DRD4 Research Proposal

July 24, 2023

Abstract

This document describes a proposal for joint research and development work in the fields of photodetectors and particle identification techniques in high-energy physics. For this purpose, university groups, research centres and industrial partners propose to form an international collaboration in the framework of the ECFA Detector R&D Roadmap, called DRD4. The scope of the collaboration that is anchored at CERN covers also Scintillating Fibre Tracking as well as Transition Radiation detectors based on solid state X-ray detectors. The collaboration consists of a set of Working Groups and Work Packages. The formal aspects of the DRD4 collaboration will be defined in a Memorandum of Understanding. This proposal contains a research program, topics, planning, resources and the sharing of the joint projects The work is primarily focused on technologies that are needed to upgrade the current or build the next generation of high-energy physics experiments. The DRD4 collaboration performs R&D on hardware, readout electronics and software. The outcome will be proofs of principle, prototypes, and reduced-scale demonstrators. R&D needed to adapt detectors to the specific needs of an experiment as well as specific integration and industrialization are generally not part of DRD4 and shall remain under the full responsibility of the experiment.

Contents

1 Introduction

Photon detectors are at the heart of most experiments in particle physics. Moreover, they are also finding applications in scientific fields as distant as chemistry and biology and are ubiquitous in society in general. As we encounter new environments where we need to collect the light, we require both advances in existing technology and transformative, novel ideas to meet the demanding requirements. Advancement in photon detector technology is therefore essential to address all the science drivers of future high-energy physics experiments.

Reliable particle identification (PID) methods have become an indispensable experimental tool, particularly for the physics of heavy flavors, in studies of heavy-ion collisions, and in electron-hadron experiments.

PID has significantly contributed to our present understanding of elementary particles and their interactions and will continue to be an essential ingredient in several of the planned experiments. The continuous advances in the development of pixelated single photosensors and fast and low-noise read-out electronics have pushed PID detectors, in particular Ring Imaging Cherenkov (RICH) counters, to unprecedented levels of performance. This has allowed a very efficient identification of charged particles and an outstanding background rejection in a vast momentum range from a few 100 MeV/c up to several 100 GeV/c. However, the ever-growing demands of the future physics program, from underground facilities to high luminosity colliders, require mastering a novel generation of PID detectors with high separation power over four to five orders of magnitude in momentum.

As discussed in the ECFA Roadmap in great detail, R&D will be pursued in four main themes: DRDT 4.1 - Enhance timing resolution and spectral range of photon detectors; DRDT 4.2 - Develop photosensors for extreme environments; DRDT 4.3 - Develop RICH and imaging detectors with low mass and high-resolution timing; DRDT 4.4 - Develop compact, high-performance time-of-flight detectors.

DRD4 research work scope will be as follows. DRD4 shall cover the following photodetector technologies: PMT including MA-PMT, MCP PMT, SiPM (including the digital version), APD, and HPD, as well as any new (quantum) sensor promising to be compatible with the size, cost, and radiation constraints of a particle physics experiment. In most cases, the primary application is the detection of single photons in PID detectors. DRD4 is also interested in other applications of these technologies such as calorimetry (readout of fibers, crystals, organic scintillators) - DRD6, as well as medical imaging and industrial application (e.g., automotive).

DRD4 shall cover the following PID technologies: RICH, DIRC, TOF, TOP, and TORCH. DRD4 will also cover Transition Radiation Detectors (TRD) with semiconductor sensors. DRD4 is also interested in other PID technologies and will maintain contact with the corresponding DRDs: dE/dx with gaseous detectors and TRD with gas-based X-ray detectors (both covered by DRD1).

DRD4 shall cover the following technologies related to PID and photodetectors: Cherenkov radiators (solid, liquid, gaseous, aerogel, low GWP), optical components (mirrors, windows,..), readout ASICs for PD testing, and any other auxiliary equipment (operation, testing, and characterisation). DRD4 shall cover analysis and simulation techniques related to PID detectors, fast photon tracking including the GPUs, and pattern recognition including neural networks. DRD4 will also cover scintillating fiber (SciFi) detectors.

Note that the resources quoted in this document have been estimated to the best of our knowledge; they will be consolidated for the final version of the document.

2 The DRD4 collaboration and its organisation

DRD4 counts 56 research institutes and six (semi-)industrial partners. They are listed in Annex A and B. The status of the industrial partners is somewhat restricted compared to "normal" groups from universities or research labs. The main purpose for this distinction is the avoidance of conflicts of interests.

Most participating groups have a high energy physics background with experience in photodetection and particle identification from ongoing experiments like LHCb, ALICE, BELLE, COMPASS, DUNE and their planned upgrades. There are also groups that work on more far future studies including particle ID at a future electroweak and Higgs factory (e.g. FCC-ee).

DRD4 collaboration has a dual structure reflecting the broad range of ambitions and goals of the participating members. As shown in the organigram (see Fig. 1) DRD4 comprises six Working groups (WG), WG4.1 - WG4.6, and a number of Work Packages (WP) arranged in four themes defined by the ECFA Roadmap process. WPs are numbered from 4.1.1. - 4.5.x. All items numbered in DRD4, incl. milestones and deliverables, begin with '4.'

The WGs are currently addressing the thematic fields: WG4.1 Photodetectors, WG4.2 Particle ID, WG4.3 Technologies, WG4.4 Software, WG4.5 Scintillating Fiber Tracking and Transition Radiation Detectors, WG4.6 Future and *bluesky* R&D. Collaboration members can belong to one or several working groups.

A WG represents a forum (or more modern a social network) in which members exchange information, expose problems, ask for advice, agree on best practices and standards, possibly also exchange equipment and provide access to facilities. WG meetings are convened by an expert who steers the WG to progress along the thematic field.

The WGs allow groups to learn and evolve in order to become members of existing Work Packages (WP)

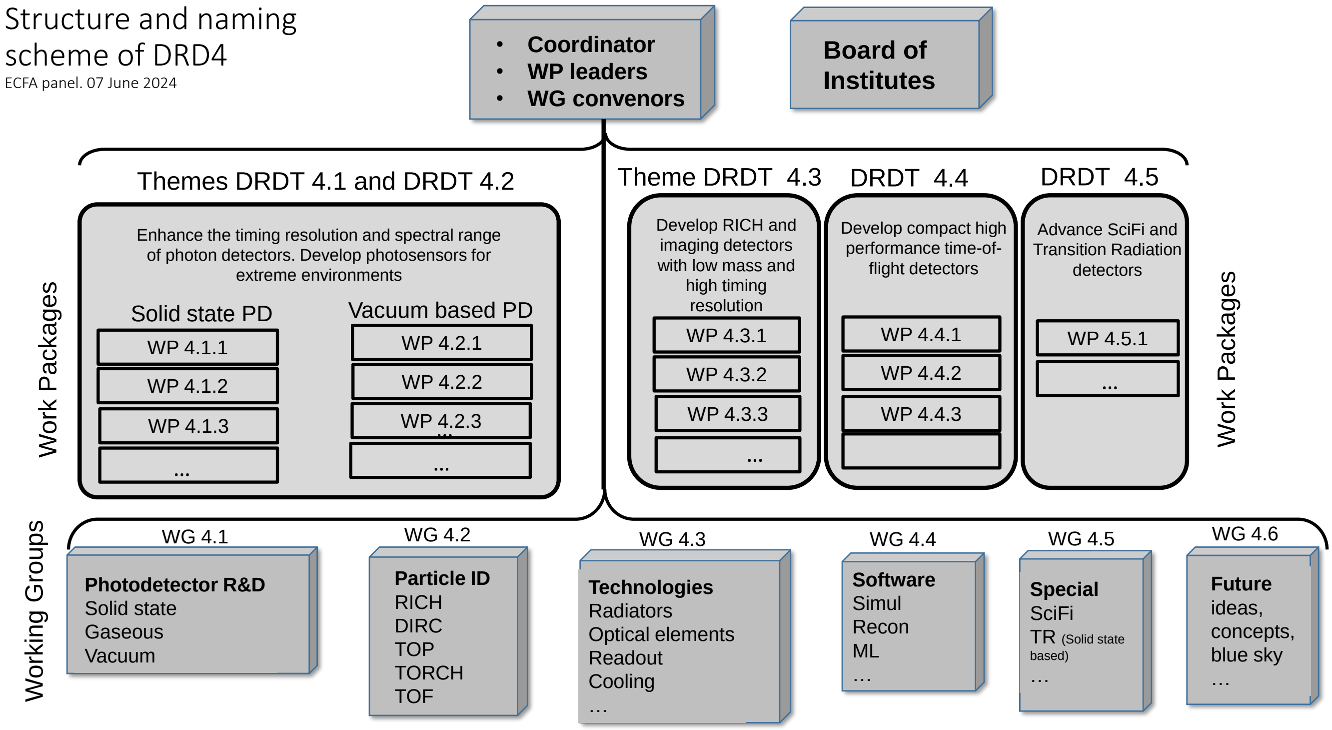

Figure 1: Organigram of DRD4 collaboration.

or initiate new ones. Work Packages are run like projects. They have agreed goals, milestones, and are jointly financed by the resources of the participants. Work packages address the main goals of the roadmap or new topics of high relevance. At present the Packages are foreseen in the following themes : Solid-state photodetectors (DRDT4.1), Vacuum-based photodetectors (DRDT4.2), Develop RICH and imaging detectors with low mass and high-resolution timing (DRDT4.3), Develop compact high-performance time-of-flight detectors (DRDT4.4), Advance the performance of SciFi trackers and solid state Transition Radiation detectors (DRDT4.5). More themes can be considered according to the evolution of the Collaboration.

The collaboration is managed by a Coordinator who is elected from the team of WG convenors and WP leaders. The Coordinator reports to the Board of Institutes. During the pre-approval phase of DRD4, the collaboration is managed by the DRD4 preparation team that consists of volunteers approved by the proto-collaboration in a meeting on 28 of July 2023. The management team will be elected in the first DRD4 collaboration meeting in 2024.

3 Working Groups

As described earlier, the working groups WG4.1 - WG4.6 act as scientific social networks and ensure an efficient exchange among the DRD4 members. This concerns information, know-how, samples, students, etc.

Six WGs cover the following thematic fields:

- WG4.1 - Photon Detectors (48)
- WG4.2 - Particle ID (34)
- WG4.3 - Technological activities (32)
- WG4.4 - Software (11)
- WG4.5 - Scintillating Fibers and Transition Radiation Detectors (13)
- WG4.6 - Future, blue sky, other (11)

The numbers in parenthesis indicate how many groups have signed up for the respective WG.

Fig. 2 gives an overview of which DRD4 group signed up for which working groups. The popularity of the WGs is reflected by the fact that, on average, participating groups sign up for 2.48 WGs.

WG4.1 - Photon Detectors

WG4.1 aims to focus on the studies and development of novel photo-detectors, which include solid-state (SiPM) and vacuum-based (MCP-PMT) photo sensors, and provide an exchange of information with DRD1 on gas-based photo-detectors. The following topics will be discussed:

- The resistivity of photon detectors to irradiation;
- Long-term operation of photon detectors and mitigation measures to prolong their lifetime, e.g., low gain operation and annealing of SiPMs;
- Operation of photon detectors in other extreme conditions, including cryogenic and high magnetic field operations;
- Development of SiPMs with improved timing;
- Development of large-area SiPMs;
- Studies of large-area vacuum photo sensors, e.g., LAPPDs;
- Development of fine granularity detectors for future high-rate experiments;
- Development of new technologies and their feasibility studies: CMOS-SPAD-based sensors, SiPMs with different internal structures, back-side illuminated SiPMs, etc;
- Studies of novel materials for photon detection, e.g., Ge-on-Si APDs;
- Studies of hybrid photon sensors, e.g., Timepix-HPDs and MCP-HPDs;
- Studies and development of read-out electronics suitable for extreme environments (high radiation, high magnetic field, low temperature);
- Development of interconnection techniques for optimal sensors and readout electronics integration;
- Simulations of photo-detector response.

Group members will work on standardizing procedures for the characterization of photon detectors, especially after exposure to extreme environmental conditions. The goal of the information and knowledge flow is to advance the detectors for PID and TOF identification systems of future HEP experiments. The group will also have regular knowledge exchange with groups working on gas-based photodetectors (DRD1), on the development of photosensors for cryogenic detectors (DRD2) and for calorimeters (DRD6), as well as with groups working on novel concepts in read-out electronics (DRD7).

WG4.2 - Particle ID

WG4.2 - Particle ID comprises all Cherenkov-based imaging and TOF detectors employed for particle identification, such as RICH, DIRC, TOF, TOP, TORCH, plus any new concepts. The participation of the groups is motivated by the following interests:

- Study of advanced PID technique
- Developing the new compact RICH concept
- Optimal operation of new detectors
- Future DIRC detector applications
- Development of innovative RICH configurations, like pressurized argon RICH (ePIC at EIC), Aerogel-based RICH0 (AMBER at CERN)

List of WGs

4.1	Photon Detectors	4.4	Software
4.2	Particle ID	4.5	SciFi
4.3	Technological activities	4.6	Future, blue sky, other ...

List of Institutiions

	4.1	4.2	4.3	4.4	4.5	4.6
Aachen	x		x			
Armenia	x	x	x	x		x
Barcelona	x		x		x	
Bari	x	x	x			
Bari 2					x	
Birmingham	x					
Bologna	x	x	x			
Bristol	x	x	x	x		
Bucharest	x	x	x			x
Cambridge		x	x	x		
CEA	x			x		x
CERN					x	
CERN ALICE	x		x			
CERN EP	x	x	x			
CERN LHCb	x	x	x	x	x	
CERN SY-BI	x				x	
Edinburgh	x	x	x			
EPFL					x	
Erlangen	x				x	
FBK	x	x	x		x	
Ferrara	x	x	x			
FNAL	x					
Genova	x	x	x	x		x
Georgia	x	x				
Giessen		x	x			
Glasgow	x	x				
Grenoble	x					
GSCAN					x	
GSI	x	x	x	x		
HPK	x	x	x			
Heidelberg					x	
HFR	x	x				x
IC London			x			
IHEP Beijing	x		x			
imXgam Marseille	x			x		
INFN team	x					
Iowa	x		x			x
Istanbul	x		x		x	
Leicester	x	x				
Ljubljana	x	x		x		x
Lyon	x					x
Lyon	x	x				
Marche			x			
Marseille			x			
Maryland	x					
Michigan	x					
Milano	x	x				
Milano Bicocca			x			
Monash	x	x			x	
Nagoya	x	x				
Omega			x			x
Oxford	x	x	x			
Padova B2	x	x				
Padova LHCb	x	x	x			
Perugia	x	x	x			
Photek	x	x				
Photonis	x	x	x		x	x
Prague					x	
QMU London	x	x				
RAL	x	x		x		
Seoul	x	x				x
Tokyo	x					
Trieste	x	x	x			
USTC Beijing	x	x				
Virginia	x					
Warwick	x	x		x		
Wuppertal		x	x			
Zurich					x	

Figure 2: Participation of institutions in Working Groups.

- Study the impact of time-resolved readout for future RICH detectors. Initially in the framework of LHCb Upgrade 2 but more generally for future detectors/accelerators.

The work in WG4.2 focuses on new and improved detector concepts, achievable performance and intrinsic limitations. Often, the studies will be based on Monte Carlo codes and analytical calculations.

WG4.3 - Technological activities

WG3 focuses on the key technologies for RICH and other imaging detectors systems, including the full readout chain.

The specific fields of interest of WG3 are listed below: they cover a wide range of technical aspects and are grouped in four areas plus the readout electronics topic.

Radiators: Study of gas, aerogel, liquids, solids and new materials; radiator design and characterization; combination of radiators; optimization of refractive indexes and photon yield; optical purity; scintillation; fluid circulation systems; properties monitoring.

Optical technologies: Design, construction, characterization; mirrors, plates, lenses (standard and micro); light-weight components; mechanical, thermal, chemical properties; material compatibility; optical contacts; new concepts for optics design, aspherical surfaces, coatings (anti-reflection, filtering, wavelength shifting); chromatic correction, segmentation, multiplexing.

Thermo-mechanical engineering design: Light materials, low radiation/interaction length design; temperature monitoring, stabilization, shielding; active local cooling; annealing in situ techniques; coolants; active optics/alignment systems; high-pressure vessels; radiation shielding.

Ancillary instrumentation Instrumentation for control of systematic uncertainties; calibration/alignment/monitoring; measurement, online/offline of: sound speed, refractive index, transparency, fluid purity, temperature/pressure of radiators, mirrors/others position/alignment/transmissivity/reflectivity, light intensity; gain, photo-detection efficiency; devices for DSS.

Readout electronics

The availability of high performance but easy-to-use full readout electronics chain is key to the success of most R&D projects. It is therefore intended to study integrated electronics for the fast low-noise full readout chain of PMT/MCP/SiPM, targeting single-photon counters. Modularity, deep integration and scalability will be essential requirements for future systems.

WG4.3 covers the following items: readout electronics, FE/BE, high-rate/high-bandwidth DAQ, trigger/self-trigger; low-consumption; rad-hard components; designs for extended temperature ranges; mitigation of radiation effects.

The development of a full readout system chain for fast low-noise pixelated single photon counters with at least order of thousands channels, is a necessary prerequisite for many tasks in the whole DRD4. It is, in fact, required for laboratory tests, test-beam setups, both as a primary and as a redundant photo-detector, and to enable a broad range of studies targeting RICH detectors and similar imaging applications.

On the sensor side, it must be compatible with either existing or in-development imaging arrays, based on PMT/MCP/SiPM and targeting single-photon counters for RICH or other imaging detectors; on the back-end side, it must be compatible with USB/Ethernet-like standard interfaces to connect to a DAQ system and ultimately to a PC.

Vertical integration of photodetectors to the readout electronics will be studied, to optimize timing resolution by means of reducing the parasitic inductances and capacitances of the interconnections.

The design of the system will likely be based on existing or soon-to-be-ready ASICs. One promising development is the FastIC ASIC family, currently under development by Barcelona and CERN.

Operation in harsh radiation environments and at cryogenic temperatures will need to be considered in the longer term, but will not be a strict requisite, at least for a first iteration.

We foresee to continue generic developments in WG4.3, de facto as a service to the collaboration. We hope to receive support for this activity from DRD7, e.g., in the form of technical consultancy and reviews. However, it is understood that the implementation of specific geometries and functionalities, as needed to achieve the goals of various work packages, may require dedicated developments which would need to rely on the more stable structure of work packages with solid planning and adequate funds.

WG4.4 - Software

The goal of this WG is to address the software issues related to the next generation of detectors expected to be developed in DRD4. Some of the recent advances in software technologies can provide significant improvements in the simulation and analysis of the data produced in Cherenkov detectors.

In the coming years some of the HEP experiments need to simulate and reconstruct billions of events which will have data from Cherenkov detectors. If one uses standard CPUs the cost of running these programs will be prohibitively expensive. The simulation of optical photons takes up a significant part of the time needed for simulating a RICH and it can be speeded up by using GPUs. The parallelization offered by the GPUs would reduce the time taken up by particle identification (PID) algorithms when processing many combinations of charged tracks and photon hits in the data.

The advances in machine learning techniques may offer a better alternative to the PID algorithms used these days, such as the log-likelihood algorithm. In this context there is interest to work on the following topics:

- Usage of software architectures such as GPUs to speed up the simulation and reconstruction of data.
- Usage of machine learning and other novel techniques for particle identification.
- Development of tools for modelling the photon detectors and the associated readout electronics.
- Development of algorithms for real-time data analysis and detector calibration
- Creation of software tools that may help with the development of new PID techniques that are of interest in WG 4.2.

The members of this WG may develop software packages of common interest to the DRD4 community and share experiences from software developments in different projects. There would be opportunities to collaborate with experts in other software organizations such as WLCG (Worldwide LHC computing grid), HSF (HEP software foundation) as well as the EP R&D program when appropriate. The tools developed in this WG are expected to be introduced later into the software frameworks of the relevant HEP experiments. It is also planned to develop software that will be used to verify the performances of the novel algorithms that are developed in this WG.

WG4.5 - Scintillating Fibers and Transition Radiation Detectors

WG4.5 will be dedicated to the R&D of segmented detectors based either on scintillating fibers or on pixelated semiconductor detectors for high precision tracking, eventually exploiting the transition radiation for particle identification. The activities of this WG will be connected with those of WG4.1 (photon detectors).

Scintillating Fibers WG4.5.A focuses on the improvement of the performance SciFi trackers in high rate and high radiation environments. The topics listed below focus on improving the radiation hardness, granularity, light yield, and other performance characteristics of the scintillating fibre trackers. This working group is interested in the following topics:

- Studying the performance of scintillating fibres under ionising irradiation
- Development of novel fast, more radiation-hard scintillating fibres
- Studying the aging of the base polymer over time, and its effect on fibre performance
- Development of SciFi detectors with photon timing information
- Development of beam instrumentation at future accelerators with fibres
- Development of higher granularity trackers beyond 0.25 mm for higher rate experiments
- Simulation and Development of novel fibre claddings
- Development of improved optical connections techniques with SiPMs and other photodetectors, e.g. microlenses
- Development of fibre ribbon and detector plane production techniques.
- Development of scintillating fibre trackers compatible with cryogenically cooled SiPMs

Transition Radiation Detectors WG4.5.B aims to develop a new type of device combining precise tracking and particle identification properties. Transition Radiation Detectors (TRDs) exploit the transition radiation (TR) emitted in the X-ray region by fast charged particles for PID. Traditional TRDs based on gaseous detectors are typically applied for electron/hadron separation exploiting the threshold Lorentz factor for TR emission. Here we propose to develop a novel TRD based on highly segmented pixel semiconductor detectors, which will be able to measure both the energies and the emission angles of TR X-rays. The simultaneous measurement of energies and emission angles will improve the PID performance with respect to TRDs based on gaseous detectors, where only the X-ray energies can be eventually measured. Such a TRD will be able not only to perform electron/hadron identification, but also to separate different species of hadrons in the TeV region, where other PID techniques cannot be applied. In addition, it will also provide precise tracking of charged particles.

An R&D activity on solid state TRDs is already in progress since a few years. Several beam test campaigns have been carried out and, in parallel, dedicated Monte Carlo (MC) simulations of the TR process and of the detectors have been implemented. The working group is interested in the following activities:

- analysis of existing data;
- development of MC simulations;
- development and optimization of new radiators;
- development of highly pixelated detectors based on Si, GaAs and CdTe;
- development of readout chips associated to the detectors;
- beam test studies.

WG4.6 Novel ideas and far-future R&Ds

The history of the photodetection field is full of exciting breakthroughs that changed not only the course of this field but also many others. SiPM is one recent example which transformed the photon detection field in the last decades. WG4.6 intends to play the role of the DRD4 collaboration's gate for novel ideas and revolutionary concepts. The WG will provide these new ideas with the right environment to prosper and will help the new concepts to reach the required level of maturity, with the hope to transform some of them into breakthroughs in the field.

Several original concepts have been presented during the formation phase of the DRD4 Collaboration, including - for example - new photodetectors with extended wavelength sensitivity range or the use of nano-technology techniques to achieve detectors with unprecedented spatial and timing resolutions. All these ideas, as well new ones, will benefit from WG4.6 to find the ideal environment to grow and become new concepts which might impact the future of photon detection.

The WG will exploit the expertise of DRD4 members to evaluate the new ideas and compare them with the state-of-the-art, assessing their potential but also finding their limitations. WG4.6 will help the groups to find the right techniques to transform their new concepts into prototypes for validation. To achieve this, strong connections with the other WG will be established. Novel photon detection concepts developed within this WG might have a strong impact not only in HEP, but also in life sciences, quantum optics/imaging and other emerging fields.

4 Themes and Work Packages

In the following we describe the core activities of the DRD4 R&D work, organised in currently five themes, closely aligned with the main gaols of the ECFA Roadmap. For every theme, a number of work packages has been defined in order to achieve the required progress in the respective fields. The work and resource sharing among the participating groups as well a set of milestones and deliverables have been agreed. They are summarised in resource summary tables, one per theme.

4.1 Solid-State Detectors

The Silicon Photomultiplier (SiPM) has revolutionised photodetection - in HEP and other fields. Its properties have paved the way to new applications and will continue to do so in the coming decade. The following WPs focus on the further improvement of the SiPM technology.

WP4.1.1 - SSPD with new configurations and new modes

Long-term goals: In this work package new SiPM technologies, ultra-high granularity, and integration with readout electronics will be studied. The main goal will be higher efficiency and the study of properties of solid-state photo-sensors for future high-energy physics experiments. The sensors will be further optimized in the subsequent work packages of this theme to allow for operation in extreme working conditions ranging from cryogenic temperatures to extreme photon densities where high timing is required together with ultra-fine fine granularity.

Objectives:

1. In the first phase, the work will be focused on the backside illuminated (BSI) technology of SiPMs. A carefully designed device's electric field and dopant layer configuration, together with the uniform light entrance window on the backside of the detector, enable advanced processing, such as plasma doping molecular beam epitaxy, which could eventually provide both an enhanced PDE and a better radiation tolerance. The sensitivity of SiPMs typically covers the entire visible range, but in some applications, sensitivity in the vacuum ultraviolet (VUV) or near-infrared (NIR) range is required, posing significant challenges in technology development and device design.
   The main objective is designing, fabricating, and characterizing new types of photon detectors, which will follow the first demonstration of BSI SiPMs obtained by thinning SiPM wafers to about 10 μm, with an anti-reflective coating on the backside and bonded to a glass substrate for mechanical stability. If successful, the development would be useful for different applications: from RICH and TOF detectors in HEP experiments, to imaging readout in liquid argon and space instrumentation, with impact on future projects such as the upgrades at LHCb, DUNE, EIC, Belle II, and the ALICE 3 outer TOF detector.
2. A successful BSI SiPM technology paves the way towards the second objective: developing ultra-granular SiPM that closely integrates with the readout electronics by using 2.5D or 3D interconnection techniques. Such deep integration with the Front-end electronics is extremely important for achieving improved timing addressed in WP4.1.4
3. The development of a digital SiPM with two realizations: by using the development of the previous step or the developments of CMOS-SPADs from the work package WP4.1.4.
4. Study the photo-detectors for dual-readout homogeneous calorimetry.

Description of work: In collaboration with the SiPM producers, the requirements and possibilities will be reviewed. Early BSI samples will be evaluated and characterized, and further design steps will be defined. The new samples will be produced and later characterized by the groups involved.

Partners: Bari, Bologna, CERN-EP, FBK, FNAL, Ferrara, Genova, Maryland, Michigan, Milano, Padova, Pavia, Virginia

Milestone: M4.1.1 Tested Back-side illuminated SiPM samples (M24)

Deliverable: D4.1.1 Demonstrator of Back-side illuminated SiPM array (M36)

WP4.1.2 - Fast radiation hard SiPMs

Long term goals:

In Cherenkov Ring Imaging detectors (RICH), detecting single photons with high efficiency and good position resolution is crucial. SiPMs are competitive sensors compared to complex-to-operate vacuum devices with a limited magnetic field tolerance. However, their use is constrained due to their sensitivity to

WP / Institute	4.1.1	4.1.2	4.1.3	4.1.4	4.2.1	4.2.2	4.2.3	4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.4.1	4.4.2	4.4.3	4.4.4	4.5.1
Aachen														X			
Barcelona			X											X			
Bari 1									X	X			X	X			
Bari 2																	
Bejing IHEP						X	X				X						
Bejing USTC							X		X	X					X	X	
Birmingham					X		X										
Bologna	X	X	X														
Bristol					X			X			X	X					
Bucharest		X							X	X							
Cambridge							X		X	X		X					
CEA																	
CERN																	
CERN ALICE		X											X	X			
CERN EP								X			X						X
CERN LHCb	X		X					X	X	X	X	X					X
CERN SY-BI		X											X				
Darmstadt																	
Edinburgh					X	X	X										
Erlangen					X		X		X	X							
FBK		X							X	X			X	X			
FERMILAB	X		X														
Ferrara		X	X		X		X	X	X	X							
Genova	X	X	X						X	X		X					
Georgia									X	X		X					
Giessen		X							X	X		X					
Glasgow							X		X	X							
Grenoble																	
GSCAN																	
Heidelberg																	X
HFR																	
HPK		X				X			X	X			X	X			
INFN team	X																
Iowa		X		X	X	X											
Istanbul							X									X	
Lausanne																	X
Leicester					X		X		X	X				X			
Ljubljana			X		X		X	X				X					
London IC								X									
London QMU																	
Lyon						X	X										
Marche																	
Marseille								X									
Marseille imXgam													X	X			
Maryland	X			X													
Michigan	X		X	X													
Milano Bicocca									X	X							
Milano Statale		X															
Monash			X														
Nagoya		X			X		X										
Omega			X				X										
Oxford								X	X	X					X	X	
Padova B2		X			X				X	X							
Padova LHCb																	
Perugia		X	X						X	X						X	
Photek					X	X	X										
Photonis																	
Prague FZU																	
Prague IEAP CTU																	
RAL								X				X					
Seoul		X		X													
Tokyo		X	X														
Trieste							X	X	X	X							
Virginia																	
Warwick					X		X					X					
Wuppertal																	
Yerevan							X									X	
Zurich																	

Table 3: Participation of institutions in Work Packages. A number of groups prefer not to sign up to any WPs and concentrate instead on activities in one or several WGs.

bulk damage, particularly due to neutron irradiation. The long-term goal is the development of radiation-hardened SiPMs and radiation mitigation techniques that would result in an acceptable complexity of the operation for detecting single photons in extreme radiation conditions. As the definition of neutron resistance depends on the experimental requirements, we will first focus on the current and, in the next stage, on future experiments. An important goal will be standardizing characterization procedures and standards to measure SiPM performance after irradiation.

Objectives:

1. Establish procedures for quantification of radiation effects.
2. Characterize the irradiated SiPMs and determine the working conditions when used in extreme environments. Test operation of SiPMs with associated electronics in a wide range of temperatures down to -200°C.
3. Development of procedures for the annealing of SiPMs after irradiation. The annealing has great potential to improve SiPM performance after irradiation however a widely accepted standard doesn't exist yet.
4. Study and Quantify other measures enabling the use of SiPM in highly irradiated areas, e.g., using smaller SiPMs to reduce the radiation-sensitive volume and macro- and micro-light collectors to maximize the yield and extend operation at low temperatures.

Partners: Bologna, Bucharest CERN SY-BI, FBK, Ferrara, Genova, Giessen, Iowa, Ljubljana, Nagoya, Padova, Padova B2, Perugia, SNU

Description of work: After establishing the protocols, the samples developed in WP4.1.1 will be characterized and compared to existing technologies. Mitigation techniques will be studied, and results will be extrapolated to different use cases.

Milestone: M4.1.2 Standardization of characterization procedures and standards to measure SiPM performance after irradiation (M18)

Deliverable: D4.1.2 Report on state-of-the-art fast and radiation hard SiPMs (M36)

WP4.1.3 - Timing of SSPD – including the appropriate readout electronics

Long term goals: Particle identification algorithms of the future particle identification systems will rely on measuring the arrival times of single or few photons. To achieve the ultimate timing performance of silicon photomultipliers, fine segmentation of the sensor active area and local interconnection to ASIC is needed. In this work package, we will focus on optimizing the timing of photon sensors, the front-end electronics, and their integration.

Objectives:

- Study and improve the timing of Silicon Photomultipliers.
- Enable the exploitation and co-design of a suitable, multi-channel readout ASIC capable of exploiting all the detection's timing potential.
- Develop an optimized, reliable, cost-effective integration scheme and packaging solution with integrated cooling.
- Study the vertical integration of dedicated SiPM arrays to the readout electronics to optimize timing resolution by reducing the interconnections' parasitic inductances and capacitances.

Partners: Barcelona, Bologna, Bucharest, CERN-EP, Ferrara, FNAL, Genova, Ljubljana, Michigan, Monash, Omega, Padova, Perugia, Virginia

Description of work:

Milestone: M4.1.3 Demonstrated high-performance readout electronics for solid-state photon detectors (M24)

Deliverable: D4.1.3 Performance report on the ultra-fast SiPM with optimized readout electronics (M36)

WP4.1.4 - Novel sensor materials

Long term goals: This work package focuses on developing low-level light sensors with novel materials and production techniques, such as CMOS-based SPAD arrays and photodetectors built from materials other than Si.

Development of SPAD based on CMOS Image Sensor (CIS) technologies for large instrumented surfaces with high-granularity and low-time jitter sensors. Standard CMOS processes provide a mature and reliable technology, which allows the co-integration of SPADs and electronics at low costs. Combining SPAD and CMOS readout electronics on a single chip with tailor-made readout architectures can provide digitized output signals with low power consumption and fast read-out.

Color centers in silicon carbide (SiC) have recently emerged as one of the most promising emitters for bright single-photon emitting diodes. Some theoretical studies and computational simulations predict that germanium carbide (GeC) exhibits semiconducting properties similar to Ge and Si. The precise properties of GeC, such as its bandgap and electrical conductivity, would depend on its crystal structure and specific composition. As it could potentially be integrated into semiconductor devices and electronic components, its unique properties may offer advantages in applications in solid-state photon detectors.

Partners: Iowa, Maryland, Michigan, Seoul

Objectives:

- Implementation and characterization of CMOS-SPAD sensors for light detection in high energy physics.
- Fundamental studies of potential materials for light detection, e.g., SiC, GeC
- Investigation of InGaAs, GaAs technology for photon detectors

Description of work:

Milestone: M4.1.4 Performed tests of solid-state photo sensors with new sensor materials (M24)

Deliverable: D4.1.4 Report on achieved performance of novel sensor materials (M36)

Theme: Solid State Photodetectors

List of WPs:

4.1.1	New configurations and new modes SSPD
4.1.2	Fast radiation hard SiPMs
4.1.3	Timing of SSPD – including the appropriate readout electronics
4.1.4	Blue sky research: novel sensor materials

Participating institutions:

	4.1.1	4.1.2	4.1.3	4.1.4
Barcelona			x	
Bari	x			
Bologna		x	x	
Bucharest		x	x	
CERN SY-BI		x		
CERN-EP	x		x	
FBK		x	x	
Ferrara	x	x		
FNAL	x		x	
FZU Prague				
Genova	x	x	x	
Giessen		x		
Iowa		x		x
Ljubljana		x	x	
Maryland	x		x	
Michigan	x		x	
Monash			x	
Nagoya		x		
Omega			x	
Padova			x	
Padova B2		x		
Padova LHCb		x		
Pavia, Trento, Mila	x			
Perugia		x	x	
SNU		x		x
Virginia	x		x	

Resources:

	FTE available				add. FTE needed				funds available (kEUR)				add. funds needed (kEUR)			
	2024	**2025**	**2026**	**>2026**	**2024**	**2025**	**2026**	**>2026**	**2024**	**2025**	**2026**	**>2026**	**2024**	**2025**	**2026**	**>2026**
4.1.1	6.0	5.9	5.9	5.1	7.5	8.5	8.5	9.5	27.5	27.5	27.5	22.5	177.5	277.5	297.5	302.5
4.1.2	11.2	11.2	11.2	10.9	5.0	5.0	5.0	6.0	195	192.5	192.5	190	135	135	135	140
4.1.3	9.8	9.8	9.8	10.3	5.4	6.4	6.4	6.4	73.8	73.8	73.8	78.8	88.8	108.8	108.8	108.8
4.1.4	0.0	0.0	0.0	0.0	4.0	4.0	4.0	4.0	0.0	0.0	0.0	0.0	115.0	115.0	115.0	115.0
Total	**22.4**	**28.2**	**28.2**	**27.6**	**15.7**	**25.2**	**25.2**	**27.2**	**303.8**	**328.8**	**328.8**	**326.3**	**383.8**	**681.3**	**701.3**	**711.3**

Deliverables:

		date*)
D4.1.1	Demonstrator of Back-side illuminated SiPM array	36
D4.1.2	Report on state-of-the-art fast and radiation hard SiPMs	36
D4.1.3	Performance report on the ultra-fast SiPM with optimized readout electronics	36
D4.1.4	Report on achieved performance of novel sensor materials	36

Milestones:

		date*)
M4.1.1	Tested Back-side illuminated SiPM samples	24
M4.1.2	Standardization of characterization procedures and standards to measure SiPM performance after irradiation	18
M4.1.3	Demonstrated high-performance readout electronics for SiPMs	24
M4.1.4	Performed tests of solid-state photo sensors with new sensor materials	24

*) date in months after project start

Table 4: Resource overview of Theme 4.1.

4.2 Vacuum-based Photon Detectors

Vacuum-based Photon Detectors (VPD) are still leading the course in many areas of the photon detection field even after 90 years from their "invention", especially in terms of gain and timing resolution. These performances make PMT, MCP-PMT and HPD - just to quote few examples - the most suitable detectors to equip most Cherenkov-based and Time-of-Flight detectors used in particle identification. These same features are also behind the use of VPD in crystal-based calorimeters like CMS electromagnetic calorimeter allowing to fully exploit the performances of the $PbWO_4$ crystals.

The continuous progress in nano-technology and solid-state physics to produce regular micro- and nano-structured plates using electrochemical, laser and plasma-based techniques and the big progress achieved by chemists in coating such structures with different kinds of material allow one to envisage to improve the performances of the VPD even more, and at the same time to extend their lifetime and their rate capabilities even in harsh conditions. This will possibly lead to a new generation of VPDs for which a time resolution of a few picoseconds with submicron spatial intrinsic resolution as well as robustness are achievable.

VPD with such extraordinary intrinsic resolutions are useless unless associated to electronics read-out systems that allows the exploitation of their time and spatial performances simultaneously, and allows in addition to cope with the high detection rates required in some of the future experiments.

This Theme is structured in 3 Work Packages, with the goal of developing a new generation of VPDs in partnership with European and international companies, including the development of read-out electronics to fully exploit their performance.

WP.4.2.1 - VPD: New materials, new coatings, longevity and rate capability studies

A microchannel plate (MCP) is an array of miniature electron multipliers oriented parallel to each other. An MCP plate contains millions of hollow tubes of 2 to 25 μm diameter and several hundreds of microns length. A typical MCP-based photodetector is a vacuum tube equipped with a photocathode, providing the desired sensitivity for a given range of wavelengths, and "collecting" the signals with anodes having from simple to complicated geometries.

MCP-based detectors feature excellent timing resolution (<20 ps), excellent granularity, negligible dark-count rate at room temperature, and low sensitivity to magnetic fields. However, current MCP-PMTs suffer from limitations that prevent them from being used in very high photon rate experiments, like for example the long microchannel recharge times, the saturation current, and ageing effects which lead to a strong QE reduction.

Long-term goals: Develop a new generation of MCPs with high-rate capabilities and long lifetime for use in future HEP experiments

Objectives:

New techniques aiming to simplify the production process and, therefore, the cost while allowing the realization of large-area MCPs have been initiated by the LAPPD collaboration a few years ago. Plates made of float glass are perforated to create micrometer holes, and Atomic Layer Deposition (ALD) techniques are then used to coat the hole walls with resistive and emissive material to transform the holes into amplification cavities like the standard MCP tubes. ALD techniques were also used by international commercial companies to increase the longevity of the standard MCP providing an important asset for the use of MCP in future experiments.

Reducing the diameter d of the MCP tubes/holes while keeping the same Open Area Ratio (OAR) and the same aspect ratio (L/d) results in reduced Time Transit Spread (TTS) and then improved intrinsic timing of the MCP and naturally better spatial resolution. New technologies using chemical processes like the Aluminum Anodization Oxide (AAO) applied on thin aluminum plates or electrochemical etching techniques applied on Silicon or GaAs or other wafers can produce regular nanometric structures. Applying ALD techniques in a similar way to the one proposed by LAPPD can result in what one may call NanoChannel Plates (NCP).

1. Develop new material and techniques to prolong the lifetime of a MCP-PMT tube, improving at the same time rate capabilities
2. Use new techniques with new materials to achieve high aspect ratio with small diameter, to have better gain, time and spatial resolution

Description of work:

In collaboration also with VPD producers, review state-of-the-art techniques and aim at the production of new materials with the requested performance. The produced samples will be evaluated and characterized in detail by the groups involved in the WP, and further design steps for future improvements will be defined.

Milestones:

M4.2.1.1 Report on state-of-the-art technologies to produce electron multipliers with excellent timing and spatial resolutions (M18)

M4.2.1.2 Report on state-of-the-art long lifetime and high-rate capability VPDs (M24)

Deliverable:

D4.2.1 Prototype production of a new generation of MCP-PMT using innovative techniques (M36)

WP.4.2.2 - VPD-PMT: New photocathode materials, structure and high quantum efficiency VPD

The progress on photocathode material has never stopped. New materials are still being discovered and studied. Searching for a combination of several photocathode materials providing high photoelectron yield for a large range of wavelengths is one of the important topics in the photoelectron detection field. Another important topic is the robustness of the photocathodes against return ions, namely in the case of MCP-PMT where the photocathode is separated from the MCP. New photocathode structures featuring increased surfaces can increase the photoelectron yield but also the addition of new materials with appropriate negative affinity can help reduce the energy gaps of the photocathode allowing the electrons to leave more easily.

Long-term goals:

Develop different types of photocathodes (transmissive and reflective) with increased QE and extended spectral sensitivity with long lifetime

Objectives:

1. Search for new materials with the required characteristics to be used as photocathodes
2. Develop a photocathode on new structures with high granularity to improve QE and position resolution

Description of work:

We propose to study in collaboration with industrial partners the performance of new photocathodes in terms of quantum efficiency as well as their stability under intense radiation environments. We also propose to study new topological configurations of the photocathodes, either in transmission or reflective modes, to assess the impact of these configurations on the VPD performance.

Milestones:

M4.2.2 Realization of granular structure (M24)

Deliverable:

D4.2.2 Production of photocathodes made of different materials using either granular structure or different structure (M36)

WP.4.2.3 VPD time and spatial resolution performance

Readout electronics developed for HL-LHC has achieved significant progress in the time measurement. ASICs developed for HGCAL of CMS, HGTD for ATLAS, for instance, have reached a precision of a few tens of picoseconds. New TDC like the picoTDC recently developed at CERN has reached a precision of a few picoseconds, a performance similar to that obtained with waveform TDC like SAMPIC. Exploiting the existing electronics and adapting it to fully exploit the precision that present and future VPDs can provide is now at reach.

VPD can also provide a spatial measurement with excellent precision. Combining VPDs with the new Timepix4 chip, for instance, will allow the exploitation of this important VPD feature while still providing an excellent time measurement.

New concepts such as the PICMIC intend to fully exploit both the intrinsic spatial and temporal resolution of the present VPDs. A precision of a few tens of picoseconds and a few microns seems at reach thanks to a new readout scheme. The concept could be adapted to reach a time resolution of picosecond and submicron spatial resolution to cope with the intrinsic resolution that the nanostructured VPD could provide.

To summarize, we propose to adapt the existing electronics readout systems for present VDPs in order to fully exploit their intrinsic time resolution and/or their intrinsic spatial resolution. As a next step, we propose to develop new readout electronics to cope with the expected picosecond and submicron resolutions the new generation of VPD will be able to deliver.

Several techniques to exploit both spatial and timing resolution

Long-term goals:

Development of large area photodetector with combined excellent timing and position resolution

Objectives:

Development of a photodetector with full 4D-capability

Description of work:

We will develop read-out systems fulfilling the requirements of excellent time and spatial, and we will work on the integration aspects with dedicated companies to improve compactness.

Milestones:

M4.2.3 Design of read-out electronics capable to reach $O(10\ \mathrm{ps})$ timing resolution (M24)

Deliverable:

D4.2.3 Production of a read-out system demonstrator able to fully exploit timing and spatial resolution of MCPs (M36)

Theme 4.2: Vacuum Photon Detectors (VPDs)

List of WPs

- 4.2.1 VPD: New materials, new coatings, longevity and rate capability studies
- 4.2.2 VPD-PMT: New photocathode materials, structure and high quantum efficiency VPD
- 4.2.3 VPD time and spatial resolution performance

Participating institutes

	4.2.1	4.2.2	4.2.3
Birmingham	x		x
Bristol	x		
Cambridge			x
Edinburgh	x	x	x
Erlangen	x		x
Ferrara	x		x
Glasgow			x
IHEP-CAS-FPMT		x	x
Istanbul			x
Leicester	x		x
Ljubljana	x		x
Lyon	x	x	x
Milano Bicocca			x
Nagoya	x		x
Omega			x
Padova	x		x
Trieste			x
Univ. S.T. China	x		x
Warwick	x		x

Resources

	FTE available				add. FTE needed				funds available (kEUR)				add. funds needed [kEUR]			
	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026
4.2.1	8,4	7,9	6,6	5,3	4,0	4,0	4,0	4,3	282	257	152	25,5	123,5	153,5	138,5	130
4.2.2	2,5	3,2	2,3	2,0	0,0	0,0	0,0	0,0	80	130	80	0	60	60	50	50
4.2.3	13,2	13,4	12,4	7,5	4,2	5,2	5,2	3,5	231	231	166	44,5	283,5	333,5	328,5	195
Total	24,1	24,4	21,3	14,8	8,2	9,2	9,2	7,7	593	618	398	70	467	547	517	375

Deliverables		**date*)**
D4.2.1	Prototype production of a new generation of MCP-PMT using innovative techniques	36
D4.2.2	Production of photocathodes made of different materials using either granular structure or different structure	36
D4.2.3	Production of a read-out system demonstrator able to fully exploit timing and spatial resolution of MCPs	36

Milestones		**date*)**
M4.2.1.1	Report on state-of-the-art technologies to produce electron multipliers with excellent timing and spatial resolutions	18
M4.2.1.2	Report on state-of-the-art long lifetime and high-rate capability VPDs	24
M4.2.2	Realization of granular structure	24
M4.2.3	Design of read-out electronics capable to reach O(10 ps) timing resolution	24

*) date in months after project start

Table 5: Resource overview of Theme 4.2

4.3 RICH and other imaging detectors for future experiments

RICH detectors will be one key element for hadron identification in future experiments. In most cases, performance improvements and better control of systematic uncertainties will be required, with respect to currently running experiments. Moreover, external requirements might drive the overall detector design, calling for challenging engineering solutions. Therefore, new concepts for implementing the RICH approach are being investigated to satisfy the requirements. This also includes all of the software chain, a key ingredient for the more challenging future experiments.

This theme focuses on the concept, design, feasibility, prototyping, characterization and validation of future RICH detectors, including related technologies.

It strongly relies on the availability of sensors and their dedicated full readout chain, with known characteristics, as from DRDT 4.1 and DRDT 4.2, and will provide detector requirements on the sensors.

The activities of this DRDT 4.3, on one side, and DRDT 4.1/4.2, on the other side, will require continuous reciprocal consultations and information exchange. In fact, this DRDT 4.3 needs some flexible enough readout system, from the sensor to DAQ, see 3.

This DRDT 4.3 has a large parallelism with DRDT 4.4: continuous reciprocal consultations and information exchange will be needed to rationalize the work. This DRDT 4.3 also deals with all the thermo-mechanical engineering aspects and it is therefore highly connected to activities in DRD8. In fact, a large engineering support for detector R&D will be necessary for the WPs of this theme, in coherence with ECFA GSR 2.

Finally, many interconnections and dependencies exist among different task/sub-tasks, with other DRDT in DRD4 as well as outside DRD4.

The timeline, deliverables and milestones are subject to timely availability of the required FTE and funding.

Additional goals include the following.

- Gather the RICH scientific community in a common framework to favor: exchange of knowledge and competence, new ideas and fresh results, contamination of the competences, cross-fertilization, common developments, cross-contamination among different research groups.
- Provide relevant technology transfer from/to the HEP community and relevant industrial technology import from other fields (engineering, material science, ...);
- Provide rationalization and optimization of the research programs, by avoiding duplication and ensuring adequate coverage of all important topics.
- Develop cost-effective technologies and trigger cost-effective R&D processes by rationalization.
- Take a snapshot of current knowledge, define future directions, define the required R&D program.

WP4.3.1 - New Materials Radiators and Components.

Future RICH detectors will most likely require exploitation of new materials, new radiators and new components, with specific properties, in order to reach the desired performance.

This WP deals with the R&D to identify requirements and study and develop the solutions; the methods and tools to characterize materials, radiators and components; the methods and models for measurements and quality control.

- Study Of Radiator Gases Alternative To Per-Fluorocarbons
- Aerogel Optimization And Characterization
- Development of meta-materials as Cherenkov radiators.
- Development And Characterization Of Low-Mass Mirrors
- Development Of Materials And Mechanical Solutions
- Development Of Laboratory Instrumentation And Techniques

Partners:

Bristol, CERN-LHCb, Ferrara, Ljubljana, London-IC, Marche, Marseille, Padova, RAL, Trieste.

Milestone: Interim report on requirements for future detectors, survey of possible solutions and definition of the R&D to carry on during years 2 and 3; (M12).

Deliverable: Validation of the selected technological solutions by means of prototypes and/or technological demonstrators and final report; (M36).

WP4.3.2 - Development of new RICH detector concepts for improved performance. This WP concerns specifically the R&D to be carried on during the next three years, targeting detectors with approximately start-date in ten years from now (2035).

It deals with new concepts and detector designs implementing the requirements, validation of design concepts via proof-of-concept or technological demonstrators.

These include the following.

- Feasibility study for a combined RICH/TOF.
- Feasibility study for high-pressure gas radiator based RICH.
- Feasibility study for use of fast timing in RICH/DIRC.
- Feasibility study for a cryo-RICH.
- Investigation of performance limits of existing technologies (gas detectors, LAPPD).
- Developing new concepts for modular RICH detectors.

Work will be paper-work plus simulations plus technological demonstrators or proof of concepts of the selected concepts.

Partners: Bucharest, Cambridge, CERN-LHCb, Ferrara, Hefei-USTC, RAL, Trieste.

Milestone: Interim report on requirements, technological challenges and required R&D to carry on during years 2 and 3; (M12).

Deliverable: Report on feasibility study for new RICH detector concepts for improved performance; technological demonstrators and/or proof of concepts of the selected concepts; (M36).

WP4.3.3 - Prototype Single-Photon Sensitive Module for Imaging Arrays from sensor to DAQ and self-calibration systems.

This WP concerns specifically the R&D to be carried on during the next three years, targeting detectors with an approximate start date in ten years from now (2035).

Future RICH and imaging detectors will typically have common challenging requirements, including: suitable radiation-hardness for a large squared meter area, mm-pixelated space resolution, O(100ps) time-of-arrival resolution, with large and uniform geometrical acceptance and O(>100MHz) rate capability per pixel. On the other hand, a limited number of specific requirements might be present or missing, for some specific applications.

The work deals with the following three topics, to be integrated into a single autonomous module of a modular array.

- Prototype RadHard fast low-noise scalable front-end readout electronics for single-photon counters, see also 3.
- Prototype Single-Photon Sensitive Module for Imaging Arrays (from sensors to DAQ).
- Prototype systems for on-detector calibration/alignment/monitoring.

The objective of this WP includes use/implementation of full readout chains, strongly coupled to both sensors and rest of the detector. It does not include the study of sensors themselves, but only sensors as devices of the imaging array, including all system and integration aspects. The sensors themselves are the subject of DRDT4.1 and DRDT4.2, with which two-ways consultation and information is required. It also includes developing suitable on-detector instrumentation to keep systematic uncertainties under control as follows from the typically challenging requirements of future experiments.

PMT, MCP-based imaging arrays are, a priori, included, in addition to SSPD; MCP-based imaging arrays should be considered as well, a priori, as the step following MCP-based sensors validation; PMT imaging arrays, in addition to possible use in future experiments, do exist, are well known and very nicely working and could be very useful for early use in laboratory and test beams as well as for (cross-)characterization of SSPD and/or MCP PMT arrays.

The housing of the sensors is a complex task, regardless of the sensor choice, due to the large number of sensors/channels and the many requirements. The first challenge will be to include some sort of active cooling into the module, together with the other ancillary services, and some sort of radiation-shielding. Combination of different functions into an integrated systems is a key goal.

Work will target design, prototyping and characterization of one, or a few, fully functional and autonomous module of arrays for readout of clusters of PMT/MCP/SiPM, with O(50) ps time resolution and mm size pixelization, including integrated full readout chain, integrated system for self-calibration, integrated local cooling (whenever required) and suitable for tiling a large surface.

The emphasis is on the system level of the design. In fact, the close-packing and integration architecture need to be studied carefully, taking into account the requirements for stability, reliability and low cost.

The collaboration will first investigate requirements, leading to possible different developments, and will decide among options for the R&D as a result of the milestone. The module will used both as a technological demonstrator and as a real detector for laboratory or test-beam studies.

Availability of a suitable full readout system is assumed.

Availability of a sufficient thermo-mechanical engineering support is required.

Partners: Bucharest, Cambridge, CERN-LHCb, FBK, Genova, Georgia, Hefei-USTC, Leicester, Milano-Bicocca, Milano-Statale, Padova, Perugia.

Milestone: Interim report on requirements, survey of possible solutions and definitions of R&D to carry on during years 2 and 3; definition of specifications for the prototype(s), according to physics; (M12). requirements.

Deliverable: Prototype(s) Single-Photon Sensitive Module for Imaging Arrays (from sensors to DAQ), including the ancillary system for self-calibration and local cooling for SiPM; Design Report; (M36).

WP4.3.4 - Study of RICH detectors for the FCC

The focus of this Work Package is the conceptual design, and the investigation of the key components, of a RICH detector for a future high-energy e^+e^- collider, in particular FCC-ee. The physics capabilities of an experiment at such a machine can be greatly enhanced by the addition of particle-identification capabilities. Applications include heavy-flavour studies, and the flavour tagging of jets in Higgs, W, and top decays. These goals imply a momentum range of around 1 to 50 GeV/c, which can naturally be covered by a RICH detector with dual radiators. This detector must be compact, taking no more than $\sim$20 cm in extent, and low mass, so as not to compromise the other aspects of the experiment's design. An initial design, the ARC detector, has been proposed, comprising an aerogel and gas radiator, low-mass mirrors and SiPM photodetectors, deployed in an array of cells.

The goals of the Work Package are to optimise the layout of the ARC and investigate other possible solutions. Important challenges involve the possible use of aerogel as a thermal insulator, as well as a radiator, the choice of radiator gas, and whether it must be pressurised, lightweight mirrors, and the need for compact photodetectors with high geometrical efficiency.

Partners: CERN, CERN-EP, Oxford.

Milestone: Full conceptual design for ARC detector (M12).

Deliverable: Evaluation of prototype ARC cell (M36).

WP4.3.5 - Software and Performance.

Future RICH and imaging detectors will face new challenges in terms of events/hits multiplicity, rate, amount of data and background/noise levels, calling for new approaches and/or new implementations to detector simulations and analysis.

Moreover, to cope with future challenges, a number of specialized software tools are necessary, for optimization of specific subsystems, before feeding in the full detector simulation the optimized subsystem. These include tools for optimization, design and performance evaluation such as: CAD for geometrical optics ray tracing, dedicated software for optimization of reflection/anti-reflection coatings and filters, dedicated software for modeling the internal workings of PMT/MCP-PMT/SiPM and photon transport in gases and solids.

Important topics emerged include the following.

- Study ML and AI algorithms applied to RICH or other imaging detectors;
- Development of a common framework for tracing of optical photons;
- Define agreed benchmarks for evaluation and comparison of RICH performance;
- Establish tools for Fast Optical Photon Tracing In RICH;
- Establish Fast Pattern Recognition For RICH In High-Multiplicity Environment;
- Study Novel Architectures For RICH PID: Development Of A Test-bench/Framework;
- Study Novel Reconstruction Algorithms For RICH PID: Development Of A Detector-Agnostic Software Framework;
- Map And share satellite SW for studies of specific aspects preliminary to GEANT4-like simulations;
- Investigate tools for evaluation of systematic uncertainties in simulation and analysis SW;
- Establish (possibly experiment-dependent) tools and standards for validation of simulation against real data;
- Evaluation of the Anticipated RICH performance;
- Optimization of Detector Configuration;
- Simulation of the internals of PMT, MCP, SiPM.

Partners: Bristol, Cambridge, CERN-LHCb, Genova, Ljubljana, Milano-Bicocca, Perugia, RAL.

Milestone: Survey of existing software and techniques and definition of requirements and solutions for the future challenges; (M12).

Deliverable: Establish a common framework for tracing of Cherenkov optical photons; Develop A Detector-Agnostic Software Framework for reconstruction in RICH; report on software and performance evaluation of RICH detectors; (M36).

Resource tables

Theme: RICH and other imaging detectors for future experiments

List of WPs

4.3.1 - New Materials Radiators and Components.
4.3.2 - Development of new RICH detector concepts for improved performance.
4.3.3 - Prototype Single-Photon Sensitive Module for Imaging Arrays from sensor to DAQ and self-calibration systems.
4.3.4 - RICH detectors for the FCC.
4.3.5 - Software and Performance.

Participating institutes

	4.3.1	4.3.2	4.3.3	4.3.4	4.3.5
Bari		X			
Beijing IHEP			X		
Beijing USTC					
Bristol	X	X			X
Bucharest		X	X		
Cambridge		X	X		X
CERN EP				X	
CERN LHCb	X	X	X	X	X
FBK			X		
Ferrara	X	X			
Genova		X	X		X
Georgia		X			X
Giessen					
Glasgow			X		
Leicester			X		
Ljubljana	X				X
London IC	X				
Marche	X				
Marseille	X				
Milano Bicocca		X	X		X
Milano Statale		X	X		
Oxford				X	
Padova	X	X	X		
Perugia		X	X		X
RAL	X	X	X		X
Trieste	X	X			
Warwick					

The list of participating institutes and their commitment is still preliminary, due to late arrivals and some institutes not being in a condition to declare their resources, yet.

The resurce table is still preliminary in the "needed" part.
Additional FTE and funds needed are, for the time being, an educated guess, based on the proposed reaearch program.

Resources

	FTE available				add. FTE needed				funds available				add. funds needed			
	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026
4.3.1	3.5	3.5	3.5	3.4	2.8	2.8	2.8	1.8	21	21	21	15	75	75	75	150
4.3.2	3.7	4.2	4.7	3.2	1.0	1.5	1.5	1.0	19	21	21	10	100	100	100	200
4.3.3	8.6	9.0	9.0	9.0	2.8	2.5	2.5	3.5	90	85	85	65	205	205	205	410
4.3.4	2.0	2.0	2.0	2.0	0.0	0.0	0.0	0.0	0	0	0	0	25	25	25	50
4.3.5	2.4	2.4	2.4	2.4	3.7	3.7	3.7	3.7	12	10	10	10	70	70	70	140
	20	21	22	20	10	10	10	10	142	137	137	100	475	475	475	950

	Deliverables	date*)
D4.3.1	Validation of the selected technological solutions by means of prototypes and/or technological demonstrators and final report.	36
D4.3.2	Report on feasibility study for new RICH detector concepts for improved performance; technological demonstrators and/or proof of concepts of the selected concepts.	36
D4.3.3	Prototype(s) Single-Photon Sensitive Module for Imaging Arrays (from sensors to DAQ), including the ancillary system for self-calibration and local cooling for SiPM.	36
D4.3.4	Full conceptual design for ARC detector.	36
D4.3.5	Establish a common framework for tracing of Cherenkov optical photons; Develop A Detector-Agnostic Software Framework for reconstruction in RICH; report on software.	36

	Milestones	date*)
M4.3.1	Interim report on requirements for future detectors, survey of possible solutions and definition of the R&D to carry on during years 2 and 3.	12
M4.3.2	Interim report on requirements, technological challenges and required R&D to carry on during years 2 and 3.	12
M4.3.3	Interim report on requirements, survey of possible solutions and definitions of R&D to carry on during years 2 and 3; definition of specifications for the prototype(s), according to physics.	12
M4.3.4	Evaluation of prototype ARC cell.	12
M4.3.5	Survey of existing software and techniques and definition of requirements and solutions for the future challenges.	12

*) date in months after project start

Table 6: Resource overview of Theme 4.3.

4.4 Time of Flight Detectors

Detectors providing the particle time of flight (TOF), in conjunction with momentum measurement, have been used in high energy physics experiments since ever to identify charged particles. Colliding beam experiments have so far required large area TOF detectors at a few meters distance from the interaction region, with an overall time resolution ~100 ps able to separate charged particles in the momentum region of few GeV/c. The challenges of future HEP experiments have aroused the necessity to extend the identification of charged particles to higher momenta. Along with the collider luminosity increase, timing will also be compulsory for pile-up suppression and 4-D tracking.
Consequently, TOF systems based on faster sensors, by an order of magnitude better than the current ones, are being actively developed. These devices must be radiation hard, nearly edgeless for reducing the dead regions and segmented for allowing independent timing measurements of several particles.

WP4.4.1 - Study the coupling of a thin Cherenkov radiator to a single-photon detector array, for TOF of charged particles
Cherenkov light is prompt and therefore ideal for fast timing. Although the amount of light is small compared with that produced by scintillators, such limitation can be overcome by using Cherenkov devices capable of detecting single Cherenkov photons. Indeed, if the Cherenkov detector has an intrinsic time resolution SPTR (Single Photon Time Resolution), the time resolution due to the photoelectron statistics with Npe photoelectrons is then σ_t=SPTR/$\sqrt{Npe}$.
In this WP, we plan to develop high precision timing (σ_t~10-15 ps) systems based on high refractive index solid Cherenkov radiators coupled to arrays of silicon photomultipliers (SiPMs) or multichannel plates (MCPs) as photon sensors. The entrance MCP window or a thin (a couple of mm) slab of a high refractive index transparent material added in front of the SiPM array acts as a Cherenkov radiator providing about a hundred photons per single charged particle traversing it. The independent measurement of the time for each of the photoelectrons resulting from the conversion of the Cherenkov photons in the MCP or the SiPMs will enable to achieve a precise timing with a sub-25 ps resolution. SiO_2 (fused silica) with n=1.47 at 400 nm, and MgF_2 with n=1.4 at 400 nm are potential radiator materials, although also Sapphire (Al_2O_3) (n = 1.7 at 400 nm) and Corning glass (n = 1.8 at 400 nm), both with a higher refractive index than fused silica, could also be used resulting in more Cherenkov photons. The transmission of these materials extends down to 350 nm.
Goals: The timing performance of the proposed device depends not only on the type of Cherenkov radiator material, photon sensor geometry, pixel size, and read-out electronics but also by the optical coupling between the radiator window and the photon detector since the way the Cherenkov photons propagate introduces either a loss of signal or a spread in the timing.
Description of work: Carry-out detailed GEANT4 simulations emulating the time spread introduced by the optical cross/talk (OCT) to neighboring pixels and lab tests with SiPMs and MCPs equipped with different window materials.
Partners: Bari, Ljubliana, Marseille, CERN, FBK.
Milestone: M4.4.1 Selection of suitable material for the Cherenkov radiator and its coupling to the sensor (M18)
Deliverable: D4.4.1 Fully characterized prototype TOF detector, with a report on design and performance (M36)

WP4.4.2 - Develop a SiPM array for single-photon detection, with mm-scale pixellization, suitable for use in TOF prototypes
This task concerns R&D on SiPM detectors and electronics to provide mm scale position sensitivity and fast timing of Cherenkov light at the very high rates expected with HL-LHC and future colliders. Large arrays of $1 \times 1mm^2$ mm SiPMs, the smallest size generally available, would be complex and risky to manufacture, so larger SiPMs with segmentation providing several pixels per device are a preferred option. Additionally, event timing to ~10-20 ps will require close integration of the sensor and electronics package, and the power dissipation in the sensor due to the microcell Geiger discharge at the very high count rates anticipated for HL-LHC will require active cooling of the SiPM to maintain stable device gain and prevent increase in dark noise.
Goals: The preliminary tests obtained on single SiPMs should be generalised on larger array systems, equipped with more optimised front-end electronics.
Description of work: A vigorous research program will be pursued for the deployment of arrays of SiPMs

that will allow to make a step forward in TOF systems.

Partners:

Aachen, Barcelona, Bari, CERN, FBK, Leicester, Oxford.

Milestone: M4.4.2 Demonstrate performance for single-photon detection of SiPM array with FastIC readout (M18).

Deliverable: D4.4.2 Prototype of array of cooled, mm-scale segmented SiPMs with integrated readout, with report on design and performance (M36)

WP4.4.3 - Develop lightweight mechanical supports for DIRC-type TOF detectors

The aim of this work package is to develop lightweight mechanical supports for DIRC-type TOF detectors. The Cherenkov radiators typically comprise a set of highly polished quartz plates several tens of of square metres in area, coupled with other optical components to the detectors, all manufactured to very high precision. All optical components require adjustable and highly accurate positioning by means of suitable, lightweight mechanical supports which should minimize both contact with optical surfaces and material in the detector acceptance. The supports must also maintain geometrical distortion to a minimum while adequately supporting the considerable overall weight of the quartz and services such as detectors, and potentially some of the electronics. Mechanical designs using various of lightweight materials, such as carbon-fibre based composites, including removable handling jigs for installation, will be investigated and reported, leading to a candidate design from which a prototype lightweight mechanical structure will be developed and its performance verified.

Description of work: Develop lightweight mechanical supports for DIRC-type TOF detectors, supporting the polished quartz radiator and services.

Partners:

GSI, Oxford, USTC.

Milestone: M4.4.3 Report on material choices and mechanical design for a lightweight TOF module (M18)

Deliverable: D4.4.3 Prototype of a lightweight mechanical support for a DIRC-type TOF detector, with report on design and performance (M36)

WP4.4.4 Develop techniques for measuring the optical properties of optical components for TOF detectors

This work package focuses on the development of techniques for the measurement and characterization of the quartz Cherenkov radiators and techniques used for coupling of optical components. To achieve the necessary performance characteristics, the radiator requirements are demanding, including a very high level of polish to achieve very low surface roughness required together with a high degree planarity. These are both challenging to achieve during manufacture and difficult to accurately measure accurately afterwards with the required accuracy. Facilities already exist within the project partners for evaluating the surface quality of polished fused silica bars or plates. An existing setup housed in a temperature-stabilized optical lab comprises motion-controlled stepper motors and diodes, as well as polarized laser beams with six different wavelengths, to determine the coefficient of total internal reflection and the bulk attenuation of TOF/DIRC bars or plates, which will be available on request to collaborators within WP 4.4.4. We will develop these techniques further to measure the specifications of all optical components with a suitably high degree of precision.Additional measured parameters will include component planarity, optical transmission and scattering, defect size and density, radiation darkening, together with parameters specifically relating to the optical coupling materials used.

Description of work: Develop techniques for measuring the optical properties of polished quartz radiators, and the coupling of optical elements in DIRC-style TOF detectors.

Partners:

Armenia, GSI, Oxford, Perugia, USTC.

Milestone: M4.4.4 Report on progress in setting up optical laboratory for characterizing TOF radiator (M18)

Deliverable: D4.4.4 Report on the characterization of the optical performance of a DIRC-style quartz radiator plate (M36)

Theme: Time-of-Flight Detectors

List of WPs

4.4.1 Study the coupling of a thin Cherenkov radiator to a single-photon detector array, for TOF of charg

4.4.2 Develop a SiPM array for single-photon detection, with mm-scale pixelization, suitable for use in T

4.4.3 Develop lightweight mechanical supports for DIRC-type TOF detectors

4.4.4 Develop techniques for measuring the optical properties of optical components for TOF detectors

Participating institutes

	4.4.1	**4.4.2**	**4.4.3**	**4.4.4**
Ljubljana	x			
Bari	x	x		
Marseille	x			
FBK	x	x		
CERN	x	x		
Barcelona		x		
Leicester		x		
Aachen		x		
Oxford		x	x	x
GSI			x	x
USTC			x	x
Armenia				x
Perugia				x

Resources

	FTE available				**add. FTE need**				**funds available**				**add. funds needed**			
	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026
4.4.1	4.5	4.5	4.5						127	127	127					
4.4.2	12.9	12.9	12.9						106	106	106					
4.4.3	2.9	2.9	2.9						60	60	60					
4.4.4	8.5	8.5	8.5						130	130	130					

Deliverables

D4.4.1 Fully characterized prototype TOF detector, with report on design and performance

D4.4.2 Prototype of array of cooled, mm-scale segmented SiPMs with integrated readout

D4.4.3 Prototype of a lightweight mechanical support for a DIRC-type TOF detector

D4.4.4 Report on characterization of the optical performance of a DIRC-style quartz radiator plate

Milestones

M4.4.1 Selection of suitable material for the Cherenkov radiator and its coupling to the sensor

M4.4.2 Demonstrate performance for single-photon detection of SiPM array with FastIC readout

M4.4.3 Report on material choices and mechanical design for a lightweight TOF module

M4.4.4 Report on progress in setting up optical laboratory for characterizing TOF radiators

*) date in months after project start

Table 7: Resource overview of theme 4.4.

4.5 SciFi tracking and Transition Radiation Detectors

At this stage we have defined only a single work package for this theme and expect further WPs to arise in the future.

WP4.5.1 - Develop an improved radiation hard scintillating fibre with a fluorescence decay time near 4 ns.

Long term goals: The aim of this work package is to develop a scintillating optical fibre with a peak detected emission wavelength greater than 500 nm with a fluorescence decay time near 4 ns for use in LHC or future collider experiments, as well as beam instrumentation where a large total integrated dose could be expected. The characteristics should be comparable to or better than the SCSF-78MJ from Kuraray, which has a peak emission of 450 nm, attenuation length of 3.5 m, and decay time of 2.8 ns. A large Stoke's Shift would allow for extending the lifetime of the detector performance in high radiation environments, as well as being able to reduce the material in the acceptance while still producing the light yield needed for a high hit efficiency. While the transmission of the base polymer, such as polystyrene, is expected to degrade, the organic scintillator dyes should also be stable under ionising radiation such that the emission light yield does not degrade. Developments of new scintillators in recent years in block form factors (specifically SP33 from Nuvea), as well as nano-materials, and other base polymers, indicate the potential for an improved fibre over the standard fast fibre that is over 25 years old (SCSF-78M and -78MJ from Kuraray).

Objectives:

- Identify new, suitable but existing scintillators (e.g. SP33 from Nuvea).
- Develop the scintillating fibre with manufacturers (Kuraray) in small batches.
- Measure the emission light yield, attenuation length, and decay time of the resulting fibres.
- Irradiate samples to relevant ionising radiation doses ($10^4 - 10^6$ Gray.)

Partners: CERN-EP, CERN-LHCb, EPFL, Universitaet Heidelberg Physikalisches Institut

Description of work: Identify and produce new scintillating fibres based on newly developed scintillators or techniques with industry partners. The resulting fibre will need to be measured for its decay time, light yield, attenuation length, and ionising radiation hardness.

Milestone: M4.5.1.1 Selection of a suitable scintillator or cladding modification for a fibre prototype batch (M18).

M4.5.1.2 Production of a prototype fibre (M24).

Deliverable: D4.5.1.1 Performance report on the development of prototype fibre(s). (M36)

Theme: Scintillating Fibre Trackers and Transition Radiation Detectors

List of WPs

4.5.1 A novel fast and radiation hard scintillating fibre.

Participating institutes

	4.5.1																
CERN-EP	x																
CERN-LHCb	x																
EPFL	x																
Heidelberg	x																

Resources

	FTE available				**add. FTE need**				**funds availabl**				**add. funds needed**			
	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026	2024	2025	2026	>2026
4.5.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	7.0	7.0	7.0	0.0	3.0	3.0	3.0	

Deliverables		**date*)**
D4.5.1	Performance report on the development of prototype fibre(s	36

Milestones		**date*)**
M4.5.1.1	Selection of a suitable scintillator or cladding modification for a fibre prototype batch	18
M4.5.1.2	Production of a prototype fibre	24

*) date in months after project start

Table 8: Resource overview of Theme 4.5.

5 Relations to other DRDs

DRD4 is primarily dealing with single-photon sensitive photodetectors as required for many Cherenkov and TOF detectors as well as for SciFi trackers. The performance of a SciFi tracker depends of course also on the property of the scintillating fibre, in particular its light yield, spectrum, attenuation length and the degradation of those during operation in a radiation field. Some of these points are also addressed in other DRDs on other photodetectors. This can lead, if properly exploited, to a number of synergies. We intend to maintain a structured information exchange and cooperation with several DRDs. A possible approach could be that the convenors of concerned DRD4 WGs are invited on a permanent basis to the photodetector-related meetings of the other DRDs - and vice versa.

We see potential in the following areas:

DRD1 : Gas-based photodetectors, in particular the PICOSEC technology, which promises excellent time resolution over large areas. Contact point in DRD4: Convenor of WG4.1 (photodetectors).

DRD1 : Studies of environment-friendly detector gasses may inspire studies of Cherenkov gaseous radiators. Contact point in DRD4: Convenor of WG4.3 (technology).

DRD2 : Design and operation of SiPMs at very low temperatures. Contact point in DRD4: Convenor of WG4.1 (photodetectors).

DRD3 : Design and test of LGADs for fast timing. Contact point in DRD4: Convenor of WG4.2 (particle ID).

DRD6 : Fast and radiation-hard scintillating fibres could boost the performance of both (spaghetti) calorimeters and SciFi trackers. Contact point in DRD4: Convenor of WG4.5 (SciFi trackers and TR detectors).

DRD7 : R&D on electronics, in particular the design of readout electronics. Contact point in DRD4: Convenor of WG4.3 (technology).

6 Infrastructure - available and needed

Dedicated surveys show that DRD4 members have access to a large number and variety of facilities built up in past projects and experiments. There is a large number of clean and conventional labs available for detector testing and assembly. Also mechanical and electronics workshops exist at many institutes (>40). This is an excellent basis for the collaborative R&D work ahead and will allow for mutual sharing and exchanging. In the far future one can even think of more innovative approaches like e.g. shared regional competence centres.

Many groups have in principle access to test-beam and irradiation facilities, however in the coming years the availability of beams for detector testing will be strongly affected by a number of effects. As a measure introduced in 2023, the winter shutdowns of CERN's accelerator complex get longer in order to save electricity. Starting in 2026, with the begin of the CERN North Area consolidation, beam tests in this zone will be impossible for at least 28 months. Also the CERN PS will shut down in 2026 but allow a test beam program re-starting in mid 2027. Also from 2026 onwards, the Fermilab beams will be unavailable for 3 years. And finally from 2027 on, the DESY II test beam facility will go in an at least two-years shutdown with unclear future. The coincident shutdowns may be a serious bottle neck for detector testing, as radioactive sources and cosmic rays may only cover a small part of the need. Careful planning and cooperative sharing may mitigate the shortage at least a bit.

Annex A: List of participating research groups

Official group name	Short name for internal use	Principal Investigator	No. of WGs	No. of WPs
FH Aachen	Aachen	Karl Ziemons	2	1
University of Barcelona ICCUB	Barcelona	David Gascon	3	2
INFN Bari	Bari	Eugenio Nappi	3	3
INFN and University Bari	Bari 2	M. Nicola Mazziotta	1	0
University of Birmingham	Birmingham	Angela Romano	1	2
INFN - Sezione di Bologna	Bologna	Alessandro Montanari	3	4
University of Bristol	Bristol	Jonas Rademacker	4	4
IFIN-HH Bucharest	Bucharest	Florin MACIUC	4	2
Cambridge UK	Cambridge	Paula Alvarez Cartelle	3	3
DPhP, IRFU, CEA	CEA	Viatcheslav Sharyy	3	0
CERN TRD	CERN	Christoph Rembser	1	0
CERN ALICE	CERN ALICE	Antonello Di Mauro	2	3
CERN (ARC activity)	CERN EP	Roger Forty	3	2
CERN LHCb	CERN LHCb	Carmelo D'Ambrosio	5	6
CERN SY-BI	CERN SY-BI	Inaki ORTEGA	2	2
GSI	GSI	Jochen Schwiening	4	0
University of Edinburgh	Edinburgh	Silvia Gambetta	3	3
Erlangen Centre for Astroparticle Physics	Erlangen	Thilo Michel	2	4
FBK	FBK	Alberto Gola	4	5
Fermilab	Fermilab	Jim Hirschauer	1	2
INFN Ferrara	Ferrara	Roberto Calabrese	3	6
INFN and University Genova	Genova	Roberta Cardinale	5	5
Georgia State University	Georgia	Xiaochun He	2	2
University Giessen	Giessen	Claudia Hoehne	2	3
University of Glasgow	Glasgow	Bjoern Seitz	2	2
LPSC Grenoble	Grenoble	Sara Marcatili	1	0
GSCAN	GSCAN	Madis Kiisk	1	0
Physi. Inst. Universitaet Heidelberg	Heidelberg	Ulrich Uwer	1	1
HFR, Inc	HFR	Chan Yong Park	3	0
Hamamatsu Photonics Italia Srl	HPK	Mauro Bombonati	3	6
EPFL Lausanne	Lausanne	Lesya Shchutska	1	0
Imperial College London	IC London	Michael McCann	1	1
IHEP-CAS-FPMT	IHEP Bejing	QIAN Sen	2	4
imXgam CPPM	imXgam Marseille	MOREL Christian	2	2
INFN Pavia, Trento, Milano, Padova	INFN team	Roberto Ferrari	1	1
Iowa	Iowa	Yasar Onel	3	5
Istanbul University-PARDET	Istanbul	Suat Ozkorucuklu	3	3
University of Leicester	Leicester	Jon Lapington	2	4
Jožef Stefan Institute	Ljubljana	Rok Pestotnik	4	6
IP2I-Lyon	Lyon	Imad Laktineh	2	3
Università Politecnica delle Marche	Marche	Luigi Montalto	2	0
Centre de Physique des Particules de Marseille	Marseille	Greg Hallewell	1	0
University of Maryland	Maryland	Sarah Eno	1	2
University of Michigan	Michigan	Junjie Zhu	1	3
INFN Milano Statale	Milano Statale	Elisabetta Spadaro Norella	1	1
INFN Milano Bicocca	Milano Bicocca	Claudio Gotti	2	1
Monash University	Monash	Ulrik Egede	1	1
Nagoya university	Nagoya	Kenji Inami	3	1
IN2P3 OMEGA	Omega	Selma Conforti da Lorenzo	2	3
University of Oxford	Oxford	Guy Wilkinson	2	2
INFN Padova B2	Padova B2	Ezio Torassa	3	4
INFN Padova LHCb	Padova LHCb	Gabriele Simi	2	3
INFN Perugia	Perugia	Mauro Piccini	3	4
Photek Ltd	Photek	James Milnes	2	3
Photonis Technologies	Photons	Emile Schyns	5	0
IEAP CTU in Prague	Prague	Benedikt Bergmann	1	0
FZU Prague	Prague	Jaroslav Zalesak	2	1
Queen Mary University of London	QMU London	Jon Hays	2	0
RAL	RAL	Antonis Papanestis	3	3
Seoul	Seoul	Do-Won Kim	3	2
Tokyo Metropolitan University	Tokyo	Hidekazu Kakuno	1	2
INFN Trieste	Trieste	Fulvio Tessarotto	3	3
University of Science and Technology of China	USTC Bejing	Jianbei Liu	2	4

University of Virginia	Virginia	Bob Hirosky	1	2
University of Warwick	Warwick	Tim Gershon	3	3
Bergische Universität Wuppertal	Wuppertal	Karl-Heinz Kampert	2	0
A. I. Alikhanyan national laboratory	Yerevan	Amur Margaryan	5	4
ETH Zurich	Zurich	Rainer Wallny	1	0

Table 1: List of participating institutes, including industrial partners. The table is sorted according to the column ”short name”. The last two columns show for how many Working Groups and Work Packages the groups have signed up. The number of signatures is 153 for WGs and 146 for WPs.

Annex B: Industrial partners (will later on appear in MoU)

The nature of photodetectors often implies a complex production method involving special infrastructure, equipment, materials and know-how. Apart from a few exceptions, photodetectors are developed and fabricated by specialised companies. DRD4 collaboration welcomes industrial and semi-industrial partners to participate in its activities.

Organisations that perform research but have to finance part of their budget by selling commercial products are considered as semi-industrial partners. They can still become full members of the Collaboration (i.e. ”Collaborating Institutions”). In cases where conflicts could arise with their commercial interests, e.g., when the collaboration is going to tender products that they are able to sell, the CB shall decide not to allow them to discuss and vote about these issues in the BI.

The Board of Institutes (BI) can grant the status of “Industrial Partners” to collaborating industrial partners. The role of industrial partners are restricted in order to avoid conflicts of interest.

The main restrictions are that (1) Industrial partners are not represented in the BI. On the other hand they aren’t required to contribute to the Common Collaboration Fund.

(2) Industrial partners can participate in Working Groups but direct participation in Work Packages is not possible. Indirect participation, through collaboration with a normal collaborating institute, requires agreement by the BI.

Team members of industrial partners are listed as co-authors on common publications (same rules as applicable to all other collaboration members).

At this moment, the following companies have declared their interest in joining DRD4. Two are considered as semi-industrial.

- FBK, semi-industrial
- Omega, semi-industrial
- HFR
- Hamamatsu Photonics KK
- GScan
- Photonis
- Photek

Annex C: DRD4 preparation team

A team of volunteers from the DRD4 community agreed to prepare the proposal. Teams of two were attributed to the working groups and the themes. The success of the endeavour is to a large extent due to the active and motivated cooperation of this team. DRD4 thanks the colleagues listed below for their invaluable efforts in forming the collaboration and writing this proposal.

It was also agreed by the DRD4 community that the preparation team shall act as DRD4 collaboration management until the first collaboration meeting in early 2024, when the DRD4 collaboration will officially constitute.

Name	institute	function
Sajan Easo	RAL, UK	WG4.4, WG4.2
Massimiliano Fiorini	Ferrara, IT	WG4.6, WP4.2
Silvia Gambetta	Edinburgh, UK	WP4.1 and WP4.2
Christian Joram	CERN, CH	WG4.2, WG4.5 and Coordinator
Peter Križan	JSI, Ljubljana, SLO	WG4.1 and Coordinator
Imad Laktineh	IN2P3, Lyon, FR	WG4.6 and WP4.2
Jon Lapington	Leicester, UK	WP4.4
Blake Leverington	Heidelberg, D	WG4.5
Francesco Loparco	Bari, IT	WG4.5
Eugenio Nappi	Bari, IT,	WP4.4
Rok Pestotnik	JSI, Ljubljana, SLO	WG4.1, WP4.1
Alessandro Petrolini	Genova, IT	WG4.3, WP4.3
Fulvio Tessarotto	Trieste, IT	WG4.3, WP4.3

Table 2: DRD4 Preparation Team

Special thanks go to Roger Forty, CERN, CH, who supported the DRD4 preparation in the early phase but had to leave this effort when he was asked to become a member of the DRDC panel.