
- Hot Disk;
- Laser Flash;
- Active Thermography;
- Through Plane Thermal Conductivity ”Tower” Apparatus;

Further more the following expertise and equipment can be offered to support WP2;

- CAD Software and Design Skills;
- CFD and FEA simulation throguh ANSYS;
- CMM with touch probe;
- Mechanical Workshop;

4.14 Project/Task : Contractable Inner Tracker Structure for High Energy Physics Particle Detectors- Purdue University

PI - Kawai Kwok, Sushrut Karmarkar

This project aims to design and develop a contractable inner tracker structure to enable positioning of the vertex layer close to the interaction point. At compact detectors of the future like ePIC conceptualized to be built at the Electron Ion Collider at Brookhaven National Labs the insertion of the inner most silicon vertex detectors close to the beam pipe pose a challenge in both mechanical and thermal integration and stability. The conical sections on the beam pipe force a pre-build of the barrel SVT layers before beam pipe installation and bake out. The bake out at high temperatures increases the risk of thermal damage to the silicon modules. Thus, creating the need for contractable and reconfigurable integrated supports to allow for close to IP positioning of the SVT layers while being able to successfully integrate and service the detector elements. Our proposed concept will use pantographic mechanisms to allow reconfiguration of the aperture diameter between injection and operation. Pantographic mechanisms are formed by a combination of rigid bars connected through scissor hinges. Specifically, we will employ angulated pantographic elements, which are bars with a kink angle, to form closed-profile structures with a single degree of freedom during contraction or expansion. The single degree-of-freedom characteristic ensures geometric compatibility during contraction. The mechanism will be constructed with low mass, thermally conductive, thin-walled structural elements with embedded channels available for active cooling. To simultaneously achieve the desired mechanical, thermal, and physical properties, a composite architecture composed of carbon nanotube (CNT) film, pyrolytic graphite sheet (PGS), and spread-tow carbon fabric will be studied, and its corresponding manufacturing method will be developed.

The major technical objectives are stated as follow:

- Development of a contraction scheme for the vertex detector using pantographic mechanisms. Geometric and kinematic design of the mechanism will be determined based on the target detection layer diameters, cooling and vacuum requirements. Thermal and mechanical simulations will be conducted to generate designs. Physical prototypes will be built to evaluate kinematic and geometric characteristics.
- Development of a low-mass, thermally conductive, thin-walled composites. Thin composites with a multilayer architecture of CNT film, highly oriented PGS, and spread-tow carbon fabric embedded in high temperature thermoplastic matrix will be developed via thermoforming processing methods. Performance of the composites will be evaluated via characterization tests.

- Integration and characterization of the tracker. The interface of the contractable structure with the connecting elements inside the beampipe will be investigated for system operation. Vacuum tightness and temperature profile under approximate operating conditions will be experimented tested to evaluate the performance of the proposed concept.

4.15 Project/Task : Low-mass Support Structures and Active Sensing for Future Tracking Detectors- Purdue University

PI - Andreas Jung, Eduardo Barocio
We propose to develop structural, lightweight, and highly thermally conductive composite tracking detector support structures that address a variety of critical needs of future particle physics detectors, all aimed at the Instrumentation Frontier (Precision support structures and cooling). Furthermore, our rapid progress during the previous funding period allows us to leverage our expertise in individual CF "manipulations" and 3D-printing and propose a highly synergistic and closely related research direction. Namely, we propose R&D towards an **all CF low mass multi-wire proportional chamber** utilizing CF sense wires and optimized CF based support structures to hold them in place. Such a technology is an ideal match for the needs of an FCC-ee tracking device. A calculation of material budget between state-of-the-art gold-plated tungsten wires and CF wires of similar dimension show a drastic potential reduction of X_0 by a factor 10.

4.15.1 Detailed Proposed Research and Methods

The entire manufacturing process needs to be optimized so that any deviations from the nominal design can be predicted by manufacturing process simulations (FEA), compensated, and ultimately mitigated in the manufacturing of a final mechanical support structure. This is particularly important to overcome deformation of the structure due to cooling from the ambient temperatures to the low operating temperature. In addition, fatigue life is of paramount importance for the reliable operation of a support structure throughout its lifetime at future colliders with extreme radiation levels such as FCC-hh. Hence, we propose investigating the fatigue life of highly irradiated support structures (via parasitic runs at Sandia Lab in connection with the HL-LHC pixel project) that are subjected to pressure cycling at the low operating temperatures typical of HEP applications. Our initial radiation tests were done up to fluences corresponding to 300 MRad, which is substantial but not yet high enough for future colliders. To augment the reliability of this new technology for support structures and to develop further understanding on the fatigue performance, we propose embedding sensing elements during the manufacturing process of the support structure. Data collected from the sensing elements will be utilized along with machine learning techniques to establish correlations between the measured field variables (pressure, strain, temperature, moisture) and the structural integrity of the support structure. Our proposed R&D will allow us to minimize mass as required by future high energy physics collider applications at FCC-hh, FCC-ee, or muon-Colliders. Our rapid progress during the previous years (2021 – 2023) has allowed us to leverage our expertise to propose R&D towards an all-CF low mass multi-wire proportional chambers using CF sense wires and optimized CF based support structures to hold them in place.
Support Structures with Integrated Services: Now, to reduce the radiation length per layer of a silicon detector at future experiments from the current 2% X_0 to a level of 1% X_0 for future hybrid silicon pixel detectors, the entire mass budget has to be reduced, which includes the mechanical support and cooling structure as well as the sensor and chip assembly (not part of this project). Hence, we propose harvesting our excellent progress and innovations towards solutions involving integrated cooling and mechanical support structures, which are **already manufactured at CMSC (and applied to the EIC detector design, externally funded)**. Novel techniques, materials, and other design and manufacturing solutions allow to solve issues related to increasingly more demanding detector environments.

To realize these multifunctional materials and structures, the Purdue team relies on a physics-based Integrated Simulation Workflow (ISW) developed at CMSC for 3D printing. Utilizing ISW, unfavorable designs and material selections will be discovered in silico without expending material, machine time, and engineering effort prior to any prototypes. A dedicated simulation effort informed by prototypes and measurements will yield optimized manufacturing techniques to obtain a most optimal support structure. Tests and measurements include irradiation campaigns, verifying TC by measurements, performance of cooling structures in terms of ability to hold high-pressure coolant, and finally system tests employing realistic silicon-based mock heaters as a lowest order approximation of how a future silicon detector module might perform. This approach allows to study various common issues in the cooling of silicon detector modules, such as specific failure modes with much higher power demands, hot spots, and more.

All Carbon Fiber Wire chamber: We propose a highly synergistic and cost-effective additional R&D activity towards an **all-CF low mass multi-wire proportional chamber**, which is an ideal match for the needs of an FCC-ee tracking device. A calculation of material budget between state-of-the-art gold-plated tungsten wires and CF wires of similar dimension show a drastic potential reduction of X_0 by a factor 10. Such a tracking device offers unique and cost-effective tracking detector coverage for large detectors at about a factor ten lower X_0 compared to tungsten-based "standard" wire chambers. Multiwire chambers (Physics Nobel prize in 1992) have been used extensively in the past, with the current standard being gold plated tungsten wires of 30-40 micron diameter. While this is not a concern in most cases where the coverage of the wires affects a very small fraction of the events, for future colliders like FCC-ee the energy loss for the incoming nuclei must be reduced. Now, low Z-materials like carbon fibers have been under study for use as multiwire chambers since 1986. With current technologies to mitigate the short-comings of CF wires like low conductivity and difficulty to apply tension during assembly, there is tremendous interest in this research. Recent advancements in carbon fiber technology have introduced wires with superior mechanical properties and electrical conductivity (Toray, Nippon). Part of the proposed work relies on an assessment of mechanical properties of CF filaments after metal coating them, which can be done in-house at no cost to the project. However, we provide scoping options, and explain the impact on deliverables.

At Purdue's CMSC the technology developed for carbon fiber pultrusion to be used in structural applications for integrated multifunctional cooling structures, can be extended and studied for application to carbon fiber wire chambers. To this end we have started preliminary proof of concept studies to understand the tension needed versus CF strength. The spacing is set to 10 mm $\times$ 10 mm grid with approximate wire bundle diameter of 40-microns, which in the future will be investigated with individual fibers. The fiber tows are separated using a solvent under a stereoscope. The prototyping efforts are done using standard modulus Hexcel AS4-D fibers with the end plates made from Hexcel AS4-8552 plain weave pre-preg laminate. Individual 40-micron fiber bundles were first tested for tensile strength with a pulley to introduce sequentially increasing static loads. Both the tests yield results consistent with the expected tensile strength values from the manufacturer datasheet, proving that our method of separating and twisting the carbon fiber bundles into smaller 40-micron cross-sections does not significantly compromise the integrity of the fibers. Our initial tests made us confident to propose R&D for an all-CF wire chamber including a viable coating process of fiber bundles (and individual fibers) with the pultrusion technology developed at Purdue CMSC and then to coat the pultruded 40-micron CF wires with silver or gold to improve the electrical conductivity of the wires is a viable future technology for HEP. The signal to noise ratio and functioning of such a active sensing layer will be measured and compared against standard gold-plated tungsten wires by using a Co_{60} source readily available at the PSDL from pixel sensor setups.

4.16 Project/Task : Terahertz Time Domain Spectroscopy for degree of cure and strain measurement in composites and adhesives- Purdue University

PI - Sushrut Karmarkar, Vikas Tomar, Diyanun Zhang

4.17 Project/Task : Terhertz Time Domain Spectroscopy and Acoustic testing for Non-Destructive Evaluation of Composite Structures- Purdue University

PI - Sushrut Karmarkar, Vikas Tomar, Luz Sotello

5 WG 3: Detector Cooling

5.1 Project/Task: New cooling fluids and systems

Contact: Bart Verlaat (CERN)

Silicon detectors require accurate and reliable thermal control under operation and standstill. During operation and hence powered on, large amount of heat need to be absorbed by the cooling keeping the temperature of the detector low enough to avoid thermal runaway. Cooling must also be performed when the power is off, to avoid the collected radiation damage to be revealed. Current applications require cooling in the range of +20'C down to -40'C, which is the domain of the well developed cooling with evaporative CO2. The default used method is the 2PACL (2-Phase Accumulator Controlled Loop), a method which is able to circulate a given temperature of saturated flow through the detector. A key feature is the stability of the pressure and hence cooling pipe temperature and the ability of cooling down the detector in a controlled way which is typically about 1'C per minute.

In the future colder cooling is needed. Cooling temperatures in the range of -90'C / -50'C are possibly needed. This is beyond the application of CO2, as CO2 freezes at -56'C. A novel cooling fluid has been identified which works theoretically well in this lower temperature range. Krypton (R784) has fluid properties which makes it a promising candidate.

CO2 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 well used 2PACL method the detector is liquefied and cooled down in liquid state. This allows a controlled cool down and thermal shocks are avoided. In case of Krypton a trans critical cool down in a compressor cycle is foreseen as a method for a controlled cool down. This cycle is completely different from any other system used at CERN and in industry.

This proposed research activity comprises the demonstration of Krypton as a cold detector cooling fluid and the development of a new Krypton trans critical cool down cycle with an internal ejector for detector circulation. The project is already ongoing by a PhD finishing in 2025. This PhD will demonstrate the feasibility of a Krypton cooling cycle. Krypton is a refrigerant with different fluid properties compared to other known refrigerants. Therefor specific components need to be developed or modified from standard to be able to work for Krypton. A follow up PhD is foreseen to work on the 2 major component upgrades which are the compressor and the ejector. This PhD is already half funded by NTNU, the 2nd half to be financed.

Project Name	Project/Task: New cooling fluids and systems (WG 8.3)
Project Description	Cold detector cooling using Krypton as a new refrigerant
Innovative/strategic vision	Exploration of a new cooling domain using a natural refrigerant in a novel cycle
Performance Target	Cooling detector structures with high dissipation in the temperature domain between -90 °C and -50 °C
Milestones and Deliverables	Label / M / Target: D1 / 48 / Deliver of a concept demonstration (3 papers, 2 already published). D2 / 36 / Deliver of a working Krypton cooling prototype (2 papers). D3 / 24 / Deliver of component prototypes (2 papers). D4 / 24 / Deliver of heat and mass transfer performance data (1 paper).
Multi-disciplinary, cross-WG content	xxxx
Contributors	CERN, NTNU-Trondheim, Companies • Norway – NTNU - Trondheim - Armin.Hafner@ntnu.no • Switzerland- CERN – Bart.Verlaat@cern.ch
Available resources (FTE)	Grand Total FTE: 9 (Sep-21 / Aug-28)
Resource request (FTE)	Grand Total FTE: 2 (Jan-27 / Dec-28)
Resource request (Material)	Grand Total 200 kCHF (Sep-24 / Dec-28)

Milestones and Deliverables

Label	Topic	Period	Description
D1	System demonstration (PhD)	Sep-21 / Aug-25	Development of a demonstration system proving the system concept
D2	System development (fellow)	Sep-25 / Aug-28	Development of a working prototype
D3	Krypton Component development (PhD)	Jan-25 / Dec 26	Development of specific components special for Krypton, like Ejectors and (oil free) Compressors
D4	Krypton Cooling performance (PhD)	Jan-27 / Dec 28	Performance testing of evaporative Krypton in detector cooling tubes

Reports, papers and presentations will be delivered when either a milestone is reached or when a test is carried out.

Multi-disciplinary, transversal content

Novel cooling system design and integration are critical aspect to consider in view of the advanced layouts for the next generation Mechanics. There is a clear overlap with DRD7 and DRDX which will be covered by communications via the respective liaisons and workshops (e.g.: Forum on tracking mechanics). Krypton being a new refrigerant have much 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 component development. The use of R784 as refrigerant has been picked up as an interesting natural refrigerant candidate for cold applications.

Contributors and areas of competence

- CERN, EP-DT-FS (CH), Detector cooling and fluid property expertise
- NTNU-Trondheim (NO), Natural refrigerants and system expertise
- Companies, component development

List of contributions to WG8.3 (Preliminary):

- Switzerland- CERN – Bart.Verlaat@cern.ch, Luca.Contiero@cern.ch
- Norway - Norwegian University of Science and Technology (NTNU) – Armin.Hafner@ntnu.no, krzysztof.banasiak@sintef.no, new PhD

Available resources, existing funding and frameworks

Table 3 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial four-year project duration. The values are given as averaged annual amounts.

Table 7: Available resources and areas of contribution.

Institute	Framework	Areas of Contribution
CERN	AIDAInnova EU National Funding	Fluidic and thermal testing, detector integration, technology development
NTNU	AIDAInnova EU national funding	Technology development, system development
	FTE/yr	**Annual Funding** [EUR]
Total available	1.5 (2024-2028)	0k (

Estimate of to be requested resources

Table 4 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement from the DRD8 will help to enable those initiatives in the medium/long-term.

Table 8: esources to be requested. One should consider that requests will be answered in the year following submission.

Institute	Framework	Areas of Contribution
CERN	AIDAInnova EU National Funding	Fluidic and thermal testing, detector integration, technology development
NTNU	AIDAInnova EU national funding	Technology development, system development
	FTE/yr	**Annual Funding** [EUR]
To be requested	1 (2027-2028)	50k (2024-2028)

5.2 Project/Task: Silicon Microchannel Cooling and Active Interposers

<table>
<tr><td>Project Name</td><td>Project/Task: Silicon Microchannel Cooling and Active Interposers</td></tr>
<tr><td>Contact person</td><td>Miguel Ullán (miguel.ullan@csic.es)</td></tr>
<tr><td>Project Description</td><td>Development of the silicon microchannel compatible manufacturing process compatible with a commercially available CMOS technology and active interposers to integrate the detector to the front-end electronics.</td></tr>
<tr><td>Innovative/strategic vision</td><td>Better integration of detector electronics features to the cooling plates especially in dense electronics applications.</td></tr>
<tr><td>Performance Target</td><td>Explore the cooling parameter space of low material budget (down to ≤ 0.2 %X_0) and low power dissipation ($\sim$10-100 mW/cm^2). The progress will be tracked via public reports through presentations, public notes and/or papers.</td></tr>
<tr><td>Milestones and Deliverables</td><td><table><tr><td>Label</td><td>M</td><td>Target</td></tr><tr><td>D1*</td><td>15</td><td>Fluidic and thermal results from integrated system</td></tr><tr><td>D2*</td><td>30</td><td>Public note or paper</td></tr></table></td></tr>
<tr><td>Multi-disciplinary, cross-WG content</td><td>Communication with DRD7 and DRD3 via liaisons and workshops (e. g.: Forum on tracking mechanics).</td></tr>
<tr><td>Contributors</td><td>ES: IMB-CNM, IFIC-Valencia
GE: DESY</td></tr>
<tr><td>Available resources</td><td>?, ?</td></tr>
<tr><td>Resource request</td><td>?, ?</td></tr>
</table>

Project Description

We propose technological developments in two lines: On one hand, 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 the compatibilization of different silicon sensor technologies, but the final aim would be to create a post-processing technology that can incorporate buried micro-channels to a commercially available CMOS technology. On the other hand, we propose the development of "active interposers" which hold the mechanical support and the buried micro-channels to provide the 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).

Milestones and Deliverables

Label	Month	Description
M1	6	Compatibilization of cooling interposers with RDL
M2	8	Demonstrate the integration of microchannels in a sensor process
M3	12	3D integration of interposers in sensor system
D1*	15	Fluidic and thermal results from integrated system
M4	24	Compatibilization with CMOS detector technology
D2*	30	Public note or paper

*Major or main deliverable or milestone

Available resources, existing funding and frameworks

Table 13 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial three-year project duration. The values are given as averaged annual amounts.

Contributors and areas of competence

- **IMB-CNM**: Technology development, 3D integration, electronic testing.
- **IFIC**: Full system integration, cooling interconnection, mechanics, services.
- **DESY**: Fluidic and thermal tests, system development.

Estimate of to be requested resources

Table 14 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds

Table 9: Available resources and areas of contribution.

Institute	Framework	Areas of Contribution
IMB-CNM	AIDAInnova EU National Funding	Technology development, 3D integration, electronic testing
IFIC	AIDAInnova EU national funding	Fluidic and thermal tests, system development
DESY	National funding	Fluidic and thermal tests, system development
	FTE/yr	**Annual Funding** [EUR]
Total available	?	?

to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement or co-funding from the DRD8 will help to enable this initiative in the medium/long-term.

Table 10: Resources to be requested. One should consider that requests will be answered in the year following submission.

Institute	Framework	Request submission year
IMB-CNM	TBC	2024
IFIC	TBC	2024
DESY	TBC	TBC
	FTE/yr	**Annual Funding** [kEUR]
To be requested	?	?

5.3 Project/Task: Silicon Microchannel via thermocompression

Project Name	Project/Task: Silicon microchannels via thermocompression
Contact person	Julien Cogan (cogan@cppm.in2p3.fr)
Project Description	Development of the silicon microchannel via thermocompression aiming for a more cost-effective process and sensor/fluidic integration
Innovative/strategic vision	Cost reduction to make the technology more easily accessible and easier integration of sensor/fluidic connector to the cooling plate.
Performance Target	Explore the parameter space of high power density (1.5W/cm^2), vacuum, low material budget and high cooling performance. The progress will be tracked via public reports through presentations, public notes and/or papers.
Milestones and Deliverables	Label: M3* — M: 36 — Target: Bi-phase CO2 Thermo-fluidic models development for microchannels/ nuclear and annular flows. Heat exchangers characterization and interconnections
Multi-disciplinary, cross-WG content	Communication with DRD7 and DRD3 via liaisons and workshops (e. g.: Forum on tracking mechanics).
Contributors	FR: *French Collaboration**.
Available resources	?, ?
Resource request	?, ?

*The French institutes involved in this project have expressed their preference to be treated as a single body. Therefore, they are referenced as *French Collaboration*.

Project Description

This project covers several developments carried by a collaboration of French laboratories: 1) the setting up of a dedicated cooling test bench; 2) the fabrication of cooling plates with micro-channels of various geometrical and surface form factors; 3) the development of numerical 3D models - based on dedicated measurements - and their implementation in numerical simulation tools to optimize the micro-channel heat exchanger design; 4) the development a low-cost silicon cooling-plates fabrication process, mainly based on an innovative bonding technique: "the hyperbaric bonding", which uses thin layer of gold - similarly to the thermo-compression - and is performed at room temperature inside a hyperbaric chamber; 5) the developments of cooling-plates interconnects to allow the fabrication of heat exchangers covering large areas.

Milestones and Deliverables

Label	Month	Description
M1	12	Bi-phase CO_2 Thermo-fluidic models development for microchannels/ Slug flow with heat mass transfer
M2	18	Prototypes bonded with thermo-compression or hyperbaric process characterization
M3*	36	Bi-phase CO_2 Thermo-fluidic models development for microchannels/ nuclear and annular flows. Heat exchangers characterization and interconnections

*Major or main deliverable or milestone

Available resources, existing funding and frameworks

Table 13 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial three-year project duration. The values are given as averaged annual amounts.

Table 11: Available resources and areas of contribution.

Institute	Framework	Areas of Contribution
French Collaboration	In2p3 R&T "Micro-canaux"	Microchannel cooling plates low cost fabrication process, thermo-fluidic simulation tools, optimisation of microchannel designs, 3D printing ceramic and low temperature (down to -45°C) characterisation.
	FTE/yr	**Annual Funding** [EUR]
Total available	?	?

Contributors and areas of competence

- **CPPM (Aix Marseille Univ, CNRS/IN2P3) -** *French Collaboration*: Experience in the assembly, testing, and validation of silicon detectors in general (ATLAS) and in the development of microchannel cooling plates (NA62 GigaTracKer). Recently, the development of bonding processes at room temperature in collaboration with the micro-fabrication CNRS laboratory FEMTO-ST.
- **LAPP -** ***French Collaboration***: Experience in CO2 microchannels heat exchanger studies, thermal and mechanical simulations, characterization and measurement on bi-phase CO2 cooling test

bench.

- **LEGI - *French Collaboration***: Experience in numerical modeling to simulate the flow of bi-phase coolant inside micro-channels. Microchannel heat exchanger production (etching, anodic silicon/Pyrex bonding and connectors brazing)

- **LPNHE - *French Collaboration***: Experience in assembly, construction and characterization of silicon pixel modules, design of micro-channel cooling plates and interconnections.

Estimate of to be requested resources

Table 14 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement or co-funding from the DRD8 will help to enable this initiative in the medium/long-term.

Table 12: Resources to be requested. One should consider that requests will be answered in the year following submission.

Institute	**Framework**	**Request submission year**
French Collaboration	TBC	TBC
	FTE/yr	**Annual Funding** [kEUR]
To be requested	?	?

5.4 Project/Task: LTCC/HTCC cooling plates

<table>
<tr><td>Project Name</td><td>Project/Task: LTCC/HTCC cooling plates</td></tr>
<tr><td>Contact person</td><td>Oscar Augusto de Aguiar Francisco (oscar.augusto@manchester.ac.uk)</td></tr>
<tr><td>Project Description</td><td>Development of the next generation of cooling plates based on the LTCC/HTCC process to manufacture high-performance cooling plates with microchannels embedded with the possibility of front-end electronics integration. The main goal is to explore the feasibility of this technique and build a demonstrator using the LHCB VELO Upgrade 2 as benchmark. The project duration is 2+ years.</td></tr>
<tr><td>Innovative/strategic vision</td><td>Better integration of electronics features to the cooling plates especially in dense electronics applications.</td></tr>
<tr><td>Performance Target</td><td>Explore the parameter space of high power density (1.5W/cm^2), vacuum, low material budget and high cooling performance. The progress will be tracked via public reports through presentations, public notes and/or papers.</td></tr>
<tr><td>Milestones and Deliverables</td><td><table>
<tr><td>Label</td><td>M</td><td>Target</td></tr>
<tr><td>D1*</td><td>15</td><td>Ceramics cooling tests and cooling performance (Demonstrator)</td></tr>
<tr><td>M4*</td><td>18</td><td>Feasibility tests public note or paper</td></tr>
<tr><td>D3*</td><td>28</td><td>Ceramics cooling tests (Demonstrator) and cooling performance</td></tr>
<tr><td>M6*</td><td>30</td><td>Final public note or paper</td></tr>
</table></td></tr>
<tr><td>Multi-disciplinary, cross-WG content</td><td>Communication with DRD7 and DRD3 via liaisons and workshops (e. g.: Forum on tracking mechanics).</td></tr>
<tr><td>Contributors</td><td>UK: The University of Manchester</td></tr>
<tr><td>Available resources</td><td>1 FTE/yr (First year), 10k/yr (First year)</td></tr>
<tr><td>Resource request</td><td>0.5 FTE/yr (on 2024-2025), 30k/yr (on 2024-2025)</td></tr>
</table>

Project Description

Micro-channel cooling plates are extremely efficient in removing the heat from the front-end electronics and/or sensors since the coolant is very close to the heat source. This project aims to improve its integration and cost and explore alternative base materials while minimizing its material budget, increasing its ability to dissipate more power and integrating more electronics features.

In this scenario, low-temperature cofiring ceramic (LTCC) and high-temperature cofiring 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 for those structures will be the LHCb VELO Upgrade 2 which has very challenging requirements (high power density, high pressure, and high vacuum operation). The project is currently on-going and initial sample have already been produced.

Performance Target

The goal of this project is to design, manufacture, and validate microchannels cooling plates based on the LTCC/HTCC process. The main deliverables are the feasibility study of this technique and the integration of electronics.

Milestones and Deliverables

Label	Month	Description
M1	6	Vacuum compatibility
M2	6	High pressure and Leak tightness tests
M3	12	New production run (design optimization)
D1*	15	Ceramics cooling tests and cooling performance (Demonstrator)
M4*	18	Feasibility tests public note or paper
D2	24	Manufacturing run: more realistic design and electronics integration
M5	25	High pressure and Leak tightness tests
D3*	28	Ceramics cooling tests (Demonstrator) and cooling performance
M6*	30	Final public note or paper

*Major or main deliverable or milestone

Multi-disciplinary, transversal content

Designing, manufacturing, and validating cooling plates are critical to dense front-ends, at the interface between electronics, sensors, mechanics, and integration. There is a clear overlap with DRD7 and DRD3 which will be covered by communications via the respective *liasons* and workshops (e.g.: Forum on tracking mechanics).

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. Recently, played a major role in the LHCb VELO Upgrade 1 module assembly.

Available resources, existing funding and frameworks

Table 13 shows the manpower and funding currently assured in participating institutes from the relevant funding framework for an initial three-year project duration. The values are given as averaged annual amounts.

Table 13: Available resources and areas of contribution.

Institute	Framework	Areas of Contribution
University of Manchester	LHCb VELO Upgrade 2 (UK-STFC)	Microchannel cooling plates and Silicon detectors
	FTE/yr	**Annual Funding** [EUR]
Total available	1.0 (2024)	30k (on 2025-2026)

Estimate of to be requested resources

Table 14 shows the manpower and funding foreseen to be requested by participating institutes. The table indicates the current framework (project name/funding agency) which provides (the current) partial funds to cover the topics. To be able to achieve the milestones/deliverables more funds will be required. Hence, the endorsement or co-funding from the DRD8 will help to enable this initiative in the medium/long-term.

Table 14: Resources to be requested. One should consider that requests will be answered in the year following submission.

Institute	Framework	Request submission year
The University of Manchester	TBC	2025
	FTE/yr	**Annual Funding** [kEUR]
To be requested	0.5 (2025-2026)	30k (2025-2026)

5.5 Cooling testing facility

How to add a test facility?

CERN has a long time experience developing, characterizing and validating cooling structures and plants for different applications. Access to different set-ups potentially including local expertise can requested. A not exhaustive list is presented below:

- Fluidic characterization and thermal performance of microchannels cooling plates or cooling structures with CO_2, liquid coolants, C_6F_{14}, ...
- High pressure validation cooling structures to fullfill the detector requirements
- Ultra-cold krypton cooling plant (down to -90°C) for testing cooling structures (based on section 5.1)
- High precision metrology survey using different devices including Keyence VR-3200
- Leak test with high pressure helium (> 60 bar) in a vacuum environment down to 10^{-10}mbar.l/s
- Leak test with sample under vacuum and helium spray down to 10^{-10}mbar.l/s

Contact person: ???

6 WG 4: Design and Qualification Tools

7 Milestones, deliverables and resources

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.

A paragraph on how the communication with DRD3 and DRD will be organised.

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.

9 Infrastructure - available and needed

9.1 DRD8.WP2 Available Infrastructure

Description of Infrastructure	**Home Institute**	**Point of Contact**	**Notes**
Low Intensity Shaker Table	University of Oxford	Georg Viehhausser	>1mg acceleration
Large Thermal Chamber	University of Oxford	Georg Viehhausser	Weiss WVC C1500-70
Thermal Imaging Cameras	University of Oxford	Georg Viehhausser	
Multiline FSI System	University of Oxford	Georg Viehhausser	16 Line. Sub um precision
Capacitive Displacement Systems	University of Oxford	Georg Viehhausser	Systems for distance measurements
SPTab Bonding Interconnect Design and Fabrication	University of Oxford	Georg Viehhausser	
Precision Assembly Robot	University of Oxford	Georg Viehhausser	Used for integrating sensor on structures
CNC500 SmartScope	University of Oxford	Georg Viehhausser	2um precise non contact metrology
ThermlAir	University of Oxford	Georg Viehhausser	Thermal shock test system
X-Ray System	University of Oxford	Georg Viehhausser	Material testing and inspection
Protolaser U4	University of Oxford	Georg Viehhausser	UV flex and PCB fabrication
CATIA Composite Part Design	University of Oxford	Georg Viehhausser	Orhtotropic drape and design analysis software
ANSYS ACP	University of Oxford	Georg Viehhausser	Fully orthotropic FEA
CNC Recip Knife Cutter	University of Oxford	Georg Viehhausser	Cut kit ply creation
Autoclave	University of Oxford	Georg Viehhausser	750mm dia x 1.8m length
V-Stars Photogrammetry	University of Oxford	Georg Viehhausser	Dynamic and static photogrammetry
M250-2.5CT	University of Oxford	Georg Viehhausser	2.5kN Tensile Test Machine
Guarded Hot Plate	INFN Perugia	Cristiano Turrionir	
ANSYS CFD and FEA	INFN Perugia	Cristiano Turrionir	
Laser Flash	INFN Perugia	Cristiano Turrionir	
Active Thermography	INFN Perugia	Cristiano Turrionir	
Through Plane Thermal Conductivity Tower	INFN Perugia	Cristiano Turrionir	