DRD 6 Calorimetry - Input to European Strategy of Particle Physics Update (ESPPU)

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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, A.2, 2 and A.4. 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 formation of the collaboration was based on two community meetings in 2023 [10, 11] and a set of input proposals to define an initial research programme. This phase was guided by a Proposal Team that compiled the proposal [12] of the DRD that was approved by the CERN Research Board in December 2023 such that the collaboration could start on January 1st 2024.

The initial research programme targets mainly future Higgs factories, and, among those, many projects targeting 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 times. 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 until 2030 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. Despite the focus on future Higgs factories the initial programme comprises also projects that target already now far future projects such as a future hadron machine or a muon collider.

2 Organisation of the DRD-on-Calorimetry

Figure 1 shows the organisational structure of the DRD-on-Calorimetry. The Collaboration Board is the highest decision body of the collaboration. As of today the collaboration counts 125 participating institutes from 27 countries and four continents. This meets the ambition of the DRD to act as a worldwide collaboration. Most of the institutes became members by expressing an interest in joining the DRD during the proposal phase. However, around 10 institutes joined the collaboration after its approval and there are more institutes that expressed an interest to join. In 2024 two collaboration meetings were organised at CERN. The dates and venues for 2025 are also already settled. It is planned to keep the rhythm of two collaboration meetings per year and offers for possible locations exist already for 2026 (and beyond). The management of the collaboration is ensured by a Spokesperson and currently two deputies, the Collaboration Board Chair as well as the chairs of the executive bodies, Technical Board (TB), Speakers and Publication Bureau (SPB) and Resource Board. Governance Rules have been established in 2024.

The scientific programme is organised under four Work Packages. In addition Working Groups address aspects common to all Work Packages. Both Work Packages and Working Groups will be introduced in the following sections. The Technical Board provides the forum to exchange on the progress of the individual projects. The Technical Board Chair is also the main contact of the DRD with the beam test sites. Technical Board meetings are held at a three-week rhythm. The scientific output of the collaboration is organised by the SPB. The SPB has worked out Publication Rules that have been approved by the collaboration in early 2025.

[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.

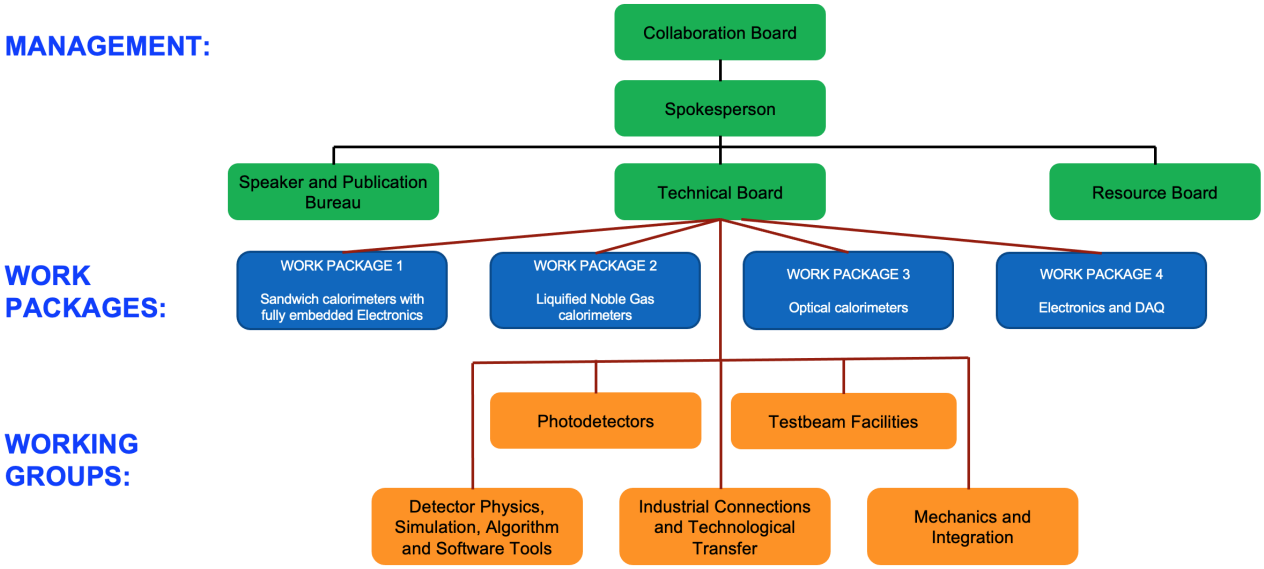

Figure 1: Schematic representation of the DRD-on-Calorimetry organisation. Please see text for details.

3 Work Package 1: Sandwich calorimeters with fully embedded electronics

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) [13, 14, 15]. 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, an almost 4π coverage with little room for services is required to optimally 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. A summary of the tasks and subtasks in WP1 is given in Tab. 1. Table A.1 in the Appendix complements the previous table with a list of milestones and deliverables. Many of the projects are a continuation of R&D so far carried out by the CALICE Collaboration [16]. General features shared within the WP1 are recapitulated below.

- Most projects feature (analogue and digital) readout electronics fully integrated into the calorimeter volume. Where this is not (yet) the case, it is recommended to adapt the design.
- It is common practice in calorimetry to build and handle electromagnetic and hadronic calorimeters as separate entities. However, 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. Note that a first combined testbeam featuring a setup of detector layers of the SiW-ECAL and the AHCAL took already place in Spring 2025. Further common beam tests are planned. Among these is a common beam test combining the MPGD HCAL as hadronic section with Crilin, a project in WP3 below, as electromagnetic section.

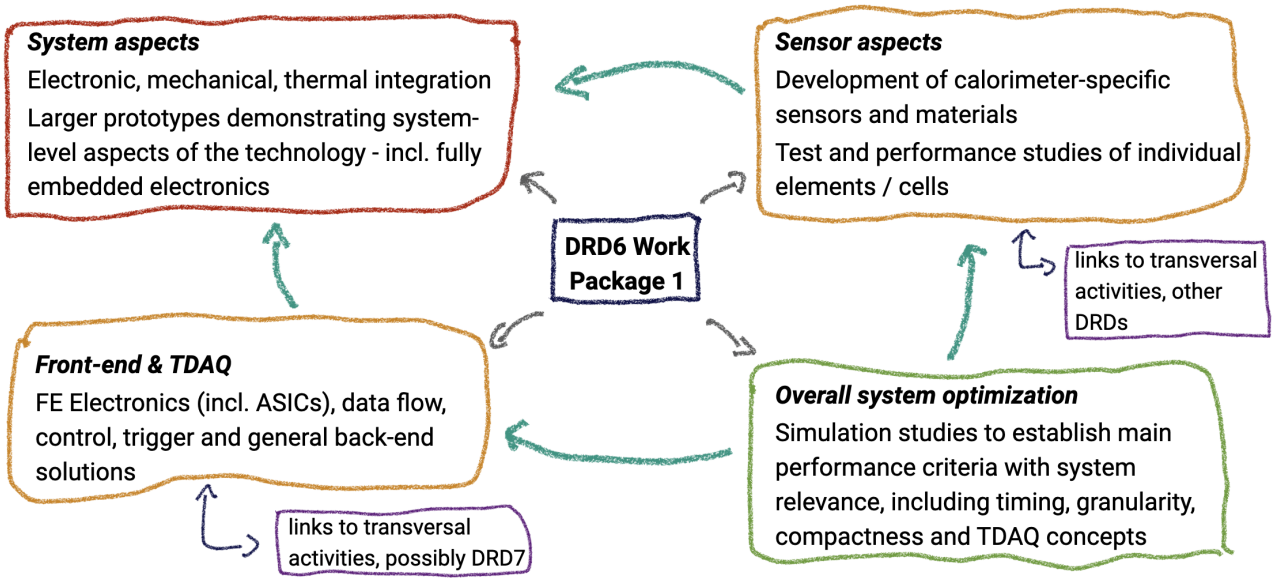

Figure 2: Synthetic overview on the main research directions common to all projects in Work Package 1.

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	Micropattern 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.

3.1 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 HGCAL) 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. In particular, the highly granular and compact calorimeters of Substasks 1.1.1 and 1.1.1 are also well suited in small-scale experiments with a dense particle final state. Examples of these experiments are LUXE at DESY [17] investigating high-field QED with electron-beam laser collisions or SHIP [18], a beam dump experiment at the CERN SPS. SHiP will search for dark matter or Heavy Neutral Leptons in mass ranges below 10 GeV. The detector construction for these experiments 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

Future experiments at 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 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 e^+e^- colliders, but also for precision measurements at future hadron or muon colliders. The unprecedented statistical precision achievable in experimental measurements at circular e^+e^- colliders, such as the FCC-ee, will have to be complemented by extremely well-controlled systematic uncertainties This requires 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.

4.1 Objectives

The main goal for the next years is to design and build a prototype module that can be studied with test beams. The work will focus on the below areas, leading to a prototype module by the end of 2028, that can be put in beam when the SPS is available again in 2029, according to the LS3 planning.

A first direction of R&D is the optimization of the detector geometry for physics performance in both barrel and end-cap regions, through simulation studies. A key aspect is to develop further the understanding of the needed granularity of an electromagnetic calorimeter for an e^+e^- experiment by studying pion rejection, axion searches as well as jet-energy reconstruction using 4D imaging techniques, machine learning and particle flow algorithms. Preliminary pion/photon identification studies indicate for instance that the "strip" layer should be moved to the third or fourth layer. In parallel, performance studies of the electromagnetic energy resolution will allow to further optimise the geometry of the calorimeter. In addition, the possibility to read out the Cherenkov light in the noble liquid might be studied to investigate potential gains in timing measurement or in dual readout energy measurement.

The readout electrodes are a crucial element in this noble liquid calorimeter design. Their task is to provide high voltage and to read out the signals with the defined granularity, with minimal cross-talk and noise. Several generations of prototypes have been produced and measured in the past few years, giving important lessons on the trade-offs of the design. Prototypes being produced still feature several options, the studies of which will inform the final design. The main directions for R&D in the next years will therefore be around the HV distribution layer, the extension of the design from the central barrel region to the end of barrel region, and the conception of a design for the specific end-cap geometry.

Two different readout designs are planned to be studied: readout via warm electronics (placed outside the cryostat) and readout via cold electronics (placed inside the cryostat). Cold electronics would provide a significant advantage in terms of readout noise, and simplify the design of the cryostat feedthroughs, but impose stringent requirements in terms of power consumption (to limit the necessary cooling) and reliability. Two ASIC

developments for the frontend readout are going to be carried in the next years. One is starting from the DUNE cold ASIC and transforming it into a faster amplifier for calorimeter applications, while the other is starting from the CMS HGCROC ASIC and improving on consumption, shaping time and DC tuning to make it work at cryogenic temperatures and adapt it to the ALLEGRO ECal requirements. Studies on the space required at the back of the calorimeter for boards and cables, in both the warm and cold electronics options, need to be performed, and they have a significant interplay with the mechanical design. Developments for the backend readout electronics are expected to be mostly common between all calorimeter projects in DRD6.

Small systematic uncertainties will only be achievable with a highly uniform and stable calorimetric measurement. This translates into high precision and stability of the calorimeter mechanics. Initial concepts for the support structures and spacers have been designed in 2023 and 2024. First prototypes of absorbers were built and tested at cryogenic temperatures in 2023. Further iterations on the designs, as well as mockups and prototypes are needed in the next few years.

Finally, the design of the prototype module should be made based on the developments of the items above. Because this calorimeter design is based on inclined planes, the size of a small module able to contain a full electromagnetic shower (22 X_0) is about 1.0 m $\times$ 0.5 m $\times$ 0.5 m. The design is going to start in 2025, and production of the required items is going to take place in the following years. An existing cryostat will be adapted or a prototype carbon fibre cryostat will be 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. A.2 in the Appendix.

5 Work Package 3: Optical calorimeters

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 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.

5.1 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 2 provides a summary of the broad scope of activities within Work Package 3. The projects are organised into four tasks addressing different technological challenges. Each activity adddresses the development of a specific calorimeter concept.

The proposed calorimeter concepts (HGCCAL, MAXICC, Crilin and OREO) grouped in (**Task 3.1**), are designed for electromagnetic (EM) shower detection using a homogeneous or quasi-homogeneous approach based on scintillating crystals and SiPM readout. Note here that OREO joined the DRD during 2024.
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**).

Project	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters				
HGCCAL	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$
OREO	oriented PWO-UF	SiPMs	6.2, 6.3	$e^+e^-/\mu^+\mu^-$
Task 3.2: Innovative Sampling EM calorimeters				
GRAiNITA	$ZnWO_4$, BGO	SiPMs	6.1, 6.2	e^+e^-
SpaCal	GAGG, organic	MCD-PMTs,SiPMs	6.1, 6.3	e^+e^-/hh
RADiCAL	LYSO, LuAG	SiPMs	6.1, 6.2, 6.3	e^+e^-/hh
Task 3.3: (EM+)Hadronic sampling calorimeters				
DRCal	PMMA, plastic	SiPMs, MCP	6.2	e^+e^-
TileCal	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 2: Overview of R&D activities on optical calorimeter concepts.

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 list of milestones and deliverables is reported in Table A.3 in the Appendix. Among these, the Deliverables D3.1, D3.4, D3.7, D3.10 and D3.18 have already been completed.

5.2 Short-term applications

Some of the subtasks proposed in WP3 have already a high level of technological readiness. For this reason they could be used in experiments that are on a shorter time scale w.r.t future accelerators. A few examples are reported in the following. The Crilin community is working together with the people in charge of the HIKE future proposal. The HIKE Small Angle Calorimeter (SAC) ([19]) is an independently proposed, highly granular, longitudinally segmented, fast crystal calorimeter with SiPM readout. Performance requirements meet 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 in LHC 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

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 with other detectors. The recent trend has been a sharp increase in granularity ("imaging calorimeters") and sub-ns timing capability ("5D calorimetry") to allow for better particle reconstruction. This has led to the development of low-power highly integrated embedded electronics, integrated inside ASICs.
R&D developments will focus on reducing the power dissipation by at least an order of magnitude, down to $\sim$ 1 mW/ch in order to further increase the granularity in 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 with 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.

6.1 Objectives

It is proposed in this Work Package to develop a family of ASICs, optimised for the different sub-detectors proposed and sharing as much as possible common back-end and readout systems. In 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, a production readiness review will be organised to which members of the DRD-on-Electronics (DRD 7) will be invited. In general, the DRD 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. 7.3.2.

7 Working Groups

Working Groups will address work that is common to all work packages in the DRD. Thus, they ensure coherence and synergy of the scientific program of the DRD itself.

In the following, a detailed description is given of the objectives of the different Working Groups that exist already or are about to be put in place as of today. The creation of the working groups on industrial connections and technological transfer and mechanics will follow. Creating the former may benefit from a coordinated effort across all DRDs, for the latter a contact person to the corresponding DRD 8 is in place.

7.1 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 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.

	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** $\sim$ HL − LHC	×	✓
Future Hadron Collider **$\sqrt{s}$=100 TeV** **Radiation level up to** $\sim 10^{18}\,\mathrm{n_{eq}/cm^2}$	×	×

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

The aim of the WG is to create a forum where the needs of different calorimetry R&D are collected and discussed and can be propagated to the DRD4, as well as new developments in the dedicated DRD can be propagated to the calorimetry community. The WG is also the place where encountered problems and found solution will be shared. The WG is presently in its setup phase and it will become operational in the coming months.

7.2 Testbeam plans, facilities and infrastructure

Beam tests play a crucial role in the development cycle of a calorimeter. It is therefore no surprise that all the input proposals plan for more than one beam tests in the coming years. Typically, small prototypes are foreseen in the beginning, followed by full containment prototypes. In almost all cases, also combined testbeam with both electromagnetic and hadronic sessions are foreseen. 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 3. 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 for all the DRDs, we expect that all the Collaborations and the DRDC will cooperate to find a suitable solution. In fact, absence of testbeam facilities will slow down the detector development, since the performance assessment with beam is an unavoidable step.
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.

7.2.1 Common needs for DRD-on-Calorimetry testbeam

Due to the large number of calorimeter technologies and the fact that calorimeters typically cannot concurrently run both in parallel with other calorimeters (except for planned combined testbeam) and with other devices, the request for calorimeter devices is in general quite large in terms of weeks for tests. Knowing the importance of the beam time, an internal coordination of the different test beams request has been put in place, to avoid possible last-minute cancellations in case of delay in detector readiness. Moreover, since there is a common set of basic requirements for a beamline for all the calorimetry testbeam, the DRD-on-Calorimetry is proposing the creation of a dedicated testbeam location in the SPS beam line, which will serve for the different prototype tests. The main characteristics of the area include:

- 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 $1\,m^3$ devices and a large area behind beam dump, to calibrate with muons during off-beam time;
- Moving tables that can carry devices of several tons;
- Storage space at beam test facilities in case of a beam test programme.

The complexity of the analysis and the particular scientific value of the recorded data require 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.

The area will be installed (except for beam line elements) and managed by the DRD-on-Calorimeter, creating a pool of expert shared among the different projects. The common hardware and software (see 7.3.2) of the infrastructure, including an implementation of the beam line in simulation, will be beneficial to the whole community. This will permit each project to focus on their own prototypes and avoid duplicating the effort of the beam line setup and simulation. The DRD-on-Calorimetry has also 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. In the example of Europe, a typical test cycle could be the 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, the SPS will be the beam test site for which the creation of a dedicated calorimeter beamline would have priority.

7.3 Detector physics, simulations, algorithms and software tools

Even though each project has its peculiarity, some common software tools can be prepared and shared within the community. The purpose 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. The working group is led by two Working Group Coordinators.

7.3.1 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. Adopting a common Event Data Model, for example, EDM4hep [20], which is widely used nowadays, could significantly contribute to this goal. This approach, possibly extended by the adoption of a common orchestration framework such as Gaudi [21], would not only facilitate direct comparisons but also enhance synergies in digitization and reconstruction algorithms, leading to more efficient and unified data processing. 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 and simulated 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.

7.3.2 DAQ software

A central aspect is the data acquisition system. The need for a common dedicated area has been outlined before. Having in addition 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 [22] 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. The development of a pool of experts needs to be coordinated among the Software WG, the test beam WG and the WP4 on electronics and DAQ since it involves several aspects at the boundary of the three mentioned activities. Examples of working DAQ in the DRD-on-Calorimetry are already available. Other projects can profit this expertise to migrate their DAQ programs in this framework.

7.3.3 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, Geant4 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 [23] 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. Adopting common and flexible tools such as DD4hep [24] for geometry modeling and Geant4 interface would be highly advantageous. Its plug-and-play approach would indeed facilitate seamless component sharing among collaboration members, fostering interoperability and efficiency. Furthermore, as the detector description toolkit used in Key4hep [25], DD4hep would greatly streamline the integration of DRD6 developments into the broader landscape of future collider studies.

7.3.4 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.

7.3.5 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 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 provides 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. The available funding, though modest (and not already earmarked for the DRD), allowed for a rapid start of the research programme. In the first year already five deliverables were met and a combined beam test was conducted. All projects envisage in the medium and long run constructing and operating sizeable prototypes. This ambitious programme requires adequate funding. At the time of writing this input document, the DRD undergoes a resource survey for a consolidated assessment of the current and expected future funding. We expect a coherent picture until Summer 2025.

A Appendix

This appendix contains the tables on milestones and deliverables to which the main text refers to.

	Milestone	Deliverable	Description	Due date
Task 1.1: Highly pixelised electromagnetic section				
Subtask 1.1.1: SiW ECAL		D1.1	Revised 15-layer stack	2025
	M1.1		Specifications for timing and cooling	2026
		D1.2	Engineering Module for Higgs Factory	>2026
Subtask 1.1.2: High compact calo	M1.2		Prototype for GaAs sensors with strip readout	2026
		D1.3	Updated set of compact detection layers based on Si sensors	2024
	M1.3			
		D1.4	Set of validated GaAs Sensors	>2026
Subtask 1.1.3: DECAL	M1.4		Requirements for DECAL-specific sensor design established	2024
	M1.5		Full evaluation of (ALPIDE-based) EPICAL-2 performance	2025
	M1.6		Design for next-generation sensor with DECAL-specific optimisation (with machine-specific options)	2026
		D1.6	New sensors, produced and evaluated in EPICAL-3 prototype	>2026
Subtask 1.1.4: Sc-ECAL	M1.7		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	M1.8		Concept for continuous readout	2024
	M1.9		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	M1.10		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	M1.11		Study of the impact of timing on PFA performance	2024
	M1.12		Specifications for first layers	2025
		D1.12	First T-SDHCAL layers	2028
		D1.13	48-layer prototype	>2028
Subtask 1.3.2: MPGD-HCAL	M1.13		Specifications for $50 \times 50\text{cm}^2$ prototype	2025
	M1.14		Design of $50 \times 100\text{cm}^2$ layers	2026
		D1.14	Completion of 6-layer $20 \times 20\text{cm}^2$ prototype	2024
		D1.15	10-layer prototype (6L:$20 \times 20\text{cm}^2$ +4L:$50 \times 50\text{cm}^2$)	2026
		D1.16	3 $100 \times 100\text{cm}^2$ layers	>2026
Subtask 1.3.3: ADRIANO3	M1.15		Small-scale test layers	2024
	M1.16		Small-scale prototype	2025
		D1.17	Large-scale prototype & testbeam	2026

Table A.1: Deliverables and milestones in Work Package 1.This table is an update as of March 31st 2025 of the corresponding table in Ref. [12].

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	2026
			D2.1	Test module assembled	> 2027
		M2.2		Test module ready for cool-down	> 2028

Table A.2: Deliverables and milestones in Work Package 2.

	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
OREO		D3.18	Two layer PWO-UFprototype fully assembled;	2024
	M3.22		First experimental tests at CERN PS&SPS and data analysis	2024
	M3.23		Report on MC simulation of the first prototype in Geant4	2025
		D3.19	Fine grained PWO UF Crystals	2025
	M3.24		First report of beamtest results data analysis	2025
		D3.20	Final MC package in Geant4	2026
	M3.25		Final report of beamtest results	2026
	M3.26		Implementation of the OREO technology in realistic experimental scenarios	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 A.3: Deliverables and milestones in Work Package 3. This table is an update as of March 31st 2025 of the corresponding table in Ref. [12] and notably adds the research plans of the OREO project that joined during 2024.

	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 A.4: Deliverables and milestones of Working Package 4

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