DRD 6: Calorimetry

Proposal Team for DRD-on-Calorimetry

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Contents

1 Introduction

Different types of calorimeters are proposed for experiments for future fixed-target facilities, electroweak and Higgs factories ([1, 2, 3, 4, 5]), hadron ([6]) and muon colliders ([7]) but also for medium and low-energy facilities. EIC [8] is also among possible recipients of the R&D program developed in this DRD-on-Calorimetry. The ECFA Detector Roadmap [9] has defined the following Detector R&D Themes (DRDTs):

- 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 Detector R&D Collaboration on Calorimetry, DRD-on-Calorimetry (sometimes also labelled DRD 6 hereafter). While the focus of the activities will be future experiments at high-energy accelerators, the programme will also cover R&D for medium and low-energy experiments. A reference to the DRDTs for the different projects is reported in Tables 1, 3, 4 and 6. The mission of the DRD-on-Calorimetry is 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 with full-scale prototypes[1]. The DRD will develop collaborative structures and tools such that a comparison between different technologies will be on equal footing. The research programme presented in this proposal is the result of community consultations. This started with a *first community meeting* in January 2023 [10], followed by a call for *input proposals* in February. For these proposals, interested groups have been asked to federate themselves behind research projects that meet the R&D themes mentioned above. These projects were briefly described and a preliminary estimation of resources was given, largely following the suggestions by the coordinators of the DRD process. Altogether, 23 input proposals were collected. In these input proposals, 110 institutes declared their interest in joining the DRD-on-Calorimetry. A summary of the input proposals and a discussion on the way towards the proposal of the DRD-on-Calorimetry and its formation were given in the *second community meeting* in April 2023 [11]. Afterwards, the input proposals were condensed into the present proposal of the DRD-on-Calorimetry. Many of the input proposals that went into the DRD-6 draft, target future Higgs factories, and, among those, many target the FCC-ee. The current timeline for the FCC-ee foresees physics in the second half of the 2040s, and requires TDRs in mid-2030s, CDRs in early 2030s. With the long production and early installation times of calorimeter systems, these are realistic lead time. TDRs should be backed by realistic prototypes, CDRs by demonstrators that address the main performance and integration challenges. Consequently, the R&D in the next 3-year period (2024-26) will focus on conceptual and component studies, but with system aspects tracked from the beginning, in order to be ready for the possible development of demonstrators in the subsequent period and for the construction and test of realistic modules by 2035. A linear collider could in principle start even earlier, but would directly benefit from the already more advanced development of power-pulsed readout concepts.

2 Organisation of the DRD-on-Calorimetry

Following the key technologies identified in the EFCA roadmap, the DRD-on-Calorimetry has collected, through both the community meetings and a dedicated input collection process, the calorimeter projects which are currently proposed or being developed within the community. The received proposals showed different levels of maturity and support in terms of personpower and funds. This section outlines the scientific as well as governance aspects of the DRD-on-Calorimetry.

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[1] Prototypes able to completely contain (actually more than 95%) either an electromagnetic or a hadronic shower, depending on the calorimeter target. For electromagnetic calorimeters this corresponds to 20 radiation lengths or more and for hadronic calorimeters to 5-6 interaction lengths or more.

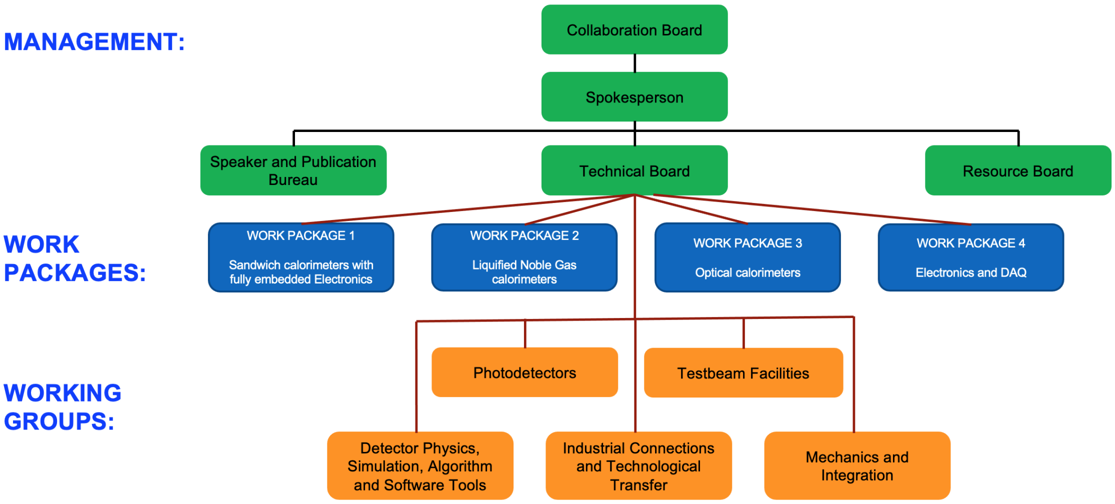

Figure 1: Schematic representation of the DRD-on-Calorimetry organisation. Please see text for details.

2.1 Scientific organisation

The projects are organised under four Work Packages, described in detail in the following and shown schematically in Fig.1.

- **Work Package 1** collects Sandwich Calorimeters (i.e. alternating absorption and sensitive layers) with fully embedded electronics. For all these projects, the system aspects of the electronics and service integration in the detector are of primary importance.
- **Work Package 2** describes calorimeters based on Liquified Noble Gases. At present it includes one proposal for R&D on further optimising Noble-Liquid Calorimetry for future accelerator experiments and building a module for beam tests.
- **Work Package 3** organises developments of optical calorimeters: scintillator-based sampling and homogeneous calorimeters. This includes the development of materials and associated photodetection readout systems as well as the study and demonstration of novel calorimetry techniques.
- **Work Package 4** projects indicated that the need for ASIC developments has, in general, common characteristics and will, anyway, benefit of a common management, e.g. for wafer production. Also in this case, a common effort should be of general interest.

The description of the different calorimeter projects is given in more details in the following sections. Besides the synergies that can be exploited within each WP, scrutinising the submitted projects highlighted the existence of several common needs which, we believe, have to be commonly addressed, to exploit synergies among projects, save money and personpower and progress faster in the overall project. For this scope, we have identified, at present, five Working Groups (WGs), which are listed below and described in the document.

- **Photodetectors**: Most of the projects will read out their detectors with Silicon PhotoMultipliers (SiPMs). Providing specifications for their use in calorimetry, performing photodetector characterisation and choosing the best options will be a common effort while taking specific needs into account. This activity will be carried on in close collaboration with DRD 4.
- **Testbeam infrastructure**: All projects foresee exposing their prototypes to particle beams in test campaigns during the lifetime of the projects. A coordination of the requests and, possibly, common infrastructure and beam instrumentation 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 the performance to be assessed and our knowledge of particle interaction with matter to be improved. In particular, shower simulation models need to be further developed in order to match the precision requirements of future e^+e^- experiments. Commonalities across the project in the software field are addressed in this WG.
- **Industrial Connections and Technology Transfer**: A connection between the detector R&D community and the companies producing the materials, photodetectors or electronics used in calorimetry is of utmost importance and will allow both to progress faster.
- **Mechanics and Integration**: The need to have a dedicated Working Group on these topics is still under discussion. This will become particularly important if there is no DRD on these subjects as these aspects play a central role in calorimetry.

Within the DRD 6 collaboration, contact persons who are also active in other DRD collaborations have been identified to provide clear channels of communication on technology needs and topics of shared interest. The list of contact persons identified at present is reported in Appendix B. The interconnections among DRDs is described in Sec. 9.

2.2 Governance

The top part of Fig.1 sketches a preliminary model of the governance of the DRD-on-Calorimetry. A detailed proposal on governance is in preparation by the Proposal Team. It will become effective once discussed and approved by the Collaboration Board, which will be introduced below. Here, only a general description can be given.

At the time this proposal is written, we work in an interim regime. The Proposal Team has identified a list of participating institutes (see Appendix A, status as of November 1st 2023) and the names of a representative person for each of them. These will constitute a proto-Collaboration Board (proto-CB). This proto-CB will collaborate with the Proposal Team on the concrete steps towards the full implementation of governance. We intend that this proto-CB will transit into the "real" Collaboration Board in early Spring 2024.

The Collaboration Board (CB) will consist of:

- Representatives of all collaborating institutes. Regardless of size, each institute is represented by one CB member.
- A chairperson, who is non-voting if she/he is not also an institute representative.
- Ex-officio (non-voting) members: Chairs of the Technical Board (TB), Speaker and Publication Bureau (SPB) and Resource Board (RB), who do not represent their institutes in the CB.

The role of the Collaboration Board is:

- to approve major decisions within the collaboration;
- to decide changes in the collaboration structure and policy;
- to decide on group/institute membership;
- to allow all participating institutes to take part in decision making.

The Spokesperson (SP) represents the collaboration and is the official contact between the DRD-on-Calorimetry and the management of external organisations. The SP organises and chairs the collaboration meetings, and coordinates the preparation of external reviews. The SP has overall authority for the production and dissemination of approved results.
The election of both the Collaboration Board Chair and the Spokesperson is preceded by a selection by a Search Committee, normally consisting of three members to identify suitable candidates. Details of the election process are subject to an agreement within the collaboration. The size of the collaboration motivates to consider that both SP and CB Chair will be supported by deputies. The number of deputies and their nomination are subject to further decisions by the collaboration.

2.2.1 Executive bodies

The Spokesperson proposes the chairs of the executive bodies: Technical Board (TB), Resource Board (RB) and Speaker and Publication Bureau (SPB). All three will be introduced in the following.

The Technical Board (TB) is an executive body of the collaboration. It:

- monitors all R&D activities;
- follows the preparation of beam-test campaigns and reviews their readiness;
- coordinates the beam time requests to test facilities;
- coordinates the development of common infrastructure, frameworks and tools;
- nominates coordinators for common tasks such as software, data acquisition and photodetectors;
- oversees run coordinators for common beam-test campaigns.

The members of the Technical Board are:

- The Technical Board Chair.
- The representatives of the Work Packages (to be decided with which level of granularity).
- The coordinators of the Working Groups.
- Ex-officio members: the Spokesperson and the Speakers-and-Publications Bureau Chair. Spokespersons emeriti and Technical Board Chairs emeriti at their discretion.

The Resource Board is constituted by:

- A representative of each funding agency (e.g. National Representative). Each FA organises itself according to its needs.
- The Resource Board Coordinator, chairperson of the body.

The role of the board is to debate and approve the sharing and usage of common resources among the different funding agencies and funds for small service works. The Resource Board is not meant to administrate the project's funds. It will, anyway, vigilante on agreed contributions. The exact mandate of the board is under discussion.

A Speaker and Publication Bureau (SPB) will decide on general rules for talks and publications. Also, in this case, the exact implementation of this Bureau is subject to further discussion and decisions once the collaboration has been established. It is however clear that for example, publication rules must be clear at a very early stage.

3 Work Package 1: Sandwich calorimeters with fully embedded electronics

3.1 Description

The devices studied in this work package seek to produce high-resolution images in 3 dimensions of the final state of particle collisions. With the inclusion of time and energy, five quantities are available per active element. The overarching goal is to provide calorimeters optimised for the application of Particle Flow Algorithms (PFAs) [12, 13, 14]. They should therefore provide an excellent particle separation complementing high-resolution tracking. The combination of the information of the two (calorimetry and tracking) systems aims at a jet energy resolution of 3-4%

which is the design goal for future, both linear and circular, Higgs factories. This will allow for efficient separation of the 2-jet final states of Z, W and Higgs bosons. The 3D granularity is at least two orders of magnitude higher than what is proposed for calorimeters in other Work Packages. In addition, a full 4π coverage with little room for services is required to fully exploit the potential of these *imaging calorimeters*. Maybe more than others, this type of detectors requires a holistic approach, i.e. to take special care of 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 feature low-power consumption without compromising performance. A summary of the main overarching R&D directions in Work Package 1 is given in Fig. 2. The technologies pursued in this work package are all considered suited to meet the goals of imaging calorimeters. Many of the projects are a continuation of R&D so far carried out by the CALICE Collaboration [15]. Before the individual projects will be introduced, some general features shared by the proposals are recapitulated below.

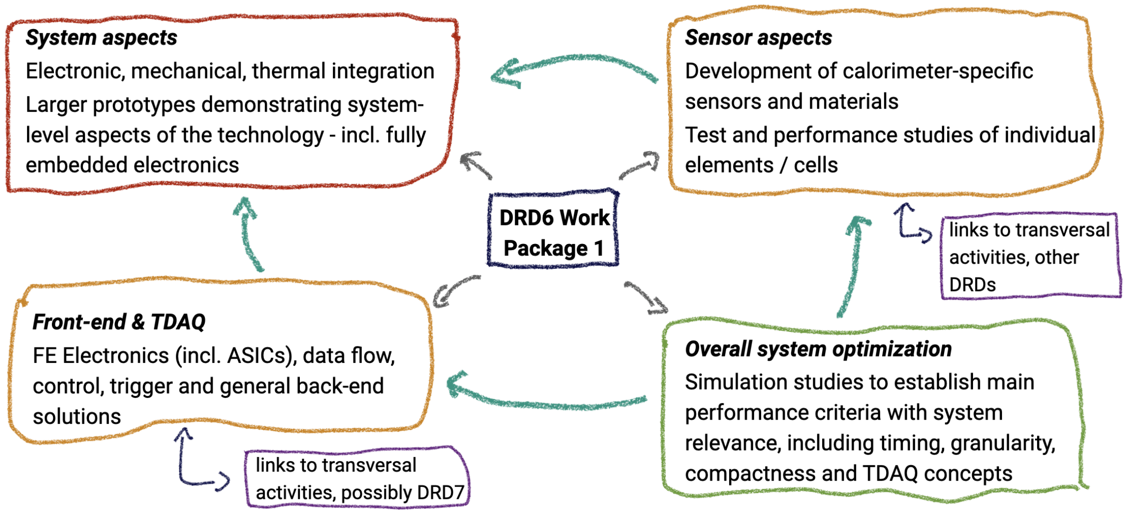

Figure 2: Synthetic overview on the main research directions common to all projects in Work Package 1.

- Most proposals feature (analogue and digital) readout electronics fully integrated into the calorimeter volume. Where this is not (yet) the case, it is recommended that the design should be adapted.

- It is common practice in calorimetry to build and handle electromagnetic and hadronic calorimeters as separate entities. Imaging calorimeters should be thought of 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. Such beam tests are comparable in size and complexity to real experiments. As outlined in Sec. 8.2, the DRD-on-Calorimetry envisages to pay particular attention to beam test infrastructures for the benefit of all projects.

3.2 Activities and objectives

In the following, the projects, that would like to deliver large-scale prototypes in the coming 3-6 years, are introduced. Either the prototypes do already exist and could be extended, or the size of the groups and the anticipated resources are large enough such that credible prospects for their realisation can be made. The projects are grouped into tasks to exploit in the best way synergies between them. These tasks are ordered by section, either electromagnetic or hadronic. Within the electromagnetic part, three tasks propose semiconductors as sensitive elements. Note already here that all proposals for the electromagnetic sections use tungsten (W) as absorber material. Tasks on hadronic sections are split according to the sensitive element, either optical or gaseous.

3.2.1 Task 1.1: Highly pixelised electromagnetic section

- Subtask 1.1.1: A *Si*licon-Tungsten *E*lectromagnetic *Cal*orimeter **SiW-ECAL** uses silicon pad sensors with analogue readout embedded between tungsten (W) absorber layers. Silicon allows for high pixelisation and tungsten for a compact design. An individual layer has to remain within an envelope of around 5 mm. Compared with the CMS HGCAL [16], currently under construction, the lateral density is about 2-4 times higher while the longitudinal density is around a factor of two higher. 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 [17] and the first step in the R&D will be to conclude the ongoing work. For future Higgs factories, the tendency is to increase the beam collision frequency, with respect to the case of the International Linear Collider. The extreme case is the Z-pole running at a circular electron-positron collider that must be supported by the front-end electronics and readout system. Excellent timing resolution is a promising avenue to considerably improve the performance of the PFA. The actual need for timing resolution will have to be determined before hardware specifications can be made. Still, both high collision frequency and excellent time resolution will yield an increase in the power consumption of the front-end electronics. On the other hand, 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 for relevant physics processes, has to be carried out in order to specify the hardware needs for future prototypes.
  Main R&D topics: Solid construction of basic detection elements; extension of current prototype(s) based on power pulsing to continuous operations; reduction of power consumption; study of the need for cooling; study of the addition of timing, with either dedicated layers or volume timing. For both linear and circular collider operation, the performance of real-size layers will have to be studied.

- Subtask 1.1.2: **Highly compact calo**rimeters will measure the luminosity and the beam-induced background in particle physics detectors ("forward calorimetry"). The reduced space and the quest for separation of close-by electron and photon showers, call for an even higher level of compactness compared with the SiW-ECAL introduced before. Therefore, the R&D focuses on the reduction of auxiliary components such as readout or transmission wires. This implies, for example, the testing of GaAs sensors with readout strips on the sensor substrate. The space available in the forward region of particle detectors is very limited. Therefore, forward calorimetry constitutes a field of application of wireless data-transfer technologies that will be developed in the DRD-on-Electronics (DRD 7). Several aspects of forward calorimetry will be addressed in the frame of the LUXE experiment [18]. In particular, partially shared with the SiW-ECAL project R&D, detector elements of forward calorimeters require the study of connectivity technologies in terms of sensor gluing.
  Main R&D topics: Testing of sensors with readout strips, solid construction of basic detection elements (study of conductive gluing), application of wireless data transfer.

- Subtask 1.1.3: **DECAL:** Separation power through high pixelisation is the main motivation for the application of calorimeters based on semiconductors. The *D*igital-*E*lectromagnetic *Cal*orimeter **DECAL** will increase the transverse granularity w.r.t. the SiW-ECAL by a factor of around 10^4 by using reconfigurable CMOS MAPS sensors. In this case, each pixel will be read out with a 1-bit resolution resulting in digital calorimetry. The aim is to produce a large, granular sensor that can be a testbed for digital calorimetry, outer tracking and preshower applications. Recent work in the context of the EPICAL-1 and -2 Ultra-High Granularity Electromagnetic Calorimeter Prototypes have confirmed the potential for digital calorimetry in terms of energy resolution and shower separation [19]. Separately, prototypes of dedicated CMOS MAPS sensors, such as the DECAL sensors, for digital calorimetry, outer

tracking and preshower applications, have paved the way for developing devices that can address the specific requirements of multiple subdetectors, including digital calorimeters [20]. The future R&D will take the best aspects of both existing projects, developing a new sensor optimised for calorimetry, either by integrating the design of the DECAL DMAPS chip with an existing mature sensor or by continuing its own development, and ultimately deploying the resultant sensor for a beam test. By taking advantage of the EPICAL-2 prototype and existing data for evaluation of performance extrapolated to what will be a custom sensor, it is envisaged 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. The development carried out here will be calorimetry specific. Still, there is a natural synergy with MAPS and CMOS sensor development for trackers in the DRD on solid state detectors (DRD 3).
  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 $10\mathrm{mW/cm}^2$, 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 $2000\,\mathrm{m}^2$. The selected sensors and technology will have to be validated by beam-test prototypes.

- Subtask 1.1.4: While the previous three projects develop electromagnetic calorimeters based on semiconductors, the **Sc-ECAL** ([21]) uses *sc*intillating strips of around $45 \times 5 \times 2\,\mathrm{mm}^3$ in size. In alternating layers, the strips are rotated by 90° yielding an effective $5 \times 5\,\mathrm{mm}^2$ transverse granularity. A prototype of this type of calorimeter has been tested in 2022 and 2023 with beam at CERN. As for the SiW-ECAL, this prototype was 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 obvious 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 technologies developed in the DRD on quantum technology (DRD 5)
  Main R&D topics: Extension of current prototype based on power pulsing to continuous operations: reduction of power consumption and of cooling, study of the addition of timing, with either dedicated layers or volume timing. For both linear and circular collider operations, the performance of real-size layers will have to be studied.

3.2.2 Task 1.2: Hadronic section with optical tiles

- Subtask 1.2.1: The *A*nalogue *Ha*dron *Cal*orimeter **AHCAL** is based on the SiPM-on-Tile technology previously developed in the CALICE collaboration and now also applied in the CMS-endcap calorimeter upgrade (HGCAL). For hadron calorimeters, primarily targeted at Higgs Factories, one aims at maximum compactness, with considerably tighter requirements, in particular in the barrel region, than for CMS. Channel count and instrumented area are also more than an order of magnitude larger. A full technological prototype capable of containing high-energy hadronic showers has been constructed [22], with electronics optimised for linear e^+e^- colliders using power pulsing to eliminate cooling requirements in the active detector volume. The SiPM-on-Tile technology is relatively mature, shifting the main focus of the R&D to system aspects. A central theme is the development of a full system suitable for circular colliders which requires continuous high-rate readout, as well as a consolidation and further improvement of the cell-by-cell time resolution. In addition, alternative scintillator-integration concepts such as mega-tiles will be studied, in connection with the development of new plastic scintillating materials.
  Main R&D topics: Re-design of the full readout and powering chain for continuous readout, data rates and possible trigger requirements of circular Higgs Factories, development of appropriate electrical, thermal and mechanical integration concepts.

- The **ScintGlassHCAL** ([23])project seeks to replace plastic scintillators with tiles based on *scint*illating *glass*es. As pointed out in the ECFA Detector R&D Roadmap, this material is

supposed to be cheaper than traditional inorganic scintillators. With clear synergies with Work Package 3, the development of this type of calorimeter requires some groundwork on that type of detector. 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 photodetectors. The concept of an imaging calorimeter requires, as for the other proposals in this Work Package, a high level of integration. Since the use of scintillating glasses is, as of today, uncharted territory for imaging calorimeters, this may imply additional, still unknown, R&D challenges.
Main R&D topics: Identification of optimised scintillating glass materials. 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.

3.2.3 Task 1.3: Hadronic section with gaseous readout

- Subtask 1.3.1: The *S*emi-*D*igital *H*adronic *Cal*orimeter (**SDHCAL**) is a sampling calorimeter studied by the CALICE collaboration to equip the future ILC experiments with a compact, self-supporting, hadronic calorimeter using gaseous detectors, such as RPCs, to achieve the high granularity required to successfully apply PFA techniques. A prototype of 48 units was built in 2011 [24] and tested in the following years until today. The next generation of this type of calorimeters should feature a time resolution of better than 150 ps (to be compared with around 1 ns of today). In the **T-SDHCAL** project, the amplification of the avalanche process will be boosted by moving from a single-gap RPC to a multigap RPC (MRPC). The MRPC will be developed in close coordination with the DRD on gaseous detectors (DRD 1). The main task in the DRD-on-Calorimetry is the integration of several layers into a calorimetry system. The detector has to be read out by a low-jitter, low power-consuming, ASIC. Liroc, see e.g. [25], is a promising candidate for this. Operation at circular e^+e^- colliders requires, 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 readout ASIC, such as Liroc. Development of a few layers of $1 \times 1\,\mathrm{m}^2$ that could be inserted in the current SDHCAL prototype replacing some of the existing single-gap RPCs to allow for the study of full hadronic showers.

- Subtask 1.3.2: As a complement to the RPC-based sensors, the *m*icro*p*attern *g*as *d*etector *h*adronic *cal*orimeter **MPGD-HCAL** proposes gaseous sensors based on Micromegas or μRWELL chambers. The main motivation for this approach is that both Micromegas and μRWELL chambers are able to stand high particle fluxes. These characteristics make them suitable, not only for future e^+e^- colliders, but in particular for a future muon collider. As of today, seven μRWELL chambers and four Micromegas layers of size $20 \times 20\,\mathrm{cm}^2$ have been constructed within the project. From these, the six best layers will be chosen, yielding an "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 $50 \times 50\,\mathrm{cm}^2$ yielding a total depth of three interaction lengths. In the long run, chambers of size $50 \times 100\,\mathrm{cm}^2$ and $100 \times 100\,\mathrm{cm}^2$ are planned. The development of all mentioned chambers will be carried out in cooperation with DRD 1. For the larger chambers, the project will integrate with the general development of readout systems within the DRD.
  Main R&D topics: Simulation studies to assess the performance needs for a hadronic calorimeter at a future muon collider, development of large-area MPGD chambers including adequate readout electronics.

- Subtask 1.3.3: The **ADRIANO3** is a high-granularity triple-readout calorimeter with fast timing, designed by adding a third active element to the ADRIANO2 ([26]) technique. It is a highly granular, integrally active, dual-readout calorimeter with 5D shower measurement, aiming at disentangling the neutron component of a hadronic shower. ADRIANO3 is composed of a sandwich of heavy-glass tiles, plastic scintillator tiles, and thin RPCs, assembled

Task/Subtask	Sensitive Material/ Absorber	DRDTs	Target Application	Current Status
Task 1.1: Highly pixelised electromagnetic section				
Subtask 1.1.1: SiW-ECAL	Silicon/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.1.2: Highly compact calo	Solid state (Si or GaAs)/ Tungsten	6.2	e^+e^- collider forward part	Prototypes with non-optimised sensors, Sensor optimisation and data transfer studies ongoing
Subtask 1.1.3: DECAL	CMOS MAPS/ Tungsten	6.2, 6.3	e^+e^- collider central detector. Future hadron collider	Prototypes with non-optimised sensors, Sensor optimisation ongoing
Subtask 1.1.4: Sc-Ecal	Scintillating plastic strips/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Task 1.2: Hadronic section with optical tiles				
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/ Steel	6.2	e^+e^- collider central detector	Material studies and specifications for prototypes
Task 1.3: Hadronic section with gaseous readout				
Subtask 1.3.1: T-SDHCAL	Resistive Plate Chambers/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Subtask 1.3.2: MPGD-HCAL	Multipattern Gas Detectors/ Steel	6.2, 6.3	$\mu^+\mu^-$ collider central detector	Small prototype for proof-of-principle, Lateral and longitudinal extension envisaged
Subtask 1.3.3: ADRIANO3	Resistive Plate Chambers +Scintillating plastic tiles/ Heavy Glass	6.1, 6.2, 6.3	e^+e^- collider central detector BSM searches in MeV-GeV range	RPC, Scintillating Tiles advanced status, R&D on heavy glass needed

Table 1: Table summarising the projects in Work Package 1, their grouping into tasks and their status and plans.

as a single readout layer. The heavy glass is mostly sensitive to the 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, are sensitive to all the ionising particles, but not to neutrons, allowing for 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: Optimisation of the construction technique in terms of light yield, RPC efficiency, timing resolution, and cost; construction of a few prototype layers; finally, production of a medium-scale prototype, and test 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.

A summary of the introduced projects is given in Tab. 1. Tab. 2 complements the previous table with a list of milestones and deliverables.

In addition to the described projects, the work package will also follow up on 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)* [27]. Here, passive absorber material is replaced by lead glass 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

	Milestone	Deliverable	Description	Due date
Task 1.1: Highly pixelised electromagnetic section				
Subtask 1.1.1: SiW ECAL		D1.1	Revised 15 layer stack	2024
	M1.1		Specifications for timing and cooling	2025
		D1.2	Engineering module for Higgs factory	>2026
Subtask 1.1.2: High compact calo		D1.3	Updated set of compact detection layers	2024
	M1.2		Prototype for GaAs sensors with strip readout	2026
		D1.4	Set of validated GaAs sensors	>2026
Subtask 1.1.3: DECAL	M1.3		Requirements for DECAL-specific sensor design established	2024
	M1.4		Full evaluation of (ALPIDE-based) EPICAL-2 performance	2025
	M1.5		Design for next-generation sensor with DECAL-specific optimisation (with machine-specific options)	2026
		D1.5	New sensors producted and evaluated in EPICAL-3 prototype	>2026
Subtask 1.1.4: Sc-ECAL	M1.6		Improved components (engineering for production, timing, active cooling, etc.)	2024
		D1.6	40-layer prototype and testbeam	2025
Task 1.2: Hadronic section with optical tiles				
Subtask 1.2.1: AHCAL	M1.7		Concept for continuous readout	2024
	M1.8		First layer with continuous readout	2025
		D1.7	EM prototype demonstrating system aspects	2026
		D1.8	Full-size layer and multi-layer demonstrator	>2026
		D1.9	Engineering prototype	>2026
Subtask 1.2.2: GlassScintHCAL	M1.9		cm-scale tiles	2024
		D1.10	15-layer EM module	2025
		D1.11	40-layer prototype	>2026
Task 1.3: Hadronic section with gaseous readout				
Subtask 1.3.1: T-SDHCAL	M1.10		Study of the impact of timing on PFA performance	2024
	M1.11		Specifications for first layers	2025
	M1.12		First T-SDHCAL layers	2026
		D1.12	40-layer prototype	>2026
Subtask 1.3.2: MPGD-HCAL		D1.13	Completion of 6-layer 20 × 20 cm^2 prototype	2024
	M1.13		Specifications for 50 × 50 cm^2 prototype	2025
	M1.14		Design of 50 × 100 cm^2 layers	2026
		D1.14	10-layers prototype (6L: 20 × 20 cm^2 +4L: 50 × 50 cm^2)	2026
		D1.15	3 100 × 100 cm^2 layers	>2026
Subtask 1.3.3: ADRIANO3	M1.15		Small-scale test layers	2024
	M1.16		Small-scale prototype	2025
		D1.16	Large-scale prototype & testbeam	2026

Table 2: Deliverables and milestones in Work Package 1.

with the ADRIANO3 project. Both DSC and ADRIANO3 will benefit from the Work Package 3 on optical calorimeter R&D.

3.3 Short-term applications

The technologies of SiW-ECAL and AHCAL, originally developed within CALICE, have been adopted by the CMS-HGCAL for the upgrade of the endcaps of the CMS detector. The experience gathered in the construction of this new type of calorimeter will feed back into the R&D of Work Package 1. The system integration of the detection elements (Si-Modules and TileBoards in the case of the CMS HCGAL) is one of the main challenges. The detectors proposed here are typically more compact than those of the HGCAL and will have to meet the precision requirements for future e^+e^- colliders. Two of the described projects, the SiW-ECAL and the highly compact calorimeter, are also foreseen as detectors at the DESY experiment LUXE. The detector construction for LUXE and the DRD-6 program will mutually benefit from each other. This concerns, in particular, detector integration, a crucial aspect of the detectors studied in Work Package 1.

4 Work Package 2: Liquified Noble Gas Calorimeters

4.1 Description

Future experiments at $\mathrm{e^+e^-}$, 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 programme of $\mathrm{e^+e^-}$ colliders, but also for precision measurements at future hadron or muon colliders. The unprecedented statistical precision achievable in experimental measurements at circular $\mathrm{e^+e^-}$ colliders, such as the FCC-ee, will have to be complemented by extremely well-controlled systematic uncertainties, which require an excellent understanding of the detector and the event reconstruction. Highly uniform, linear and stable measurements 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 $\mathrm{e^+e^-}$, hadron or muon collider experiment. The goal for the next years is to design and build a small module for characterisation with test beams. Work will focus on the below areas 1-4, leading to a prototype module by the end of 2027:

1. Further develop the understanding of the needed granularity of an electromagnetic calorimeter for an $\mathrm{e^+e^-}$ experiment by studying pion rejection (tau-lepton physics), axion searches as well as jet-energy reconstruction, using 4D imaging techniques, machine learning and/or – in combination with the tracker measurements – 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, passive material correction, absorber composition and shape). In addition, the possibility of reading out the Cherenkov light in the liquified noble gas might be studied to investigate potential gains in timing measurement or in dual-readout energy measurement.

2. Optimise the readout 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 crosstalk and electronic noise

Project	DRDTs	Milestone	Deliverable	Description	Due date
Noble-Liquid Calorimeter	6.1, 6.2, 6.3	M2.1		Design review of test module - sign-off	2025
			D2.1	Test module assembled	> 2026
		M2.2		Test module ready for cool-down	> 2026

Table 3: Deliverables and milestones in Work Package 2.

(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 the 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 readout electronics, whereas the other part should be read out via coaxial cables and warm electronics sitting outside of the cryostat.

3. Study two different readout designs: readout via cold electronics, sitting inside the cryostat, as well as readout via warm electronics, sitting outside the cryostat. It is our intention to reuse existing readout chips (e.g. from ATLAS LAr, DUNE, HGCAL,…) and adapt them for our use. There are synergies as well with other projects in the DRD, on very-low-power integrated front-end electronics for future calorimeters. The necessary cables and 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, readout 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, $\geq 22X_0 : \sim 1.0\,\mathrm{m} \times 0.5\,\mathrm{m} \times 0.5\,\mathrm{m}$) will be designed. A final design review will be held in Q4 2025, after which the production of the test module shall start. The goal is to have the module assembled and tested at warm temperatures by the beginning of 2028. Cold tests and tests with beams are planned for 2028 and/or later, depending on the CERN SPS beam schedule. 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).

All milestones and deliverables as well as references to the addressed DRDTs are summarised in Tab. 3.

5 Work Package 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 Package 3 is to explore, optimise and demonstrate with full shower-containment prototypes, new concepts of sampling and homogeneous calorimeters based on scintillating materials. 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 concepts discussed in Sec. 3, the calorimeter designs in this section do not plan to embed electronics and services inside the calorimeter but rather route

Project	Calorimeter type	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters					
HGCCAL	EM / Homogeneous	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	EM / Homogeneous	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	EM / Quasi-Homog.	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters					
GRAiNITA	EM / Sampling	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	EM / Sampling	GAGG, organic	MCP-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	EM / Sampling	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: Hadronic sampling calorimeters					
DRCal	EM+HAD / Sampling	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	HAD / Sampling	PEN, PET	SiPMs	6.2, 6.3	e^+e^-/hh
Task 3.4: Materials					
ScintCal	-	-	-	6.1, 6.2, 6.3	$e^+e^-/\mu^+\mu^-$/hh
CryoDBD Cal	-	TeO, ZnSe, LiMoO NaMoO, ZnMoO	n.a.	-	DBD experiments

Table 4: Overview of R&D activities on optical calorimeter concepts.

the signal away from the active elements (while photodetectors are in some cases embedded). The vast majority of the proposed calorimeters exploit 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

For the next three years, the overall goal of Work Package 3 is to increase the level of technological readiness (TRL) of various calorimeter concepts based on scintillators or other optical media. 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 and hadron colliders) and thus different operating environments and unique challenges (e.g. time resolution or radiation tolerance). Table 4 provides a summary of the broad scope of activities within Work Package 3. The projects are organised into 4 tasks addressing different technological challenges. Each activity concerns the development of a specific calorimeter concept.

Three of the proposed calorimeter concepts (HGCCAL, MAXICC and Crilin) are designed for electromagnetic (EM) shower detection using a homogeneous or quasi-homogeneous approach based on scintillating crystals and SiPM readout. (**Task 3.1)**
A second group of ECAL concepts develops innovative approaches for sampling calorimetry that provide radiation tolerance (SpaCal, RADiCAL) or very fine sampling capabilities (GRAiNITA). (**Task 3.2**)
A fibre-based dual-readout sampling calorimeter (DRCal) 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. (**Task 3.3**).
Another task aims at identifying the best-suited materials for applications in calorimetry. Needs for new optimised materials will be identified and R&D will be carried on in this framework. This task 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.(**Task 3.4**).
A brief description of each activity is given in the following.

5.2.1 Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters

- Subtask 3.1.1: The *H*igh-*G*ranularity *C*rystal *Cal*orimeter (**HGCCAL**) [28] 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 programmes at future e^+e^- colliders. The application of PFA would benefit from shorter bars of $1 \times 1 \times 4.5$ cm^3 is size that are also considered. About the front-end electronics for the SiPM readout, it is expected that there will be synergies in many aspects (e.g. single photon calibration, a high dynamic range, low power dissipation, high event rate) with other projects in DRD 6 and possibly in DRD 7.
Key R&D required: Mechanical design and integration, development of an EM shower-scale prototype; pattern recognition issues and PFA performance for the long crystal bar design; studies and developments of SiPMs and ASICs with a large dynamic range, which is a new technical challenge for the homogeneous calorimetry structure.

- Subtask 3.1.2: The *Max*imum *I*nformation *C*rystal *C*alorimeter (**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 [29]. 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 instance) 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 about $30\%\sqrt{E}$ when combined with a dual-readout hadron calorimeter.
Key R&D required: Identification of optimal components (crystal, optical filters, SiPMs) for the isolation and extraction of the Cherenkov signal, development of an EM-shower-scale prototype.

- Subtask 3.1.3: The *Cr*ystal calor*I*meter with *L*ongitudinal *I*nformatio*N* (**Crilin**) [30] 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 EM energy resolution in the $5 - 10\%\sqrt{E}$ range, limited by BIB and SiPM noise effects due to radiation-induced damage (for an 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. Time resolution measurements will be performed in test beams.
Key R&D required: Validation of the concept design and simulations with an EM-shower-scale prototype.

5.2.2 Task 3.2: Innovative sampling EM calorimeters

- Subtask 3.2.1: The **GRAiNITA** concept [31] 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 supposed to be 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 photodetectors (SiPMs) 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.

- Subtask 3.2.2: The Spaghetti Calorimeter (**SpaCal**) [32] 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-hard crystal fibres as active elements makes such a calorimeter a viable technology for applications in extreme radiation environments at future hadron colliders. An optimisation of the calorimeter for e^+e^- collider applications is also possible. EM-shower-scale prototypes with tungsten and lead absorbers were successfully tested with high-energy electron beams.
Key R&D required: Optimisation of absorbers, light guides, photon detectors, scintillating fibres and simulation software. Development of ASIC optimised for waveform sampling with 15 ps time resolution.

- Subtask 3.2.3: The **RADiCAL** detector is a compact sampling EM calorimeter with fast-timing capabilities, designed to achieve a sufficient radiation tolerance for operation in extreme radiation environments [33]. It is based on a Shashlik-type geometry with crystal plates alternated with tungsten plates and uses quartz capillaries filled with a WLS filament and quartz rods to bring the light signals towards both the front and rear sides of the calorimeter cell where SiPMs are used as photodetectors. The front side sees WLS light; the rear side sees both WLS and Cherenkov light. Precise timing and spatial localisation of EM showers is derived from WLS filaments positioned longitudinally within the capillaries at the maximum of EM showers. Beam test measurements were performed with earlier prototypes.
  Key R&D required: Development of radiation-hard wavelength shifters, construction of EM-shower-size prototype.

5.2.3 Task 3.3: Hadronic sampling calorimeters

- Subtask 3.3.1: 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 single hadrons and jets exploiting the dual-readout method to correct for fluctuations of the electromagnetic fraction of hadronic showers [34]. The calorimeter can also be optimised for electromagnetic shower measurements with resolutions in the $12-15\%\sqrt{E}$ range. The goal of this activity (**DRCal**) is to build prototypes with full hadron-shower containment and qualify them with beam tests to assess performance and validate large-scale assembly processes and scalability of the highly granular, SIPM-based, readout.
  Key R&D required: Development of a readout system and construction of prototypes with containment of hadronic showers.

- Subtask 3.3.2: Scintillator tiles readout with wavelength shifting fibres, 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 hadron colliders [35] and explore new PEN and PET materials as well as optimise the WLS fibre and SiPM readout efficiency.
  Key R&D required: Characterisation of PEN (Polyethylene naphthalate) and PET (polyethylene terephthalate) scintillators. Mechanical design and construction of prototypes.

5.2.4 Task 3.4: Materials

The calorimeter concepts proposed in Work Package 3, and some of those in Work Package 1, have common requirements regarding the performance of scintillating materials such as good optical quality, high light yield, fast decay time, sufficient radiation hardness, high density for homogeneous calorimeters and cost-effective mass production.

- Subtask 3.4.1: **ScintCal** This subtask on materials aims to identify the key R&D activities necessary to be carried out on various scintillators and wavelength shifters (inorganic, organic, glasses, ceramics) to achieve the required performance for the various calorimeter concepts proposed in Work Package 3. They will depend on the radiation environment conditions expected in future experiments and the type of calorimeter (sampling or homogeneous) 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 of available state-of-the-art scintillation materials that potentially fulfil the requirements of the detector concepts to be developed. Then, identify the most appropriate materials for each detector concept and key R&D areas for further property improvements. In this respect, while activities in WP3 are specific to the need for scintillators in HEP and specifically to calorimeter applications, the Crystal Clear Collaboration will continue for generic R&D on scintillators (e.g., understanding of the scintillation process, development of new materials and their use in many applications). Not all the institutes participating in WP3.4 are members of the Crystal Clear Collaboration. On the other hand, the Crystal Clear members participating in the task can bring their expertise in fundamental aspects of scintillators to advise for the choice and quslification of materials and help interpret the results but not necessarily perform the full R&D needed to have a specific scintillator used in a particular detector. 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 ionisation 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 (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 ps domain.
  - **Ultrafast inorganic scintillators for ultrafast calorimetry:**
    - ∗ Screen/survey/develop cross-luminescence materials for ultrafast timing with a focus on shifting cross-luminescence emission towards the 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.

- Subtask 3.4.2: **Cryogenic DBD-calorimeters** Future generations of double beta decay experiments based on cryogenic calorimeters (CUPID-1ton and beyond) would also benefit from a joint development of new scintillating materials to be used both as targets (scintillating crystals containing the isotopes under study) and as active structural components of the setup or veto systems for external background. In this case, radiopurity and compatibility with a cryogenic environment are of paramount importance.

5.3 Milestones and deliverables

The major objective of Work Package 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 different optimisations, 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 of 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 this WP and in the working groups discussed in Section 8. The testing of calorimeter prototypes, foreseen for all the proposed technologies, will strongly benefit in terms of resources from a coordinated effort on common beam-test infrastructures as described in Section 8.2.

A list of milestones and deliverables is reported in Table 5. Deliverables usually include the construction and testing of calorimeter prototypes. Milestones include reports on material and photodetector characterisation studies, the definition of technical specifications and are used to monitor progress and evaluate the completion of a corresponding deliverable. Particularly milestones also indicate steps toward developments that go beyond the scope of the R&D programme described here.

5.4 Short-term applications

Some of the subtasks proposed in WP3 have already a high level of technological readiness. For this reason they can be evaluated by experiments which are on a shorter time scale w.r.t future accelerators. A few examples, where connection has already been established, are reported below.
The Crilin community is working together with the people in charge of the HIKE future proposal. The HIKE Small Angle Calorimeter (SAC) ([36]) is an independently proposed, highly granular, longitudinally segmented, fast crystal calorimeter with SiPMs readout and performance requirements similar to those for Crilin. A successful development and test of the Crilin prototype will automatically translate into a successful R&D for the Hike SAC.
The SpaCal technology, as developed in subtask 3.2.2, is foreseen for the inner region of the proposed LHCb Upgrade II ECAL (PicoCal). The high particle fluxes expected from Run 5 mandate timing capabilities with $\mathcal{O}(10)$ ps precision. After LS4, the innermost SpaCal modules with tungsten absorbers are planned to be equipped with radiation-hard scintillating crystal fibres. SpaCal modules with lead absorbers and radiation-tolerant organic scintillators are suitable for the surrounding region.

6 Work Package 4: Electronics and readout

6.1 Description

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 $\sim 1\,\mathrm{mW/ch}$ in order to further increase the granularity in Work Package 1 or allow cryogenic operation without creating deadly bubbles in Work Package 2. For Work Package 3, improving the timing performance will also be an important asset. It will be pursued by exploiting the lower occupancy of future experiments at e^+e^- colliders, compared to HL-LHC, allowing slower shaping and on-chip data processing in order to reduce the output bandwidth. Various front-end electronics will be studied to optimise the dynamic range handling (dynamic gain switching, multi-gain preamps, ToT technique...). ADC/TDCs, digital logic will also be studied in order to reduce their power dissipation and in particular their instantaneous current spikes and minimise digital noise, which is a recurrent issue in calorimetry mixed-signal ASICs.

6.2 Objectives

It is proposed in this Work Package to develop a family of ASICs, optimised for the different subdetectors proposed and sharing as much as possible common back-end and readout systems. In

	Milestone	Deliverable	Description	Due date
HGCCAL	M3.1		Specifications of crystal, SiPM and electronics for highly granular EM crystal calorimeter prototype	2024
		D3.1	Development of 1-2 crystal EM modules to be exposed to beam tests	2024
	M3.2		Beam tests characterisation of a full containment highly granular EM crystal calorimeter prototype	2025
	M3.3		A first mechanical design for a final detector with crystal modules	2025
	M3.4		New reconstruction software for the long-bar design and updated PFA	2026
		D3.2	Large crystal module for hadronic performance, system integration studies and combined testbeam with HCAL	>2026
MAXICC	M3.5		Completion of qualification tests on components and selection of crystal, filter and SiPM candidates for prototype	2025
	M3.6		Report on the characterisation of crystal, SiPM and optical filter candidates and their combined performance for Cherenkov readout	2025
		D3.3	Full containment dual-readout crystal EM calorimeter prototype and testbeam characterisation	2026
	M3.7		Joint testbeam of EM module prototype with dual-readout fibre calorimeter prototype (DRCAL)	>2026
Crilin		D3.4	Acquisition and tests of crystals and SiPMs; design and production of electronics boards; design and production of the mechanical components	2024
		D3.5	Calorimeter fully assembled	2025
	M3.8		Beam test characterisation of a full containment EM calorimeter prototype	2025
	M3.9		Report on testbeam results	2026
GRAiNITA	M3.10		Characterisation of materials, wavelength shifters and SiPMs and identification of best technological choices	2024
		D3.6	Development of a GRAiNITA demonstrator as EM calorimeter prototype for e+e- collider (full shower containment)	2026
SpaCal		D3.7	Tungsten and lead absorbers for module-size prototypes	2024
	M3.11		Design of optimised light guides	2025
		D3.8	Set of crystal samples, SPIDER ASIC prototype	2026
	M3.12		Specification of photon detector and improved simulation framework available	2026
		D3.9	Module-size prototypes (significantly larger than EM showers) built and validated in beam tests	>2026
RADiCAL		D3.10	Single module with prototype scintillating crystals, SiPMs and front-end electronics cards built and tested.	2024
		D3.11	3x3 array of RADiCAL modules built and tested	2026
	M3.13		Paper on beam-test results for EM shower position, timing and energy	2026
	M3.14		Continue beam testing with alternative scintillation and wavelength shifting materials - for improved cost/performance.	>2026
DRCal		D3.12	Construction of full-scale dual readout module with hadronic shower containment	2025
	M3.15		Testbeam campaign to assess module performance: result paper	2026
	M3.16		Continue beam testing with alternative readout elx	>2026
TileCal	M3.17		Characterisation of PEN- and PET-based scintillating tiles including optimisation of readout with WLS fibres and SiPMs	2025
		D3.13	Construction of up to 3 prototypes of a sampling tile calorimeter module with WLS fibres and SiPM readout (for beam tests after 2026)	2026
	M3.18		Paper on beam test results	>2026
		D3.14	Full hadron-shower containment prototype built and tested	>2026
ScintCal	M3.19		Dataset of scintillation and radiation hardness properties of various scintillation materials studied	2026
		D3.15	Samples of a set of scintillators produced and characterised	2026
		D3.16	Samples of most promising glasses produced and characterised	>2026
	M3.20		Material selected for future detectors	>2029
CryoDBDCal	M3.21		Report crystals in terms of optimisation of growing/doping procedures	2024
		D3.17	Scintillating polymer for 3D-printing, with optimal mechanical and light-production properties, produced and tested	2025

Table 5: Deliverables and milestones in Work Package 3.

	DRDTs	Milestone	Deliverable	Description	Due date
Electronics and DAQ	6.1, 6.2, 6.3	M4.1		Specifications for common ASIC production	2024
			D4.1	Common ASIC production	2025

Table 6: Deliverables and milestones of Working Package 4

order to remain in phase with the overall direction of the R&D on electronics, the development of the ASICs will make use of component libraries that will be shared with the DRD-on-Electronics (DRD 7). Shared engineering runs in 65 and/or 130 nm will allow the production of enough chips (likely 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. The details of the sharing should be fixed in an addendum to the MOU, in the ideal case complemented with an agreement on the testing of the ASICs and an eventual need for a 2nd production of debugged ASIC versions. If possible, to save funding, we will seek for opportunities to hook onto a large-scale ASIC production for an approved project such as the EIC. Before a production will happen, we will organise a production readiness review to which members of the DRD-on-Electronics (DRD 7) will be invited. In general, we will report regularly at DRD 7 meetings and will invite DRD 7 members to DRD-on-Calorimetry meetings. Let us point out that a similar procedure was and is followed in the various European AIDA projects.
It is also proposed to develop a common DAQ framework so that different ASICs could be supported within this DAQ and different detectors and/or chips could be efficiently jointly operated, as described in Sec. 8.3.2.

7 Resources

In Tab. 7 and 8 the present understanding of the available resources and those required to complete the proposed R&D is reported, both in terms of personpower and funds. In general, the additional requests need yet to be discussed and agreed with the funding agencies. This will be a matter of discussion in view of the sign-off of the MoU.

8 Working Groups

Working Groups will address work that is common to all work packages in the DRD. They thus ensure coherence and synergy of the scientific program of the DRD itself. Since the work carried on in the Working Groups is required by the different projects to successfully reach the experimental goals, funds and personpower need to be included in the budget of the Working Packages concerned with. For some of the activities, funding does already exist or the need is directly connected to the construction of prototypes. Other Working Groups cover service tasks such as the organisation and conduction of beam tests, if possible in a dedicated beam line for calorimetry, and the provision and maintenance of software tools. The funding of these service tasks should be the subject of dedicated discussions in the course or shortly after the formation of the DRD. The idea of a Working Group on mechanics was born just recently and will be worked out further soon.

In the following, a detailed description of the objective of the different Working Groups that have been identified so far will be given. The detailed organization of the work within each working group is under the responsibility of the coordinator(s) who will be elected.

8.1 Photodetectors

Photon detection, from the viewpoint of future highly granular optical calorimeters, requires addressing radiation hardness, time resolution and extended sensitivity, in both the UV and infrared regions, 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

	FTE Available				Additional Expected FTE			
	2024	**2025**	**2026**	**$\geq$ 2027**	**2024**	**2025**	**2026**	**$\geq$ 2027**
DRD CALO WORK PACKAGE 1								
Task 1.1: Highly pixelised electromagnetic section								
Subtask 1.1.1: SiW-ECAL	9.7	9.7	9.7	9.7	1.0	1.0	1.0	10.0
Subtask 1.1.2: Highly compact calo	5.5	6.0	5.5	3.0	0.5	1.0	1.5	1.0
Subtask 1.1.3: DECAL	2.0	2.0	2.0	2.0	11.2	11.2	11.2	11.2
Subtask 1.1.4: Sc-ECAL	7.3	7.3	7.3		0.0	0.0	0.0	
Total	24.4	24.9	24.4	14.6	12.7	13.2	13.7	22.2
Task 1.2: Hadronic section with optical tiles								
Subtask 1.2.1: AHCAL	8.2	8.2	8.2	11.0	3.8	3.8	3.8	7.0
Subtask 1.2.2: GlassScintHCAL	14.1	14.1	14.1	16.0	0.9	0.9	0.9	4.0
Total	22.3	22.3	22.3	27.0	4.7	4.7	4.7	11.0
Task 1.3: Hadronic section with gaseous readout								
Subtask 1.3.1: T-SDHCAL	15.4	15.4	15.4		2.5	2.5	2.5	
Subtask 1.3.2: MPGD-HCAL	5.0	5.0	5.0	4.0	2.0	3.0	5.0	16.0
Subtask 1.3.3: ADRIANO3	1.5	1.5	1.5		4.0	4.0	4.0	
Total	21.9	21.9	21.9	4.0	8.5	9.5	11.5	16.0
DRD CALO WORK PACKAGE 2								
Liquified noble gases	9.1	9.1	9.1	8.6	5.5	6.5	5.5	6.5
DRD CALO WORK PACKAGE 3								
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters								
Subtask 3.1.1: HGCCAL	6.0	6.0	6.0	6.0	4.0	4.0	4.0	5.0
Subtask 3.1.2: MAXICC	8.0	8.0	8.0		5.0	5.0	5.0	
Subtask 3.1.3: CRILIN	7.2	7.2	7.2		0.0	2.3	2.3	
Total	21.2	21.2	21.2	6.0	9.0	11.3	11.3	5.0
Task 3.2: Innovative Sampling EM calorimeters								
Subtask 3.2.1: GRAiNITA	2.0	2.0			1.3	1.3	3.3	
Subtask 3.2.2: SpaCal	16.8	16.8	16.8	16.8	6.5	6.5	6.5	6.5
Subtask 3.2.3: RADiCAL	4.0	4.0	4.0		4.0	6.0	6.0	
Total	22.8	22.8	20.8	16.8	11.8	13.8	15.8	6.5
Task: 3.3: Hadronic sampling calorimeters								
Subtask 3.3.1: DRCal	18.5	18.5	18.5	18.5	0.0	12.0	12.0	12.0
Subtask 3.3.2: TileCal	8.0	8.0	8.0	8.0	0.0	2.0	2.0	2.0
Total	26.5	26.5	26.5	26.5	0.0	14.0	14.0	14.0
Task: 3.4: Materials								
Subtask 3.4.1: ScintCal	30.4	30.4	29.2		25.0	26.0	22.3	
Subtask 3.4.2: CryoDBDCal	2.7	2.7	0.5		1.4	1.4	24.9	
Total	33.1	33.1	29.7		26.6	27.4	24.9	
DRD CALO WORK PACKAGE 4								
Electronics and DAQ	4.0	4.0	4.0		0.0	0.0	0.0	

Table 7: Existing and required FTE (Full Time Equivalent) to realise the programme sketched in Tables 2, 3, 5 and 6. Up to 2026 the estimation of required FTE is based on realistic assumptions on funding and progress of R&D. Beyond 2026 the uncertainty on available resources is very large in many cases. These numbers come from the needs of the projects. At present, they are not agreed with funding agencies.

	Funds Available (k€)				Additional Expected Funds (k€)			
	2024	**2025**	**2026**	**$\geq$ 2027**	**2024**	**2025**	**2026**	**$\geq$ 2027**
DRD CALO WORK PACKAGE 1								
Task 1.1: Highly pixelised electromagnetic section								
Subtask 1.1.1: SiW-ECAL	205	0	0		0	40	0	1000
Subtask 1.1.2: Highly compact calo	90	115	75		30	35	75	
Subtask 1.1.3: DECAL	150	10	10	10	40	115	130	130
Subtask 1.1.4: Sc-ECAL	485	35	35		0	0	0	
Total	930	160	120	10	70	190	205	1130
Task 1.2: Hadronic section with optical tiles								
Subtask 1.2.1: AHCAL	100	100	100	150	40	40	40	100
Subtask 1.2.2: GlassScintHCAL	125	0	0		200	200	200	
Total	225	100	100	150	240	240	240	100
Task 1.3: Hadronic section with gaseous readout								
Subtask 1.3.1: T-SDHCAL	10	140	70		20	90	90	
Subtask 1.3.2: MPGD-HCAL	100	30	35		60	50	65	
Subtask 1.3.3: ADRIANO3	150	150	150		150	250	350	
Total	260	320	255		230	390	505	
DRD CALO WORK PACKAGE 2								
Liquified noble gases	63	63	260	560	60	100	110	280
DRD CALO WORK PACKAGE 3								
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters								
Subtask 3.1.1: HGCCAL	125	0	0	0	100	100	200	0
Subtask 3.1.2: MAXICC	280	80	10		22	285	262	
Subtask 3.1.3: CRILIN	50	20			80	80	20	
Total	455	100	10	0	202	465	482	0
Task 3.2: Innovative Sampling EM calorimeters								
Subtask 3.2.1: GRAiNITA					150	150	150	
Subtask 3.2.2: SpaCal	125	125	125	125	58	58	58	58
Subtask 3.2.3: RADiCAL	60	60	60		140	240	240	
Total	185	185	185	125	348	448	448	58
Task: 3.3: Hadronic sampling calorimeters								
Subtask 3.3.1: DRCal	920	110			0	260	360	275
Subtask 3.3.2: TileCal	29	39	69	130				284
Total	949	149	69	130	0	260	360	559
Task: 3.4: Materials								
Subtask 3.4.1: ScintCal	156	156	156	30	162	162	72	0
Subtask 3.4.2: CryoDBDCal	60	60	60		55	55	55	
Total	216	216	216	30	217	217	217	0
DRD CALO WORK PACKAGE 4								
Electronics and DAQ						750		

Table 8: Existing and required funds (in k€) to realise the programme sketched in Tables 2, 3, 5 and 6. Up to 2026 the estimation is based on realistic assumptions on funding and progress of R&D. Beyond 2026 the uncertainty on available resources is very large in many cases. These numbers come from the needs of the projects. At present they are not agreed with funding agencies.

increase. However, e.g., both parameters play an important role also at a muon collider. A time resolution of O(10-20) ps, for pile-up mitigation, and a radiation tolerance up to several 10^{15} 1-MeV n_{eq}/cm^2 are required already for the LHCb Upgrade II (during LS4, data taking from 2035). A time resolution in the range of 10-30 ps is a quite general requirement for optical calorimetry, for example also in fixed-target experiments at the intensity frontier. In addition to fast sensors, it needs the development of dedicated readout ASICs. 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 (UV and IR) extended sensitivity is very relevant for the Cherenkov light detection in dual-readout calorimetry (e.g. DRCal and MAXICC) and, as well, in the PbF_2 Crilin calorimeter for the Muon Collider. MCP-PMTs and SiPMs are the photodetector families that, at present, promise to successfully deliver the above requirements. In this respect, the high liveliness of the market looks reassuring. In addition, the development of CMOS digital SiPMs would make it possible to integrate in a single chip the sensor and the front-end electronics and, in principle, allow the readout architecture to be highly simplified. This R&D will be likely pursued within the DRD on Photosensors and Particle Identification (DRD 4), with the collaboration of groups participating also to DRD 6. This should guarantee that the synergies will be fully exploited.

Many prototypes of the DRD-on-Calorimetry will be equipped with photosensors. During the designing and construction phase, we will consult with DRD4 about the best choice for a photosensor. If adaptation will be needed, then the adaptation, testing and, of course, integration into calorimetry systems will be part of the DRD 6 work.

Cryogenic calorimeters for double beta decay need specific photosensors that can operate at millikelvin temperatures. They must be sensitive both to small scintillation (or Cherenkov) signals from the main detectors (crystals containing the double-beta decay candidate isotope) and to scintillation light from active shielding and structural materials. The potential of current technology (Ge wafers instrumented with NTD-Ge thermistors) must be enhanced by implementing Neganov-Trofimov-Luke amplification of the thermal signal, by upgrading the thermistors to more sensitive quantum sensors (TES/KIDs) or, most likely, by a combination of the two actions. The actual development of these or other innovative quantum-sensors will be carried out in the DRD on quantum sensors (DRD 5) and members of the DRD-on-Calorimetry are also members of DRD 5. As for other R&D projects, the focus in the DRD-on-Calorimetry will be put on adaptation of new technologies to the need for (cryogenic) calorimeters and the overall system integration.

8.2 Testbeam plans, facilities and infrastructure

Beam tests play a crucial role in the development cycle of a calorimeter. It is therefore of no surprise that almost all the input proposals plan for one or more beam tests in the coming three to six years. The target projects are Higgs Factories 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 9. From this overview, it is clear that, in the long run, facilities 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 other DRDs, the need to cover an adequate energy range and the need for beam instrumentation for particle ID is specific to calorimeters.*

We expect beam tests throughout the coming years with an increased intensity after around 2026/27. At present, there is a known issue with the availability of beam-test facilities, in coincidence of the most requested period. Since this will be a generalised problem of all the DRDs, we expect that all the Collaborations and the DRDC will cooperate to find a suitable solution. Internally to this DRD, the economic use of resources has to be ensured. There exists, for example, already quite a set of absorber structures for electromagnetic and hadronic calorimeters. In the ideal case, these will have to be reused. Concerning the required funds and personpower, these will follow the same schema as described in 8.

	Energy Range	**Irradiation capabilities**
Higgs Factory $\sqrt{s}$**=90 - 1000 GeV** **Radiation level** $\leq 10^{14}\,\mathrm{n_{eq}/cm^2}$	✓	✓
HL-LHC $\sqrt{s}$**=14 TeV** **Radiation level** $\leq 10^{16}\,\mathrm{n_{eq}/cm^2}$	(✓)	✓
Muon Collider $\sqrt{s}$**=3-10 TeV** **Radiation level** $\sim \mathrm{HL-LHC}$	×	✓
Future Hadron Collider $\sqrt{s}$**=100 TeV** **Radiation level up to** $\sim 10^{18}\,\mathrm{n_{eq}/cm^2}$	×	×

Table 9: Synoptic summary on how existing test facilities (beam or irradiation) meet the R&D needs described in this proposal.

8.2.1 Thoughts on facilities and infrastructures

A beam test setup consists of one or more devices capable of absorbing 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 $1\,\mathrm{m^3}$. Here come basic requirements for a beamline.

- A large energy range from a few GeV to hundreds of GeV. It is clear that this is not available everywhere but the set of available beam test facilities has to cover this.
- Enough space to host $1\,\mathrm{m^3}$ devices.
- Moving tables that can carry devices of several tons.
- Storage space at beam test facilities in case of a beam test programme.
- It should be possible that data are immediately sent to mass storage devices accessible to everyone in the collaboration.

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;
- threshold Cherenkov counters to distinguish particle species;
- magnets to measure the performance in magnetic fields.

For efficient usage of these devices, it has to be ensured by the facilities that they are attended to in terms of the actual availability and working conditions but also in terms of interfaces to the devices under test. On the other hand, the DRD-on-Calorimetry has to provide contact persons who closely collaborate with the facility operators. These human resources will have to be incorporated into the funding and require agreements between funding agencies. Service work for the seamless conduction of beam tests should open career opportunities to those who 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 concurrently run with other devices, it may be considered to reserve dedicated slots per year for calorimeter beam tests. In the example of Europe, a typical test cycle is a test with a smaller setup or a dress rehearsal at DESY or the PS before moving to the SPS to have access to higher energies. Therefore, one may consider reserving slots for calorimeters at smaller facilities in the spring of a given year and corresponding slots at the SPS during summer or early autumn. Therefore, the SPS will be the beam test site for which the creation of a dedicated calorimeter beamline would have priority.

8.3 Detector physics, simulations, algorithms and software tools

Even though each project has its peculiarity, some common software tools can be prepared and shared among the community. Aims of this Working Group is to create a pool 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. A consistent software framework requires sustained support from a team that is led by a software coordinator. Concerning the required funds and personpower, these will follow the same schema as described in 8.

8.3.1 Data models and data management

One of the important missions of DRD-on-Calorimetry is to ensure that results obtained by the various technologies can be compared on an equal footing. While the actual event reconstruction is specific to the device under test, it should be possible to develop common data models. These data models may, for example, define an object `Calorimeter Hit`. In addition, information recorded from auxiliary devices, including beamline parameters, will have to be encoded in a consistent format understood by the entire collaboration. A common understanding of the recorded and reconstructed data will also facilitate cross-participation in the data analysis. Recorded data will have to be stored and made available to the entire collaboration. Here we will make use of data management tools available through the grid. The proper way to store calibration constants and other metadata such as detector-control data is a database. Therefore, DRD 6 will consider setting up database services with well-defined software interfaces.

8.3.2 DAQ software

One of the first needs for the test of prototypes on a beamline, is the data acquisition system. 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 the detector-specific parts need to be implemented, would save a large amount of time and work. EUDAQ [37] 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 factorising the calorimeter libraries from the beam-line common DAQ.

8.3.3 Simulation

Calorimetry is among the detectors which have wider support from the Geant4 collaboration and DRD 6 is willing to strengthen this collaboration. Among the most common tasks, G4 is used for optimising the detector layout and performing data to Monte Carlo comparison to better understand detector performance and physics data. Simulation is also used to extrapolate detector performance for physics reach. The rich physics content in the calorimeter test beam data can be used in the Geant-Val [38] infrastructure to improve the Geant4 code for a better agreement with data. In particular, this will allow for the improvement of accurate showering models to match the precision requirements for both future lepton and hadron colliders.

Given that the fast simulation of detector responses is widely used in particle physics experiments, the development of accurate and efficient fast calorimeter simulation algorithms will also be extensively investigated.

Important for all these 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 [39], which is widely used nowadays, could help in this respect and could ease the comparison among different detectors.

8.3.4 Particle flow algorithms

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

8.3.5 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 design, based on the hybridisation of tracking and calorimetry.

8.4 Industrial connection and technological transfer

The materials and electronics which are 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 to understand what has been already developed by industries, and what trends influence the industry production. Indeed, the products which are of interest for more general industrial applications will advance faster and at a lower price.

On the other hand, some specific needs of the scientific community will be developed in our laboratories, 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 will allow us to exploit the technical industrial capability for production addressing the needed developments.

As a first step, the coordinator will collect information from all the subtasks in the DRD-on-Calorimetry about existing contacts and collaborations with industries. This will allow the creation of a pool of industry partners of interest of the community.

There are national and international regulations for Intellectual Properties Protection in Europe [40], which will be implemented in the agreements with the companies. On the other hand, rules on how to share IP among the members of the community must be defined at the onset of the Collaboration.

8.5 Mechanics and Integration

Calorimeters are, in general, large detectors, with a sizeable weight. For this reason, mechanical supports cannot be neglected when a prototype is designed. This, of course, becomes even more important when we consider the design for a 4π geometry.

Other services, such as power supply, cooling, and signal handling are also of crucial importance in calorimetry, especially in present projects, where the number of channels becomes higher and higher.

Though the prototypes are quite different from each other, some solutions to common problems can be shared avoiding duplications and applied to each particular projects.

9 Interconnections with other DRDs

In general, the DRD-on-Calorimetry will not develop on its own sensitive material or readout devices like photodetectors or ASICs. The key goal of all projects is the construction and operation of prototypes. The prototype construction will be preceded by the selection of sensitive material and the readout system in the wider sense. This selection will happen in close coordination with other DRDs. For this, members of other DRDs will be invited to DRD-on-Calorimetry meetings or reviews. For the specific case of electronics, we expect to profit from centrally available libraries on ASIC components (see also Sec. 6). In other cases we expect that proof-of-principles are given in the DRDs before they will be applied in the prototypes of the DRD-on-Calorimetry. An example are MRPCs. Solid state sensors will be used in all future experiments, however often with diverging goals and focus. For example, requirements on feature size and power dissipation might be different for a tracker with respect to a calorimeter. Here we would expect that the DRD on solid state detectors provides at least a platform from which tracker and calorimeter sensors could be derived. The special adaptation should happen in the DRD-on-Calorimetry.

Contact persons of DRD 6 (see Appendix B) have the role of observing developments in both directions and ensuring the coherence between a given DRD and the DRD-on-Calorimetry. In the ideal case, the contact person carries out, or is at least closely connected to, basic R&D carried out in the DRD he is following and is well placed in the construction and operation of prototypes of the DRD-on-Calorimetry. Calorimetric measurements require a set of robustly working layers or modules already during the R&D phase. However, calorimeter prototypes can also provide an infrastructure for testing under quasi-real conditions cutting-edge technologies that go beyond those that are actually used for the prototypes. Contact persons, in communication with the corresponding other DRD, could help enabling those tests.

10 Conclusion

The DRD-on-Calorimetry proposes a rich programme of development of technologies that all are promising to meet the DRDTs formulated in the introduction. All major future facilities, i.e. LHC after LS4, Higgs Factories, future hadron and muon colliders are addressed. The range of activities spans from highly granular calorimeters that put emphasis on the capability of particle separation, compactness and hermeticity, to optical calorimeters where the focus is put on an excellent electromagnetic energy resolution or on a hardware separation of the electromagnetic and hadronic components of a shower. Calorimeters based on liquified noble gases are situated between these two poles and seek to port a well-established calorimetric technology to future needs. Therefore the scientific programme will provide a comprehensive coverage of viable options for future colliders. The initial programme depends largely on already available resources or modest additional investments. This is due to a realistic estimation of the current funding situation. However, all projects envisage in the medium and long run constructing and operating sizeable prototypes. This ambitious programme requires adequate funding. Details of the funding profile in the out years should become the subject of an update of the R&D programme that can be expected towards the end of 2025/beginning of 2026.

A Institute list

Institute	**WP (subtask)**
Austria	
HEPHY	WP1 (DECAL)
Belgium	
VUB	WP1 (T-SDHCAL)
China	
GlassScintColl	WP1 (GlassScintHCAL)
IHEP	WP1(Sc-ECAL, GlassScintHCAL), WP3 (HGCCAL)
SICCAS	WP3(HGCCAL)
SJTU	WP1(Sc_ECAL,T-SDHCAL), WP3 (HGCCAL)
TDLI	WP3(HGCCAL)
USTC	WP1(Sc-ECAL)
Czech Rep.	
CTU	WP3 (Materials)

Continued on next page

Table 10 – continued from previous page

Institute	WP (subtask)
CU	WP2, WP3 (TileCal)
FZU	WP1 (AHCA) WP3 (SpaCal, TileCal, Materials)
Estonia	
IPUT	WP3 (Materials)
France	
CEA-Irfu	WP3 (ScintCal, CryoDBDCal), WP4 (Electronics)
DMLAB	WP1 (SiW-ECAL)
ILM	WP3 (Materials)
IN2P3-APC	WP2
IN2P3-CPPM	WP2 , WP3 (ScintCal)
IN2P3-IJCLab	WP1 (SiW-ECAL), WP2, WP3 (SpaCal, GRAiNITA)
IN2P3-IP2I	WP1 (T-SDHCAL), WP3 (SpaCal, Materials)
IN2P3-LLR	WP1 (SiW-ECAL)
IN2P3-LPC Caen	WP3 (SpaCal)
IN2P3-LPC CF	WP1 (T-SDHCAL), WP3 (GRAiNITA, SpaCal)
IN2P3-LPNHE	WP1 (SiW-ECAL), WP2
IN2P3-OMEGA	WP1 (SiW-ECAL, T-SDHCAL, AHCAL), WP2, WP4(Electronics)
UCA	WG (SW)
Germany	
DESY	WP1 (DECAL, AHCAL)
FH Aachen	WP3 (Materials)
Giessen U	WP3 (Materials)
Goethe Universität Frankfurt	WP1 (DECAL)
Göttingen U.	WP1 (AHCAL)
Hamburg U.	WP1 (AHCAL)
Heidelberg U.	WP1 (AHCAL)
Humboldt U.	WP1 (DECAL, AHCAL)
HZDR	WP3 (Crilin)
JGU (Mainz)	WP1 (AHCAL)
KIT	WP1(AHCAL), WG(SW)
MPP Munich	WP2
RPTU	WG (SW)
TU Dresden	WP2
Greece	
NTUA	WP1 (DECAL)
India	
TIFR	WP3 (Materials)
Israel	
TAU	WP1(HighCompactCalo)
Weizmann Inst.	WP1(MPGD_HCAL)
Italy	
FBK	WP4 (Electronics)
GSSI	WP3(CryoDBDCal)
INFN and Uni Bari	WP1(MPGD_HCAL)
INFN and UNI MIB	WP3 (MAXICC, SpaCal, ScintCal,CryoDBDCal)
INFN CT	WP3 (DRCal)
INFN-BO	WP3 (DRCal)
INFN-LNF	WP3 (Crilin)
INFN-MI and Uni Insubria	WP3 (DRCal)
INFN-NA	WP3 (MAXICC)
INFN-PD	WP3 (Crilin), WG (SW)

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Table 10 – continued from previous page

Institute	WP (subtask)
INFN-PI	WP3 (DRCal)
INFN-PV	WP3 (DRCal)
INFN-RM1	WP3 (DRCal, CryoDBDCal)
INFN-TO	WP3 (Crilin)
INFN-TS	WP3 (Crilin)
LNGS	WP3(CryoDBDCal)
LNL	WP3(CryoDBDCal)
UNIVPM	WP3 (ScintCal)
Japan	
ICEPP	WP1 (Sc-ECAL, Adriano3)
KEK	WP1 (SiW-ECAL)
Kyushu U.	WP1 (SiW-ECAL)
Shinshu	WP1 (Sc-ECAL, Adriano3)
Lithuania	
Vilnius U	WP3 (Materials)
Netherlands	
Utrecht U.	WP1 (DECAL)
Norway	
UiB	WP3 (TileCal)
Poland	
AGH-Cracow	WP1(HighCompactCalo), WP4 (Electronics)
Warsaw U.	WP1(HighCompactCalo)
Portugal	
LIP	WP3 (TileCal, ScintCal)
Romania	
IFIN-HH and UPB	WP2
INCDTIM	WP3 (TileCal)
ISS	WP1(HighCompactCalo)
Slovakia	
U. Kosice	WP2
South Africa	
iThemba LABS	WP1 (SiW-ECAL)
South Korea	
GWNU	WP1 (T-SDHCAL), WP3 (DRCal)
Hanyang U.	WP3 (DRCal)
KNU	WP3 (DRCal)
Korea U	WP3 (DRCal)
Pusan U.	WP3 (DRCal)
Seoul U,	WP3 (DRCal)
SKKU	WP3 (DRCal)
YCC	WP1 (T-SDHCAL)
YU	WP3 (DRCal)
Spain	
CIEMAT	WP1 (T-SDHCAL)
DIPC	WP3 (Crilin)
IFIC	WP1 (SiW-ECAL), WP2, WP3 (SpaCal, TileCal)
UB	WP3 (SpaCal)
UCO	WP1 (T-SDHCAL)
UVO	WG (SW)
Sweden	
LTU	WG (SW)
Switzerland	

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Table 10 – continued from previous page

Institute	WP (subtask)
CERN	WP1 (SiW-ECAL), WP2, WP3 (MAXICC, SpaCal, TileCal, ScintCal)
Tunisia	
Tunis U.	WP1 (T-SDHCAL)
Turkey	
Beykent U.	WP1 (Adriano3)
Istanbul Technical University	WP3 (RADiCAL)
Istanbul University	WP3 (RADiCAL, ScintCal)
Istanbul University Cerraphasa	WP3 (RADiCAL)
Yildiz Technical University	WP3 (RADiCAL)
UK	
Birmingham U.	WP1 (DECAL)
Imperial Coll.	WP1 (DECAL)
Rutherford	WP1 (DECAL)
U. Sussex	WP1 (DECAL), WP3 (DRCal)
Ukraine	
ISM-NASU	WP3 (GRAiNITA, ScintCal)
USA	
Argonne	WP1(Adriano3), WG3(MAXICC)
BNL	WP2
Caltech	WP3 (MAXICC, RADiCAL, ScintCal)
Coe College	WP3 (RADiCAL)
Columbia U	WP2
Fairfield	WP3 (Adriano3)
FNAL	WP1(Adriano3), WG3(MAXICC)
Hofstra University	WP3 (RADiCAL)
Kansas U,	WP3 (Adriano3)
Michigan	WP3 (MAXICC)
MIT	WP3 (MAXICC)
NIU	WP3 (Adriano3)
Notre Dame	WP3 (RADiCAL, ScintCal)
ORNL	WP3 (MAXICC, ScintCal)
Princeton	WP3 (MAXICC)
Purdue	WP3 (MAXICC)
SLAC	WP1 (DECAL)
Southern Methodist University (SMU)	WP2
Stony Brook	WP2
Texas Austin	WP2
TTU	WP3 (MAXICC, DRCal)
U Minnesota	WP1 (AHCAL)
U Oregon	WP1 (DECAL)
U. Arizona	WP2
U. Iowa	WP1 (Adriano3), WP3 (RADiCAL, ScintCal)
U. Maryland	WP3 (MAXICC, ScintCal)
U. Virginia	WP3 (MAXICC, RADiCAL, ScintCal)
UT Arlington	WP1 (AHCAL)

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