# DRD 6: Calorimetry

June 28, 2023

## Contents

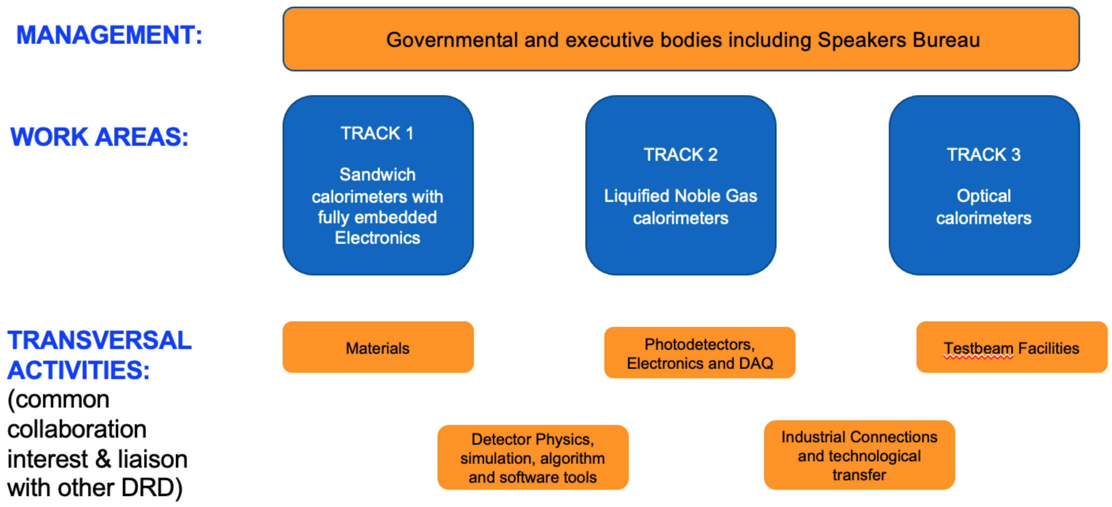
# 1 Introduction

Different types of calorimeters are proposed for experiments for future fixed-target facilities, EWK/Higgs factories, hadron and muon colliders. THE ECFA Detector Roadmap [1] has defined the following Detector R&D Themes.

- DRDT 6.1: Radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution;
- DRDT 6.2: Highly-granular calorimeters with a multi-dimensional readout for optimised use of particle flow methods;
- DRDT 6.3: Calorimeters for extreme radiation, rate and pile-up environments.

These themes are the guidelines for the R&D program that will be carried out in the DRD on Calorimetry. The mission of the DRD on Calorimetry will be to bring a diverse set of calorimeter technologies to a level of maturity such that they can be considered for a technology selection of future experiments. The maturity will have to be demonstrated by full-scale prototypes. The DRD will develop collaborative structures and tools such that a comparison between different technologies will be on equal footing.

# 2 Organization of the DRD




Following the key technologies identified in the EFCA roadmap, the DRD6 has collected, through both the community meetings and a dedicated input collection process, the calorimeter projects which are currently being developed in the communities (or would like to be). The received proposals showed a different level of maturity and support in terms of person powers and funds.
Those projects could be organized under three main Working Areas, described in detail in the following and shown schematically in Fig.2

- **Work Area 1** collects Sandwich Calorimeters with fully embedded electronics. For all these projects, the system aspects of the electronics and service integration in the calorimeter are of primary importance for the calorimeter project development.
- **Work Area 2** describes calorimeters based on Liquefied Noble Gases. At present it includes one proposal based on Liquid Argon.

- **Work Area 3** organizes developments of Optical Calorimeters: scintillator-based sampling and homogeneous calorimeters. The development of materials as well as the readout systems are crucial to these calorimeters. Also working principles of novel calorimeter techniques will be proven.

The description of the different calorimeter projects is given in the following sections.
Scrutinizing the submitted projects has highlighted the existence of several common needs which we believe have to be addressed commonly, to exploit as much as possible each other competence, save money and person-power and progress faster in the overall project.
We have identified, at present, five Transversal Activities (TAs), which are listed below and described in the document.

- **Materials**: The objective of this TA is to identify the best suitable material for each application. Needs for new optimised materials will be identified and R&D will be carried on in this framework. This TA will provide a clear overview of the state-of-the-art materials and propose scintillators and other optical media with mass-scale production capability for future collider experiments.
- **Phododetectors, Electronics and Data Acquisition**: Most of the projects will read out their detector with SiPMs. Choosing the best options and/or developing new photodetectors can be done under a common effort, though specific needs will be taken in account. Also, projects have indicated that the need for ASIC developments has, in general, common characteristics. Also in this case a common effort can be carried on.
- **Testbeam facilities**: All projects foresee exposing their prototype to a particle beam campaign during the lifetime of the project. Also in this case, coordination of the requests and, possibly, a common infrastructure available for all the tests will be beneficial for the collaboration.
- **Detector Physics, Simulation, Algorithms and Software Tools** Calorimeter beam tests will provide a large amount of physics data which will allow both to asses performances and improve our knowledge of particle interaction with matter. Commonalities across the project in the software field are addressed in this TA.
- **Industrial Connections and Technological Transfer**: A connection between the detector community and the companies producing the materials, photodetectors or electronics we need is of uttermost importance and will allow both communities to progress faster.

The management of the collaboration will be discussed and put in place during the summer and autumn. This will include all the governmental and executive bodies, as in most of the existing collaborations. The focus in this period was on the scientific organization. The management will also include the speakers' bureau, which will cover at least one part of the dissemination. We will also collaborate on the dedicated DRD on the dissemination and training, in addition to offering training internships for students in their graduating and PhD thesis work.

# 3 Work Area 1: Sandwich calorimeters with fully embedded electronics

The devices studied in this work area seek to produce highly-pixelated images in 3 dimensions of the final state of particle collisions. Adding time as the fourth dimension and energy up to five quantities are available per pixel. The overarching goal is to provide calorimeters optimised for the application of Particle Flow Algorithms (PFA). They should therefore provide an excellent particle separation that complement high resolution trackers. The combination of both is supposed to provide a jet energy resolution of 3-4% which is the design goal at least for future Higgs factories. The 3D granularity is at least two orders of magnitude higher than for the calorimeters proposed in the other tracks. In addition, a full $4\pi$ coverage with little room for services is required to fully exploit the potential of these *imaging calorimeters*. Maybe more than others this type of detector

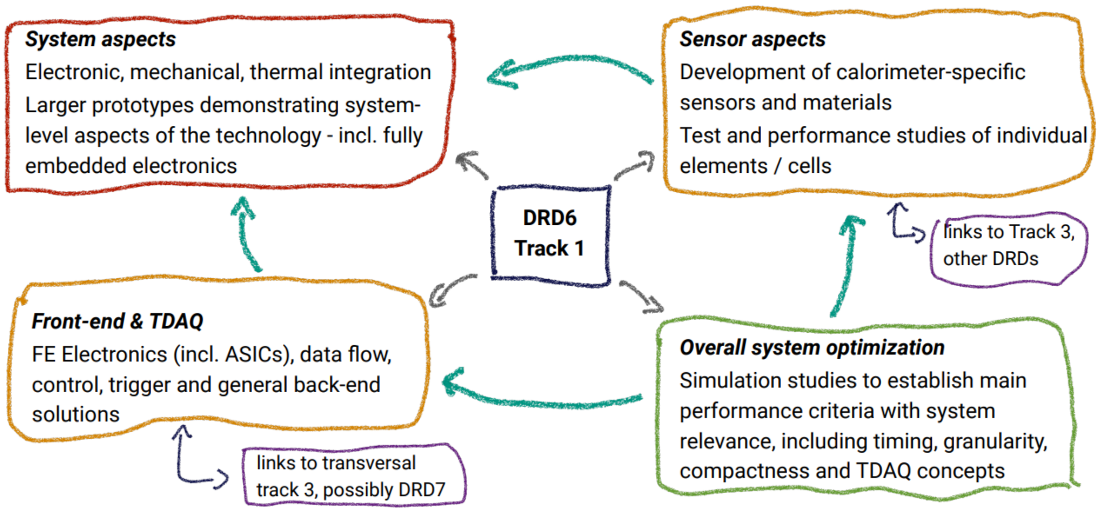



Figure 1: Synthetic overview on the main research directions common to all projects in Work Area 1.

requires a holistic approach, i.e. to take special care on high-level system integration already during the R&D phase. This applies in particular to the embedding of the front-end electronics into the detector volume. In turn, these front-end electronics have to be low power consumption without compromising performance. A summary of the main overarching R&D directions in Work Area 1 is given in Fig. 1. The technologies pursued in this work package are all considered suited to meet the goals of imaging calorimeters. Before the individual projects will be introduced some gross features shared by the proposals will be recapitulated

- Most proposals feature readout (analogue and digital) electronics fully integrated into the calorimeter volume. Where this is not (yet) the case it is recommended that the design will be adapted.
- It is common practice in calorimetry to distinguish between electromagnetic and hadronic calorimeters as separate entities. Imaging calorimeters should be thought as one device with finer pixelisation in the inner part (the electromagnetic section) and coarser pixelisation in the rear part (the hadronic section). It is therefore important that the R&D program plans from the beginning beam tests that combine electromagnetic and hadronic sections. This will allow for the development of common electrical but also mechanical interfaces and infrastructures. Common beam tests are comparable in size and complexity with real experiments. As outlined in Sec. 6.4 the DRD on Calorimetry envisages to pay particular attention to beam test infrastructure for the benefit of all work areas.

## 3.1 Projects in Work Area 1

In the following those projects will be introduced that are promising to deliver large scale prototypes in the coming 3-6 years. Either the prototypes do already exist and can be extended or the size of the groups and the anticipated resources are large enough such that a credible prospect of their realisation can be made.

- A **SiW-ECAL** using silicon pad sensors with analog readout. Silicon allows for high pixelisation and tungsten for the compact design. An individual layer must remain with an envelope of around 5 mm. The lateral density is about 2-4 times higher and the longitudinal density is still around a factor of two higher than that of the CMS HGCAL that is currently under construction. This implies that the integration of a layer has to be different from the one currently developed by CMS. The device builds on the current CALICE SiW ECAL technological prototype and the first step in the R&D will be to conclude the ongoing work.

The tendency for future Higgs factories is an increase of the beam collision frequency compared to the case of the International Linear Collider. This adds that an improved timing resolution will yield an increase in the power consumption of the front-end electronics. The electronics have to minimise the need for cooling in order to not compromise the quality of the PFA. A full system study in close coordination with detector optimisation studies with relevant physics processes has to be carried out in order to specify the hardware needs for future prototypes.
**Main R&D topics:** Extension of current prototype based on power pulsing to continuous operations: reduction of power consumption, of cooling, the study of the addition of timing, either dedicated layers or volume timing. For both linear and circular collider operation the performance of real-size layers will have to be studied.

- **DECAL:** Separation power through high pixelisation is the main motivation for the application of calorimeters based on semiconductors. The **DECAL** will increase the transverse granularity w.r.t. to the SiW-ECAL by a factor of around $10^4$ by using reconfigurable CMOS MAPS sensors. In this case each pixel will be readout with 1-bit resolution giving rise to digital calorimetry. The aim is to produce a large, granular sensor that can be a test bed for digital calorimetry, outer tracking and pre- shower applications. Recent work from the EPICAL-1 and -2 Ultra-High Granularity Electromagnetic Calorimeter Prototypes has confirmed the potential for digital calorimetry in terms of energy resolution and shower separation [2]. Separately, prototypes of dedicated CMOS MAPS sensors, such as the DECAL sensor, for digital calorimetry, outer tracking and pre-shower applications have paved the way for developing devices that can address the specific requirements of multiple subdetectors, including digital calorimeters [3]. The future R&D will take the best aspects of both existing projects, developing a new sensor that is optimised for calorimetry, either by integrating the design of the DECAL DMAPS chip with an existing mature sensor or continuing its own development, and ultimately to deploy the resultant sensor in a testbeam. By taking advantage of the EPICAL-2 prototype and existing data for evaluation of performance using what will be a custom sensor, we will be able to demonstrate the ultimate potential of this alternative approach to the traditional silicon analogue readout as used in CMS HGCAL and proposed for some future collider experiments.
  **Main R&D topics:** Development of a CMOS MAPS based DECAL sensor optimised for calorimetry. This implies in particular the reduction of the power consumption from around $10\text{mW/cm}^2$ as of today by at least an order of magnitude. Sensor size and stitching technologies have to be developed in order to equip a surface of around $2000\,\text{m}^2$. The selected sensors and technology will have to be validated by beam test prototypes.

- Forward calorimeters, **FCAL** will measure the luminosity and the beam induced background in particle physics detectors. The reduced space and the quest for separation of close by electron and photon showers call for high compactness level compared with the projects introduced before. Therefore the R&D focuses on the reduction of auxiliary components such as readout or transmission wires. One topic is the testing of GaAs sensors with readout strips on the sensor substrate. Another topic is the investigation of wireless readout that would comply particularly well with the limited amount of space available in the forward region of particle detectors. Several aspects of forward calorimetry will be addressed in the frame of the LUXE experiment. In general and as shared in particular with the SiW-ECAL detector elements of forward calorimeters require the study of connectivity technologies.
  **Main R&D topics:** Testing of sensors with readout strips, wirelass data transfer, detection module integration (study of conductive gluing).

- While the previous three projects develop calorimeters based on semi-conductors, the **Sc-ECAL** uses scintillating strips of around $45 \times 5 \times 2\,\text{mm}^3$ is size. In alternating layers the strips are rotated by 90 degrees yielding an effective $5 \times 5\,\text{mm}^2$ transversal granularity. A prototype of this type of calorimeter has been tested in 2022 and 2023 in beam at CERN. As the SiW-ECAL this prototypes has been operated with ASICs designed for power-pulsed operation at a Linear Collider. The technology needs thus to be adapted to the operation at circular colliders. This implies also the development of a cooling system. Apart from these

"straightforward" R&D items the project also will engage in the R&D of new scintillator material to improve light yield, radiation hardness, ageing and timing performance. The Sc-Ecal is a potential field of application for future quantum-dot technology.
**Main R&D topics:** Extension of current prototype based on power pulsing to continuous operations: reduction of power consumption, of cooling, the study of the addition of timing, either dedicated layers or volume timing. For both linear and circular collider operation the performance of real size layers will have to be studied.

- AHCAL

- The **ScintGlassHCAL** project seeks to replace the plastic scintillators by tiles based on scintillating glass following, therefore, a recommendation of the ECFA Detector R&D Roadmap to investigate this material since it's supposed to be cheaper than traditional inorganic scintillators. With clear synergies to Work Area 3 and the Transversal Activity on Materials, the development of this type of calorimeter requires some groundwork on that actual sensor. A trade-off will have to be found between material density and the actual light yield. Special attention will also have to be paid to the selection of the photodetector. The concept as an imagine calorimeter requires, as for the other proposals in this track, a high level of integration. Since the use of scintillating glass is as of today unchartered territory for imaging calorimeters, this may imply R&D challenges that are still unknown today.
**Main R&D topics:** Identification of optimised scintillating glass material. Selection of photodetectors and readout ASICs in synergy with other projects in the DRD. Small "electromagnetic" prototypes as a proof of principle with the medium term goal of a full-scale hadronic prototype.

- The Semi-Digital Hadronic Calorimeter (**SDHCAL**) is a sampling hadronic calorimeter that is studied by the CALICE collaboration to equip the future ILC experiments with a compact, self-supporting hadronic calorimeter using gaseous detector such RPC to achieve the high granularity one needs to successfully apply PFA techniques. A prototype of 48 units was built in 2011 and tested in the following years until today. The next generation of this type of calorimeter should feature a time resolution of better than 150 ps (compared with around 1 ns today). In the **T-SDHCAL** project the amplification of the avalanche will be improved by moving from a single-gap RPC to a multigap RPC (MRPC). The detector has to be readout by a low-jitter ($\approx$10 ps) low power consuming ASIC and Liroc is a promising candidate for this. Operation st circular $e^+e^-$ colliders require in addition the development of a cooling system to sustain the higher rates.
**Main R&D topics:** Development of multigap RPC (MRPC) to improve timing and study of an adequate read-out ASIC such as Liroc. Development of a few small layer with the aim of a larger prototype in the medium run.

- As complement to the RPC based sensors the **MPGD-HCAL** proposes gaseous sensors based on Micromegas or $\mu$RWELL chambers. The main motivation for this approach is that both Micromegas and $\mu$RWELL chambers are supposed to be able to stand higher beam rates. This characteristics would make them suitable not only for future $e^+e^-$ colliders but in particular for a future muon collider. As of today the project disposes already six MPGD layers of size $20 \times 20\,\text{cm}^2$ (how many Micromegas and $\mu$RWELL?) Together with corresponding steel absorber this yields a "electromagnetic" prototype with a depth of two interaction lengths. For this prototype readout ASICs and DAQ systems are available. This will allow for a proof-of-principle of the MPGD-HCAL This prototype will be complemented by four layers of size $50 \times 50\,\text{cm}^2$ yielding a total depth of three interaction lengths.
**Main R&D topics:** Simulation studies to settle the needs for a hadronic calorimeter at a future muon collider.

- The **ADRIANO3** is a high-granularity triple-readout calorimetry with fast timing by adding a third readout to the ADRIANO2 technique, which is a high-granularity, integrally-active, dual readout calorimeter with 5D shower measurement, aiming at disentangling the neutron component of a hadronic shower. The ADRIANO3 is composed of a sandwich of heavy-glass tiles, plastic scintillator tiles, and thin RPCs. The heavy-glass is mostly sensitive to the

| Name | Calorimeter Section | Sensitive Material/<br>Absorber | Target Application | Current Status |
|---|---|---|---|---|
| SiW-ECAL | Electromagnetic | Silicon/Tungsten | $e^+e^-$ collider<br>central detector | Prototype for<br>finalising R&D for LC,<br>Specification for CC and of Timing for<br>PFA |
| DECAL | Electromagnetic | CMOS MAPS/Tungsten | $e^+e^-$ collider<br>central detector,<br>Future hadron collider | Prototypes with non-optimised<br>sensors,<br>Sensor optimisation ongoing |
| FCAL | Electromagnetic | Solid state (Si or GaAs)/<br>Tungsten | $e^+e^-$ collider<br>forward part | Prototypes with non-optimised sensors,<br>Sensor optimisation and data<br>transfer studies ongoing |
| ScintEcal | Electromagnetic | Scintillating plastic strips/<br>Tungsten | $e^+e^-$ collider<br>central detector | Prototype for<br>finalising R&D for LC,<br>Specification for CC and of Timing for<br>PFA |
| AHCAL | | | | |
| ScintGlassHCAL | Hadronic | Heavy glass tiles/Steel | $e^+e^-$ collider<br>central detector | Material studies and specifications<br>for prototypes |
| T-SDHCAL | Hadronic | RPC/Steel | $e^+e^-$ collider<br>central detector | Prototype for<br>finalising R&D for LC,<br>Specification for CC and of Timing for<br>PFA |
| MPGD-HCAL | Hadronic | MPGD (Micromegas<br>$\mu$RWELL/Stell | $\mu^+\mu^-$ collider<br>central detector | Small prototype for proof-of-principle,<br>Lateral and longitudinal extension envisaged. |

Table 1: Table summarising the projects in Work Area and their status.

fast EM component of the shower above the Cherenkov threshold. The plastic scintillator is sensitive to all the ionising particles as well as neutrons. The newly added RPCs, based on heavy gasses and glass, is sensitive to all the ionising particles, but not to neutrons, allowing to disentangling the neutron component. The RPCs will be based on the CALICE DHCAL technology with digital readout for fine segments of $1\,\mathrm{cm}^2$.
**Main R&D topics:** The construction technique in terms of light yield, RPC efficiency, timing resolution, and cost, will be optimised. A few prototype layers will be fabricated. Finally a medium-scale ADRIANO3 prototype will be built and tested in high energy and low energy beams to evaluate energy and position resolution, PID and time resolution. In addition, the implementation of machine learning techniques will also be investigated.

In addition to the described projects the work area will also follow up activities that are as of today at a lower level of maturity. This is for example the case for the *Double readout sandwich calorimeter (DSC)*. Here, passive absorber material is replaced by lead class that acts as a Cherenkov light radiator. As for all calorimeters in this section the readout electronics and other services will be embedded in the calorimeter volume. In addition there are clear synergies with the ADRIANO3 project. Both the DSC and ADRIANO3 will benefit from the transversal activity on optical material.

### 3.2 Short term applications

The technologies of the SiW-ECAL and the AHCAL, orginally developed within CALICE, have been adopted by the CMS-HGCAL for the upgrade of the endcaps of the CMS detector. It is obvious that the experience gathered in the construction of this new type of calorimeter will feed back into the R&D of the Work Area 1. The system integration of the detection elements (Si-Modules and TileBoards in case of the CMS HCGAL) have been identified as one of the main challenges. The detectors proposed here a typically more compact than those of the HCGAL and will have to meet the precision requirements are future $e^+e^-$ colliders. Two of the described projects, SiW ECAL and FCAL, are also foreseen as detectors at the DESY Exepriment LUXE. The detector construction for LUXE and the R&D program will mutually benefit from each other. This concerns in particular detector integration, a crucial aspect for the detectors studied in Work Area 1.

## 4 Work Area 2: Liquified Noble Gas Calorimeters

### 4.1 Description

Future experiments at $\mathrm{e}^+\mathrm{e}^-$, hadron or muon colliders have an ambitious physics program. The role of calorimetry will be to precisely measure particle energies, complement the tracking system in an optimal particle-flow event reconstruction, contribute to particle identification and - where necessary - provide efficient pile-up rejection. Such functionalities will only be achievable with excellent electromagnetic energy resolution, high lateral and longitudinal granularity and - in some cases (e.g. pile-up rejection) - excellent time resolution. Calorimetry based on liquified noble gases (noble-liquid calorimetry) was successfully used in many high-energy experiments (e.g. E706 at FNAL, R806 at ISR, D0, H1, NA48, ATLAS, SLD) due to its excellent electromagnetic energy resolution, linearity, stability, uniformity and radiation hardness. While radiation hardness is a concern mainly for hadron colliders, all other above-mentioned properties of noble-liquid calorimetry will be extremely beneficial for the high precision measurement program of $e^+e^-$ colliders, but also for precision measurements in future hadron or muon colliders. The unprecedented statistical precision achievable in experimental measurements at circular $e^+e^-$ colliders such as the FCC-ee will have to be complemented by an extremely well-controlled systematic error, which requires an excellent understanding of the detector and the event reconstruction. A highly uniform, linear and stable measurement in the calorimeters will be a prerequisite to achieving this ambitious goal.

## 4.2 Objectives

This work proposal is meant to further develop calorimetry based on liquified noble gases and prepare it for a possible application in a future $e^+e^-$, hadron or muon collider experiment. The goal for the next years is to design and build a small test module that can be tested in a testbeam. Work will focus on the below areas 1-4, leading to a prototype module by the end of 2027:

1. Develop further the understanding of the needed granularity of an electromagnetic calorimeter of an $e^+e^-$ experiment by studying pion rejection (tau physics), axion searches as well as jet-energy reconstruction using 4D imaging techniques, machine learning or – in combination with the tracker measurement – particle flow algorithms. In parallel performance studies of the electromagnetic energy resolution will allow us to further optimise the geometry of the calorimeter (gap size, sampling fraction, active and passive material, dead material correction, absorber composition and shape). In addition, the possibility of readout the Cerenkov light in the noble liquid might be studied to investigate potential gains in timing measurement or in dual readout energy measurement.

2. The optimisation of the read-out electrodes for the defined granularity: a first barrel electrode prototype was built and is being tested and compared to finite element simulations. In the coming years, the electrode design will be further optimised to minimise cross-talk and electronic noise (the goal is to measure photons down to 300 MeV and to have an $S/N > 5$ for minimum ionising particles in all cells). Similar work will be performed for the endcap electrodes: after investigating possible geometries for the endcap design and optimising the granularity, the appropriate electrodes will be designed. A final prototype of the barrel electrode will be produced in Q4 2024, the design will be frozen and a call for tender will be prepared for the production of electrodes for the test module. The order will be placed with the goal to have all electrodes in hand by Q2 2027 at the latest. It is planned to optimise for and equip part of the test module with cold read-out electronics, whereas the other part should be read out via coaxial cables and warm electronics sitting outside of the cryostat.

3. Two different read-out designs will be studied: read-out via cold electronics (sitting inside the cryostat) as well as read-out via warm electronics (sitting outside the cryostat). It is our intention to re-use existing read-out chips (e.g. from ATLAS LAr, DUNE, HGCal,. . . ) and adapt them for our use. These synergies well with the transversal activity on electronics, on very low power integrated frontend electronics for future calorimeters. The necessary cables as well as feedthroughs will also be studied and procured for the test module. For the test beam, some kind of back-end electronics will be necessary to record the data.

4. Mechanical study of a noble-liquid calorimeter: Small systematic errors will only be achievable with a highly uniform and stable calorimetric measurement. This translates into high precision and stability of the calorimeter mechanics. It will be studied how such a calorimeter could be built with the required precision. This includes the design of the mechanical structure including precision spacers, absorbers, read-out electrodes and their respective precision

supports. Prototype absorbers will be procured and tested during the years 2024 and 2025. A small test module (full depth, $\geq 22X_0$ : $\sim 1.0\,\text{m} \times 0.5\,\text{m} \times 0.5\,\text{m}$) will be designed (the goal is to have detailed design drawings in Q4 2025). A final design review will be held in Q4 2025, after which production of the test module shall start. The goal is to have the module assembled and tested at warm temperatures by Q4 2027. Cold tests and test beams are planned for 2028. An existing cryostat will be adapted or a prototype carbon fibre cryostat used (R&D on such a cryostat is performed in the framework of the EP R&D program at CERN – WP4.1b).

1. Milestones (bold high-level Milestone):
   - Q4 2024: Freezing electrode design
   - **Q4 2025: Design review of test module - sign-off**
   - Q2 2026: Ready for construction of test module, start of the procurement
   - Q4 2027: Test module warm tests finished - ready for cool down
2. Deliverables (bold high-level Deliverable):
   - Q4 2024: Prototype absorbers, prototype electrodes with optimised granularity
   - Q4 2025: Design drawings of test module
   - Q2 2027: Test cryostat adapted from existing or carbon fibre prototype
   - **Q2 2027: Test module assembled**
   - Q2 2028: Ready for data taking in test beam (depending on CERN SPS schedule)

# 5 Work Area 3: Optical calorimeters

## 5.1 Description

Calorimeters based on scintillating materials and photodetectors have a long and successful history at high-energy particle colliders. Continuous technological progress in the field, from faster and more radiation-tolerant scintillators to compact and cheaper photodetectors such as Silicon PhotoMultipliers (SiPMs), has opened the possibility of novel calorimeter designs.

The goal of work area 3 is to explore, optimise and demonstrate with full shower containment prototypes new concepts of sampling and homogeneous calorimeters based on scintillating material. A common trend among different calorimeter concepts is to improve the spatial granularity, the time and energy resolution and, in some cases, the radiation tolerance compared to state-of-the-art calorimeters.

Contrary to the calorimeter design discussed in Sec. 3, the calorimeter design in this section does not plan to fully embed the electronics and services inside the calorimeter but rather route the signal away from the active elements (although photodetectors are in some cases embedded inside the calorimeter).

The vast majority of the proposed calorimeter exploits SiPMs as compact and cost-effective photodetectors insensitive to magnetic fields and envision the use of particle flow algorithms for event reconstruction.

## 5.2 Activities and objectives

The overall goal of work area 3 is to increase the level of technological readiness (TRL) of various calorimeter concepts based on scintillator materials in the next three years. Since different calorimeter concepts are at different levels of maturity, they also aim at different goals within this time scale: from proof-of-concept and definition of component specifications to the demonstration of a full-scale prototype performance with beam tests. Different R&D activities also target different types of particle colliders (future $e^+e^-$ Higgs Factories, Muon Colliders, Hadron Colliders) and thus different operating environments and unique challenges (e.g. time resolution, radiation

Table 2: Overview of R&D activities on optical calorimeter concepts.

| Name | Calorimeter type | Application | Scintillator/WLS | Photodetector |
|---|---|---|---|---|
| HGCCAL | EM / Homogeneous | $e^+e^-$ collider | BGO, LYSO | SiPMs |
| MAXICC | EM / Homogeneous | $e^+e^-$ collider | PWO, BGO, BSO | SiPMs |
| CRILIN | EM / Quasi-Homog. | $\mu^+\mu^-$ collider | $PbF_2$, PWO-UF | SiPMs |
| GRAINITA | EM / Quasi-Homog. | $e^+e^-$ collider | $ZnWO_4$, BGO | SiPMs |
| SPACAL | EM / Sampling | $e^+e^-$/hh collider | GAGG, organic | MCD-PMTs, SiPMs |
| RADICAL | EM / Sampling | hh collider | LYSO, LuAG | SiPMs |
| DRCAL | EM+HAD / Sampling | $e^+e^-$ collider | PMMA, plastic | SiPMs, MCP |
| TILECAL | HAD / Sampling | $e^+e^-$/hh collider | PEN, PET | SiPMs |

tolerance). Table 2 provides a summary of the broad scope of activities within work area 3. Each activity concerns the development of a specific calorimeter concept.

Four of the proposed calorimeter concepts (CRILIN, MAXICC, HGCCAL, GRAiNITA) are designed for electromagnetic (EM) shower detection using a homogeneous or quasi-homogeneous approach, in most cases based on scintillating crystals, to provide a measurement of electrons and photons with an energy resolution at the level of $2-5\%\sqrt{E}$. Radiation-tolerant electromagnetic sampling calorimeters (SpaCal, RADiCAL) aim at achieving an energy resolution at the level of $5-10\%\sqrt{E}$. A fibre-based sampling dual-readout calorimeter (IDEA DRC) is designed to achieve a $12-15\%\sqrt{E}$ energy resolution for electromagnetic showers and about $30\%\sqrt{E}$ for hadronic showers while the TILECAL offers a cost-effective technology to instrument the hadronic section of a sampling calorimeter with scintillating-light readout using wavelength shifting (WLS) fibres. A brief description of each activity is given in the following.

### 5.2.1 Homogeneous and quasi-homogeneous EM calorimeters

- The High-Granularity Crystal Calorimeter (**HGCCAL**) [4] is a homogeneous calorimeter with high transverse and longitudinal segmentation based on $1 \times 1 \times 40$ cm$^3$ crystal bars arranged in a grid structure with double-ended SiPM readout. The calorimeter is optimised for event reconstruction based on particle flow algorithms (PFA) to achieve about a $3\%\sqrt{E}$ resolution for electromagnetic showers and a $30\%\sqrt{E}$ energy resolution for jets, crucial for the physics programs of future $e^+e^-$ colliders.
  **Key R&D required:** Mechanical design and integration, development of an EM shower-scale prototype.

- The Maximum Information Crystal Calorimeter (**MAXICC**) is a cost-effective homogeneous calorimeter concept for $e^+e^-$ Higgs factories based on high-density crystals (e.g. PWO, BGO, BSO) readout with SiPMs [5]. It features a moderate longitudinal segmentation and includes the dual readout of scintillation and Cherenkov light from the same active element (by means of optical filters) for optimal integration with a dual-readout hadronic calorimeter. It targets an electromagnetic energy resolution of $3\%\sqrt{E}$, a time resolution of O(30) ps and a jet energy resolution of $30\%\sqrt{E}$ when combined with a dual-readout hadron calorimeter.
  **Key R&D required:** Identification of optimal components (crystal, optical filters, SiPMs), development of an EM shower-scale prototype.

- The CRystal calorImeter with Longitudinal InformatioN (**CRILIN**) [6] is a quasi-homogeneous calorimeter based on $PbF_2$ crystals and SiPMs for a future Muon Collider. It relies on longitudinal segmentation and fast detector response to mitigate the Beam Induced Background (BIB) expected at muon colliders. It targets an energy resolution in the $5-10\%\sqrt{E}$ range, limited by BIB and SiPM noise effects due to radiation-induced damage (expected $10^{14}$ 1-MeV $n_{eq}/cm^2$ fluence). The series connection of SiPMs for signal readout allows close events (below 100 ps) to be temporally resolved.
  **Key R&D required:** Validation of concept design and simulations with an EM-shower-scale prototype.

- The **GRAiNITA** concept [7] consists of a very fine sampling calorimeter in which sub-millimetric grains of high-Z and high-density inorganic scintillator crystals (e.g. $ZnWO_4$, BGO) are evenly distributed in a bath of transparent high-density liquid (e.g. $CH_2I_2$). The scintillation light is locally collected and transported to the photodetector (SiPM) using wavelength-shifting fibres. Preliminary simulations indicate an energy resolution at the level of $2\%\sqrt{E}$.
  **Key R&D required:** Characterisation of scintillator grains, Monte Carlo simulations, development of prototypes.

### 5.2.2 Radiation-tolerant sampling EM calorimeters

- The Spaghetti Calorimeter (**SpaCal**) [8] is a sampling electromagnetic calorimeter made of scintillating fibres inserted in a high-density absorber material such as tungsten with a tunable energy resolution and time resolution of O(10-20) picoseconds. The possibility to use radiation-tolerant crystal fibres as active element makes such a calorimeter a viable technology for applications in extreme radiation environments at future hh colliders. An optimisation of the calorimeter for $e^+e^-$ collider applications is also possible.
  **Key R&D required:** Optimisation of absorbers, light guides, photon detectors, scintillating fibres and simulation software. Development of electronics with a 15 ps time resolution.

- The **RADiCAL** is a compact sampling EM calorimeter with fast-timing capabilities, designed to achieve a sufficient radiation tolerance for operation in extreme radiation environments [9]. It is based on a Shashlik-type geometry with crystal plates alternated with tungsten plates and uses capillaries filled with a WLS filament to bring the light signal towards the rear side of the calorimeter cell where SiPMs are used as photodetectors.
  **Key R&D required:** Development of radiation-hard wavelength shifters, construction of EM-shower-size prototype.

### 5.2.3 Hadronic sampling calorimeters

- A longitudinally unsegmented dual-readout sampling calorimeter, made of scintillation and Cherenkov fibres inside an absorber groove, can provide a $30\%\sqrt{E}$ energy resolution for hadrons and jets exploiting the dual-readout method to correct for fluctuations in the electromagnetic fraction in hadronic showers [10]. The calorimeter can also be optimised for electromagnetic shower measurement with resolutions in the $12 - 15\%\sqrt{E}$ range. The goal of this activity (**DRCal**) is to build prototypes with full hadron-shower containment to be qualified with beam tests and demonstrate large-scale assembly processes.
  **Key R&D required:** Development of a readout system, construction of a prototype with containment of hadronic showers.

- Scintillator tiles readout with wavelength shifting fibres and interleaved to a high-density material are a consolidated technology used in a variety of LHC experiments for cost-effective instrumentation of hadronic calorimeters. The objective of the **TILECAL** activity is to optimise such technology for application at future $e^+e^-$ and hh colliders [11] and explore new PEN and PET materials as well as optimising the WLS fibres and SiPMs readout efficiency.
  **Key R&D required:** Characterisation of PEN and PET scintillators. Mechanical design and construction of prototypes.

## 5.3 Milestones and deliverables

The major objective of work area 3 is to demonstrate the viability of a set of scintillator-based calorimeter systems for future lepton and hadron colliders. To some extent and with some different optimisation, various EM and HAD calorimeter concepts can be used in different collider environments.

Some calorimeter concepts are more advanced in terms of specifications and prototyping and thus aim at demonstrating the scalability to a large-scale detector and the possible solutions to the corresponding integration and readout challenges.

Conversely, there are novel calorimeter concepts that require more R&D at the single component level to identify (if not develop custom) optimal scintillators, optical elements and photodetectors. In this latter case, the goal of the activity is mainly the proof-of-concept of the proposed calorimeter technology and the definition of the technical specifications of the components. These activities are thus strictly connected to developments that will take place in the transversal working groups on materials, photodetectors and electronics readout, discussed in Section 6. The testing of calorimeter prototypes, foreseen for all the proposed technologies, will strongly benefit in terms of resources from a coordinated effort on common test beam infrastructures as described in Section 6.4.

A list of milestones and deliverables is reported in Table 5.3. Deliverables include reports on material and photodetector characterisation studies, the definition of technical specifications and the construction and testing of calorimeter prototypes. Deliverables will be used to monitor progress and evaluate the completion of a corresponding milestone.

| Related calo concept | Milestone | Deliverable | Description | Due date |
|---|---|---|---|---|
| CRILIN | MS 3.CR.01 | | Construction and beam test characterization of a full containment EM calorimeter prototype for muon collider | Q4 2025 |
| | | D.3.CR.01 | | |
| | | D 3.CR.02 | | |
| | | D 3.CR.03 | | |
| | | | | |
| HGCCAL | MS 3.HG.01 | | Specifications of crystal, SiPM and electronics for high granularity EM crystal calorimeter prototype for e+e- collider | |
| | | D 3.HG.01 | | |
| | MS 3.HG.02 | | Beam test characterization of full containment high granularity EM crystal calorimeter prototype for e+e- collider | |
| | | D 3.HG.02 | | |
| | | D 3.HG.03 | | |
| | | | | |
| GRAiNITA | MS 3.GR.01 | | Characterization of materials, wavelength shifters and SiPM and identification of best technology | Q2 2025 |
| | | D 3.GR.01 | | |
| | MS 3.GR.02 | | Proof-of-principle of fine sampling opaque EM calorimeter prototype for e+e- collider (no full shower containment) | Q2 2026 |
| | | D 3.GR.02 | | |
| | | | | |
| MAXICC | MS 3.MA.01 | | Specifications of crystal, SiPM and optical filters candidates for dual-readout crystal EM calorimeter prototype for e+e- collider | Q2 2025 |
| | | D 3.MA.01 | Report on characterization of crystal, SiPM and optical filter candidates and their combined performance for Cherenkov readout | Q2 2025 |
| | MS 3.MA.02 | | Beam test characterization of full containment dual-readout crystal EM calorimeter prototype for e+e- collider | Q4 2026 |
| | | D 3.MA.02 | Report on EM shower scale module tested on beam | |
| | | | | |
| SPACAL | MS 3.SP.01 | | Optimised components for module-size prototye (significantly larger than EM shower) selected and/or characterised in test beams | Q4 2026 |
| | | D 3.SP.01 | Tungsten and lead absorbers for module-size prototypes | Q3 2024 |
| | | D 3.SP.02 | Optimised light-guide design | Q4 2025 |
| | | D 3.SP.03 | Specififaction of photon detector, crystal samples, SPIDER ASIC prototype, improved simultion framework | Q4 2026 |
| | | | | |
| RADICAL | MS 3.RA.01 | | Test beam measurements using a 3x3 array of RADiCAL modules | Q4 2025 |
| | | D 3.RA.01 | | |
| | | D 3.RA.02 | | |
| | | | | |
| DRCAL | MS 3.DR.01 | | Construction of full-scale dual readout module with hadronic shower containment and test beam campaign to assess the performance of the prototype completed | Q4 2026 |
| | | D 3.DR.01 | | |
| | | D 3.DR.02 | | |
| | | | | |
| TILECAL | MS 3.TI.01 | | Characterization of PEN and PET based scintillating tiles including optimization of readout with WLS and SiPMs | Q2 2025 |
| | | D 3.TI.01 | | |
| | MS 3.TI.02 | | Construction of up to 3 prototypes of a sampling tile calorimeter module with WLS and SiPM readout (for beam tests after 2026) | Q4 2026 |
| | | D 3.TI.02 | | |

# 6 Transversal Working Groups

In the following, a detailed description of the objective of the different transversal activities group is given. There will be the need to include a dedicated transversal activity group on the mechanics and integration, since this is not addressed in other DRDs, and is of general interest for the calorimetry community.

## 6.1 Materials

The calorimeter concepts proposed in work area 3 have common requirements regarding the performance of scintillation materials such as good optical quality, high light yield, fast decay time, sufficient radiation hardness, high density for homogeneous calorimeter and the possibility of a cost effective mass production.

The aim of the transversal working group on materials is to identify the key R&D activities necessary to be carried out on various scintillators, and wavelength shifters (inorganic, organic, glasses, ceramics, quantum materials) to achieve the required performances for various calorimeter concepts proposed in work area 3 depending on the radiation environment conditions expected in future experiments and the type of calorimeter (sampling or homogeneous) with the goal to identify the best-suited scintillators for future optical calorimetry in the next decades.

The goal of the first R&D phase (2024-2026) is to get an overview on available state-of-the-art scintillation materials potentially fulfilling the requirements of the detector concepts developed within work area 3 and to identify the most appropriate materials for each detector concepts and key R&D areas for further properties improvements.

One aspect to be considered within the R&D effort is the potential use of such materials in beyond colliders and/or beyond HEP and NP experiments.

Three axes of R&D have been identified:

- **Fast and radiation hard organic and inorganic scintillators:**
  - Search for new materials and improve fabrication and processing conditions.
  - Understand radiation damage mechanism for ionization dose and hadrons and the dependence of light output on dose rate, material composition and temperature.
  - Identify and develop radiation hard scintillators based on the study of radiation damage mechanisms.
  - Investigate approaches to cure radiation-induced damage in situ to mitigate such damage (e.g., by optical bleaching during and after irradiation).
  - Develop radiation hard wavelength shifters for timing and position resolution, e.g., at EM Shower Maximum and for potential depth segmentation.
  - Study excitation energy transfer in activated scintillators and radiation-induced phosphorescence that is the limiting factor for the time resolution of fast radiation detectors in the 10-picosecond domain.
- **Ultra fast inorganic scintillators for ultrafast calorimetry:**
  - Screen/survey/develop cross-luminescence materials for ultrafast timing with a focus on shifting cross-luminescence emission towards visible region and optimising/improving UV transmission and photodetection.
  - Screen/survey/develop Cherenkov materials with a focus on optimising UV transmission and photodetection.
  - Develop Deep-Learning (DL) analysis combined with ray-tracing simulation to extract high-precision time information from Cherenkov and cross-luminescence materials.
- **Cost effective inorganic scintillators**
  - Improve fabrication technologies for low-cost crystal growth, including low-cost crucibles in Czochralski or micro pulling-down technologies, increasing the size of crystal ingots by optimising crystal growth using AI.

– Investigate low-cost fabrication technologies for ceramic and glass scintillators and improve their density, temporal response, light output, uniformity and radiation hardness.

## 6.2 Photodetectors

Photon detection, from the viewpoint of future optical calorimeters, requires to address radiation hardness, time resolution and extended sensitivity in both the UV and infra-red regions - often at the same time - over a large, and linear, dynamic range. Radiation hardness and time resolution are particularly relevant for experiments at hadron colliders, roughly following the instantaneous-luminosity increase. However, for example, both parameters play an important role also at the muon collider. The R&D on a scintillating sampling ECAL for the LHCb upgrade II (during LS4, after 2035) is targeting a time resolution of O(10-20) ps, for pile-up mitigation, and a radiation tolerance above $10^{15}$ 1-MeV $neq/cm^2$. For comparison, at FCC-hh, the required radiation tolerance will be above $10^{16}$ 1-MeV $neq/cm^2$ while at the Muon Collider it should be about two order of magnitude less. All these values look quite challenging to be met.
A time resolution in the range of 10-20-30 picoseconds is a quite general requirement for many proposed experiments adopting optical calorimetry. In addition to the LHCb Upgrade II, experiments at EWK/Higgs factories and at FCC-hh, the list includes as well fixed-target experiments at the intensity frontier. It requires not only fast sensors but also the development of dedicated readout ASICs. In this respect, the high liveliness of the market looks promising.
A special case is the longitudinally unsegmented fibre-sampling dual-readout calorimeter where the timing information may provide information about the depth the shower development started. However, a time resolution of about 100 ps should allow a position resolution of 5 cm to be reached.
The development of sensors with UV and IR-extended sensitivity is very relevant for the Cherenkov light detection in dual-readout calorimetry and, as well, in the $PbF_2$ Crilin calorimeter for the Muon Collider.
Finally, high granularity and linear response over a large dynamic range are general requirements for all calorimetric proposals envisaged. At $e^+e^-$ colliders, the dynamic range is smaller than at hadron machines but the precision required is higher. Also in this respect, the market developments look reassuring.
MCP-PMTs and (mainly) SiPMs are the photodetector families that, at present, look to be able to successfully meet the above requirements.
In particular, the development of CMOS digital SiPMs would make possible to integrate in a single chip the sensor and the front-end electronics and, in principle, it would allow the readout architecture to be highly simplified.

## 6.3 Electronics and Readout

Calorimeter electronics exhibit several commonalities, such as large dynamic range (10-16 bits), very low noise, high accuracy ($< 1\%$) and usually large capacitance (100's of pF). This also makes them specific compared to other detectors. The recent trend has been a sharp increase in granularity ("imaging calorimeters") and sub-ns timing capability ("5D calorimetry") to allow better particle reconstruction. This has led to the development of low-power highly integrated embedded electronics integrated inside ASICs.
R&D developments will focus on reducing the power dissipation by at least an order of magnitude, down to $\sim 1$ mW/ch in order to further increase the granularity in track 1 or allow cryogenic operation without creating deadly bubbles in track 2. For task 3, improving the timing performance will also be an important goal. These goals will be pursued by exploiting the lower occupancy of future experiments compared to HL-LHC, allowing slower shaping and on-chip data processing in order to reduce the output bandwidth. Various front ends will be studied to optimise the dynamic range handling (dynamic gain switching, multi-grain preamps, ToT technique...). ADC/TDCs, digital logic will also be studied to reduce their power dissipation and in particular their instantaneous current spikes and minimise digital noise, which is a recurrent issue in calorimeter mixed-signal ASICs.
It is proposed in this track to develop a family of chips, optimised for the different sub-detectors proposed and sharing as much as possible a common back-end and readout. Shared engineering

| | **Energy Range** | **Irradiation capabilities** |
|---|---|---|
| **Higgs Factory**<br>$\sqrt{s}$**=90 - 1000 GeV**<br>**Radiation level** $\leq 10^{14}\,\mathrm{n_{eq}/cm^2}$ | ✓ | ✓ |
| **HL-LHC**<br>$\sqrt{s}$**=14 TeV**<br>**Radiation level** $\leq 10^{16}\,\mathrm{n_{eq}/cm^2}$ | (✓) | ✓ |
| **Muon Collider**<br>$\sqrt{s}$**=3-10 TeV**<br>**Radiation level** $\sim \mathrm{HL-LHC}$ | × | ✓ |
| **Future Hadron Collider**<br>$\sqrt{s}$**=14 TeV**<br>**Radiation level up to** $\sim 10^{18}\,\mathrm{n_{eq}/cm^2}$ | × | × |

Table 3: Synoptic summary on how existing test facilities (beam or irradiation) meet the needs of the R&D described in this proposal.

runs in 65 and/or 130 nm will allow producing enough chips (hundreds) to read out full prototypes and study different architectures while minimising the overall cost (currently $\sim$ 300 K$ for an engineering run in 130 nm and twice more in 65 nm). These shared runs would be open to the whole HEP community and the common readout specification would allow other groups to design and compare other readout architectures.
It is also proposed to define a common DAQ so that different chips can adapt to this DAQ and different detectors and/or chips can be operated jointly efficiently.

## 6.4 Testbeams plans, facilities and infrastructure

Beam tests play a crucial role in the development cycle of a calorimeter. It is therefore of no surprise that 19/23 input proposals plan for one or more beam tests in the coming three to six years. The target projects are Higgs Factoires but also future muon and hadron colliders. A rough overview of how currently existing beamlines meet the needs of the calorimeter R&D is given in Table 3. From this overview it is clear that in the long run facilties will need to be extended in order to meet the needs of the detector R&D. *While the need for performant irradiation facilities is shared with the R&D in other DRD, the need to cover an adequate energy range is specific to calorimeters.*

We expect test beams throughout the coming years with an increased density after around 2026/27. Internally to the DRD, the economic use of resources has to be ensured. There exist for example already quite a number of absorber structures for electromagnetic and hadronic calorimeters. In the ideal case, these will have to be reused.

### 6.4.1 Thoughts on facilities and infrastructure

A test beam setup consists of one or more devices capable to absorb electrons and hadrons in the energy range of a few GeV up to hundreds of GeV. the typical size of a beam test setup ranges from around $20 \times 20 \times 20\,\mathrm{cm}^3$ up to around $1\,\mathrm{m}^3$. The complexity of the analysis and the particular scientific value of the recorded data requires the availability of auxiliary devices and a profound understanding of the operation and the characteristics of a beam line. Examples of auxiliary components are:

- Beam telescopes to determine the impact point of the primary particle
- Beam telescopes with ps time reference
- Cerenkov counters to distinguish particle species.
- Eventually magnets to measure the performance is magnetic fields.

For efficient usage of these devices, it has to be ensured by the facilities that they are attended in terms of the actual availability but also in terms of interfaces to the devices under test. On the other hand, the DRD Calorimeter has to provide contact persons that stay in close contact with the facility operators. These human resources will have to be incorporated into the funding and requires agreements betqeen funding agencies. A service work for the seamless conduction of beam tests with the DRD should open career opportunities to those that ensure this important task.

The complexity and the scientific value of calorimeter beam tests justify the creation of a dedicated calorimeter beam line with the corresponding funding. Since calorimeters typically cannot be run concurrently with other devices it may be considered to reserve dedicated slots per year for calorimeter beam tests.

## 6.5 Detector Physics, Simulations, Algorithms and Software Tools

Even though each project has its own peculiarity, there are some common software tools that can be prepared and shared among the community. Aims of this Transversal Activity Group is to create a working group of experts in the different Software tools described below, which can help in the core development of the different tools and can assist newcomers from the particular project to develop the detector-specific part.

### 6.5.1 DAQ Software

One of the first needs for the test of the prototype on the beamline is Data Acquisition. We already described the need for a common dedicated area. Having also a Generic Framework for the DAQ, where all the common aspects are already described, and only detector-specific part needs to be implemented, would save a large amount of time and work. EUDAQ [12] is a Generic Multi-platform Data Acquisition Framework, which seems to be a good candidate for this task. It has a modular structure, based on a finite-state machine, which should allow for factorizing the calorimeter library from the beam line common DAQ.

### 6.5.2 Simulation

Calorimetry is among the detectors which have wider support from the Geant4 collaboration and the DRD6 is willing to strengthen this collaboration. Among the most common task, G4 is used for optimising the detector layout and performing data to Montecarlo comparison to better understand detector performance and physics data. Simulation is also used to extrapolate detector performance for physics reach. Rich physics content in the calorimeter test beam data can be used in the Geant-Val [13] to improve the Geant4 code for a better agreement with data.
Important for both these two software aspects is the need to preserve the data for a long time, after they were acquired. A common Event Data Model, for example, EDM4HEP [14], which is widely used nowadays, could help in this respect and could ease the comparison among different detectors.

### 6.5.3 Particle Flow Algorithms

Most of the proposal aims at developing a high-granularity calorimeter in order to exploit this capability for the application of Particle Flow Algorithms, which combine calorimeters and track information in order to improve jet resolution. PFA algorithm packages are already available and will need to be adapted to the particular calorimeter needs.

### 6.5.4 Machine Learning approach

The machine learning approach is gaining more and more importance in HEP, and in calorimetry in particular, due to the highly complex data with a large number of detailed information that present calorimeters offer. A dedicated project has been submitted that aims at exploiting such information richness to improve Particle Identification from nuclear reactions, apply some intelligence on board the front-end electronics and help in the optimisation of an experiment designed, based on the hybridization of tracking and calorimetry.

### 6.6 Industrial Connection and Technological Transfer

The material and electronics which is needed for the development and construction of the proposed prototypes will require the scientific community to get in close contact with the industrial world. This connection will cover different aspects. On one hand, we need to perform a wide market survey in order to understand what has been already developed by industries, and what trends influence the industry production. Indeed, those elements which are of interest to the general production will advance faster and at a lower price.
On the other hand, some specific needs of the scientific community will be developed in our laboratory, and a good connection with the industries will allow us to transfer this know-how to the companies, helping in general progress, but also finding partners for mass production.
Another important element of this synergy will be the shared R&D with the industry, where we can develop the needed elements in collaboration with them. This way will allow us to exploit the technical industrial capability for production addressing the needed development.

## 7 Path to the DRD collaboration

The current model of the organisational structure of the DRD on Calorimetry has been given in Fig. 2. While this document concentrates on the scientific part and the available and prospected resources for the R&D programme, the formation of the R&D requires a management structure. The management level will have to comprise a gouverning body such as an institution board and executive bodies such a Technical Board and a Speakers Bureau. In consultation with the community the Proposal Team will work out a proposal for the management structure during late Summer/early Autumn 2023. This proposal will be guided by examples from existing R&D Collaborations. It will be particular important that the individual R&D projects and transversal activities will be adequately represented in the management structure. An open question is whether the management structure will be decided and voted at a Community Meeting in Autumn 2023 or at a first Collaboration Meeting in early 2024.

## 8 Personnel and Funds

The final resource table will be put here

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