DRD1

DRD1 EXTENDED R&D PROPOSAL
Development of Gaseous Detectors Technologies
v1.5

Abstract

This document, realized in the framework of the newly established Gaseous Detector R&D Collaboration (DRD1), presents a comprehensive overview of the current state-of-the-art and the challenges related to various gaseous detector concepts and technologies. It is divided into two key sections.

The first section, titled "Executive summary", offers a broad perspective on the collaborative scientific organization, characterized by the presence of eight Working Groups (WGs), which serve as the cornerstone for our forthcoming scientific endeavours. This section also contains a detailed inventory of R&D tasks structured into distinct Work Packages (WPs), in alignment with strategic R&D programs that funding agencies may consider supporting. Furthermore, it underlines the critical infrastructures and tools essential for advancing us towards our technological objectives, as outlined in the ECFA R&D roadmap.

The second section, titled "Scientific Proposal and R&D Framework," delves deeply into the research work and plans. Each chapter in this section provides a detailed exploration of the activities planned by the WGs, underscoring their pivotal role in shaping our future scientific pursuits. This DRD1 proposal reinforces our unwavering commitment to a collaborative research program that will span the next three years.

On-line version: `https://cernbox.cern.ch/s/QOTuKXTQQ9FQV0Y`
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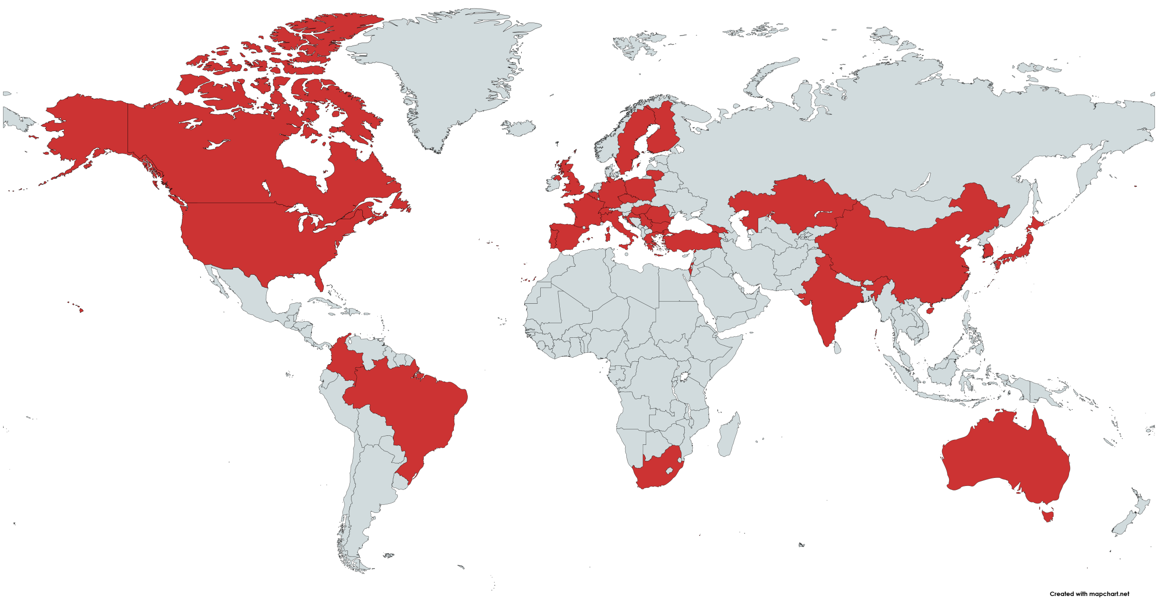

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Part I
Executive Summary

I.1 Introduction

Gaseous Detectors (GDs) are fundamental research tools for exploring nature's laws. They were initially used in nuclear physics, particle and astroparticle physics, and additionally in x-ray and neutron imaging as well as in other daily-life applications. The pioneering Geiger counter (1908) has been replaced by parallel-plate avalanche chambers and various types of discharge detectors. The introduction by Charpak of the MultiWire Proportional Chamber (MWPC) in 1968, revolutionized the field of experimental particle physics (Nobel in 1992). It paved the way towards very large-area particle detectors, capable of detecting events at high repetition rates and with very good spatial resolution. Over the years, the basic principles of charge-avalanche multiplication in gas media have evolved. While the ionization electrons deposition and drift towards an amplification element remained, the latter has followed over the years a dramatic evolution - dictated by the ever-growing accelerators, thus experimental needs. In the new approaches, wires, typically used in MWPC, Drift Chambers and Time Projection Chambers (TPC), have been replaced by Micro-patterned structures created by photo-lithographic techniques on glass, thin polymer foils, and other thicker insulator substrates, etc. These so-called Micro-Pattern Gaseous Detectors (MPGD), including also thin-mesh electrodes, have become the leading tools in current experiments and design of future ones [1].

A description of the various gas-based detector technologies is given in Section II.1.1. These include wire-based detectors like Drift Chambers or Straw Tubes, as well as Resistive Plate Chambers (RPC) and various Micro Pattern Gaseous Detectors (MPGD). The proven success of Gaseous Detectors continues due to their ever-improving characteristics. They are capable of cost-effectively instrumenting large areas, have (in most cases) a low material budget, can operate in the presence of magnetic fields and are radiation-hard. Additionally, their spatial and temporal resolution, along with their high-rate capability, are continuously improving thanks to the efforts of the worldwide community dedicated to research and development in this field. Modern Gaseous Detectors are suitable for a variety of applications in fundamental research domains and beyond, despite the complexity posed by the requirements for high voltage and gas supplies. Their importance in particle physics experiments continues to be crucial, as evidenced by their incorporation into all major LHC experiments (ALICE [2], ATLAS [3], CMS [4], LHCb [5]) and into numerous other experiments conducted at CERN and worldwide (KLOE-2 [6], CLAS12 [7], T2K [8], BELLE II [9], BESIII [10], COMPASS++/AMBER [11], ePIC [12]), which primarily use extended Gaseous Detectors systems. Moreover, novel concepts are being developed within these experiments. Nowadays, every technology has a community working on various aspects to extend their application fields and overcome their current limitations.

It is important to note that many of the challenges faced by different gas detector technologies are shared between them, and a common and extensive research and development effort would be beneficial for all. Despite the different R&D requirements, there is potential for overlapping in many aspects, allowing for a larger community of gaseous detectors to benefit. The most straightforward example is the classic ageing issues, but many others can be mentioned. For MPGDs, the main challenges remain large areas, high rates, precise timing capabilities, and stable discharge-free operation. The focus for RPCs stays on improving high-rate and precise timing capabilities, uniform detector response, and mechanical compactness. For straw tubes, requirements include extended length and smaller diameter, low material budget, and operation in a highly challenging radiation environment. Large-volume drift chamber operation with a reduced material budget in a high-rate environment requires searching for new materials. Avalanche-induced Ion Back Flow (IBF) remains the primary challenge for TPC applications in future facilities. TPCs for rare event searches represent a specific class of applications that probe fundamental physics through the properties of rare interactions of radiation with specific gas or liquid media. Overlap is found between the research interests of the Gaseous Detectors community and the Detector R&D Roadmap [13]. The challenges from the wide range of cutting-edge technologies must be addressed to lead future innovations of high relevance to future collider facilities, as well as in future research programs in areas such as nuclear, astroparticle, neutrino, rare-event studies, and applications having an impact on the society, all of which require the use of advanced Gaseous Detectors. These challenges are referred to as Detector Community Themes listed below:

- DRDT 1.1 - Improve time and spatial resolution for gaseous detectors with long-term stability.
- DRDT 1.2 - Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different readout schemes.
- DRDT 1.3 - Develop environmentally friendly gaseous detectors for very large areas with high-rate capability.
- DRDT 1.4 - Achieve high sensitivity in both low and high-pressure TPCs.

Future experiments will require instrumentation of large area coverage with timing capabilities never attained before. This is essential for identifying particles based on their time of flight and for accurate tracking. The scientific objectives of these experiments require an enhanced momentum resolution, and the instrumentation must be able to function effectively for many years with little intervention. Various readout techniques are necessary for tracking detectors that cover significant volumes, such as MPGD, optical readout, and direct links to ASICs. Ensuring low multiple scattering and precision in measuring ionization (by deposited energy or clusters per unit length) is crucial for superior particle identification. The largest detector systems used in experiments are typically gaseous detectors, which are frequently included in outer muon spectrometers. These detectors need to be easy to maintain, capable to operate stably and, in some cases, capable of handling large amounts of charged particles. To support future applications, it is crucial to develop gas mixtures that are more environmentally friendly for gaseous detectors. Additionally, mitigation procedures should be implemented when the use of greenhouse gases is unavoidable. Large-volume gas detectors offer a crucial technology for effectively searching for rare events with high efficiency. These detectors have various readout options, which can be optimized to enhance the signal-to-noise ratio and minimize detector background noise.

DRDTs are implemented through applications outlined in Section II.1.2, and each of these applications is mandatory for the Working Group to allow the community to focus on common needs, including gas and material studies, detector physics simulation and software tools, electronics, detector development manufacturing and production, common test facilities, and training and dissemination. These applications can benefit from transversal activities to develop and meet the DRDT. The Working Group serves as the scientific collaboration core, identifying the future strategic direction for detector R&D. Each strategic R&D initiative becomes a Working Package that shares research interests with a focus on specific tasks related to a particular DRDT challenge. The Working Group connects these tasks to milestones and institutes. The proposed organization is shown in Fig. 2.

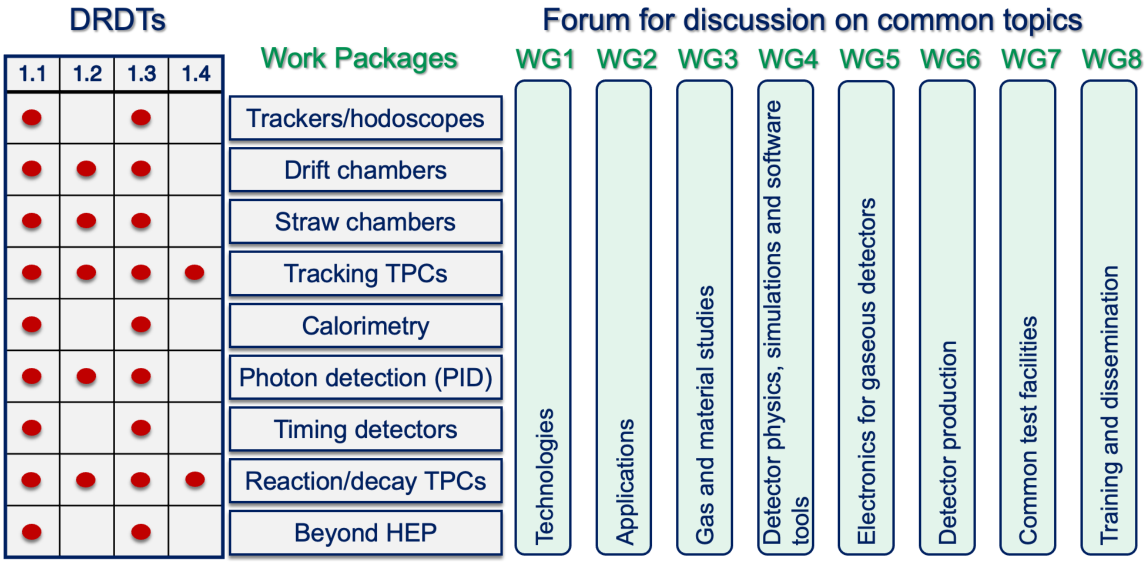

Figure 2: DRD1 Scientific Organization

A solid community is necessary to reach the objectives outlined in the DRDT and go beyond them. This community should facilitate the sharing of knowledge and a concerted effort towards advancing science. There is a lot to be gained from collaborating on ideas, scientific breakthroughs, and logistical support for common infrastructures. While the primary focus of R&D should be on particle physics research, it is also important to consider the impact on adjacent fields and high-tech research centers and industries. Furthermore, the reinforcement of the community and the promotion of collaborations is an essential goal. This can be achieved through the provision of training schemes throughout Europe, including the establishment of a core syllabus for Masters's degrees in particle physics instrumentation that consolidates essential elements from a wide offer of existing courses. As access to education and training in instrumentation can vary significantly across different regions of the world, it is important to prioritize the inclusivity of future programs, workshops and schools, and encourage the participation of a diverse range of individuals.

I.2 Scientific Organization of the DRD1 Collaboration

The DRD1 Collaboration aims at promoting the development, diffusion and applications of gaseous detectors, and is organized according to the General Strategic Recommendations outlined in the ECFA Detector R&D Roadmap Document [14]. The following pillars form the foundation of this Collaboration:

- **Community-Driven Collaboration**: The Collaboration is driven by the community, providing a vital forum for exchanging ideas and establishing synergies to minimize duplicated efforts.
- **Recognition and Support for young R&D Experts**: The Collaboration will promote proper recognition and support for the careers of instrumentation R&D experts. This support will be facilitated through the member institutes and their interface with the scientific community and institutions.
- **Dynamic and Open R&D Environment**: The Collaboration will strive to create and maintain an up-to-date, dynamic, and open R&D environment. This environment will support the development of necessary tools such as simulation and electronics, as well as the infrastructure required to undertake R&D on novel detectors and to validate their performances against the demanding specifications of future facilities and applications.
- **Global Network and Access to Facilities**: Leveraging its worldwide international network, the Collaboration will facilitate access to testing facilities and advanced engineering support available at DRD1 research laboratories and institutes.
- **Support for "Blue-Sky" R&D**: The Collaboration will actively support "Blue-Sky" research and development, which can lead to breakthroughs driven by technology. Common resources will be allocated, leveraging the aforementioned R&D environment.
- **Efficient Resource Pooling**: The Collaboration aims for the most efficient pooling of resources through joint projects that will undergo international review. It will promote and support research plans that attract long-term funding, enabling the community to effectively address future technical challenges. These efforts will also help to build strong relationships between institutes and industrial partners.
- **Increasing Research Potential**: By adding critical mass to the needs of individual institutes, the Collaboration aims to reduce research costs and enhance potential and results.

In the next paragraphs, the Scientific organization will be presented.

I.2.1 Scientific Organization

The Collaboration will have a scientific organization based on Working Groups (WGs). These WGs will be a scientific reference for the community and will provide a platform for sharing knowledge, expertise, and efforts. They will play a crucial role in identifying, guiding, and supporting strategic detector R&D directions, facilitating the establishment of joint projects between institutes. Two types of joint projects will be implemented: Common Projects (CP) and Work Packages (WP). CPs are short-term projects with limited time and resources, supported by the Collaboration. WPs, on the other hand, encompass long-term projects with significant strategic R&D goals and corresponding funding lines. The following sections will provide a brief description of Working Groups, Common Projects, and Work Packages.

I.2.1.1 Working Groups

The Collaboration will be organized into Working Groups (WGs), serving as the backbone of the proposed R&D environment and framework. WGs will support the development of novel technologies and the consolidation of existing ones. They will facilitate the exchange of ideas and foster synergies between institutes, serving as a knowledge and technology hub. Additionally, they will be recognized as a scientific reference for the community. The proposed WGs are the following ones:

WG1: Technological Aspects and Developments of New Detector Structures, Common Characterization and Physics Issues

Working Group 1 will be dedicated to studying and monitoring advancements in technologies such as wire, RPC, MPGD, TPC and Large Volume Detectors (LVD) such as TPC and Drift Chambers. A diverse range of technologies must be developed to meet the requirements of future experiments while considering cost-effectiveness and sustainability. Enhancing existing detectors to increase their size, operate at higher rates, function with lower backgrounds, improve stability, and enhance performance demands the exploration of new technologies and innovations. The collaboration's objective is to foster information exchange among member groups. Working Group 1 will function as a scientific benchmark for the community, providing valuable peer review, guidance and expertise.

WG2: Applications

Working Group 2 will focus on applications that use gaseous detectors technologies as sensing and amplification mediums. Events will be organized to foster scientific and technical collaboration across a wide spectrum of applications, both common and diverse. The initiatives carried out within DRD1 Work Packages will be closely monitored throughout WG2 activities, ensuring continuous oversight and a rigorous peer-review process within the collaboration. During Collaboration events, WG2 will host sessions, providing all members the opportunity to showcase their work. Furthermore, special-topic events will be organized with the aim of integrating inputs from other communities into our own.

WG3: Gas and Material Studies, and link to Novel Technologies

Working Group 3 is dedicated to tackling critical issues related to gas and material studies that are universally applicable to all existing gaseous detectors technologies. Topics such as high-performance and environmentally friendly gas mixtures, gas systems, and material studies, including wires, resistive materials and solid converters, as well as considerations for long-term operation, are central to advancing knowledge in this field and are covered by WG3. The primary goal is to explore new possibilities and to address existing or potential limitations that could impede the application of gaseous detectors technologies in future experiments. This working group provides a platform to establish common objectives, encourage collaborative efforts, guide systematic studies, and facilitate the availability of community resources and facilities.

WG4: Detector Physics, Modelling and Simulation frameworks

Working Group 4 aims at understanding and modelling the basic physical processes taking place in gaseous detectors, the development of suitable simulation and software tools able to reproduce the physical processes and predict detector performance. Advanced detector physics simulations are indispensable tools for the development and optimization of modern particle detectors. They allow to confirm or challenge the understanding of the physics and they are nowadays used standardly to understand the performance of existing detectors or to evaluate the validity of newly designed detection schemes. WG4 will represent a platform to review different approaches and solutions, to exchange best practices and developments, to cluster and optimize resources.

WG5: Electronics for Gaseous Detectors

Working Group 5 is dedicated to developing, applying, and disseminating electronic components necessary for advancing, qualifying, and operating Gaseous Detectors. WG5 serves as a hub for pooling interests and resources among DRD1 groups. This includes optimizing analog front ends for specific needs, designing new front-end ASICs (from specifications to pre-production prototyping and testing), supporting the development of DAQ systems for R&D and application in small- to mid-size experiments (like the RD51 Scalable Readout System), implementing spark protections, managing high- and low-voltage systems, and deploying monitoring equipment.

WG6: Production and Technology Transfer

Working Group 6 focuses on the manufacturing and production aspects of gaseous detectors, covering all essential construction elements, enabling the realization of innovative solutions and the efficient implementation of industrial technology. The group supports the development of cost-effective industrial technology solutions by improving production processes and assisting the transfer to industry. The proposed objectives within Working Group 6 include the development and maintenance of common production facilities and equipment, the support for quality control and large-volume productions, the collaboration with industrial partners., and the sharing of experiences, knowledge, and best practices.

WG7: Common Test Facilities and Infrastructures

Working Group 7 aims to facilitate access to analysis, characterization and testing facilities for prototypes and the final detector system. Irradiation and test beam facilities will be under the focus of WG7 in addition to specialized laboratories for specific measurements (in synergy with WG3). A strategic worldwide distributed network of research laboratories will be established to cover the wide community and the wide research interest in DRD1. instrumentation and software sharing will be covered, avoiding duplication of efforts, standardizing methodologies and measurements, and optimizing resources.

WG8: Knowledge Transfer, Training and Career

Working Group 8 concentrates on knowledge exchange, training opportunities, outreach and education, promotion of positive environment and better recognition for early career researchers. Its objective is to facilitate scientific exchanges in the gaseous detectors community and to educate and retain experts in the field of gaseous detectors development. By organizing regular knowledge-sharing and training events, WG8 provides opportunities for scientific exchange and assists in identifying common interests among DRD1 members. Strong connections will be established with the other Working Group to identify topical areas of focus.

These Working Groups will guide new developments and provide support for the research activities of Collaboration members.

I.2.1.2 COMMON PROJECTS

Common Projects (CPs) will support "Blue-Sky", generic R&D, and projects that are crucial for the community. These projects promote collaborative efforts involving a minimum number of participating institutes. CPs will be approved and reviewed by the DRD1 management and supported by DRD1 Common Funds, along with matching resources from participating institutes. CPs are limited in duration and financial support. CPs proposed by early-career researchers will be promoted; they will offer an opportunity for these researchers to gain experience in starting and managing small-scale R&D projects and to gain visibility within the Collaboration. Successful Common Projects may evolve into Work Packages.

I.2.1.3 WORK PACKAGES

Work Packages (WPs) will consolidate the activities of institutes with shared research interests in specific areas, including applications (e.g., TPC, Muon Systems, Calorimetry), challenges (e.g. Precise Timing, High Rate, Longevity), technologies (e.g. Resistive Electrodes, Photocathodes), detector technologies (e.g., MPGDs, RPCs, Wires), and Working Group tasks (e.g., electronics, software). These WPs will actively contribute to the scientific program, R&D environment, infrastructure, and R&D tools within DRD1. Whenever feasible, WPs will integrate activities from the Working Groups (e.g., simulation, electronics). WPs can be initiated at any time and will be internally organized and coordinated by the participating institutes. They will define their scope, deliverables, work plan, and the necessary resources in detail. The participating institutes will have complete control and operational authority over the allocated resources.

To establish the proposed activities and secure the required resources, a formal agreement will be established among the participating institutes, funding agencies, DRD1 management, and the host lab (CERN). Each Work Package Agreement will be included as an annexe in the DRD1 MoU. WPs will report to DRD1 and undergo review by the Detector Research and Development Committee (DRDC). The funding for WPs will be provided to the participating institutes by their respective Funding Agencies through major funding lines aligned with the strategic detector R&D priorities outlined in the ECFA detector R&D roadmap [14]. While the internal scientific review will be done by the Collaboration Bodies, the involved Funding Agencies will be asked to approve their financial commitment in the WPs.

I.2.2 Work Packages

The next section will give a general description of the Work Packages that will be considered in the starting phase of DRD1. The following tables present the high-level Milestones (M) and Deliverables (D) for the upcoming three years. The tables presented in the proposal aim to contextualize the activities and highlight relevant research lines in a more general way to cover the long-term perspectives in this field of research.

A comprehensive list of detailed milestones and deliverables for each WP is available in the annexed documents. The progress will be monitored by the collaboration bodies and will be easily accessible for reference during the annual reviews in the upcoming years, as well as upon DRDC or funding agencies request.

I.2.2.1 WP1:TRACKERS/HODOSCOPES

The primary objective of WP1 is to strategically advance R&D in the domain of resistive gaseous detectors for applications such as trackers, hodoscopes, and large-area muon systems for new challenges at future facilities. The goal is to strengthen their stability, robustness, and long-term performance, as well as to optimise cost-effective manufacturing together with industrial partners.

The main challenges for future muon systems include the following:

- Extending the state-of-the-art rate capability by at least one order of magnitude up to a few MHz/cm^2 with longevity compatible with decades of operation. This involves advancements in detector resistive configurations, new materials and geometries for improved signal pick-up, low-noise electronics, and fine granularity readout to reduce occupancy.
- Enabling reliable and efficient operation with suitable low-GWP gas mixtures.
- Improving time resolution at the level of nanosecond and achieving resolutions up to 10-100 ps for applications in high-rate collider experiments to mitigate pile-up effects
- Establishing large-scale serial production and cost reduction measures
- Addressing low/medium-rate applications involving muon tracking in HEP experiments like at FCCee, and exploring applications beyond HEP for large areas (in connection with WP9)

In addition to muon tracking, segmented tracking/vertexing is nowadays accomplished with MPGDs in the inner regions of experiments at low-energy electron colliders, where this technology can be conveniently applied. Examples include low-mass cylindrical GEMs (KLOE, BESIII) as well as the recent developments on cylindrical micro-RWELL (proposed for SCTF and EIC). Although the geometrical characteristics of inner and outer trackers differ significantly, they share many of the challenges mentioned above.

Activities dedicated to new ideas of detector structures for this purpose are considered, including the hybridization of novel detectors with established technologies.

A work package (WP1) addressing the R&D needed for such trackers/hodoscopes (large area muon systems, inner tracking/vertexing) is presented in Table 1.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable 12M	Milestones/Deliverable 24M	Milestones/Deliverable 36M	Institutes
T1	New RPC structures	- Develop low-cost resistive layers - Increase rate capability from 10 kHz to 1 MHz per cm^2 - Improve timing resolution from sub-ns to ps levels	WG1, WG2, WG3, WG4, WG5, WG6, WG7, WG8	1.1, 1.3	**M1.1** **Review of Detector Prototypes:** examining the current status and future prospects of innovative resistive materials, novel structures, and challenges in hybridizing Resistive Plate Chambers (RPC) and Micro-Pattern Gas Detectors (MPGD). This evaluation includes compiling of a comprehensive report highlighting comparative performance, along with the respective advantages and disadvantages of available technologies. **[T1, T2, T5, T6, T7, T8]** **M1.2** **Review of the status of the art of ASICs and DAQ systems**, and definition of the requirements for next-generation large area muon systems. **[T3, T4]**	**M2.1** **Detector Prototypes Enhancement:** building upon the insights from M1.1. Proof of rate capability above 100 kHz/cm^2, assessing the status and potential improvements of RPC and MPGD detectors, informed by feedback from the previous phase. **[T1, T2, T5, T6, T7, T8]** **M2.2** **Design and Simulation studies of new ASIC**: Building blocks for MPGD and RPC and technical note(s) about the chips expected performance. **[T3]** **M2.3** **Design of a novel readout system for Gaseous Detectors**: assessment of performance achievements based on DAQ modelling. **[T4]**	**D1** **Large area RPC and MPGD prototypes:** design, construction, and test of RPC and MPGD-based prototypes **[T1, T2]** with advanced solutions for extensive surface coverage **[T6]**, optimized for medium-high flow rates (range tens kHz/cm^2 – few MHz/cm^2), precise tracking (100 µm) and timing (ns and sub-ns time resolution). This includes considerations for the compatibility of eco-friendly gases. **[T5, T7]** **D2** **New frontend and DAQ systems:** completion of the innovative ASICs' final design; compilation of comprehensive production documentation; if applicable, initiation of the engineering run for the first chip, should it be in an advanced stage **[T3]**. DAQ system prototyping for gaseous detectors, aiming to push the boundaries in terms of timing, radiation resistance, multi-channel high rate acquisition and performance, for large systems **[T4]**.	INFN-BA, UniBA, PoliBA, INFN-LNF, INFN-RM2, UniRomaTOV, INFN-BO, INFN-FE, INFN-NA, INFN-RM3, INFN-TO, IRFU/CEA, IFIN-HH, Istinye U, CERN, CIEMAT, LMU, WIS, Wigner, U Kobe, U Cambridge, USTC, U Oviedo, UNSTPB, UTransilvania, VUB and UGent, U Genève, U Hong Kong, MPP, BNL, FIT, JLab, MSU, Tufts, UC Irvine, U Florida, U Massachusetts, Amherst, U Michigan, UW–Madison, IGPC
T2	New Resistive MPGD Structures	- Stable up to gains of $\mathcal{O}(10^6)$ - High gain in a single multiplication stage - High rate capability (1 MHz/cm^2 and beyond) - High tracking performance (100 μm) - Development of low-granularity 2D-readout with high-tracking performance						
T3	New Front-end electronics	- New front-end - 1 fC threshold - High-sensitivity electronics to help achieve stable and efficient operation up to ≈MHz/cm^2 - High granularity detector capability						
T4	Optimization of scalable multichannel readout systems	- Front-end link concentrator to a powerful FPGA with possibilities of triggering and ≈20 GBit/s to DAQ for high-rate experiment -Develop robust, compact, and low power DAQ for low-rate experiment						
T5	Eco-friendly gases	- Guarantee long-term operation - Explore compatibility and optimized operation with low-GWP gases						
T6	Manufacturing	- Technological transfer for cost-effective production of high-quality, high-performance large area resistive MPGD. - Reliable production of homogeneous resistive large DLC foils with the CERN-INFN sputtering machine						
T7	Longevity on large detector areas	- Study discharge rate and the impact of irradiation and transported charge (up to C/cm^2) - Study the impact of low-GWP gases and new materials on high radiation hardness environment						
T8	New Hybrid-multi-technologies Structures	- Development of new ideas of detector structures and hybridization						

Table 1: WP1 - a work package on trackers/hodoscopes (large area muon systems, inner tracking/vertexing). Area of application: future electron colliders (ILC/C^3, FCC-ee, CEPC), Muon collider, Hadron Physics, FCC-hh, muography. Technologies: RPC, MICROMEGAS and GEM, micro-RWELL, GridPix, micro-PIC, FTM, MWPC (DT, CSC, TGC).

The main drivers of R&D will involve the study and implementation of new materials, such as HPL, low-resistivity glass, semiconductors, printer-resistant patterns, and DLC-sputtered electrodes. Furthermore, there will be a focus on improving the detector layout to address the challenges mentioned above, along with enhancements in manufacturing. In conjunction with these detector-related efforts, advancements in electronics and readout technology will be essential to push the boundaries of state-of-the-art applications.

I.2.2.2 WP2: Inner and Central Tracking with PID Capability, Drift Chambers

The project aims to cover strategic R&D towards the development of large-volume drift chambers proposed as tracking and particle identification devices for the next generation of lepton colliders both at FCC-ee (CERN) and at CEPC (IHEP China). Analogous proposals exist for the next generation of flavour factories SCTF (Russia, China) and could easily be adapted for Electron-Ion Colliders. Drift chambers provide high-precision tracking even at low transverse momentum thanks to the high transparency and excellent particle identification by profiting from the cluster counting information. Key aspects of the R&D challenges are related to the mechanics, the electronics and the choice of gas mixture. The list of tasks and their goals, milestones, and deliverables, together with the list of participating institutes is summarized in Table 2.

I.2.2.3 WP3: Inner and Central Tracking with PID Capability, Straw and Drift Tube Chambers

Straw chamber and drift tube technologies are widely used in particle physics experiments and can cover a broad range of future applications from high-energy physics (HEP) and hadron physics at future accelerators (e.g. FCC-ee, CEPC, FCC-hh, FAIR) to Dark sector, rare event searches and neutrino physics experiments. The aim of this work package is the optimization of the technologies, including the development of straw tube and detector designs, materials, production techniques, electronic readout with ASIC design, and prototype and demonstrator setups with test measurements. The covered broad application range requires investigation of a large variety of technical topics. Key research aspects are:

- Minimal material budget by ultra-thin straws and self-supporting modules.
- Large detector areas by ultra-long straws with thin film walls in vacuum.
- Central straw tracker with enhanced 4D+PID measurements (3D, time t0, dE/dx).
- Straw and drift tube technologies including ASIC design for high rate applications.

Table 3 lists tasks, performance goals, milestones, deliverables and participating institutes in this work package.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable			Institutes
					12M	24M	36M	
T1	Front-end ASIC for cluster counting	- High bandwidth - High gain - Low power - Low mass	WG1, WG2, WG3, WG4, WG5, WG7	1.1, 1.2, 1.3	**M1.1** **At least 80% efficiency** of the cluster counting/timing with resolution in dn/dx smaller than 30% for a single hit. **[T1]** **M1.2** **Design of the frontend ASIC** optimized for cluster counting. **[T1]**	**M2.1** **Completion of the mechanical design** of the full length drift chamber prototype. **[T3]** **M2.2** **Validation of the tension recovery scheme. [T3]**	**D1** **Realization of a scalable front-end/digitizer/DAQ** electronics chain for cluster counting/timing. **[T1-T2]** **D2** **Performance of** ***K*-π separation** in the momentum range from 2 to 30 GeV/*c*. **[T1-T2]**	CNRS-IN2P3/IJCLab, INFN-BA, UniBA, PoliBA, INFN-LE, INFN-RM1, U Massachusetts, Amherst, U Michigan, UC Irvine, Tufts, BNL, FIT, U Florida, UW–Madison, U Nankay, U Tsinghua, IHEP CAS, U Wuhan, U Jilin, USTC, IMP-CAS, Bose
T2	Scalable multichannel DAQ board	- High sampling rate - Dead-time-less - DSP and filtering - Event time stamping - Track triggering						
T3	Mechanics: wiring procedures, new end-plate concepts	- Feed-through-less wiring procedures - More transparent end-plates ($X < 5\% X_0$) - Transverse geometry						
T4	High rate High granularity	- Smaller cell size and shorter drift time - Higher field-to-sense ratio						
T5	New wire materials and wire metal coating	- Electrostatic stability - High YTS - Low mass, low Z - High conductivity - Low ageing						
T6	Study ageing phenomena for new wire types	- Establish charge-collection limits for carbon wires as field and sense wires						
T7	Optimize gas mixing, recuperation, purification and recirculation systems	- Use non-flammable gases - Keep high quenching power - Keep low-Z - Increase radiation length - Operate at high ionization density						

Table 2: WP2 - a work package on inner and central tracking with PID (Drift Chambers). Area of application: future electron colliders (FCC-ee, CEPC), flavor factories (SCTF).

I.2.2.4 WP4:Inner and Central Tracking with PID Capability, Time Projection Chambers

Time Projection Chambers (TPCs) have been extensively studied and used in many fields, especially in particle, nuclear and neutrino physics experiments. Their good tracking performance is complemented by their ability to do excellent dE/dx measurements in the range of 2-20 GeV, their excellent performance in high-density environments, because of their intrinsic 3D measurements, and their low and homogeneously distributed material budget. Therefore, TPCs are planned to be used as main tracking devices in future HEP experiments and further developments are mandatory to adapt the current readout to the requirements of the new accelerators, where in particular the high rates pose new challenges. Also, smaller size TPCs are a good choice for beam diagnostics operating in high particle rate environments. The ECFA detector R&D roadmap lists four Detector Research and Development Themes, which are all relevant for the future developments of TPCs and therefore are priority topics in this work package as stated in Table 4. The 5 tasks of the work package reflect the most important challenges to be addressed for future applications.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable			Institutes
					12M	24M	36M	
T1	Optimize straw materials and production technologies	- Thin film materials - Film metallization - Low cross-talk - Resistance to ageing - Production techniques	WG1, WG2, WG3, WG4, WG5, WG6, WG7, WG8	1.1, 1.2, 1.3	**M1** **Work plan consolidation:** finalise work package objectives and decide final straw designs including simulation studies. Setting up laboratories, production and test facilities. Tendering and procurement of materials. **[T1-T7]**	**M2.1** **Prototype design and construction:** optimization of straw materials, designs and production technologies for low radiation length, thin-wall tubes, small diameter tubes, long tubes and straws with enhanced longevity. **[T1-T3, T6]** **M2.2** **Optimization of the prototype mechanical system** with low material budget and high mechanical precision. Development of the alignment method. **[T3, T5, T7]** **M2.3** **Optimization of front-end electronic and ASIC design** based on existing ASICs and simulation studies for fast timing, signal leading and trailing edge time readout with high resolution and charge measurement for PID. **[T4, T5]**	**D** **Prototype tests and results:** performance of prototype designs and measurement resolutions (3D-space <150 µm, time t0 of $\mathcal{O}$(1 ns), dE/dx < 10%). **[T1-T7]** Evaluation of WP tasks with review of further enhancement and new potential. **[T1-T7]**	GTU, FZJ-GSI-U Bochum, U Hamburg, MPP, IITG, IITK, NISER Bhubaneswar, U Delhi, U Punjab, INFN-TO, INP-Almaty, JU-Krakow, IFIN-HH, CERN, U South Carolina, U Duke, BNL, FIT, JLab, U Massachusetts, Amherst, U Michigan, UC Irvine, UW–Madison, Tufts
T2	Develop straw tubes of 5mm diameter	- Thin film wall - Fast timing < 100 ns - Rates $\simeq$ 50 kHz/cm^2						
	Develop straw with ultra-thin film walls	- Film wall < 20 μm - X/X0 $\simeq$ 0.02% / straw - Film metallization						
	Develop ultra-long straws with thin film walls	- 4-5 m tube length - Film walls < 30 μm - Good mechanical properties						
	Develop straws with ultra-small diameter	- Diameter < 4mm - Rates > 500 kHz/cm^2 - Fast timing <50ns - Charge load >10 C/cm						
T3	Optimize the detector mechanical system	- Develop self-supporting modules - Control material relaxation - Straw alignment method						
T4	Optimize the front-end electronics (ASIC) and readout system	- Leading and trailing edge time readout - Charge readout - Time readout with sub-ns precision						
T5	Enhance the tracker measurement information (3D/4D and PID via dE/dx)	- Spatial resolution < 150 μm - Time t0 extraction with O(ns) resolution - dE/dx resolution <10% - p/K/π-separation						
T6	Enhance the detector longevity	Ageing resistance up to - 1 C/cm for thin-wall straws - >10 C/cm for straws for highest particle rates						
T7	Optimize the online-/offline software	- Straw tube simulation - Straw calibrations - Tracking simulation - Pattern recognition - Tracking and PID - Tracker alignment						

Table 3: WP3 - a work package on inner and central tracking with PID (Straw and Drift Tube Chambers). Area of application: future electron colliders (FCC-ee, CEPC), FCC-hh, FAIR, Dark Matter, rare event searches, and neutrino physics.

I.2.2.5 WP5: Calorimetry

Gaseous detectors have been playing an important role in sampling calorimeters since the birth of this kind of instrument. The possibility to produce large area detectors at affordable cost but still with excellent efficiency and high spatial precision makes them a choice of reference. Although many sampling calorimeters of the LHC experiments have opted for scintillators-based active media, gaseous detectors are being proposed again to equip future sampling calorimeters that use the Particle Flow Algorithm (PFA) concept. The latter requires the different detector systems and in particular, the calorimeters to be highly granular. Contrary to other technologies, the granularity of gaseous detectors can be very fine thanks to the small extension of the avalanches produced by the charged particles crossing

<table>
<tr><th rowspan="2">#</th><th rowspan="2">Task</th><th rowspan="2">Performance Goal</th><th rowspan="2">DRD1 WGs</th><th rowspan="2">ECFA DRDT</th><th colspan="3">Milestones/Deliverable</th><th rowspan="2">Institutes</th></tr>
<tr><th>12M</th><th>24M</th><th>36M</th></tr>
<tr><td>T1</td><td>IBF reduction</td><td>- Reduce IBF in case of gated operation
- Reduce IBF in case of ungated operation</td><td rowspan="5">WG1, WG2, WG3, WG4, WG5, WG6, WG7</td><td rowspan="5">1.1, 1.2, 1.3, 1.4</td><td rowspan="5">M1
Evaluation of various readout technologies: studies of various gas amplification and readout technologies including pixelised structures to estimate their potential performance in a TPC. [T1, T2, T4, T5]</td><td rowspan="5">M2.1
Improvement of dE/dx performance: experimental tests to optimize the dE/dx resolution in various gas mixtures.[T1, T2, T5]
M2.2
Improvement of IBF performance: experimental tests to reach an IBF performance optible with gain×IBF < 5. [T1, T2, T5]
M2.3
Electronics implemented in the SRS and ready for operation with small-scale prototypes. [T4]</td><td rowspan="5">D
Prototype TPC A small scale prototype detector with good spatial and dE/dx resolution to fulfil the requirements of future accelerators with a gated or ungated operation mode of the TPC. [T1-T5]</td><td rowspan="5">IFUSP, U Carleton, IHEP CAS, U Tsinghua, HIP, U Jyväskylä, IRFU/CEA, TUDa, U Bonn, GSI, Wigner, INFN-BA, UniBA, PoliBA, INFN-RM1, U Iwate, CERN, PSI</td></tr>
<tr><td>T2</td><td>pixelTPC development</td><td>- Develop different technologies for pixelized readout
- Build small prototypes to verify spatial resolution
- Study dE/dx resolution</td></tr>
<tr><td>T3</td><td>Optimization of mechanical structure</td><td>- Reduce material budget of mechanical and electrical field cage
- Reduce material budget of the endcap, in particular, the cooling infrastructure</td></tr>
<tr><td>T4</td><td>FEE for TPCs</td><td>- Develop a low-power ASIC for TPC readout
- Implement a readily available ASIC, which fulfils MPGD-TPC requirements in the Scalable Readout System
- Increase the readout rate of TPC-readout with SRS</td></tr>
<tr><td>T5</td><td>Gas mixtures</td><td>- Study drift properties of gas mixtures to find low diffusion gases
- Study gases with low $\omega\tau$ for improved performance of TPCs in magnetic fields
- Study eco-friendly gases.</td></tr>
</table>

Table 4: WP4 - a work package on inner and central tracking with PID (Time Projection Chambers). Area of application: future electron colliders (ILC/C^3, FCC-ee, CEPC), heavy ion, neutrino facilities.

them. Another important feature of the gaseous detectors used in sampling calorimeters is their capability to provide excellent efficiency with a thickness of a few mm. This represents an important asset since the PFA-based calorimeters are required to be enclosed in a magnetic field implying that a thinner active medium corresponds to lower cost. Several concepts of gaseous detectors were proposed to equip the sampling elements of hadronic calorimeters for experiments of future colliders. Large prototypes of Digital and Semi-Digital Hadronic calorimeters were built and successfully operated using RPC layers of a size up to 1 m x 1m equipped with embedded 1-threshold or 3-threshold digital readout electronics. These prototypes were originally proposed for the International Linear Collider (ILC). A similar but smaller system with a few 50 cm × 50cm MicroMegas and RPWELL sampling elements was built and characterized, demonstrating good performance. Other technologies like micro-RWELL have also very interesting features that allow them to be an excellent candidate to be active media in future calorimeters. To completely validate gaseous calorimeters for future Higgs factory for both linear and circular colliders further R&D are needed.
A work package summarising the main R&D tasks for calorimetry (WP5) is presented in Table 5.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable			Institutes
					12M	24M	36M	
T1	Conception, construction and characterization of large sampling elements for calorimeters	- High efficiency with thin large detectors - Compactness of the active unit including cassettes and possible cooling system - Uniformity in terms of thickness, resistivity and gas circulation	WG1, WG2, WG4, WG7	1.1, 1.3	**M1** **Construction of medium-sized gaseous detector** fulfilling the requirements on efficiency and small dead zones. **[T1]**	**M2.1** **Uniformity study** including efficiency and cluster size distribution with medium-size detectors. Expected timing performance better than 3 ns in the case of MPGD, 0. ns for RPC and 0.15 ns for MRPC with 4 gaps. **[T2]** **M2.2** **Construction of large and thin detectors** (few mm) of different technologies (MRPC, RPC, MM, µRWELL, RPWELL) with small dead zones (< 2% dead zone). We propose to build detectors larger than 50 cm × 50 cm in the case of MPGD and larger than 100 cm × 100 cm for (M)RPC, featuring dead zones < 2%. The detectors should feature an efficient gas circulation to be used as active layers in granular calorimeters. **[T1]**	**D1** **Performance and uniformity** studies of the large and thin detectors of different technologies. Performance goals in terms of: - detector uniformity: < 10% in terms of efficiency an in terms of cluster size **[T1]**, - time resolution below few ns **[T2]**, - high detection rate capabilities up to a few kHz/cm^2 **[T4]**, to be obtained with different kinds of gas mixtures. **D2** **The readout electronics [T3]** associated with pickup pads of the order of 1 cm^2: - threshold down to a few fC for MPGD and tens of fC for (M)RPC - time resolution better than 100 ps	IP2I, CIEMAT, VUB and UGent, GWNU, SJTU, MPP, WIS, INFN-BA, UniBA, PoliBA, INFN-RM3, INFN-NA
T2	Timing performance of gaseous detectors for calorimeters	- Timing performance of different technologies - Uniformity of the detector response in terms of timing						
T3	Readout electronics for calorimeter gaseous detectors	- Low-jitters readout electronics - Low power consumption per channel - Active Sensitive Unit (ASU) of large size with good flatness						
T4	High-rate capability gaseous detectors for circular collider calorimeters	- High-rate capability exceeding a few KHz in case of (M)RPC and tens of KHz in case of MPGD - Impact of high particle rate on the detector performance (efficiency, spatial resolution, timing..etc)						

Table 5: WP5 - a work package on calorimetry. Area of application: Future electron colliders (ILC/C^3, FCC-ee, CEPC, Muon collider, Hadron Physics). Technologies: RPC, MICROMEGAS, GEM, RWELL/RPWELL, micro-RWELL, GridPix, PICOSEC, FTM.

I.2.2.6 WP6: Photo-Detectors

Gaseous photon detectors have played an essential role in RICH applications and represent a potentially key element for future detectors in various domains. They can provide coverage of very large areas with photosensitive detectors at moderate cost, low material budget and magnetic insensitivity. The main R&D challenges for this application include:

- optimization of photocathodes efficiency by suppressing ion backflow and developing more robust photoconverters;
- develop photon detectors equipped with visible light sensitive photocathodes;
- improvement of the detector performance in terms of space and time resolution, along with a fast charge collection to maximize the rate capability;
- optimization of front-end electronics and DAQ systems for single photon signals.

A work package addressing the challenges of photo-detection (WP6) is presented in Table 6.

<table>
<tr><th rowspan="2">#</th><th rowspan="2">Task</th><th rowspan="2">Performance Goal</th><th rowspan="2">DRD1 WGs</th><th rowspan="2">ECFA DRDT</th><th colspan="3">Milestones/Deliverable</th><th rowspan="2">Institutes</th></tr>
<tr><th>12M</th><th>24M</th><th>36M</th></tr>
<tr><td>T1</td><td>Development of robust UV photoconverters for gaseous photon detectors</td><td>- Robustness against accumulated charge dose: < 20% deterioration of quantum efficiency for 100 mC/cm^2</td>
<td rowspan="9">WG1,
WG2,
WG3,
WG4,
WG5,
WG6,
WG7</td>
<td rowspan="9">1.1,
1.2,
1.3</td>
<td rowspan="9">M1
Design and production of small-size photon detector prototypes, e.g. THGEM + Micromegas equipped with hydrogenated nanodiamond photocathode [T1], PICOSEC Micromegas equipped with novel photocathodes [T6], Double Micromegas photon detectors [T3], etc. to test the proposed technological improvements.</td>
<td rowspan="9">M2
Results of simulations and measurements of IBF suppression [T7, T3], photocathode robustness [T1], a test of small-size prototypes [T2, T5] and new readout development, with low noise at low input capacitance [T9].</td>
<td rowspan="9">D1
Demonstrator prototypes for Large area Double Micromegas [T8], Space resolution < 1 mm [T5], Time resolution < 200 ps [T6], IBF < 1%.
Test bench for visible sensitive photocathodes studies [T4].
D2
Report on novel robust photocathode performance [T1] and PDE achievements [T2].
D3
New ASIC chip prototype integration [T9].</td>
<td rowspan="9">AUTH ,
USTC,
NISER Bhubaneswar,
CERN,
WIS,
INFN-PD, DFA-UNIPD,
INFN-TS,
HIP,
U Aveiro,
MSU,
TUM</td></tr>
<tr><td>T2</td><td>Increase the photon detection efficiency</td><td>- Photoelectron efficiency in gas ≥ 75% of that under vacuum</td></tr>
<tr><td>T3</td><td>Suppression of ion feedback to the photocathode, increase of stability and longevity</td><td>- Stable detector operation at 10^5 gain.
- IBF reduction down to 10^{-4}
- Stable operation in harsh environment (10^{11} n_{eq}/cm^2)</td></tr>
<tr><td>T4</td><td>Develop gaseous photon detectors sensitive to visible light</td><td>- Sustained photosensitivity to visible light in gaseous photon detectors</td></tr>
<tr><td>T5</td><td>Increase spatial resolution and readout granularity</td><td>- Spatial resolution ≤ 1 mm</td></tr>
<tr><td>T6</td><td>Increase time resolution</td><td>- Time resolution ≤ 100 ps</td></tr>
<tr><td>T7</td><td>Modelling and simulation of gaseous photon detectors</td><td>- Accurate simulation of IBF to the photocathode, gain and stability</td></tr>
<tr><td>T8</td><td>Large area coverage</td><td>- Gain and QE variation ≤ 10% over 1 m^2 area with ≤ 10% dead area.</td></tr>
<tr><td>T9</td><td>Readout electronics for single photon signals</td><td>New frontend ASIC chip with 64 channels, ENC 0.5 fC at 20pF</td></tr>
</table>

Table 6: WP6 - a work package on gaseous photon detectors. Area of application: nuclear physics, hadron physics, future ee, and eA machines.

I.2.2.7 WP7: Timing Detectors

Two main technologies are currently considered and developed in the field of timing detectors in the sub-nanosecond time domain: timing RPCs based on the multi-gap technology and MPGDs sensing Cherenkov light (PICOSEC). Depending on the application, developments focus on timing capabilities down to 20-200 ps, rate capabilities up to 30-150 kHz/cm^2 and large area coverage including with tileable modules, where different technologies can be used to fulfil the most challenging requirements. A work package (WP7) addressing the challenges for timing is presented in Table 7.

I.2.2.8 WP8: TPCs as Reaction and Decay Chambers

TPCs used as reaction and/or decay chambers are instrumental to the progress in the fields of Rare Event Searches, Neutrino and Nuclear physics. There is a general aim here to reach keV-sensitivities or lower, across pressures (10's of mbar up to 10's of bar). Ultimately, some of the new concepts will explore the possibility of achieving single-electron

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable			Institutes
					12M	24M	36M	
T1	Optimize the amplification technology towards large-area detectors	- Uniformity over m^2 (time resolution, rate capability, efficiency)	WG1, WG2, WG3, WG4, WG5, WG6, WG7	1.1, 1.3	**M1.1** **Prototypes review** (proof of concept, enhancing time resolution, active area of about 100 cm^2): status and perspectives. **[T1, T2, T5, T10]** **M1.2** **Common activities and material studies**: Support and development of modelling and simulation (time resolution, rate capabilities) tools and testing facilities (time resolution, rate capability, space resolution, gas and material studies). **[T3, T4, T6, T7, T8, T11]**	**M2.1** **Prototypes suitable for large area coverage systems** review: status and perspectives. **[T1, T3, T10]** **M2.2** **Multichannel readout electronics**: evaluation (on small prototypes, 100 cm^2 active area) of different multichannel readout solutions. **[T9]**	**D** **Prototypes with time resolution below 200 ps based on RPC/MRPC and MPGD technologies**: demonstrate the scalability of the technologies targeting m^2 size coverage. Prototypes will be characterized in terms of time resolution, rate capability, space resolution, efficiency and multi-hit response. Different examples of multichannel readout electronics will be provided. **[T1, T3, T4, T5, T9, T10]** **Guidelines for future developments**: At the end of the three years, development directions will be summarized based on future facilities' requirements and the achievable performances of the studied solutions. Status and strategies towards the use of sustainable gas mixtures will be given. **[T7]**	AUTH , CERN, CIEMAT, CNRS-IN2P3/Omega, DGIST, GWNU, HYU, HIP, INFN-BA, UniBA, PoliBA, INFN-PV, UniPV, UniBG, INFN-RM2, UniRomaTOV, IRFU/CEA, IP2I, JLab, LIP-Coimbra, MPP, RBI, SIAT, SJTU, U Heidelberg, U Kyoto, U Tsinghua, USTC, VUB and UGent
T2	Enhance timing performance	- Time resolution < 50 ps up to 30 kHz/cm^2						
T3	Enhance rate capability	- Time resolution < 200 ps up to 100-150 kHz/cm^2						
T4	Spatial resolution and readout granularity	- Spatial resolution of mm with low number of readout channels						
T5	Stability, robustness and longevity	- IBF <1% with <100 ps time resolution for single photoelectrons - Stable, high-gain operation						
T6	Material studies	- Radiation-hardness - Longevity						
T7	Gas studies for precise timing applications	- Eco-friendly mixtures - Recuperation - Ageing mitigation - CO_2-based mixture with geometrical quenching						
T8	Modelling and simulation of timing detectors	- Accurate modelling of charge transport and signal induction processes in precise timing detector geometries						
T9	Readout electronics for precise timing	- Low-noise FEE – High input capacitance – Large dynamic range – Fast rise time – Sensitivity to small charges - Multi-channel readout solution for timing detectors						
T10	Precision mechanics and construction techniques	- Precise mechanics (μm) over relatively large active areas (hundreds of cm^2)						
T11	Common framework and test facilities for precise timing R&D	- Test bench for precise timing studies						

Table 7: WP7 - a work package on gaseous timing detectors. Area of application: ToF-based PID, fast triggering system, timing calorimetry.

counting for either Dark Matter or neutrino coherent-scattering. At the same time, at low pressure, reconstruction of nuclei down to 10-100 keV through particle tracking is aimed at, for experiments requiring particle ID and/or directional information. At higher pressures of at least 10 bar, reconstruction of muon interactions with mm-sampling, MeV-threshold and ns-timing is of relevance to TPCs operating in neutrino beams. For the study of nuclear reactions, achieving a product $G * IBF$ of 10 or better is desirable towards operation in high-intensity rare-isotope beams, including a stable response for both high and low ionizing particles (large dynamic range). Improving radiopurity is key in most Rare Event TPCs, with background rates needed to go down to 10^{-6} c/keV/cm^2/s for axion research or $\times 10$ reduction in optical cameras, to name some of the most pressing cases. Developing new techniques to achieve T_0 determination is necessary to provide spill-synchronization, event fiducialization, PID, improve track-matching or provide a start time for time-of-flight measurements, depending on the application. For optical readout, be it for T_0 or track imaging, alternatives to CF_4 are needed or otherwise finding sensible ways to reduce its environmental footprint through recirculation or flow reduction, for instance. Electroluminescence keeps being a relevant imaging and (especially) calorimetric technique, and new technologies for large-area coverage will be explored, focusing on the suppression of sagging and deformation at scales of 50 cm $\times$ 50 cm and beyond.

I.2.2.9 WP9: Beyond HEP

The aim of the Work Package is the coordinated development of detector technologies which are based on those applied in HEP, but need adaptation to the requirements for a broad range of non-laboratory applications, including those outside fundamental science. The key application areas are the following:

- cosmic muon imaging (muography) and large area applications; public safety and mining industry
- dosimetry/beam monitoring and medical imaging applications (PET, CT, X-ray, SPECT, Gamma cameras, or X-ray fluorescence imaging)
- fast/thermal neutron imaging with solid converters for neutron science, neutron beam monitoring, tomography and nuclear waste monitoring

The objectives are grouped around these applications rather than gaseous technologies, facilitating communication with the application experts and allowing comparison of various solutions. The goals and deliverables are presented in Table 9 and will lead to prototypes demonstrating field measurements, detectors in medical environments and detectors fully optimized for neutron facilities such as the ESS.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable			Institutes
					12M	24M	36M	
T1	Enhanced operation of optical readout across gas densities	- $\mathcal{O}$(mm)-sampling, $\mathcal{O}$(MeV)-threshold, $\mathcal{O}$(ns)-timing for ν-interactions. - Large-area amplification structures ($\gtrsim$ 50 cm $\times$ 50 cm) at optical gain $\sim 10^4$. - Tracking of low-energy nuclei (down to 10-100 keV) with good PID.	WG1, WG2, WG3, WG4, WG5, WG6, WG7	1.1, 1.2, 1.3, 1.4	**M1.1** **Review and design**: review of TPC technologies for reaction/decay studies: status and perspectives; design/construction of small R&D chambers. **[T1-T7]** **M1.2** **Development and tuning of simulation tools**: design, development and/or tuning of modelling and simulation tools (IBF, ionization, optical response, Geant4). **[T1-T7]**	**M2.1** **Construction of prototypes**: start construction of technology demonstrators for large area coverage. **[T1-T7]** **M2.2** **Characterization of key technologies**: characterize electronics, amplification structures and overall TPC behaviour in small R&D chambers, comparison with simulations. **[T1-T7]**	**D1** **TPC commissioning and proof of principle demonstration**: characterization of mid-size technology demonstrators for reaction/decay studies, focusing on energy and tracking thresholds, energy resolution, dynamic range and IBF. **[T1-T7]** **D2** **Analysis and definition of next steps**: establish guidelines for future developments based on requirements from future facilities and the achieved/achievable performances. **[T1-T7]**	ANU, AstroCeNT, CERN, DIPC, Fermilab, GANIL, CNRS-IN2P3/UGA, GSSI, HIP, IFAE, Imperial, INFN-BA, UniBA, PoliBA, U Bonn, RHUL, RWTH Aachen, STFC-RAL, U Bonn, IGFAE/USC, INFN-PD, DFA-UNIPD, INFN-RM1, IRFU/CEA, ISNAP, LIP-Coimbra, MSU, SINP Kolkata, U Aveiro, U Coimbra, U Genève, U Hamburg, UH Manoa, U Indiana, U Kobe, U Liverpool, U Bursa, U New Mexico, UPV, U Vigo, U Warwick, CAPA, IFIC
T2	Enhanced operation of charge readout across gas densities	- Large-area MPGDs ($\gtrsim$ 50 cm $\times$ 50 cm) at $\sim 10^3 - 10^4$ gain. - Large-area MPGDs ($\gtrsim$ 50 cm $\times$ 50 cm) with a large dynamic range. - $\mathcal{O}$(1 keV) threshold across pressures (100 mbar-10 bar) in $\mathcal{O}$(1000 cm^3) technology demonstrators. - IBF suppression by G*IBF=10 or better.						
T3	Enhanced operation of pure or trace-amount doped noble gases	- EL operation at 2m (15bar) and 0.5m (>20bar) scale, with <10% deformation. - Single-electron thresholds on large areas for mixtures of noble gases. - MPGD concepts with enhanced EL-response (up to or above 1000 ph/e). - Improve light collection for large volumes. - Integrated, low-power and radiopure electronics for EL-based tracking.						
T4	Ultra-low-energy reconstruction of highly ionizing tracks (including R&D on negative-ion readout)	- Tracking of low-energy nuclei (down to 10-100 keV) with good PID. - High dynamic range for the reconstruction of low and highly ionizing particles. - Single electron counting at $\mathcal{O}$(100 µm) in 3D, and diffusion at the thermal limit.						
T5	Determination of the interaction time (T_0)	- Develop new gaseous WLS and novel gaseous scintillators, comparable or better than CF_4. - Demonstration of T_0-determination for low-energy deposits with at least $\mathcal{O}$(cm) resolution.						
T6	Microscopic gas properties and gas handling	- Develop the science and technology of novel eco-friendly gases. - Derive microscopic parameters for new gases.						
T7	Radiopurity	- Background levels below 10^{-6} c/keV/cm^2/s for axion research and at least $\times$10 more radiopure cameras. - New radiopure amplification structures and techniques.						

Table 8: WP8 - a work package on TPCs used as reaction/decay chambers. Area of application: rare event searches (DM, solar axions, $\beta\beta0\nu$-decay), active targets for nuclear and neutrino physics.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable 12M	Milestones/Deliverable 24M	Milestones/Deliverable 36M	Institutes
T1	Cost-efficient large-size outdoor detector structures: design and construction	- Robust, cost-efficient large detectors - Design chain, materials and construction compatible with outdoor use	WG1, WG2, WG3, WG4, WG5, WG6, WG7	1.1, 1.3	**M1.1** **Muon imaging and extreme environment solutions:** evaluation of proposed technologies and solutions leading to applicability in environments and configurations relevant to BHEP. This includes maintenance-free operation, extreme or outdoor temperature- and humidity ranges. **[T1-T6]** **M1.2** **Evaluation of detector technology for medical applications:** characterization of application-specific radiation fields and of different gaseous detectors for beam monitoring, beam characterization and photon-based imaging using detailed simulations and already existing prototypes. Assessment of suitability of respective detector technology and customization of design to application. **[T7-T9]** **M1.3** **Study of neutron converter materials realisation processes:** definition of realisation processes and characterisation of solid/gas converters of different areas. Estimation of expected detection efficiency. Evaluation of intrinsic background due to employed materials and definition of common strategies to limit it. **[T10-T12]**	**M2.1** **Muon imaging and extreme environment demonstrations:** demonstration of the technological concepts and proposed solutions in conditions relevant to BHEP applications: field installation of cosmic imaging detectors, demonstration of portability and low (zero) flow operation. **[T1-T6]** **M2.2** **Characterization of prototype detectors for medical applications:** demonstration and characterization of the developed prototype detectors in pre-clinical and clinical environments, for medical photon detection and in space radiation simulating beams. Optimization of detector performance. **[T7-T9]** **M2.3** **Characterisation of key aspects of gaseous neutron detectors:** determination of efficiency and maximum achievable rate capability of different detector prototypes. Evaluation of gamma-ray sensitivity and neutron discharge probability. Measurement of spatial resolution and image capability reconstruction.Determination of radiation hardness of front-end electronics. **[T4,T10-T12]**	**D1 Performance evaluation of cosmic imaging detectors and operation in extreme conditions:** summary report on prototype performance, including available and demonstrated technological solutions to address long-term outdoor operation (more than 1 year, temperature 0 – 40 deg), portability (meeting ASTM shipping standards), longevity, low power (below 10 W). Critical comparison of various technologies and solutions, identification of general guidelines for high-performance instruments and for technological transfer towards commercialisation. **[T1-T6]** **D2** **Performance evaluation of detectors for medical applications:** assessment and description of realization, operation and performance of different detector technologies in clinical and pre-clinical environments, for medical photon detection and related applications. Description of integration possibilities. **[T7-T9]** **D3** **Performance evaluation of gaseous neutron detectors:** comparison of performances of the different detector technology prototypes in terms of efficiency (1-40% for thermal neutrons), rate capability (order MHz/cm^2), background suppression, spatial resolution (sub-mm) and image capability reconstruction. Determination of the most suitable technologies for specific applications. Definition of next steps for future gaseous neutron detectors development. **[T10-T12]**	UNIMIB, IRFU/CEA, NISER Bhubaneswar, U Coimbra, LMU, Wigner, U Bonn, AGH-Krakow, ESS, Istinye U, U Hamburg, U Sofia, VUB and UGent, CNRS-LSBB, GSI, UCLouvain, MedAustron, OXY, U Johannesburg
T2	Mechanical and environmental stability of detectors under outdoor or extreme conditions	- Mechanical stability during transportation - Long-term sustainment of daily and yearly temperature cycling - Compatibility with medical equipment guidelines						
T3	Detector portability and low maintenance operation	- Portable structure, low weight, integrity - Fast installation and low maintenance need - Low or zero gas consumption						
T4	Cost-efficient, low power, long-lived Front-End and DAQ systems	- Low power, high channel number, high efficiency - Readout optimized and operating in an intense neutron field						
T5	Detector optimization and simulation methods for muons and neutrons	- Low background for surface- and underground muon imaging - Optimized structures using novel neutron converters						
T6	Benchmarking performance, infrastructures and knowledge transfer	- Definition of benchmarking parameters for muography, medical and neutron science - Characterization of benchmark sites, comparative measurements						
T7	Optical readout MPGDs for bio-marker imaging and beam characterization in ion beam therapy	- Ability to measure sub-Becquerel activities in single cells - Reliably determine pre-clinical and clinical beam parameters with well-characterized detector						
T8	Gaseous photon detectors for in-beam monitoring for ion beam therapy and imaging	- Optimization of detector concept with good time resolution for in-beam range verification - Study detection efficiency for annihilation photons and temporal resolution						
T9	Beam monitors with high temporal resolution for ion beam therapy and space radiation simulation	- Monitor clinical ion beams at normal and high dose rates with µs resolution - Monitor space radiation simulating secondary beams at high and low fluence in real-time						
T10	Study of Innovative neutron converters with gaseous amplifying structures for high-rate, efficient, low-background detectors	- Optimizing 2/3D solid-state large area and gaseous converters - Enhancement of combined converter and amplification structures -Evaluation and limitation of intrinsic background.						
T11	Spatial resolution, readout granularity and rate capability impact on neutron imaging and dosimetry	- Enhancement of spatial resolution and evaluation of image-capability reconstruction, sensitivity and dosimetry capability.						
T12	Study of Gamma Ray sensitivity and neutron discharge probability	-Evaluation of gamma rays sensitivity at high flux facilities -Study of neutron-induced discharge probability -Study in clinical environments						

Table 9: WP9 - a work package on Beyond HEP applications. Area of application: muography, neutron sciences, medical physics

I.3 Collaboration Organization

I.3.1 Collaboration Organization

The organization of the collaboration will be determined and agreed upon during the initial formation phase, where the management structure and roles will be defined.

The Collaboration aims to implement the following:

- **Collaboration Meetings**: Regular collaboration meetings will be organized to provide a forum for collaboration members to discuss progress, share updates, and address any challenges. These meetings will promote collaboration and ensure alignment with the overall goals and objectives of the collaboration.
- **Communication Channels**: Effective communication channels will be established to facilitate seamless information exchange among collaboration members. This will include a dedicated collaboration website[1], email lists, and online collaboration tools to enable real-time communication and document sharing.
- **Reporting and Evaluation**: Collaboration members will be required to provide regular progress reports on their activities. These reports will be evaluated by the relevant committees, such as the Detector Research and Development Committee (DRDC), to ensure accountability and assess the overall progress of the collaboration.
- **Intellectual Property and Publication Policies**: Clear guidelines will be established to address intellectual property rights and publication policies. Collaboration members will be encouraged to publish their research findings while respecting any confidentiality requirements and adhering to the appropriate acknowledgement of the collaboration and its members.

I.4 Resources and Infrastructures

I.4.1 DRD1 Funding Framework

DRD1 presents a lightweight funding framework inspired by the RD51 model, whereby each institute contributes limited and fixed yearly contributions to the Collaboration Common Fund. This framework aims to facilitate the international organization of common R&D activities by providing the necessary flexibility and adaptability to meet the evolving needs and requirements of the collaboration. It enables efficient coordination and implementation of common R&D projects, fostering streamlined collaboration among member institutes. Additionally, to promote the establishment of long-term strategic funding lines, the framework incorporates resource-loaded Work Packages that govern the allocation of major resources provided by the respective Funding Agencies to the participating institutes.

[1] `https://drd1.web.cern.ch/`

WP	Description	Material [kCHF] (2024)	Material [kCHF] (2025)	Material [kCHF] (2026)	FTE (2024)	FTE (2025)	FTE (2026)
WP1	Trackers/Hodoscopes	651	516	501	47.45	50.9	50.7
WP2	Inner and Central Tracking with PID Capability, Drift Chambers	394	163	167	19.45	21.45	23.45
WP3	Inner and Central Tracking with PID Capability, Straw and Drift Tube Chambers	163.5	70	65	32	37.3	40.3
WP4	Inner and Central Tracking with PID Capability, Time Projection Chambers	268	268	253	15	15	14.5
WP5	Calorimetry	150	150	150	12.75	12.75	12.75
WP6	Photo-Detectors	275	325	315	11.9	11.4	11.4
WP7	Timing Detectors	420	311	311	24.1	21.7	20.7
WP8	TPCs as Reaction and Decay Chambers	495	505	405	78.35	73.05	72.55
WP9	Beyond HEP	803	783	694	40.5	37.5	35.2
	SUM	**3456**	**3091**	**2861**	**281.5**	**281.05**	**281.55**

Table 10: DRD1 Workpackages, cumulative resources (Material [kCHF] and FTE) available in existing funding lines covering the ECFA strategic R&D for the years 2024, 2025, 2026.

I.4.1.1 Common Fund

A Common Fund will be established, supported by limited and fixed yearly contributions from each DRD1 institute. This fund will serve as a valuable resource for supporting activities of common interest within the collaboration. Examples of such activities include Common Projects, Software and Electronics development, Common Facilities, Collaboration events (such as meetings, conferences, workshops, schools, and training events), and Collaboration Management. The Collaboration Board, composed of one representative from each collaborating institute, will be responsible for coordinating the financial planning and addressing other resource-related matters. To ensure transparency and accountability, the specific contribution details, including the amount and frequency of contributions, will be clearly defined in the MoU. This agreement, to be signed by all member institutes, will serve as the guiding document for financial obligations and expectations within the collaboration.

I.4.1.2 WORK PACKAGES

In addition to the Common Fund, the DRD1 Funding Framework incorporates the concept of Work Packages. Each Work Package focuses on specific areas of research and development and contributes to the strategic R&D objectives identified by DRD1 and DRDC. The participating institutes will have full control and operational autonomy over the resources allocated to them through the Work Packages. This approach enables efficient utilization of funding and resources, as institutes can tailor their activities according to their research interests and expertise. The MoU will include annexes that cover the specifics of each Work Package, ensuring clear guidelines and expectations for their implementation. The involved Funding Agencies will be asked to approve their financial contribution presented in the annexes. By leveraging the Work Packages, DRD1 aims to create a sustainable funding schema that supports long-term strategic goals and maximizes the impact of collaborative R&D efforts, optimizing the utilization of available funding and promoting collaboration among the institutes. Cumulative expected and additional resources connected to the DRD1 Work Packages to cover the ECFA strategic R&D for the years 2024, 2025, and 2026 are shown in Tables 10 and 11, respectively. The estimate of the required resources for the 2027-2029 period is shown in Table 12. Resources information not available at the time of the proposal submission will be added at a later stage.

WP	Description	Material [kCHF] (2024)	Material [kCHF] (2025)	Material [kCHF] (2026)	FTE (2024)	FTE (2025)	FTE (2026)
WP1	Trackers/Hodoscopes	716	1040	670	21.8	23.55	23.55
WP2	Inner and Central Tracking with PID Capability, Drift Chambers	79	89	93	3.15	8.4	9.15
WP3	Inner and Central Tracking with PID Capability, Straw and Drift Tube Chambers	525	325	330	11.7	12.9	12.9
WP4	Inner and Central Tracking with PID Capability, Time Projection Chambers	238	238	238	11.3	11.3	11.3
WP5	Calorimetry	50	50	50	1	1	1
WP6	Photo-Detectors	180	270	250	4.6	5.1	5.6
WP7	Timing Detectors	257	307	346	3	5.5	6.9
WP8	TPCs as Reaction and Decay Chambers	516.5	471.5	436.5	35.1	40	40
WP9	Beyond HEP	140	225	275	15.9	20.4	23.9
	SUM	**2701.5**	**3015.5**	**2688.5**	**107.55**	**128.15**	**134.3**

Table 11: DRD1 Workpackages, additional (not existing) funding request to cover the ECFA strategic R&D for the years 2024, 2025, 2026.

WP	Description	Material (2027-2029) [kCHF/year]	FTE/year (2027-2029)
WP1	Trackers/Hodoscopes	1365	73
WP2	Inner and Central Tracking with PID Capability, Drift Chambers	328	28
WP3	Inner and Central Tracking with PID Capability, Straw and Drift Tube Chambers	438	49
WP4	Inner and Central Tracking with PID Capability, Time Projection Chambers	501	26
WP5	Calorimetry	200	14
WP6	Photo-Detectors	538	17
WP7	Timing Detectors	651	27
WP8	TPCs as Reaction and Decay Chambers	943	113
WP9	Beyond HEP	973	58

Table 12: DRD1 Workpackages, annual resources projections for years 2027-2029.

I.4.1.3 Common Investments

Common investments, such as materials and infrastructure, within the DRD1 Collaboration, will be covered, depending on the interest in the community and the required resources, by common funds or by mechanisms similar to the Work Packages. For what concerns the second option and drawing inspiration from the RD51 Collaboration model[2], the participating parties in DRD1 will have the flexibility to collectively agree on cost-sharing for these common investments. This cooperative approach allows for the sharing of expenses related to essential requirements like base material, production or testing equipment, large-scale electronics production or other procurement activities.

I.5 Partners and Their Fields of Contributions

I.5.1 Contributions of the DRD1 Institutes.

Interest of each DRD1 Institute in the collaborative tasks undertaken within the Working Groups (Fig. 3, 4) will be regularly updated and documented in the publicly accessible repositories of the DRD1 Collaboration. This approach ensures that the specific involvement of each institute in common activities is well-documented and easily accessible to the collaboration members and the wider scientific community. The detailed contributions of the institutes to specific Work Packages will be clearly outlined in the relevant annexes of the Memorandum of Understanding (MoU). The available facilities at the DRD1 Institutes (Fig. 5, 6) will be also regularly updated and documented in the publicly accessible repositories, together with the contact person and access modality.

[2] Art. 9.3 of the MoU for the RD51 Collaboration

		WG1					WG2													WG3							WG4						WG5					WG6				WG7					WG8			
	DRD1 Institutes	LVD (TPC+DC)	MPGD	RPC	TPC	WIRE	Trackers/Hodoscope	[DRIFT] Inner and Cenral Tracking with Particle ID Identification	[STRAW] Inner and Cenral Tracking with Particle ID Identification	[TPC] Inner and Cenral Tracking with Particle ID Identification	Calorimetry	Photon Detector (PID)	Timing Detectors (PID & Trigger)	TPC as reaction and decay chambers	Medical Application	Neutron Science	Muography	Space Applicatios	Oher (Dosimetry, Beam Monitoring, Cultural Heritage, Homeland Security,..)	Measurement of Gas Properties	Studies on Eco-friendly Mixtures	Ageing and Outgassing studies	Gas systems	Resistive Materials	Photocathodes	Precision Mechanics	Garfield++	Simulation of Large Charges and Space Charge	Simulation of Detectors with Resistive Elements	Modelling and Simulation of Eco-friendly Mixtures	Optimization of Simulations (time, hw/sw resources)	Specific Processes (e.g. Electroluminescence)	Front-End Electronics for Gaseous Detectors	Modernised Readout Systems (DAQ): high performances	Modernised Readout Systems (DAQ): FE integration	Modernised Readout Systems (DAQ): portability	Instrumentation (e.g. HV,LV, monitoring)	Common Production Facilities and Equipments	QA/QC	Collaboration with Industrial Partner	Gaseous Detector FORUM (know-how)	Detector Laboratories Network	Test Beam Common Facilities	Irradiation Common Facilities	Specialized laboratories (outgassing/ageing, gas analysers, photocathodes)	Common instrumentation and software	Knowledge Exchange and Facilitating Scientific Collaborations	Training and Dissemination Initiatives	Career Promotion	Outreach and Education
1	ANU	*	*											*		*	*	*	*	*	*						*															*	*	*			*	*		*
2	U Melbourne		*		*									*																										*							*			*
3	UCLouvain			*													*					*					*						*			*							*			*	*	*	*	*
4	ULB		*				*						*		*		*																	*		*						*					*			
5	VUB and UGent		*	*			*				*		*				*				*			*																									*
6	Rio-CBPF			*									*		*		*				*									*																			
7	IFUSP	*	*			*		*	*	*		*			*	*			*	*	*	*					*			*			*	*	*								*	*			*	*		*
8	UERJ			*			*													*																									*		*		*
9	INRNE			*																																	*												
10	U Sofia			*											*												*		*	*																			
11	U Carleton				*					*					*												*	*																			*	*	*	*
12	CUHK			*			*																																										
13	HKU			*			*																																										
14	HKUST			*			*																																										
15	IHEP CAS		*		*	*	*	*	*	*	*	*	*			*		*		*	*	*			*	*	*	*			*		*	*	*	*		*		*			*			*	*	*	*	*
16	IMP-CAS							*																																									
17	U Jilin	*						*																																									
18	U Nankay	*						*																																									
19	U Shandong		*		*					*					*																										*									
20	SIAT			*									*											*									*													*	*			
21	SJTU			*							*																																							*
22	U Tsinghua			*				*		*			*							*	*			*				*					*							*										
23	USTC	*	*	*	*		*	*			*	*	*	*	*	*	*	*			*	*		*	*		*	*	*				*	*	*	*		*		*		*					*	*	*	*
24	U Wuhan	*						*																																								
25	U de Antioquia																										*	*	*	*																			
26	U de Los Andes																										*	*	*	*																			
27	RBI		*										*												*	*																							
28	CTU		*		*																						*								*							*	*						
29	HIP				*					*		*	*																													*							
30	U Jyväskylä																																																
31	CNRS-IN2P3/Omega										*																						*																
32	GANIL				*		*	*	*	*										*		*	*																										
33	IP2I			*							*		*				*							*											*	*						*									
34	IRFU/CEA	*	*		*		*			*		*	*	*	*	*	*				*	*	*	*	*				*				*		*		*			*			*					*		*
35	LPSC		*		*									*	*	*				*								*																					
36	LPC																																																
37	CNRS-LSBB	*	*				*	*	*	*						*	*		*		*	*	*																									*		
38	CNRS-IN2P3/IJCLab	*	*	*	*	*	*	*	*	*			*																													*	*	*				*		
39	GTU			*			*													*	*	*												*	*	*													
40	DESY																																																
41	FZJ-GSI-U Bochum					*			*																																								
42	HISKP Bonn	*	*		*	*	*			*					*		*	*	*	*	*	*			*	*	*							*	*	*		*	*				*	*	*			*	*		
43	GSI	*	*	*	*	*	*	*	*	*			*	*	*			*		*	*	*	*			*								*		*		*		*	*		*	*		*		*	*		*
44	U Hamburg					*	*		*																		*						*	*	*							*	*	*	*	*	*	*		
45	JGU Mainz		*		*		*			*										*			*		*			*					*										*							*
46	U Wurzburg		*																	*	*						*			*																			
47	LMU		*				*								*					*	*		*				*		*	*			*					*		*		*					*			*
48	MPP			*		*	*	*	*		*		*							*	*	*		*		*				*			*							*			*							
49	U Heidelberg			*			*						*						*	*		*	*	*																			*	*				*		
50	U Bonn	*	*					*	*	*		*		*		*		*	*				*	*									*	*	*							*	*	*				*		
51	RWTH Aachen		*		*					*				*						*	*		*							*																			
52	TUDa		*		*					*																		*														*								*
53	TUM		*									*												*	*		*																						
54	AUTH											*	*				*										*	*											*			*	*							
55	NCSR Demokritos		*										*																					*	*								*	*				*		*
56	NTU Athens		*										*																								*						*			*				
57	WIGNER RCP		*			*	*									*	*					*												*		*		*			*	*						*	*		*
58	Bose	*	*	*		*	*	*		*						*		*				*		*										*					*				*			*	*	*	*		
59	IIT Guwahati																																																
60	IIT Kanpur																																																
61	IIT Mandi		*	*	*		*			*				*	*												*		*														*	*	*	*	*	*		*
62	NISER Bhubaneswar		*	*		*	*					*					*		*		*	*			*		*						*	*				*		*		*	*	*	*		*	*		
63	U Punjab		*	*					*			*			*		*	*					*																*									*		*
64	SINP Kolkata																*										*	*														*								
65	U Delhi		*	*					*			*			*					*	*	*								*			*							*		*		*		*	*			*
66	VECC Kolkata	*	*	*		*	*				*	*	*		*	*	*	*		*	*	*			*		*	*	*	*								*		*	*		*	*			*				
67	Ben-Gurion U																																																
68	HUJI	*	*	*		*	*	*	*	*		*	*	*		*		*	*	*		*	*	*		*							*					*		*		*								
69	WIS	*	*			*	*				*			*	*	*	*		*	*		*	*	*	*		*						*	*	*		*	*			*	*	*	*	*	*	*	*		
70	GSSI		*		*							*		*				*		*	*						*			*		*									*									
71	INFN-LNS	*	*		*																						*																							
72	INFN-LNF		*	*			*	*	*	*	*	*		*		*	*	*	*	*	*	*		*										*			*	*		*	*	*	*	*	*	*	*	*		*
73	INFN-BA, UniBA, PoliBA		*	*	*	*	*	*		*	*		*	*						*	*	*		*			*		*				*					*		*	*	*	*	*	*	*	*	*	*	*
74	INFN-BO		*	*			*	*												*		*	*					*				*					*		*		*	*				*			
75	INFN-FE		*				*									*												*				*		*															*
76	INFN-LE	*				*	*	*												*	*	*	*	*		*	*	*					*	*	*	*	*					*			*	*				*
77	INFN-NA		*				*				*																																			*		*
78	INFN-PD e DFA-UNIPD		*		*					*		*		*										*	*				*			*					*			*	*	*	*		*	*	*	*	*	*
79	INFN-PV, UniPV, UniBG		*	*			*		*				*							*	*	*	*	*	*				*	*			*									*	*	*		*				*
80	INFN-PI		*															*		*						*	*						*				*											*		*

Figure 3: Areas of Interest of the DRD1 Institutes (Part 1). The table provides preliminary information, and additional data will be supplied in the near future.

		WG1					WG2													WG3							WG4						WG5					WG6				WG7					WG8			
	DRD1 Institutes	LVD (TPC-DC)	MPGD	RPC	TPC	WIRE	Trackers/Hodoscope	[DRIFT] Inner and Cenral Tracking with Particle ID Identification	[STRAW] Inner and Cenral Tracking with Particle ID Identification	[TPC] Inner and Cenral Tracking with Particle ID Identification	Calorimetry	Photon Detector (PID)	Timing Detectors (PID & Trigger)	TPC as reaction and decay chambers	Medical Application	Neutron Science	Muography	Space Applicatios	Other (Dosimetry, Beam Monitoring, Cultural Heritage, Homeland Security,..)	Measurement of Gas Properties	Studies on Eco-friendly Mixtures	Ageing and Outgassing studies	Gas systems	Resistive Materials	Photocathodes	Precision Mechanics	Garfield++	Simulation of Large Charges and Space Charge	Simulation of Detectors with Resistive Elements	Modelling and Simulation of Eco-friendly Mixtures	Optimization of Simulations (time, hw/sw resources)	Specific Processes (e.g. Electroluminescence)	Front-End Electronics for Gaseous Detectors	Modernised Readout Systems (DAQ): high performances	Modernised Readout Systems (DAQ): FE integration	Modernised Readout Systems (DAQ): portability	Instrumentation (e.g. HV,LV, monitoring)	Common Production Facilities and Equipments	QA/QC	Collaboration with Industrial Partner	Gaseous Detector FORUM (know-how)	Detector Laboratories Network	Test Beam Common Facilities	Irradiation Common Facilities	Specialized laboratories (outgassing/ageing, gas analysers, photocathodes)	Common instrumentation and sofware	Knowledge Exchange and Facilitating Scientific Collaborations	Training and Dissemination Initiatives	Career Promotion	Outreach and Education
81	INFN-RM1		*		*	*		*		*				*						*	*	*	*																												
82	INFN-RM2			*			*				*		*				*			*	*	*	*	*										*				*		*	*	*							*	*		*
83	INFN-RM3		*				*				*											*		*																	*								*		
84	INFN-TS		*									*								*	*	*	*		*													*				*				*		*	*		*
85	INFN-TO		*			*	*		*			*	*		*												*				*		*		*	*	*		*								*	*		*
86	UCA-INFN-CO	*	*	*		*							*		*		*	*		*	*	*		*	*	*			*	*								*		*	*	*					*		*		*
87	UNIMIB															*																																		
88	KEK-IPNS																																																	
89	U Iwate		*		*					*																																								
90	U Kobe		*	*		*	*							*	*	*		*	*	*			*	*	*		*							*				*		*		*	*	*			*	*		
91	U Kyoto			*			*						*				*																																	
92	RIKEN		*		*	*	*	*		*				*		*												*					*	*		*							*		*	*	*			
93	INP-Almaty	*		*	*	*	*	*	*	*					*	*	*	*	*	*	*	*	*	*		*	*						*	*	*	*	*	*		*	*		*	*	*	*		*		
94	KTU		*									*	*												*												*			*		*			*		*	*	*	*
95	AGH-Krakow		*			*			*			*				*				*		*											*		*						*	*					*			
96	AstroCeNT	*										*		*																																			
97	IPPLM		*									*										*	*				*				*						*													
98	JU-Krakow		*			*			*													*																												
99	U Coimbra																																																	
100	LIP-Coimbra	*	*	*	*	*							*	*		*	*						*	*			*									*	*	*	*										*		*
101	U Aveiro		*									*		*									*		*		*			*		*					*				*				*					
102	IFIN-HH		*			*	*		*														*					*	*		*		*	*	*	*	*													
103	UNSTPB																																																	
104	TU Brasov																															*	*	*	*														
105	IGPC						*														*	*					*			*		*														*				
106	U Johannesburg													*				*									*												*							*			
107	DGIST											*		*																	*							*				*						
108	GWNU					*				*				*		*		*													*										*	*						
109	HYU																																																	
110	SNU			*							*	*	*		*		*		*		*								*				*					*	*	*	*			*						
111	U Zaragoza	*	*		*									*														*												*	*				*				*
112	CIEMAT			*		*	*				*		*									*				*	*						*					*				*	*	*	*	*	*	*	*	*
113	DIPC																																																	
114	IFAE	*	*					*	*	*		*		*	*								*				*																*			*	*	*		
115	IFIC																																																	
116	U Oviedo		*	*	*								*						*	*	*	*	*	*		*		*			*						*			*	*	*	*			*	*		*
117	U Vigo	*					*																																										
118	USC/IGFAE																																																	
119	UPV	*											*	*				*	*		*	*			*							*					*				*								
120	ESS		*												*																																			
121	U Lund																																																	
122	CERN	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
123	PSI					*				*				*		*																																		
124	U Genève				*									*						*												*											*		*					
125	U Bolu-Abant		*	*								*			*					*	*			*	*		*							*																
126	U Bursa		*	*		*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*		*	*				*						*				*			*	*	*	*		
127	Istinye U			*			*		*						*		*				*										*							*				*								
128	U Warwick	*	*									*		*					*	*			*		*							*								*							*	*		
129	Imperial																																																	
130	RHUL																																																	
131	STFC-RAL		*									*		*							*	*	*																								*			
132	U Cambridge						*																																											
133	U Liverpool	*	*		*																																										*		*	
134	U Manchester					*		*	*			*	*														*						*	*	*							*				*				
135	U Boston																																																	
136	BNL	*	*		*	*	*	*		*		*	*														*						*	*	*															
137	U Duke																																																	
138	FRIB/MSU		*		*							*		*								*			*		*	*					*	*	*							*				*	*	*	*	
139	Fermilab				*									*			*			*													*																	
140	FIT		*				*								*		*					*											*					*					*	*	*	*	*	*		
141	U Indiana																																																	
142	ISNAP													*																																				
143	U Northeastern																																																	
144	OXY																																																	
145	SBU	*	*							*			*							*	*				*		*	*	*									*			*				*		*			*
146	JLAB		*				*	*	*	*		*	*		*	*	*		*														*					*				*	*			*	*	*		
147	U Tufts					*																			*																			*					
148	UCA Davis																																																	
149	UCA Irvine																																																	
150	U Colorado	*	*							*				*																							*					*				*	*		
151	U Florida																																																	
152	UH Manoa	*	*											*	*	*			*		*	*	*	*			*						*	*								*						*		
153	U Massachusetts Amherst																																																	
154	U Michigan																																																	
155	U New Mexico																																																	
156	U South Carolina					*			*														*			*					*		*						*				*							
157	UT Arlington	*	*		*		*				*		*	*																			*		*														
158	UW–Madison		*			*	*																																											
159	U Yale		*		*					*											*		*					*																							

Figure 4: Areas of Interest of the DRD1 Institutes (Part 2). The table provides preliminary information, and additional data will be supplied in the future.

	DRD1 Institutes	A: Detector Characterization Laboratory	B: Manufacturing and Production Workshop	C: Assembly Facilities	D: Clean Rooms	E: Gas system design and production	F: Mechanical Workshop	G: Electronics Workshop	H: Analysis Laboratory	I: Metrology Laboratory	J: Radioactive Sources (active, passive)	K: Irradiation Facilities	L: Test Beam	M: Other
1	ANU	*			*	*	*	*			*	*	*	*
2	U Melbourne	*	*	*	*						*			*
3	UCLouvain		*		*		*	*					*	
4	ULB	*			*		*	*						
5	VUB and UGent	*		*	*		*	*			*			
6	Rio-CBPF					*	*	*						
7	IFUSP	*			*		*	*	*		*	*	*	
8	UERJ	*												
9	INRNE	*					*							
10	U Sofia	*												*
11	U Carleton			*	*	*	*		*		*	*		
12	CUHK													
13	HKU													
14	HKUST													
15	IHEP CAS	*	*	*	*	*		*	*		*	*		
16	IMP-CAS													
17	U Jiling				*									
18	U Nankay													
19	U Shandong													
20	SIAT													
21	SJTU			*	*						*			
22	U Tsinghua													
23	USTC	*	*	*	*						*			
24	U Wuhan													
25	U de Antioquia													
26	U de Los Andes													
27	RBI										*		*	
28	CTU	*									*	*	*	
29	HIP	*	*		*						*		*	
30	U Jyväskylä													
31	CNRS-IN2P3/Omega													
32	GANIL	*		*	*	*	*	*			*		*	
33	IP2I	*	*				*				*			
34	IRFU/CEA	*	*	*	*		*			*	*			
35	LPSC											*		
36	LPC													
37	CNRS-LSBB	*	*	*	*			*		*	*			*
38	CNRS-IN2P3/IJCLab	*	*	*	*		*	*	*		*		*	
39	GTU													
40	DESY													
41	FZJ-GSI-U Bochum	*	*		*		*	*			*			
42	HISKP Bonn				*	*	*	*			*	*	*	
43	GSI	*		*	*	*	*	*			*	*	*	
44	U Hamburg	*			*		*				*		*	
45	JGU Mainz													
46	U Wurzburg	*									*			
47	LMU	*	*	*	*	*	*	*			*	*		
48	MPP	*	*	*	*	*	*	*		*	*			
49	U Heidelberg			*	*		*	*			*		*	
50	U Bonn	*	*	*	*	*	*	*			*	*	*	
51	RWTH Aachen	*			*	*	*	*			*			
52	TUDa	*					*	*			*			*
53	TUM	*			*		*				*			
54	AUTH			*	*									
55	NCSR Demokritos	*			*		*	*			*	*	*	
56	NTU Athens											*	*	
57	WIGNER RCP	*	*	*	*	*	*		*		*			
58	Bose	*		*							*			
59	IIT Guwahati													
60	IIT Kanpur													
61	IIT Mandi	*		*	*		*	*	*	*	*			*
62	NISER Bhubaneswar	*		*	*		*				*			
63	U Punjab	*	*	*	*		*	*	*					
64	SINP Kolkata	*					*				*			
65	U Delhi	*	*	*	*	*	*	*	*		*			
66	VECC Kolkata	*		*	*		*				*		*	
67	Ben-Gurion U													
68	HUJI	*	*		*	*	*	*	*		*			
69	WIS	*	*	*	*	*	*	*	*		*			
70	GSSI	*									*			
71	INFN-LNS	*									*			
72	INFN-LNF	*		*	*	*	*	*			*	*	*	
73	INFN-BA, UniBA, PoliBA	*	*	*	*		*	*		*	*			
74	INFN-BO	*					*	*						
75	INFN-FE	*			*		*	*						
76	INFN-LE	*		*	*	*	*	*			*			
77	INFN-NA	*			*		*	*	*		*			
78	INFN-PD e DFA-UNIPD													
79	INFN-PV, UniPV, UniBG	*		*	*		*	*			*	*		
80	INFN-PI	*			*		*	*	*		*	*		*

Figure 5: List of available facilities at the DRD1 Institutes (Part 1). The table provides preliminary information, and additional data will be supplied in the future.

	DRD1 Institutes	A: Detector Characterization Laboratory	B: Manufacturing and Production Workshop	C: Assembly Facilities	D: Clean Rooms	E: Gas system design and production	F: Mechanical Workshop	G: Electronics Workshop	H: Analysis Laboratory	I: Metrology Laboratory	J: Radioactive Sources (active, passive)	K: Irradiation Facilities	L: Test Beam	M: Other
81	INFN-RM1				*	*	*	*			*			
82	INFN-RM2	*												
83	INFN-RM3	*			*		*	*	*		*	*		
84	INFN-TO	*		*	*	*	*				*			
85	INFN-TS	*					*	*						
86	UCA-INFN-CO		*	*	*	*				*				
87	UNIMIB	*		*	*	*	*		*		*			
88	KEK-IPNS													
89	U Iwate													
90	U Kobe	*			*						*	*		
91	U Kyoto				*									
92	RIKEN	*			*						*	*	*	
93	INP-Almaty	*	*	*	*	*	*		*		*	*	*	
94	KTU	*			*				*					
95	AGH-Krakow	*			*			*	*		*			
96	AstroCeNT	*			*		*	*						
97	IPPLM	*		*	*		*				*			
98	JU-Krakow	*			*		*				*			
99	U Coimbra													
100	LIP-Coimbra	*	*	*	*	*	*	*			*			
101	U Aveiro	*		*	*	*	*				*			
102	IFIN-HH	*	*		*		*	*			*	*		
103	UNSTPB													
104	TU Brasov							*						
105	IGPC								*					
106	U Johannesburg	*									*			
107	DGIST						*	*	*					
108	GWNU	*		*	*				*					
109	HYU													
110	SNU	*	*	*	*	*	*	*	*		*	*	*	
111	U Zaragoza				*	*					*			
112	CIEMAT			*			*	*				*		
113	DIPC													
114	IFAE				*		*	*			*			
115	IFIC													
116	IGFA/USC	*			*					*	*	*		
117	U Oviedo													
118	U Vigo													
119	UPV			*	*	*	*	*			*			
120	ESS													
121	U Lund													
122	CERN	*	*	*	*	*	*	*	*	*	*	*	*	
123	PSI				*		*	*			*	*	*	
124	U Genève		*		*					*				
125	U Bolu-Abant	*	*		*				*		*	*		
126	U Bursa	*				*	*	*			*			
127	Istinye U	*		*			*	*			*			
128	U Warwick	*	*	*	*	*	*	*	*		*			
129	Imperial													
130	RHUL													
131	STFC-RAL	*	*	*	*	*	*	*	*	*	*	*		
132	U Cambridge													
133	U Liverpool	*	*	*	*		*			*	*			
134	U Manchester			*	*			*	*				*	
135	U Boston													
136	BNL		*	*	*		*	*		*	*			
137	U Duke													
138	FRIB/MSU	*	*	*	*	*	*	*	*		*	*		
139	Fermilab	*		*	*						*	*	*	
140	FIT	*	*	*	*	*	*				*			
141	U Indiana													
142	ISNAP				*		*				*	*	*	
143	U Northeastern													
144	OXY													
145	SBU	*		*	*		*							
146	JLAB	*		*	*	*	*	*			*		*	
147	U Tufts						*							*
148	UCA Davis													
149	UCA Irvine													
150	U Colorado		*											
151	U Florida													
152	UH Manoa	*			*	*	*	*			*		*	
153	U Massachusetts Amherst													
154	U Michigan													
155	U New Mexico													
156	U South Carolina	*					*							
157	UT Arlington		*	*			*	*						
158	UW–Madison			*	*		*	*						
159	U Yale	*	*	*	*	*	*				*			

Figure 6: List of available facilities at the DRD1 Institutes (Part 2). The table provides preliminary information, and additional data will be supplied in the future.

I.5.2 Synergies with the other DRD Collaborations

DRD1 recognizes the value of synergistic collaborations with other DRDs and aims to maximize the efficient utilization of available resources, avoid duplication of efforts, and foster productive cooperation. To facilitate this, designated DRD1 contact persons will be appointed to actively engage with other DRD Collaborations. These contact persons will serve as liaisons and facilitators, promoting effective communication and coordination between DRD1 and other collaborations. Their role includes exploring opportunities to leverage additional resources, fostering cooperation, and ensuring the efficient use of shared resources. By leveraging these synergies, DRD1 aims to enhance its overall impact and contribute to the advancement of detector research and development on a broader scale.

I.5.2.1 DRD2: Liquid Detectors

Large-area applications requiring cryogenic infrastructures for liquefaction and purification of noble gases are covered mainly by DRD2. Notably, however, dual-phase amplification in vapour has been (and is) performed through wires, meshes, and MPGD structures, that are dealt with in this document too. Future developments in this direction will certainly profit from systematic studies performed under such extreme conditions (i.e., high gas density, no quencher), not excluding operation at room temperature (RT) as part of them. This is enabled by the fact that a significant part of the detector response can be expected to depend on the gas density, so equivalent P/T conditions can be obtained at RT and mild overpressure. On the other hand, direct operation in the liquid phase of either wires or MPGD structures for signal induction and even light amplification has been done, and future R&D along these lines remains a promising avenue. In general, teams with or without access to cryogenic infrastructures will benefit from the state-of-the-art manufacturing technologies provided by DRD1. These types of synergies between liquid and gaseous detectors can be safely taken for granted: they happened in the past and seem inevitable in the future.

Other overlapping areas that have been little explored and offer attractive possibilities are:

- **Simulations and Transport.** Electron-ion transport either in Monte Carlo or through Boltzmann-based techniques will be beneficial to both communities:
  - The CERN-maintained state-of-the-art Garfield++/Magboltz transport codes, developed originally for the gas phase, can be naturally adapted to incorporate some of the specific issues of liquid transport, in arbitrary geometries.
  - Charge recombination and Space-Charge are difficult aspects (numerically and technically) of strong common interest, that could be potentially tackled with similar tools.
- **Common techniques:**
  - Gas/liquid recirculation.
  - System purification and monitoring.
  - Fluid-dynamics simulations.
  - UV-photon detection (e.g., through gaseous photomultipliers).

  - Material selection (e.g., low outgassing, high radiopurity).
- **Barium tagging in xenon.**

I.5.2.2 DRD4: Photon Detector & PID

The interplay between DRD1 and DRD4 involves the study of gaseous photon detectors, innovative detector architectures, and innovative photoconverters. These topics are included in a dedicated work package (WP) within DRD1, with established links and synergies with DRD4 activities.

TRD R&D is present in both DRDs, with relevant overlaps and synergies. In DRD1, TRD systems utilizing gaseous photon detectors are considered, while in DRD4, the focus is on systems utilizing solid-state or alternative photon detectors.

Studies of eco-friendly gas solutions, such as low Global Warming Potential (GWP) gases, leakless systems, and recycling or destruction options, are conducted jointly. Common studies and developments in this area contribute to the shared objectives of both DRD1 and DRD4. To address these aspects effectively, two specific work packages are proposed: one for detector gases in DRD1 and one for radiator gases in DRD4. However, it is also suggested that a single cross-DRD work package, if feasible, could represent the best solution, promoting collaboration and maximizing efficiency in addressing shared objectives and challenges.

I.5.2.3 DRD5: Quantum and Emerging Technologies

Potential synergies between DRD5 activities on advanced materials, specifically nanostructures and low-dimensional systems, and DRD1 activities, primarily in WG3 - Gas and Material Studies, should be exploited:

DRD5 is proposing a work package on incorporating low-dimensional systems in larger-scale devices exploiting their unique properties. This can be relevant for tuning charge transport processes or tuning the sensitivity of photocathodes and converter materials. In combination with another work package in DRD5 on capability-driven design, the objective is to foster collaboration between material scientists and detector developers and identify common interests and facilities for evaluating promising materials under conditions relevant to HEP experiments.

The platforms for scientific exchange proposed by DRD5 offer an opportunity for fruitful cooperation between material scientists and detector developers. In addition, common approaches to screening and characterising potentially promising low-dimensional materials for applications in HEP could help to identify novel materials of interest for future detector developments.

Synergies with DRD5 may facilitate the exploration of advanced materials and their potential application in detector development within the framework of DRD1.

I.5.2.4 DRD6: Calorimetry

Clear separation exists in the development of gaseous-detectors-based calorimeters between DRD1 and DRD6.

DRD1 focuses on developing gaseous detectors for the calorimeters, capitalizing on the expertise and know-how of the gaseous detectors community. This includes addressing aspects such as gain, timing performance, rate capability, and the utilization of eco-friendly gases for their operation.

DRD6, on the other hand, addresses issues related to the calorimeter system as a whole, encompassing services and integration. Within DRD6, discussions encompass readout electronics and Data Acquisition (DAQ), with the potential for exchange with other DRD1 groups involved in similar developments for different applications.

I.5.2.5 DRD7: Electronics and On-detector Processing

In general terms and not to be considered as a request for DRD7, a comprehensive list of the desired electronics advancements in the DRD1 Collaboration is the following:

- High-performance charge-sensitive front-end circuit specific for medium and large-volume gaseous detectors (MPGD, TPC, drift chambers, straw tubes, RPC, ...)
  - High input capacitance (2-2000 pF)
  - Low noise/high sensitivity (e.g., $\sim$100e@2pF; 50mV/fC)
  - Low power ($\sim$few mW/ch)
  - High dynamic range (12-14 bits, 1:50000, several strategies)
  - Precise timing (10-100ps - linked to Ion tail processing and extraction of electron charge peaks)
  - High event-rate (1MHz/cm^2 $\rightarrow$ several MHz/channel)
- Pixelated readouts (charge- or photon-sensitive detectors with high timing resolution)
  - Optimization of pixel size (>200 μm)
  - Provide a large-area pixel-based readout
- Architectural innovations R&D
  - Versatile front-end circuitry (variable parametric front-end and shaping circuit, variable resource distribution, ...)
  - Cluster-counting (continuous readout, 1GHz analog bandwidth front-end, 2GSps high-sampling rate, online processing with direct mathematical algorithms or Machine Learning)
  - Deadtime-less readout, self-trigger vs continuous sampling with digital data compression
  - High-rate data-acquisition (>1MHz/ch, up to Tb/s total DAQ bandwidth – scalable systems mapped on switched networks, generic DAQ for different Front-Ends)
- Platform for sharing and collaborative development of Processing IPs and building blocks
  - Sharing and co-design of front-end building blocks
  - Signal/Event Processing on- or off-chip (e.g., peak finding, baseline restoration, feature extraction, etc. – reusable IP library for online use in FPGA/ASIC or offline in software)

  - Proper mechanism for open access, end-user agreement, protection of Intellectual Property, and authorship recognition
- Technological developments
  - High-voltage tolerance/spark protection
  - Detector biasing via ASIC (e.g., TSV for HV)
  - Combined detector & electronics assembly technology, cooling & services integration (integration of the FE electronics in the detector Faraday cage)

Several of those topics listed potentially align with activities of the DRD7 Working Groups (e.g., Precise timing and ADC/TDC blocks in WG 7.3; High-rate scalable DAQ in WG 7.5 or Versatile front-end in WG 7.2).
In addition to the aspects related to ASIC design within this research theme, there are several technological aspects that need to be addressed. These include high-voltage tolerance, integrated discharge protection, and assembly developments associated with bringing the front-end electronics inside or closer to the gaseous detector pressure vessel. Such advancements will necessitate the utilization of more advanced packaging and cooling technologies. It is important to note that access to these specialized technologies may pose challenges for individual institutes or project collaborations without the support of DRD7. Lastly, the DRD1 community expresses a strong interest in sharing and co-designing front-end building blocks, complete ASICs, or processing IPs with research teams across other DRD Collaborations, while ensuring proper protection of Intellectual Property and recognition of authorship. In this regard, the coordination role of the DRD7 Collaboration would be invaluable.

Within the activities proposed in DRD7, DRD1 is looking with interest to the possibility for the DRD1 groups to access WG7.7 where they may receive support in the following areas:

- Access to foundries and design kits, tools, technologies, and services
- Address potential technology access limitations
- Set up proper cooperation frameworks between groups from different institutions and countries

The possibility of hosting lively forums within DRD7 for the exchange of experiences, know-how, developments, and potentially initiating collaborations is also seen very positively and electronics experts from DRD1 may contribute to this. This could facilitate the potential development of new projects in DRD7, enlarging interests and pooling resources from the various DRD communities. New FE ASIC development is one potential example with relevant interest within our community. Electronics Developers within DRD1, interacting with the other DRDs, will evaluate if there are groups interested in creating such a project in DRD7. The feasibility of the project will be explored with the help of the experts in DRD7.
In parallel, the DRD1 teams will evaluate the possibility of contributing to DRD7 with DAQ developments, enriching and complementing the activities that have been started within RD51 and that will be carried out in DRD1.

I.5.3 Industrial, Semi-Industrial partners and Research Foundations

Industrial and Semi-Industrial partners and Research Foundations have shown interest in the DRD1 collaboration activities (EBG MedAustron, FBK, KBIOHEALTH, HFR, SRS-Technology). Private companies with commercial objectives, aiming to conduct research for commercial applications, are considered industrial partners. Semi-Industrial partners and Research Foundations are organizations, like national labs, often a combination of academic and industrial characteristics, focused on applied research without primary commercial goals. Semi-Industrial partners and Research Foundations address practical challenges, contributing to technological advancements.

The integration of industrial and Semi-Industrial partners and Research Foundations will be discussed within the teams in charge of forming the DRD1 collaboration, with the DRDC, the other DRDs and CERN. The integration modality (status, roles and rules) that it is expected to be different among the different types of partners, will be defined in the MoU.

I.6 Steps towards the formation of the DRD1 Collaboration

I.6.1 Steps towards the formation of the DRD1 collaboration

To ensure a smooth transition from RD51 to DRD1 by January 2024, it is crucial to design a comprehensive strategy for the organization of the collaboration. This will pave the way for setting up and implementing the collaboration effectively. The following steps need to be taken:

1. Submission of the DRD1 Extended Proposal: After consultations with the DRDC Chair, submit the DRD1 Extended Proposal to DRDC in July 2023.
2. Formation of the Electoral/Administrative ("Provisional") DRD1 Collaboration Board: Establish the provisional DRD1 Collaboration Board in August 2023. Designate institute "contact persons" as members of the provisional board, with a caveat that only one representative per research institute is allowed, even if the institute is involved or interested in multiple gas detector technologies. The provisional board's primary role will be electoral in nature.
3. Setting up the DRD1 Search Committee: In September 2023, the DRD1 Extended Proposal Team, comprising the DRD1 Working Group and DRD1 WG Conveners, takes charge of establishing the DRD1 Search Committee. The committee's composition needs to be endorsed by the provisional DRD1 Collaboration Board.
4. DRD1 Search Committee activities: From October to November 2023, the DRD1 Search Committee solicits community nominations for the positions of Spokespersons and CB Chair. They verify the availability of candidates and request them to prepare statements and presentations outlining their vision, strategy, structure, and implementation plans for DRD1.
5. Open meeting and election campaign: Once the DRD1 proposal receives approval from CERN DRDC and the Research Board, the Search Committee organizes an

open meeting, tentatively scheduled for December 2023. During this meeting, candidates for Spokespersons and CB Chair present their statements and address community questions. Subsequently, from December 2023 to January 2024, the Search Committee conducts an electronic election campaign, in consultation with the DRD1 Extended Proposal Team, for the two Spokesperson and CB Chair positions. Each institute within the provisional DRD1 Collaboration Board is entitled to one vote.

6. Kick-off DRD1 collaboration meeting: The DRD1 collaboration meeting takes place at CERN between January and February 2024. The scientific program is prepared by the DRD1 WG Conveners. At this meeting, the results of the Spokesperson and CB Chair elections are announced. Furthermore, the collaboration proceeds with establishing other necessary collaboration bodies.

By following these steps, the DRD1 collaboration can be properly organized and set in motion, ultimately leading to a successful transition and implementation of the project.

I.7 DRD1 Implementation Team

I.7.1 Roles covered during the DRD1 Implementation Phase

In this section, the roles covered during the formation of the collaboration are listed.

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Proposal Review Team
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WG7: A. Ferretti, R. Guida, G. Iaselli, E. Oliveri, Y. Tsipolitis
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Part II
Scientific Proposal & R&D Framework

II.1 Detailed Description of Research Topics and Work Plan

II.1.1 Technological Aspects and Developments of New Detector Structures, Common Characterization and Physics Issues [WG1]

II.1.1.1 Introduction

A large variety of technologies have to be developed to cover the needs of future experiments with cost-awareness and sustainability concerns. Improving existing detectors to make them larger, working at higher rates or with lower backgrounds, with better stability and improved performance, will require new technologies and developments. Working group 1 will study and monitor the progress in wire, RPC, MPGD and TPC technologies.

Wires
Since the invention of the MWPC at CERN (Charpak et al., 1968) [15], the technology of wire-based gaseous detectors has continuously evolved and further improved to achieve new capabilities. The MWPC technology led to the development of Drift Chambers (DC, 1973) for higher-resolution particle tracking, Cathode-Strip Chambers (CSC, 1977), Multi-Step Avalanche Chambers (MSC, 1979), and Thin-Gap Chambers (TGC, 1983) for tracking with much faster timing, and (Muon-) Drift Tubes (DT, 1980) or Straw Tube Chambers (1989) with robust mechanical and electrostatic shielding of the anode wire in the center of the cathode tube. All listed technologies, with substantial and continuous technical improvements and enhancements since their invention, are to date widely used in current state-of-the-art HEP and other experiments.

Typical spatial resolutions of these detectors are about 100 - 150 µm with drift times ranging from about 100 ns (straws, drift tubes) up to µs for DC. The robust technologies of CSC and TGC can provide large sensitive detector area (e.g. 6000 m^2 for CSC at the CMS experiment) with high-rate capability (about 100 kHz/cm^2) and typical spatial resolution of the order of 100 µm and at relatively low cost. As for timing resolutions, TGCs provide less than 100ns. Examples of future wire-based detector concepts include: an ultra-low mass and large-volume drift chamber (50 m^3) as central tracker with PID (IDEA at FCC-ee); Muon detector systems (DT, CSC, TGC) with higher rate capability, large size and faster timing (FCC-ee, FCC-hh); a self-supporting, low-mass central straw tracker with 4D-tracking (space and time) and PID for hadron physics (PANDA at FAIR); a large-area straw detector (50 m^2) in vacuum for Dark Matter searches (SHiP) and straw trackers in vacuum with minimal material budget for rare event searches (COMET, Mu2E-II, HIKE) and straw detectors in neutrino experiments (DUNE).

Single-gap and multi-gap RPCs
Introduced in 1981 by Santonico and Cardarelli [16], Resistive Plate Chambers (RPCs) are parallel-plate counters consisting of a thin (about 1-2 mm) gas gap at near-atmospheric pressure, enclosed by two electrodes made of high-resistivity materials (orders of 10^9 to 10^{13} Ωcm bulk resistivity), such as glass or High-Pressure Laminate (HPL), across which a high voltage is applied, giving electric fields up to about 50 kV/cm. RPCs are characterized by an excellent spatial resolution of the order of a few 100 µm, a good time resolution of

the order of 1 ns, a high detection efficiency (more than 95% for MIPs) and rate capability up to about 1 kHz/cm^2. Double-gap configurations exist to enhance detection efficiency. In the 90s, timing-RPCs, in literature also referred as multi-gap RPC (MRPC) [17] were developed by Fonte, Smirnitsky and Williams. Their active volume consists of multiple (up to more than 20) small-size (about 100-300 μm) gas gaps, leading to superior time resolutions down to 20-150 ps.
Single-gap and multi-gap RPCs make it possible to instrument very large active areas with chambers of up to a few square meters in size. The fabrication procedure is relatively simple, cheap and demands little in terms of mechanical precision. Those features are at the basis of their popularity in HEP experiments. Currently, RPCs appear in experiments for muon tracking/triggering (e.g. CMS, ATLAS), time of Flight (e.g. ALICE, STAR, HARP, FOPI, HADES, SHiP, BGO-EGG, CBM, CEE, Pi20), calorimetry (e.g. CALICE SDHCAL), cosmic ray experiments (e.g. EEE, Pierre Auger Observatory, ARGO) and non-HEP applications in e.g. positron emission tomography (PET), gamma tomography, muon radiography (mostly RPCs used so far, e.g. Tomuvol).

MPGD
The concept of Micro-Pattern Gaseous Detectors (MPGDs) was born with the Micro-Strip Gas Chambers (MSGC, Oed, 1988 [18]) to cope with high particle fluxes. The micro-electrodes used to multiply charges in gas were created on different substrates, exploiting patterning techniques from the semiconductor industry including photolithography and etching. From the MSGC developments, a number of new structures have been conceived with amplification around microelectrodes (e.g. MicroGap, MicroDot, Micro-Groove, Micro-PIC, Micro-WELL) and with amplification in semi-uniform electric fields (e.g. MICROMEGAS, InGrid, GEM, THGEM/LEM, RWELL, RPWELL, Micro-RWELL). The R&D done in the last years, in particular within the framework of the RD51 Collaboration, aimed to develop MPGDs for applications in High Energy Physics (HEP), Nuclear Physics experiments and beyond. Some notable examples of the employment of MPGDs are the ATLAS New Small Wheel and the CMS forward muon detector systems, and ALICE TPC. MPGD-based sampling elements are developed for DHCAL in future collider experiments MPGDs are also extensively exploited in non-collider physics experiments, such as CsI-MPGD photon detectors of COMPASS-RICH, neutrino oscillation experiments, direct Dark Matter searches, as well as for applications beyond particle physics. For instance, MPGDs are used in X-ray polarimetry experiments, UV-photon detection (with CsI-coated electrodes), muography, neutron imaging, X-ray/gamma-ray astrophysics and gamma-ray cameras. The popularity of MPGDs stems from intrinsic qualities of the technology including their high spatial resolution, high particle-flux capability, large active area with small dead surfaces, and resilience to radiation. Operating MPGDs with stable and uniform gain in certain conditions (e.g. charging up of insulators in highly ionizing environment, highly ionizing events, variable irradiation fluxes) remains a challenge to be addressed by future developments.

Another reason for the widespread use of MPGDs is the constant and cross-field R&D focusing on developments of new amplification structures, studies of new materials and coatings (e.g. resistive, low outgassing), and selection of the appropriate gas mixtures.

This makes MPGD concepts particularly versatile for varying conditions of operation and physics performance requirements.

TPC

A Time Projection Chamber (TPC) is a drift chamber where the timing of the events is used to reconstruct one of the spatial coordinates. The TPC concept (David Nygren, 1974) [19] finds nowadays applications in particle physics at colliders, fixed-target experiments, nuclear physics, non-accelerator physics (including noble-liquid based detectors) and applications such as muography. Until the end of the 1990s TPCs at colliders were read out exclusively by multi-wire chambers (e.g. DELPHI and ALEPH TPCs at LEP, the first ALICE TPC at LHC, NA61). Since the invention of MPGDs, many projects focused on their use in the readout of TPCs. Some of the advantages could be an improved spatial resolution, reduced ion backflow and mechanical robustness of large detectors. In 2009 the T2K/ND280 TPC was read out by MICROMEGAS, and in 2023 the ALICE readout was changed into 4-GEMs. Additional TPCs for T2K/ND280 under construction apply the ERAM charge-sharing technique with a resistive anode invented for ILC. As well for tracking of ions from hydrogen to Uranium at high rate the GEM-TPC in Twin configuration for the Super-FRS was developed [20]. As an alternative to the standard charge readout, optical readout in TPCs is developing rapidly, thanks for example to the R&D for the CYGNO, DUNE and MIGDAL experiments. Optical readout can also find applications in polarimetry. TPCs have an important role in Rare Event searches, in the fields of Dark Matter and neutrinoless double β decay. There, Electro-Luminescence amplification is used with success. In nuclear physics, the TPC gas can be used as an active target or decay medium, in which dE/dx combined with range measurement allows discrimination between reaction products.

Other charge-amplification techniques

In the last decades, other amplification techniques have been explored within the gaseous detectors community, bringing consolidated solutions or new potential research lines. In some cases, the interest within the gaseous detectors community is driven by the potential of the manufacturing techniques, despite the proposed solutions may not involve amplification in gas. Two relevant examples are reported here:

- The Spherical Proportional Counter: (SPC): where a small sphere (anode) maintained at a positive high voltage ensures the amplification for electrons drifting from a larger sphere (cathode). The advantage of this configuration is that the detector capacitance is very small, allowing a very reduced electronic noise. New anode geometries are under investigation (achinos) to improve the electric field uniformity and solid angle segmentation.
- TIPSY, with ‘tynodes’ (micropatterned ultra-thin dynodes): based on a set of closely spaced transmission dynodes above a pixel chip (2D sensitive anode). It uses amplification in vacuum as it is done in a photomultiplier tube. The technology is based on Microelectromechanical systems (MEMS) Technology.

II.1.1.2 CHALLENGES

For all the aforementioned technologies, new challenges appear. Some of them are common to different technologies, while others depend on the specific detector concept. Future higher particle-rate environments require reduced occupancy by increased detector granularity. Reduction of material budget (X/X_0) by new composite structures and reduced material thickness is a general prerequisite. Gas mixture components with high Global Warming Potential (GWP), e.g. CF_4, SF_6 and $C_2H_2F_4$ have to be replaced, flammable admixtures should be avoided or reduced to a minimum and/or enclosed in a recirculating gas system.

Wires

Future experiments require smaller wire cell sizes, with high mechanical precision (<50 μm) over large wire and detector lengths up to 5 m. Specific R&D topics for large-volume drift chambers with orders of 10^5 anode and field wires are new wire-stretching systems (robots) and the design of modular units of drift cells to facilitate detector assembly. The technique of ion cluster counting for higher-resolution PID has to be exploited with appropriate wire configurations and single-cluster sensitive readout electronics. Straw tube developments include smaller diameter (5 mm), shorter time range (less than 80 ns) for event timing, ultra-thin straw films (15 μm) with minimal radiation length (comparable to that of the gas volume), and long straw lengths with precise wire centering. Operation in vacuum is a unique application of straw detectors and will be extended to ultra-long straws up to 5 m and large detector gas volumes of 25 m^3. General requirements for straw detector applications in future high-luminosity accelerators are high particle-flux capability of up to 500 kHz/cm^2 and extended longevity up to charge loads of the order of 10 C/cm. The challenges with higher rates in TGC and CSC are longevity and operation stability for large detector areas, in particular with new eco-friendly gas mixtures. Research on new wire materials, e.g. new alloys or metallized carbon monofilaments with higher strength to reduce sagging and electrostatic deflection is needed. Wire and cathode-coating studies to further improve resistance against high irradiation and extend operation to higher charge loads are continuously needed.

Single-gap and multi-gap RPCs

The possible usage of RPCs in high luminosity / high background-rate environments (e.g. the HL-LHC, FAIR and other future facilities) has triggered a number of new efforts to improve their rate capability and to extend detector longevity. These include searches for new electrode materials with lower (compared to regular float glass or HPL) or tunable resistivity such as Fe-doped glass, vanadate-based glasses, ceramics, DLC, or Si-GaAs wafers; the development of low noise, i.e. low threshold, readout electronics (yet keeping a few ps time resolution at high bandwidth); studies of outgasing and material ageing. In addition, following European regulations which increasingly ban the emission of greenhouse gases, RPCs are facing an important challenge to replace the standard, tetrafluoroethane-based gas mixture with a more eco-friendly alternative. Parallel efforts to limit gas consumption or emission using recirculation and recuperation systems are ongoing. Closely related are the studies to operate RPCs with low flow or even in sealed mode, which is of particular interest also for non-HEP applications. Finally, new chamber geometries such as cylindrical or single-electrode RPCs are being developed to enhance specific performance features.

MPGDs

The next generation of MPGDs will have the challenge of operating at high rates, in stable conditions, covering large areas and offering time resolutions ranging from nanoseconds to tens of picoseconds. The typical sturdiness of the MPGD amplification structures makes them appealing for environments with harsh conditions (high irradiation flux, cryogenic operation - including in noble liquids, high and low pressures). The studies of new materials pave the way to new fabrication techniques, like 3D printing and additive fabrication, which in turn will enable manufacturing unprecedented multiplier geometries.

TPCs

To extend the use of TPCs to higher luminosity and in more noisy environments (e.g. FCC and BELLE II), avalanche-ion backflow must be minimized. Moreover, electric field distortions created by the space charge of drifting ions have to be mitigated and corrected in real time. Low-radioactivity materials will be needed in TPCs for rare events and negative-ion TPCs. The latter also require solutions for the environmental consequences of using electro-negative gases (with high GWP, like SF_6).

To help tackle these challenges, WG1 plans to have regular meetings with representatives from all the communities working with different technologies, where new ideas, new structures, goals, challenges and realizations will be presented, favouring cross-fertilization. These meetings will help the community to follow the starting of new projects, their progress, their achieved results and performances and to keep track and record of encountered problems and lessons learned.

II.1.2 Applications [WG2]

II.1.2.1 Introduction

The collaboration aims to facilitate information exchange among member groups. Working Group 2 (WG2) will serve as a reference for the community. Within WG2 events, activities will be organized to encourage scientific and technical sharing across common and diverse applications. Activities conducted within Work Packages will be closely monitored by WG2 initiatives, ensuring continuous oversight and a rigorous peer-review process within the collaboration.

II.1.2.2 Applications based on gaseous detectors technologies

The following section will describe examples of applications involving the DRD1 community. The Collaboration is open to all applications utilizing DRD1 technology, acknowledging their significant impact on the overall advancement of the technology.

Trackers/Hodoscopes (Large Area Muon Systems, Inner Tracking/Vertexing)
Muon detection systems, often employing gas detectors, serve as a fundamental technology in particle physics. They excel in covering large areas, providing precise time and space measurements, ensuring high detection rates, and keeping equipment lightweight. As muon systems progress, there's a possibility of integrating them with calorimeters in collider experiments, which presents shared challenges.
Moreover, in modern particle physics experiments at low-energy electron colliders, researchers are using Micro-Pattern Gas Detectors (MPGDs) for tracking and vertexing within the inner regions of their detectors. Notable examples include the use of lightweight cylindrical Gas Electron Multipliers (GEMs) in experiments like KLOE and BESIII, as well as recent developments in cylindrical micro-Resistive WELLs (μ-RWELLs) proposed for experiments like SCTF and EIC. While the inner and outer trackers differ in shape, they encounter many similar challenges.
The main challenges are the following:

- improving the rate capability above one order of magnitude with respect to the state of art, *i.e.* 1-10 MHz/cm^2;
- achieving a time resolution of 10-100 ps
- transferring the know-how to industries for large-scale serial production;
- enabling efficient low-GWP gas mixtures;
- developing new detector with novel materials and layouts;
- maintaining compatible longevity with decades of operation;
- developing new FEE matching the detectors and the future collider requirements: high rate, sensitivity, granularity, low noise and integration with the detector
- optimizing scalable multichannel readout systems to trigger up to 20 GBit/s.

Inner and Central Tracking with Particle Identification Capability

Drift Chambers. Large-volume drift chambers have been proposed as tracking and particle identification devices for the next generation of lepton colliders both at FCC-ee (CERN) and at CEPC (IHEP China). Analogous proposals exist for the next generation of flavour factories SCTF (Russia, China) and could easily be adapted for Electron-Ion Colliders. Drift chambers provide high-precision tracking and excellent particle identification. The main R&D challenges can be conveniently grouped as follows.
Mechanics:

- new wiring procedures:
  - High granularities (small cell size, order of 1 cm), necessary for limiting the drift cell occupancy and the total charge integration, and a very large number of wires require novel feed-through-less approaches at wiring procedures (see MEG2 drift chamber construction).
- new wire materials:
  - high gas gains ($\sim 5\times 10^5$), necessary for an efficient application of the cluster counting techniques, and electrostatic stability for longer wires (order of 4 m)

require the introduction of new light and more resistant wire materials (for example, Carbon monofilaments yield strength, YTS, is a factor 3 larger than Tungsten, and a factor 9 larger than Aluminum, with densities, respectively, 10 times and twice, smaller). Carbon monofilaments, though, require some metal coating to increase the wire conductivity and for ease of soldering.

Electronics:

- front-end:
  - large bandwidth (order of 1 GHz), high gain (> 20 dB) pre-amplifiers, necessary for an efficient application of the cluster counting techniques, together with low power consumption and low mass because of a very large number of channels, demand for designs and implementations of dedicated ASICs.
- Data Acquisition System (DAQ):
  - high sampling rate (> 2 Gsa/s), dead-time-less waveform digitizers coupled to data processing systems, based on FPGAs, need to be developed for on-line, real time signal processing aimed at filtering and reducing the data throughput (at the Z-pole and the FCC-ee design luminosity, larger than of 1 TB/s data throughput is expected from a drift chamber), for event time stamping and for track triggering purposes.

Gas:

- hydrocarbon-free mixtures:
  - safety requirements on flammable gas mixtures require the use of hydrocarbon-free gases, preserving the high quenching power and the low-Z composition - because of multiple scattering considerations – maintaining, at the same time, the high primary ionization production of isobutane.
- recirculation systems:
  - the continuous increase of the noble gases costs, the large drift chamber gas volume and the stringent purity requirements on the gas mixture demand for sophisticated and complex purification and recirculating gas systems. .

Straw chambers can cover a broad range of applications by choosing the appropriate specifications, such as straw tube diameter, tube wall thickness, length of the straw, gas mixture or the straw signal information registered by the electronic readout. This requires development of the straw production technologies, based on existing experience (e.g. ATLAS TRD). In addition to the straw signal time for spatial track information, the measurement of the charge (dE/dx) can be used for PID or at least noise hit suppression and requires dedicated ASIC developments for the electronic signal readout. The WG1 section (II.1.1) lists examples and applications for straw detector systems currently in development or planned for the future.

For applications in the future, highest-intensity accelerators, the requirements for straw detectors are a high rate capability up to 500 kHz/cm^2 and beyond, together with extended longevity to charge loads of the order of 10 C/cm.

Very large detector area coverage on the order of some 10 m^2 with low material budget

(X/X_0), required for instance in hidden sector experiments (such as SHiP and NA64), favour 2 cm diameter tubes with 4 m length. Such ultra-long straws require innovative mechanical support techniques, like carbon-fiber suspension, constant-force springs or self-supporting cemented packs of straws.
A unique application of straw detectors is their operation in vacuum, due to their robust mechanical shape when the gas inside the thin film tubes is at over-pressure. The use of very thin straw films for minimal material budget requires R&D on the film properties under mechanical stress and over a long time to investigate the relaxation and creeping of the material. The control of gas leakage and change of the gas mixture ratio by a difference in the molecular permeation through the thin film wall are key aspects.
The R&D challenges and perspectives may be summarized as follows:

- reduction of the thickness of the straw film to below 20 µm aiming at very low X/X_0, which is then comparable with the gas volume of the tube;
- minimization of the straw diameter of very thin-walled tubes down to 4-5 mm for high rate capability of the order of 100 kHz/cm^2, and drift time below 100 ns;
- maximization of the straw detector area to few 10 m^2 by ultra-long straws with 2 cm diameter, up to 4 m length and low material budget;
- extending the tracking information to 4D (space and T_0) and dE/dx for PID;
- extending the application of straw tubes in vacuum to very large volumes (orders of 10 m^3);
- extending the longevity of the detector by increasing the material purity;
- consolidating and developing new production techniques, like ultrasonic welding to minimize the usage of glue.

TPC. Future collider facilities (such as the ILC/C^3, FCC-ee or CEPC) will have increased needs for the next generation of TPCs, which should accommodate requirements such as:

- good dE/dx resolution, partly driven by a good gain uniformity;
- very low gain $\times$ Ion Back Flow figure to greatly reduce space charge distortions;
- high readout granularity to cope with high particle multiplicity;
- electronics with low power dissipation to meet the increased density of readout channels.
- large area coverage at a reduced cost, relying on lightweight mechanical structures based on composite materials.

Tracking TPCs are successfully utilized at neutrino and heavy ion facilities, conditions under which they will benefit from meeting some of the above challenges too. A work package addressing the main R&D challenges for the development of tracking TPCs at collider, heavy ion and neutrino facilities (WP4) is proposed.

Calorimetry
In future high-energy lepton colliders (ILC/C^3, CLIC, muon collider, etc) precision energy measurements and triggering (muon collider) will be challenging. Particle flow is a new

approach to calorimetry which promises to achieve a jet energy resolution that is more than a factor of two better than traditional calorimetric approaches. It is predicated on the ability to reconstruct the energies of the individual particles in a jet. In particle-flow calorimetry, the energy deposits from charged particles, photons and neutral hadrons are separated. The charged-particle energies are well measured from the associated track momenta and the calorimeters are mainly used for the (neutral) electromagnetic and hadronic components. Particle-flow calorimetry requires highly segmented calorimeters and sophisticated reconstruction algorithms for tracking individual particles within a shower. The use of alternating layers of absorbers and gaseous detectors for sampling has already been considered a promising candidate technology. In such a case, some of the main challenges refer to:

- optimizing the cell size to meet the physics requirements at a reasonable cost;
- develop low-cost electronic readouts to accommodate a large number of channels;
- introducing affordable techniques for the construction of large-area detectors;
- increasing the rate capability as well as the tolerance against radiation damage.

These R&D efforts will be coordinated keeping in mind the synergies existing with the DRD6 collaboration, which is specifically focused on the development of calorimeters for future facilities.

Photo-Detectors (PID)

Gaseous photon detectors can provide coverage of very large areas with photosensitive detectors at moderate cost, low material budget and magnetic insensitivity. The use of MPGD-based photon detectors is proposed for hadron identification at future colliders (the Super Tau-Charm Facility, for instance) The main R&D challenges for this application include:

- optimization of photocathodes efficiency by suppressing ion backflow and developing more robust photoconverters;
- develop photon detectors equipped with visible light sensitive photocathodes;
- improvement of the detector performance in terms of space and time resolution, along with a fast charge collection to maximize the rate capability;
- optimization of front-end electronics and DAQ systems for single photon signals.

Gaseous photon detectors sensitive to visible light can, unlike vacuum PMTs, operate at atmospheric pressure, which makes it possible to design very large-area detectors with flat geometry and low magnetic sensitivity. New solutions to reach this goal can now be explored thanks to recent technological advancements.

Timing Detectors

Two main technologies are currently considered and developed in the field of timing detectors for PID and trigger in the sub-nanosecond time domain: timing RPCs based on the multi-gap technology and MPGDs sensing Cherenkov light (PICOSEC). Depending on the application, developments focus on timing capabilities down to 20-200 ps and rate capabilities up to 30-150 kHz/cm^2, where different technologies can be used to fulfil the most challenging requirements:

- Multi-gap timing RPCs: Performance requirements can in principle be achieved by reducing the thickness of gas gaps to $\approx$100 µm and by increasing the number of gaps to $\approx$10 in order to maintain high efficiency provided good detector uniformity can be preserved over large areas. Rate capabilities of up to 100 kHz/cm^2, as required for detector systems in intense radiation environments, could be achieved by thinner electrodes to improve signal pick-up and lower resistivity plates to speed up the charge evacuation process, up to the conventional limit at which spark-quenching tends to weaken at $\approx 10^9$ Ωcm.
- PICOSEC and other precise-timing MPGDs: Timing performance can be scaled from small prototypes to cover larger active areas. Further developments include the optimisation of resistive amplification structures, precise mechanical integration and uniformity for gas gaps at the level of micrometers and the identification of less expensive materials for economic scaling including Cherenkov radiators. The development of robust photocathodes through the exploration of novel materials and photo-converter protection, stable operation at high gain and IBF minimisation are critical aspects for Cherenkov-based timing detectors. These R&D lines are well covered through synergies with developments required for gaseous photo-detectors. Enhanced timing performance can be obtained by optimisations of amplification structures, improved radiator and photocathode characteristics and operational parameters including gas properties.

Future R&D on timing detectors will concentrate on the following major points:

- uniform response, rate capability, enhanced time resolution, and efficiency over large detector areas in tileable detector modules;
- new materials for very high rate applications (low resistivity, radiation hardness);
- uniform gas distribution, spacer materials and spacer geometries;
- thinner structures: mechanical stability and uniformity;
- eco-gas mixtures and gas recuperation systems;
- electronics: low noise, fast rise time electronics, high sensitivity.

TPCs as Reaction and Decay Chambers (Rare Events, Neutrino Physics, Nuclear Physics)

TPCs employed in the field of rare event searches, as well as those used or envisaged for neutrino physics or as active targets for nuclear reaction/decay studies, share methodological and technological characteristics. Specifically, they may not have external triggers, a condition stemming from the frequent requirement of fully containing the reaction products down to the interaction vertex, with few or no ancillary detectors. In general, this family of TPCs must deal with requirements (not all at the same time) such as full event containment, broad dynamic range, radiopurity, T_0-tagging, diffusion close to the thermal limit, dual-phase operation, optical readout, single electron, and single ion counting, Fano-level energy resolution, tens of µm spatial sampling or keV-tracking.

Current challenges specific to this family of TPC technologies include:

- achieving track-reconstruction of low-energy nuclei and electrons, at granularities going from few mm down to potentially ≈tens of µm and close to the thermal diffusion limit:

  this is a driver for some of the future direct Dark Matter experiments, nuclear reactions on active targets, neutron detection, X-ray polarimetry, and more;
- operating in a broad range of pressures going from few tens of mbar to tens of bar, with energy-reconstruction performing generally down to a ≈1keV threshold if not less:

  this is essential to experiments with varied requirements going from Dark Matter to nuclear and neutrino physics, thus challenging state-of-the-art amplification structures that were developed and optimized in collider environments;
- achieving high and uniform amplification in nearly pure or weakly-doped noble gases:

  employing nearly pure gases instead of admixtures is an asset for active-target experiments as it eliminates spurious reactions. It enables, on the other hand, detection schemes aimed at near-Fano energy resolution and single-electron detection in rare event searches. However different these requirements and performance metrics might seem, experiments have long popularized pure-electroluminescence (EL) amplification on mm-scale gas gaps to achieve these. Only recently, alternative strategies based on hybrid GEM-mesh structures , FAT-GEMs or RWELL and RPWELL joined the effort;
- increasing optical throughput (primary and secondary):

  as optical imaging (based on scintillation either in the EL or avalanche-scintillation regime) extends over larger and larger areas, e.g. for low-energy WIMP detection, double-beta decay searches or neutrino physics, improvements in this direction become pressing and, related to it,
- developing more suitably scintillating and/or eco-friendly gas mixtures as well as recuperation systems;
- enhancing the radiopurity of the amplification structure and of the TPC as a whole.

Beyond HEP

Gaseous detectors technologies are widely used in high energy and nuclear physics, which remain the driving force of cutting-edge developments. The emergence of new technologies, as well as improvements leading to better performance, reliability, longer lifetime or radiation hardness open the possibilities to apply such detectors outside HEP – many of those with high social and economic impact. The aim is to fully exploit the achievements in fundamental science and to transfer that knowledge and technologies to areas Beyond HEP. In fact, such applications differ strongly from HEP in various aspects, including hostile or extreme conditions, very low level of maintenance, or strong requirements on safety, gas emissions or structural stability. Among a broad range of applications, three larger areas, namely cosmic muon imaging, medical applications (dosimetry, beam monitoring, imaging) and neutron science cover most of the objectives.

The key challenges and requirements can be summarized as follows:

- Extreme environments including long-term outdoor operation or conditions compatible with medical systems
- Portability, fast and highly reliable installation
- Very low or no maintenance
- Sealed mode or very low gas consumption

Technology transfer among DRDs and industrial partners is a crucial aspect, expected to expand the range of future applications.

II.1.2.3 Common Activities

WG2 will host sessions during Collaboration Events, providing all members the opportunity to showcase their work. Continuous monitoring of Work Package statuses will be conducted. Additionally, special-topic events will be arranged with the goal of incorporating inputs from other communities into our community.

II.1.3 Gas and Material Studies [WG3]

The DRD1 Working Group 3 (WG3) aims to address key issues related to gas and material studies that are common to all the existing gaseous detectors technologies. This is expected to contribute significantly towards the development of future gaseous detectors. Gas mixtures and materials are fundamental components to obtaining high-performance gaseous detectors indeed. This working group offers the potential to establish common goals, collaborative efforts and facilities for the different gaseous detectors technologies to achieve better performance and to foresee and address possible limitations, which may prevent their use in future experiments. The essential topics, common research interests and strategic infrastructures needed to advance the knowledge in this field are described in the following.

II.1.3.1 Introduction

According to an open consultation of the worldwide community of researchers working with gaseous detectors technologies, four major research categories have been identified as research areas of interest for the DRD1 WG3:

a) **Gas**: Accurate measurements of specific gas properties are at the base of R&D on gaseous detectors. Among others, studies related to photon emission by gases, gas molecules and mixtures eco-compatibility and their chemical characterisation are a strong need for the community. Improvements or new results on key parameters such as scattering cross sections, transport coefficients both at atmospheric or high pressures or scintillation mechanisms are fundamental for designing and simulating future gaseous detectors. Due to environmental concerns as well as in view of the future availability and costs of fluorinated gases (F-gases), the search and characterisation of new environmentally-friendly gas components will be crucial. Studies of gases with high scintillation light yield will also be important for future detector development. The main topics identified in this research area are gas properties, eco-gas studies and light emission in gases for optical readout.

b) **Systems for Gaseous Detectors**: For the operation of gaseous detectors, it is fundamental to have reliable gas systems for small to large experiments. In view of future applications and experiments, the use of gas recirculation and recuperation systems will play a key role in reducing consumption when expensive or greenhouse gases have to be used. Furthermore, the gas quality will be fundamental for detector performance and long-term operation. The investigation in the use of sealed detectors or small recirculation systems could also be considered a good solution for small experiments, low-rate applications and laboratories, where in the future it could be difficult to use expensive or greenhouse gases. The main topics identified in this research area are gas systems, gas recirculation and recuperation systems, sealed detectors and systems.

c) **Materials**: Studies of materials are fundamental for improved performance and long-term operation of the detectors. The use of resistive materials has played a crucial role in the last few years for stable detector operation and rate capability, and it will be essential also for future applications where the use of novel materials could lead to several improvements. Studies of solid converters and the characterisation of new photocathode materials need to be addressed to enhance spatial and time resolution, and radiation hardness as well. Research on new wire materials is needed to reduce sagging and electrostatic deflection. In view of the construction of future systems, one must not neglect studies of material properties for both detectors and infrastructures, nor engineering studies including precision mechanics and the use of low material budget structures. The main topics identified in this research area are resistive electrodes, solid converters, robust radiation-hard photocathodes, novel materials, new metal coatings, material properties for detectors and infrastructures, light (low-budget) materials and precision mechanics.

d) **Long-Term Operation**: Guarantying gaseous detectors' stable operation and optimal performance over decades is fundamental for future accelerators. It requires extensive studies of detector long-term operation in an environment that could accelerate the conditions foreseen in future experiments, especially in terms of radiation. This can be achieved with dedicated studies of current and gas-induced ageing effects as well as of the radiation hardness of the components in use, together with the evaluation of possible contributions from material outgassing. This research area will focus on all these aspects relevant to all gaseous detectors technologies. The main topics identified in this research area are detector ageing, radiation hardness, photo-converter protection and outgassing.

Among the aforementioned research topics, some of them have sparked interest in a large majority of the gaseous detectors' scientific community. In particular, the following topics have been identified as being of major interest for most of the gaseous detectors communities, where synergies can also be found:

- **Gas Properties**: strong cross-technology interest, focussing on different aspects related to the gas used. For example studies of cross-section, transport parameters, chemical characterisation, secondary (feedback) effects, discharge limits and operation at different pressures. A strong interest has also been expressed in simulations (WG4).

- **Eco-gases**: widespread interest in the study of new environmentally-friendly gas mixtures, their chemical characterisation and contribution to the detector ageing.
- **Ageing and Outgassing**: strong cross-technology interest, in view of next long-term experiments, even in combination with high-rate environments.
- **Gas Systems**: widespread interest for all technologies. Gas systems are seen as fundamental infrastructure for big detector systems or when using expensive or greenhouse gases. In this context, research interest is moving towards recirculation and recuperation gas systems for all technologies as well as improving gas purity.
- **Novel Materials**: widespread interest for all technologies to search for materials to improve detector performance. There is a common interest in resistive materials for MPGDs and RPCs, devoted in particular to very high-rate applications, as well as for low material budget, more resistant ones in TPCs and Wire chambers.
- **Precision Mechanics**: of wide interest especially in view of new experiments where new detector systems will be built. It ranges from mechanics for E and B field alignments to the construction of large detector volumes and systems.

A not exhaustive list of objectives in the WG3 activity plan is shown in Table 13. It is worth noting that the common interests in the topics are in full agreement with the ECFA Detector R&D Themes [14] as it will be described in the next Section.

II.1.3.2 Common Research Interests

WG3's objective is to enhance our comprehension and knowledge regarding the properties of gas and materials utilised in our technologies. These studies aim to optimise performance, ensure radiation hardness, and enable long-term operation. The prioritization of topics will be based on the anticipated requirements of future facilities and applications. Those are linked with the challenges identified by ECFA as DRDT 1.1, aiming to improve time and spatial resolution for gaseous detectors with long-term capability, DRDT 1.2 for large volume detectors with a very low material budget, DRDT 1.3 to develop environmentally friendly gaseous detectors, and DRDT 1.4 to achieve high sensitivity in both low and high-pressure TPCs. Some of the topics identified in WG3 will have a relevant impact on the implementation of the ECFA Roadmap. A few examples are reported below to give an idea of the importance of having common strategies in the research and development of WG3 topics:

- **Use of F-gases for Future Particle Detectors**: with the implementation of the EU F-gas regulation [21], most of F-gases will be phased out in the coming years making their availability uncertain as well as causing an increase of their price. The implementation of several strategies to reduce greenhouse gas emissions in particle detection will be fundamental for future experiments. These strategies include several

Reference	Description	Common Objective
D3.1.1	Gas properties: drift velocity, diffusion for e- and ions, gain measurements, light emission, attachment, etc.	Common gas properties database
D3.2.1	Characterisation of new eco-friendly gases: gas properties, cross-section, etc.	New data for the integration in Magboltz and Garfield++ (collaboration with WG4)
D3.3.1	Longevity and ageing studies for different technologies	Report for a common approach
D3.3.2	Characterisation of material for the construction of detectors: material properties, compatibility, outgassing, etc.	Common construction material database
D3.4.1	Development of gas recirculation and recuperation systems	New design and knowledge transfer
D3.5.1	Resistive material: characterisation of different materials	Common resistive material database and procedures
D3.6.1	Mechanics: compression, rigidity, machining precision, etc.	Common approach for the different technologies

Table 13: WG3 - Common Objectives

topics in WG3 such as gas recirculation, gas recuperation, eco-gas studies, gas properties and sealed detectors. The success of these research lines will be fundamental for muon systems, calorimetry, photon detection and particle ID/TOF detectors for future facilities.

- **Longevity of the Detectors**: in future accelerators, the accumulated charge will reach hundreds of C/cm^2. It will be therefore fundamental to validate detectors in these harsh environments by conducting studies of the ageing of detector components, outgassing, radiation hardness and material properties.
- **Improvement on Rate Capability and Time Resolution**: to cope with the new physics goals, an improved rate capability (up to 10 MHz/cm^2) and time resolution (less than 100 ps) will be necessary for the future. These developments could be achieved in gaseous detectors with studies of gas properties, resistive electrodes, solid converters, stable radiation-hard photocathodes, robust photo-converters and novel materials.
- **Construction of New Detector Systems**: future experiments and facilities will probably involve the construction of large detector systems, requiring both manufacturing on an industrial scale and optimisation of the design. These objectives could be achieved with studies of gas systems, precision mechanics, and material properties for detectors and infrastructures.

Several synergies and common aspects between technologies have been recognised as a good starting point for the implementation of a collaboration between the different gaseous detectors communities. Some of them are illustrated below by a non-exhaustive list:

a) **Gas Properties**: Gas measurements (cross sections, drift velocity, diffusion for electrons and ions) and gas simulations (Magboltz, Garfield++, GEANT4, COMSOL, etc.) are recognised as critical aspects in the design and operations of gaseous detectors. Among these studies, the ones aiming at the identification of eco-friendly gas mixtures free of greenhouse gases are considered of major importance (DRDT 1.3). This is common for all technologies. Wavelength-shifting gases are of interest for optical readout and light-detection applications. To facilitate the R&D efforts, the collaboration will encourage better dissemination of gas characterisation studies and the development of common databases of gas properties, a starting point being the *Aachen gas-database* [22].

b) **Ageing Studies**: The capability of operating gaseous detectors at very high rates for long periods represents one of the major challenges for the use of these detectors at future facilities. The collaboration will stimulate the sharing of experience and expertise in detector ageing, and promote studies of gas and material properties affecting the lifetime of the detectors. The identification of hydrocarbon-free gas mixtures, novel wire materials and coatings, the study of the radiation hardness of detector materials and photo-converter protection have been already recognised as specific subjects of interest.

c) **Gas Systems**: The purity of the gas mixtures is also recognised as a critical ingredient for the mitigation of ageing effects. Sharing and developing expertise in the construction of high-purity gas systems will be critical for the achievement of the DRD1 goals. Moreover, the increasing cost of technical gases, and the necessity to limit their consumption and dispose of the greenhouse components, call for the development of gas systems with recirculation and recuperation to become a standard for all gaseous detectors technologies.

d) **Resistive Material**: Spark protection and long-term stability is often achieved with the inclusion of resistive layers in the structure of the electrodes. The deployment of new resistive materials is one of the most relevant research topics to be pursued by the collaboration.

e) **Mechanics and Material Properties**: Precision mechanics has been always critical in gaseous detectors to achieve the required stability and resolutions. Alongside, the relevance of miniaturisation is increasing, while new fabrication techniques like additive manufacturing, micro-fabrication and nanotechnologies are becoming more and more attractive. The collaboration will promote both the consolidation of the expertise in machining, mechanical tests and outgassing tests and the exploration of the newest technologies.

A significant effort and commitment are required for the different gaseous detectors communities to share resources and conduct studies of these common research interests. In this context, it is also fundamental to have common infrastructures and facilities, that would help in the execution of the projects in a more coherent and economical way as well as they would allow a better sharing of knowledge in the different fields.

II.1.3.3 Infrastructure and Facilities

One of the possible advantages of this collaboration is to share not only the know-how but also materials, infrastructures and facilities developed for different technologies in order to reduce operational costs, improve the sharing of knowledge and possibly speed up the research work. In this section, we will discuss the available or needed facilities related to gas and material studies. This can be considered as a subset of the main topic discussed in WG7. From the survey, it turns out that some needs expressed by groups can be covered by the infrastructures and/or equipment indicated as available in other institutes. In particular, the institutes reported the availability of the following infrastructures and equipment (list not exhaustive):

Infrastructures

- Clean rooms.
- Test beam facilities.
- Irradiation facilities.
- Laboratories for analysis of the surfaces.
- Laboratories for thin film deposition (e.g. photocathodes, secondary emitters).
- Ageing/outgassing test stand.
- Precision mechanics workshop.

Equipment

- Gas systems.
- Gas analysers.
- Inspection facilities.
- Large-size sputtering systems.

Some of the listed infrastructures will be covered in WG7 and are of interest not only among the groups involved in the same technology but also to teams working on different gaseous detectors technologies: this could be for example the case of gas analyzers as well as inspection facilities, the first being important for almost all the groups while the second is nowadays necessary for MPGDs and for new amplification structures. The possibility and the protocol to access the facilities have any way to be discussed inside the collaboration. Many groups expressed willingness to contribute to common developments in the context of the DRD1 collaboration. Below are listed a few examples of common facilities or equipment that can help to support the research work on the topics of major interest for the community and that would benefit from the support, in terms of maintenance, of the DRD1 Collaboration:

- Irradiation facilities for ageing studies (common to all the technologies).
- Construction of gas systems and common gas analysis tools (common to all the technologies), including gas purity and electron lifetime monitors.
- Magnetron sputtering machine (resistive MPGD, RPC and surface-RPC).

- Sputtering of ohmic contact on semiconductor materials.
- Photocathode's evaporation system, QE measurements and ageing studies.
- Laboratories for examination and treatment of material surfaces.
- Workshops for precision mechanics (wire chambers and large volume detectors).
- Chemical laboratory for material characterisation and ageing studies.
- Laboratories for detector characterisation and operation tests.
- Laboratories for studies of outgassing and/or radiation hardness of materials.
- Workshops for precise manufacturing of detector parts.

Beyond infrastructures and equipment, there is also the possibility to profit from a gas properties database common to all the technologies based on the already mentioned Aachen gas database, common software for simulation of gas properties (WG4) and legacy from groups involved in eco-gas studies for RPCs. Synergies with WG8 on databases, information and experience sharing will be established.

II.1.4 Modelling and Simulations [WG4]

II.1.4.1 Introduction

The DRD1 Working Group 4 (WG4) aims at understanding and modelling the basic physical processes taking place in gaseous detectors, the development of suitable simulation and software tools able to reproduce the physical processes and predict detector performance. Advanced detector physics simulations are indispensable tools for the development and optimization of modern particle detectors. They allow to confirm or challenge the understanding of the physics and they are nowadays used standardly to understand the performance of existing detectors or to evaluate the validity of newly designed detection schemes.
The simulation tools used and developed in this context target the understanding of the detection physics inside the detector. They are complementary to the simulation needs of small-, medium- or large-scale physics experiments for which GEANT4 is the standard tool to track particles and register precise energy loss, which is then digitized using simplified models or parameterized simulations. There is a need to implement the simulation tools in a more versatile framework that can handle event simulation, reconstruction and analysis, which is often experiment-specific. While the development and support for such frameworks are out of the scope, the WG can be seen as a useful platform to discuss and exchange best practices.

II.1.4.2 State of the Art

Wire-based gaseous detectors (e.g. multi-wire proportional chambers, drift chambers, drift tubes, cathode strip chambers, time projection chambers with wire readout) are precisely simulated since the early 1990s with Garfield [23, 24, 25], developed by Rob Veenhof. Garfield can calculate very efficiently analytically the electric field for 2D geometries using complex algebra. Interfaces are available for HEED [26] which is used for the simulation of the primary ionization of charged particles and Magboltz [27, 28] for the transport parameters of electrons. Primary ionization due to electrons and heavy ions can be calculated using Degrad [29] and SRIM [30], respectively, and can be imported into Garfield. The induced charges on all electrodes in the device are evaluated using weighting fields and convoluted with nearly arbitrary transfer functions to simulate the signals. Wire-based gaseous detectors can be modelled very well in two dimensions, and the availability of the Garfield simulation suite has led to wire chambers being the gaseous detectors whose physics is most deeply understood and well simulated. For TPCs, the Garfield software suite has been used to evaluate the performance of the amplifying readout detectors as well as to study, identify and select the ideal gas mixture and electric field by investigating deeply their main transport properties (drift velocity and longitudinal and transverse diffusion).

Resistive Plate Chambers are parallel plate detectors with resistive electrodes, originally operated in streamer mode, and nowadays mostly in avalanche mode. Owing to their simple geometry (uniform electric field), analytical approaches have been attempted to solve parts of the problem of producing a reliable simulation, with various degrees of success: charge spectra and efficiency agreed with experiment for RPCs in avalanche mode with few mm gaps. Streamer mode description remains mostly empirical, because of the extreme difficulty in modelling the post-streamer stage [31, 32, 33, 34, 35]. These must however be considered as enlightened approximations of very complex phenomena taking place therein, because, in contrast with wire chambers, RPCs most often operate in a strong space-charge regime. Space-charge effects were first implemented by defining an arbitrary saturation value for the maximum number of electrons [36], of the order of few 10^7, close to Raether's breakdown criterion. Later improvements to a 1.5D [37] and 2D [38] model include the dynamic (analytical) calculation of the electric field contributed by the avalanche charges and allow explanation of average avalanche charges and shape of charge spectra in RPCs with thin gaps operated at high electric fields. They were however never implemented in simulation code made publicly available. Main topics studied (and understood – see [35] for an overview) include the physics and statistics of small Townsend avalanches, the timing properties in the low threshold regime, the processes related to the charge induction through resistive electrodes on readout strips and pads [39], and the signal formation and propagation in multiple long (1D) strips. Furthermore, charge transport in resistive materials and shot noise statistics arising from charge transport in these elements have been investigated as they are relevant for the simulation of these devices at high counting rates [40]. To understand the limitations of the avalanche mode operation of RPCs, the avalanche to streamer transition was a topic of study since the very beginning [41], and an interesting approach is being explored using simplified hydrodynamic simulations implemented in COMSOL [42, 43].

Micro-Pattern Gaseous Detectors (MPGDs) were developed at the beginning of the 1990s with the advent of micro-pattern techniques to improve the rate capability of wire-based detectors. They are characterised by sub-mm geometric features and use dielectric materials to separate complex electrode shapes and therefore electric fields cannot be solved analytically. The Garfield toolkit was extended [24] to read 3D field maps computed by Finite Element Method (FEM) or Boundary Element Method (BEM) programs, that exist open-source or are commercially available. The FEM method solves the Laplace equation at nodal points of a discretized (meshed) volume, and is the most widely used approach, but suffers from poor accuracy in certain critical zones. BEM on the other hand solves boundary integral equations obtained from the Poisson equation. The nearly exact BEM (neBEM) [44] program was developed and interfaced with Garfield. The simulation of MPGDs posed a second challenge to the then-existing simulation tool as the statistical charge transport approach breaks down since the mean free path of electrons is of the same size as the MPGD's electrodes. A second key improvement was the implementation of a full microscopic simulation [45] of the electron transport processes (scattering, diffusion, amplification), using the electron-atom scattering cross-sections from Magboltz. Garfield was therefore rewritten in the modern C++ language [46]. Detectors with dielectrics exposed to the gas suffer from charging-up (time-dependent gain characteristics) and this effect was modelled and simulated using computationally intensive setups using the superposition of electric field maps (a) due to the potentials on the electrodes and (b) due to accumulated charges on dielectrics [47, 48, 49]. Recently the extension of the Ramo-Shockley theorem for conductive media [39] has allowed proof-of-principle numerical simulations of signal induction in MPGDs with resistive elements [50]. Simulation of electroluminescence (VUV photon emission by excited atoms) was implemented in Garfield++ and is a starting point for the simulation of MPGDs or TPCs with optical readout [51]. To simulate the response of MPGDs to interactions of particles in material upstream of the sensitive volume (e.g. for neutron detection), an interface was developed using Garfield++ simulation as an external model inside GEANT4 [52]. Lastly, the use of hydrodynamic simulations to understand the formation and propagation of streamers has also triggered the investigation of discharge simulations in MPGDs [53, 54].

II.1.4.3 Needs of the Communities

The survey preceding the DRD1 community meeting revealed that about 2/3 of the institutes involved in the development of gaseous detectors are interested in contributing to the understanding of the detector physics and assessing the detector performance through simulations, while about 30% of them are interested in contributing actively to software development and maintenance, and about 70% indicated they are presently using commonly developed software tools for the design of detector prototypes. 40% indicated they are already involved in software development, while 55% indicated they are willing to contribute or support common software development in the context of DRD1. The institutes underlined the importance of continued maintenance and support for the existing software tools, also requesting the development of new features within these frameworks, which will be detailed here below. A speculative framework for a general gaseous detectors simulation tool is included at the end of the section.

Modernization of Garfield++ Code: Garfield++ was implemented in C++ a little more than 10 years ago and its main underlying code has not been revised for performance nor updated to use advantages offered by modern (multi-core) CPU architectures or heterogeneous architectures (CPUs and GPUs with shared memory and tasks). The code should be made thread-safe for multi-threading and should be adapted to be run on both CPU-only and CPU-GPU architectures. The first steps for parallelization have been made [55], but further testing and integration are needed. A continuous integration environment should be set up, through e.g., Jenkins [56], to have a faster and more robust code integration and code build infrastructure. Furthermore, a minimal set of tests (basic simulation tasks with known outcomes) should be run to verify performance improvement and code integrity. A basic software release planning should be made to plan and integrate the concurrent code improvements and major releases should be validated and made available on a regular basis, along with nightly builds that provide the latest version.

Reference	Description	Common Objective
D4.1.1	Garfield++ Modernization: Review Core Code (Multi-Thread, Heterogeneous Arch)	Core Code
D4.1.2	Garfield++ Modernization: Add Community Tools (Automatic Builds etc)	Software Tools
D4.1.3	Garfield++ Modernization: Review & Accelerate neBEM Code	New Release
D4.2.1	Garfield++ Framework Improvement: Recommended Set of Ion Mobilities	New Release
D4.2.2	Garfield++ Framework Improvement: Long-Term Solution for Magboltz	New Release
D4.2.3	Garfield++ Framework Improvement: Displays, Documentation, Examples	New Release

Table 14: WG4 - Common Objectives (4.1-4.2)

Improvement of Garfield++ Framework: The performance of the microscopic tracking can be further enhanced by improved interpolation of the electric field map, which is currently a very time-consuming step [57]. Interfacing an electric field solver (and not just reading field maps) would allow it to compute updates to the electric field due to space-charge on the fly, and first steps have been made to integrate neBEM in Garfield++ [55]. Several other improvements, that can be implemented, are (in random order and non-exhaustively):

- treatment of multiple scattering and energy loss of the primary charged particle and the use of molecular orbitals for the photo-absorption cross-sections in HEED;
- an interface for Degrad for primary ionisation of electrons;
- the use of a recommended set of ion mobilities for commonly used gas mixtures to simulate correctly signal length and shape, see e.g. recent efforts to modify the ion mobilities [58];
- revision of event displays and viewers in Garfield++ to make them more user friendly;
- inclusion of electron scattering cross sections of new eco-friendly gases such as HFO1234ze in Magboltz;
- interfaces for the python rewrite of Magboltz: PyBoltz [59] and other Boltzman solvers such as Bolsig+ [60], pyMethes [61] and Betaboltz [62];

- making existing interfaces more Python-friendly;
- derivation of Penning-effect parameters for ternary gas mixtures, investigation of non-linear and feedback effects at intense electric fields, extension to low pressure;
- improvement of the documentation and providing more examples on e.g., GEANT4-Garfield interface.

All possible improvements listed above should be assessed for the amount of time required and for the interest of the community and should be prioritised.

Simulation of Large Charges and Space-Charge: While the physics of small avalanches is well simulated and largely understood, the physics and statistics of large avalanches (e.g., charge spectra and time distributions) and their transformation into streamers, including realistic photonic parameters and streamer propagation and quenching are still to be understood and modelled in detail. Better understanding and modelling would not only benefit the simulation of RPCs but is also relevant for the study of discharges in MPGDs, where one would like to understand the critical charge before the breakdown, streamer formation in different detector geometries, propagating discharges and the modelling of discharges in a gem hole, including the electrode-heating and possible thermionic emission. Some possibility to model avalanche-to-streamer is already available by taking a hydrodynamic approximation to be solved using commercial FEM packages such as COMSOL Multiphysics [43]. Furthermore, the modelling and simulation of space charge within this simplified hydrodynamic approach have proven to be effective in modeling gain variations in GEM detectors observed at high particle fluxes [63]. Possible approaches within Garfield++ are grid-based avalanche statistics calculation or an extension of the particle tracking algorithm where close-by charges are clustered in deterministic behaving macro-particles or sub-avalanches when a sufficiently large number of charges is reached. The latter would preserve the statistical fluctuations in small avalanches with respect to hydrodynamical approaches that are purely deterministic. The simulation of large charge clouds in Garfield++ needs to be accompanied by the space-charge effect: Calculating the electric field induced by these charges at each step of the avalanche development can be done by interfacing a BEM or FEM solver [55] in Garfield++. Significant code improvements are required in neBEM to maintain simulations computationally feasible. Running these simulations on advanced GPUs will allow us to maintain the computational resources (memory consumption and computation time) under control. Recently a BEM solver was equipped with microscopic tracking run on a powerful GPU, and preliminary results indicate that the long-standing data Monte Carlo discrepancy for the gain in a GEM hole [64] could be resolved by including space-charge effects [65]. The software developed for the simulation of large avalanches will also be adapted and used for modelling discharge processes.

Simulation of Signals in Detectors with Resistive Elements: While signal induction in RPCs has been largely studied and understood using equivalent electrical networks, the inclusion of signal induction through resistive layers inside Garfield++ required the extension of the Ramo-Shockley theorem for conductive media [39]. Analytical solutions exist for simple geometries that can be used to model RPCs, and simulations have been performed, but this feature is not made available to the community inside one of the common simulation tools. For more complicated geometries of MPGDs numerical evaluation of time-dependent weighting fields is required [50, 66], currently being investigated with commercial FEM software. The use of BEM methods could be evaluated and eventually integrated into Garfield++. Resistive materials that collect electrons have characteristic times conducive to the spread and evacuation of the charge from the collection area. This leads on the one hand to the collapse of the amplification field, limiting the growth of the avalanche, and on the other hand the spread out of the charge that can be modelled - under certain conditions - through the telegraph equation [67]. The implementation of time-dependent weighting fields is more generally valid and would automatically take care of the charge spreading in the neighbouring readout strips.

Simulation of Rate Capability in Detectors with Resistive Elements: To understand the rate capability (under full area irradiation) of these detectors, the currents inside the resistive layers need to be modelled and the physical size of the geometry to be used in the simulation depends on the grounding scheme of the detector. A m^2 RPC with a single HV connection on the side would require a m^2 simulation geometry, while a uRWELL with a grounding grid in x and y-direction of 1cm requires just a 1 cm^2 simulation geometry to describe the detector behaviour under irradiation. Some encouraging results for MPGDs have been obtained by solving equivalent electrical circuits [68], while this could also be assessed with FEM or BEM solvers and solutions can be imported in Garfield++. An ideal deliverable of this task would be a software framework able to simulate generic gaseous detectors in specific conditions and predict a set of observables. While this is hardly feasible in a short timescale, a speculative general framework for the simulation of gaseous detectors can be envisioned, which could be progressively implemented in the coming years. A conceptual proposal is shown in Figure 7 below. The concept is based on two main pillars:

- The electromagnetic effects of the transport of charges in small time lapses can be viewed as an “impulse” and convoluted with the electromagnetic impulsive response of the detector elements to yield the full-time response, which will include all field perturbations and the induced signals.
- For a realistic simulation of resistive detectors or TPCs, the required simulated area may be very large compared with the avalanches and/or the simulation time of the order of seconds or more (e.g. GEM charging-up). It is likely impractical to simulate all avalanches for such a long time, particularly at high counting rates, calling for some form of sampling/parametrization strategy.

Dark Counting Rate and Ageing: For RPCs, some other topics that need a deeper understanding are connected to the origin of the "dark" counting rate; the gas and electrode material chemistry under irradiation; and the electrode’s localised discharge and charging-up processes taking place after streamers, as RPCs routinely operate with a small fraction of streamers present; also may require the simulation of full-size detectors.

Simulation of Large Gas Volumes (TPCs): An increase of computing power (including the use of GPUs) might be beneficial for more precise simulation of very large gas volumes in TPCs, allowing us to model small-scale features of realistic TPC designs. It will also allow us to investigate the non-uniformity of the electric fields due to these fea-

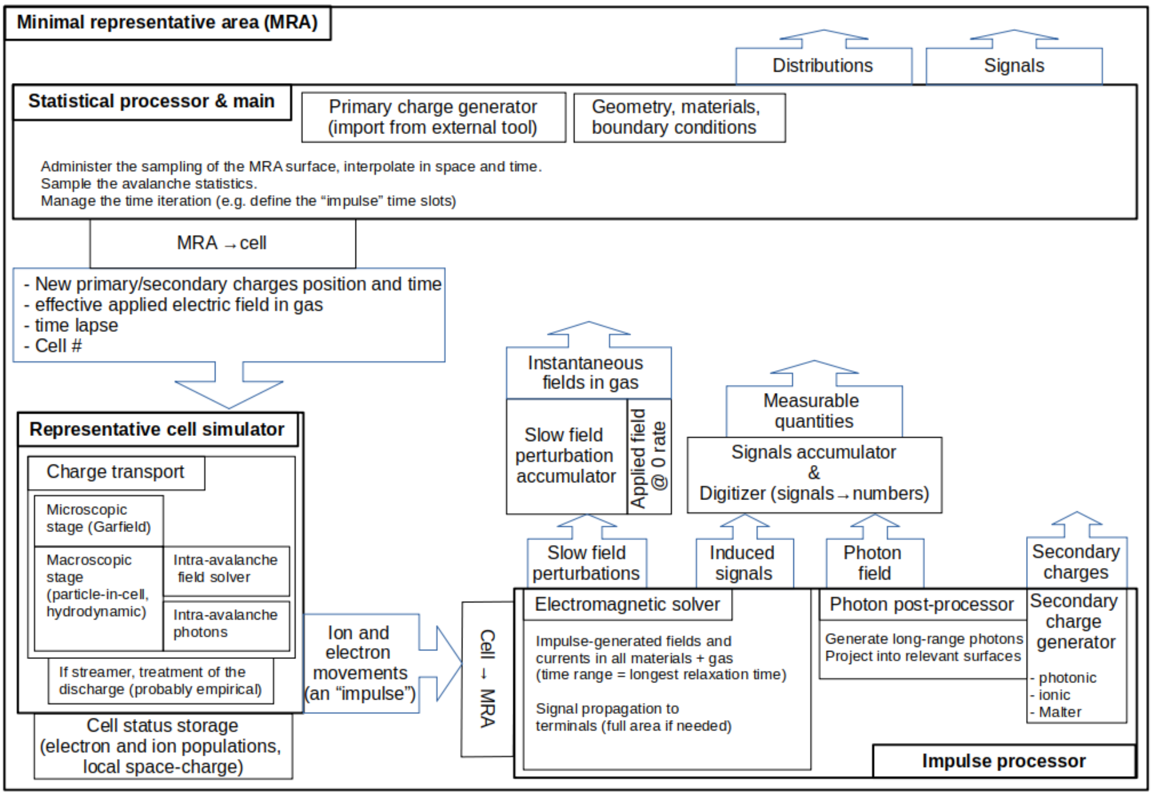

Figure 7: Scheme of an integrated simulation environment to simulate large-area resistive detectors. The representative cell simulator is called by the statistical processor to produce time lapses of the charge movements on sampling points (cells) within the minimal representative area (MRA). The impulses thus generated are processed to yield their MRA-wide physical effects, which are accumulated and will influence the subsequent steps.

tures or due to the buildup of space charge. Modelling of the pad response of the TPC readout chambers can depend on the chosen technology and can be addressed through Toy Monte Carlo simulations and Machine Learning techniques [69]. While these approaches are mostly developed in relation to particular/specific experiments, WG4 can be the ideal platform for cross-experiment discussion and exchange of ideas. Most simulation needs for large gas volume detectors can be addressed through the development of frameworks that seek to integrate simulation software such as GEANT and Garfield++. Several such frameworks already exist or are being developed (e.g. REST, LArSoft, GEMC, ATTPC-ROOT) and WG4 can serve as a cross-experiment discussion platform. Machine Learning could be eventually explored.

Modelling and Simulation of Eco Gases: The development of dedicated software for the detailed description of Eco gases properties and chemical processes will be an important tool for the whole community. It will offer significant support in the quest to minimize the environmental impact of detector operations without compromising performances. Furthermore, to simulate the detector response for new gas mixtures, the electron-atom scattering cross-sections for the new gases need to be extracted from measurements and included in the simulation tools (Garfield++, Magboltz). A collaborative effort with WG3 on the measurement of Eco gases cross-sections will be essential to allow realistic detector modelling.

Measurements and Extraction of Penning Effect: Quench gas molecules can be ionized by excited noble-gas atoms, explaining the observed higher ionization rates in gas mixtures. The simulation can describe the data with one additional parameter that describes the probability for this process to happen. This parameter was successfully extracted for the most common two-component gas mixtures used in the MPGD community. However further measurements and modelling are needed for some frequently used ternary gas mixtures used (e.g. ATLAS MICROMEGAS mixture or common RPC gas mixtures). Furthermore, the existing measurements need to be extended for low-pressure applications (e.g. RE-TPC).

Parameterized – Fast – Simulation: Parametrized simulations are fast and reliable tools that reproduce the complete response of a detector. The main physical processes are sampled from more accurate simulations to significantly reduce the simulation time. The main steps to reproduce are ionization, drift of electrons and ions, amplification, resistive effects, signal induction, and readout. Detailed simulations for each event are not required for a stable configuration, such as the one chosen to operate a single detector. The average behaviour of a detector is studied as a whole with a complete simulation, after which a parametrized simulation can be used to extract the behaviour. This method has the potential to significantly reduce the time needed for a single simulation [70] and extend it to configurations close to those extensively studied. Fast simulations are a must for optimizing detector configurations along with experimental benchmarks, such as in future colliders where the detector performance needs to match the experimental needs.

Simulation of Negative Ions: A further improvement in the spatial resolution of conventional TPCs, where electron diffusion is limited by parallel E and B fields, is the Negative Ion TPC where the electrons liberated by the primary ionisation are attached by highly electronegative atoms forming negative ions. The charge transport is performed by these negative ions, and electrons are again detached in intense electric fields where a normal Townsend avalanche of the free electrons can develop. At the expense of the much lower drift velocity of the ions $\approx$ cm/ms with respect to $\approx$ cm/μs for electrons, the longitudinal and transversal diffusion is reduced to the thermal limit, resulting in a significantly improved spatial resolution. While the low drift velocity impedes high-rate applications, this technique is perfectly suited for directional Dark Matter and neutrino experiments. Key features in the simulation are the electron attachment (in the drift volume) and detachment (in the amplification volume), for which a preliminary model in Garfield++ has been developed [71], but not yet integrated as further validation of the model is required. While pure SF_6 cross sections have been measured, a dedicated measurement campaign is deemed necessary to extract the cross section for SF6 doped gases, and to understand the dependency of the cross-section on the gas pressure. A generalised thermal limit for the negative ions should be included in Garfield++ as it differs significantly from the electron thermal limit and depends on the gas mixture, and one should investigate the possibilities of having a simulation for the diffusion in polyatomic gas mixtures using elastic and inelastic collision integrals

Reference	Description	Common Objective
D4.3a.1	Simulation of Large Charges and Space-Charge: Implement Space-Charge	Software
D4.3a.2	Simulation of Large Charges and Space-Charge: Implement Field-Update with neBEM	Software
D4.3a.3	Simulation of Large Charges and Space-Charge: Implement Clustering for Large Avalanches	Software
D4.3b.1	Simulation of Discharges: Use Code D4.3a to Simulate Different Geometries	Software, Validation
D4.4a.1	Simulation of Signals in Detectors with Resistive Elements: t-Dependent W-Fields with neBEM	Software
D4.4b.1	Simulation of Rate Capability in Detectors with Resistive Elements: Equivalent Circuits with neBEM	Software
D4.4b.2	Rate Capability Simulation in Detectors with Resistive Elements: Framework for Large-Size Detectors	Software
D4.4c.1	Dark Counting Rate and Ageing	Software
D4.5.1	Simulation of Large Gas Volumes (TPC)	Software
D4.6.1	Modelling and Simulation of Eco Gases	Software
D4.7.1	Measurements and Extraction of Penning Effect	Software
D4.8.1	Parameterized – Fast – Simulation	Software
D4.9.1	Simulation of Electroluminescence	Software
D4.10.1	Simulation of Negative Ions	Software
D4.11.1	Measurement of Ionization Quenching Factors for Low-Energy Nuclei	Software

Table 15: WG4 - Common Objectives (4.3-4.11)

II.1.5 Electronics for Gaseous Detectors [WG5]

The DRD1 Working Group 5 (WG5) takes responsibility for the development, application and dissemination of electronic components required to operate and further advance Gaseous Detectors (GDs). As an integral part of the detector system, the tools of WG5 are developed together with detector amplification structures in order to achieve the best performances. After the introduction in Section II.1.5.1 and a summary of the state-of-the-art (Section II.1.5.2) the major tasks are outlined in Sections II.1.5.3 to II.1.5.5 and summarised in Tables 16-18.

WG5 topically differentiates itself from ECFA DRD7 in the sense that it focuses on GDs and the electronics required for their R&D and application in small- to mid-size experiments. Methodologically, WG5 is based on the specific requirements of DRD1, developments by the community for the community and dissemination opportunities to future facilities and their experiments. Close exchange with DRD7 is achieved through the membership of electronic experts in both collaborations. DRD1 access to ASIC technologies, licenses, test resources and experts of DRD7 is deemed of mutual benefit for DRD7 since some basics of GD detectors are different, or non-existing in Silicon detectors.

II.1.5.1 INTRODUCTION

The development of dedicated electronics is of major relevance for the advancement of GD detectors, their operation, qualification and application in experiments. This is recognized and fully supported by large experiments, which in the past often profited from merging R&D electronics into their final DAQs, examples are the European Spallation Source and the ATLAS New Small Wheel.
WG5 will, compared to DRD7, concentrate on developing electronics readout and associated service electronics for direct use in test beams and experiments. Long-term requirements like radiation hardness, high-speed links, data reduction, dense integration and experiment-specific front-end ASICs initially have a less important role. DRD1 also aims to develop common service electronics for qualification and iterative improvement within its teams. Specific focus is also on high- and low-voltage systems, monitoring equipment (Section II.1.5.5) and standard DAQ systems (Section II.1.5.4) provided the support and training can be maintained from the resources of the community. The development of front-end ASICs for the specific needs of the different GD technologies (Section II.1.5.3) can resource-wise only be supported at the level of specifications, prototyping and testing. This general situation does however not exclude that DRD1 teams develop GD-specific ASICs with their proper funding agencies and their in-house chip designers. In summary, WG5 is primarily about R&D for DRD1 user - electronics - services and -DAQ systems with a long-term vision that these initial test systems can be scaled to systems in large experiments. A community survey has shown that the Scalable Readout System (SRS) [72] developed by the RD51 Collaboration was a huge success, and many groups familiar with the system mentioned that continued support and development of new features are among the most important tasks of DRD1. The request for additional features goes with an increased diversity of detector types ranging from analogue and discrete preamplifiers to multichannel integrated ASICs in the front end of a multi-purpose data acquisition. Also, the requirements mentioned in the survey show a large interest in pixel readout, strip readout and waveform digitization, as well as sub-ns time resolution, FPGA-based triggers and feature algorithms, low noise technologies for GD detector capacitances and larger dynamic ranges than currently available. Finally, grounding, shielding and spark protection were mentioned with similarly high numbers as other future challenges.

II.1.5.2 STATUS OF READOUT SYSTEMS FOR GASEOUS DETECTORS

The readout of multichannel gas detectors starts with a Front-End (FE) layer on the detectors, typically implemented as an array of plugin carrier cards (hybrids) each with a number n_{chip} of ASICs integrating a number n_{ch} of readout channels. Depending on the technology and detector type, multichannel ASICs convert the primary charge into voltage signals that are sampled or digitized for transmission over FE links to a Front-End Concentrator (FEC) layer, normally located in a crate-powered readout backend. Software control, associated with DAQ online software, is responsible for transmitting user-defined commands and configurations together with common clocks and optional triggers to all ASICs on the front end. In return, the ASICs may send triggered or untriggered serial channel data over FE links to the FECs.

A scalable system has a readout granularity of a single FEC and a single FE link allowing to read the minimum of 1 FE hybrid. This granularity defines a vertical readout slice with $n_{chip} \times n_{ch}$ channels connected to one of n_{link} link-port of one FEC (Fig. 8). The addition of vertical slices results in an aggregation of $N = n_{FEC} \times n_{link} \times n_{chip} \times n_{ch}$ channels, provided that the average bandwidth is non-blocking all FE links. With SRS classic N_{max}= 1024 ch/FEC (n_{link} =8 and $n_{chip} \times n_{ch}$ =128). FECs can be added via a network switch to extend N to 4096 channels however SRS classic then starts suffering from bandwidth and rate limitations. Larger systems, in particular for high rates, need to add a scalable backend, consisting of either an SRU or in the near future, an eFEC layer, boosting the channel aggregation in the extreme case for an eFEC to $N = 12k(n_{FEC} = 6, n_{link} = 16, n_{chip} \times n_{ch} = 128)$. The bandwidth scaling limit for an eFEC is 4 x 10Gbps. The input bandwidth from its 6-input links and without an optional embedded real-time trigger algorithm must be less than 40 Gbps and quasi-equally distributed over 6 input links of 10 Gbps each, allowing for some rate fluctuations between links. On the FEC layer below the scalable backend, the bandwidth per DTCCe link is 10 Gbps allowing on the FE side for 8 or 16 links of 1.25 or 0.625 Gbps. To put this figure in context, the highest bitrate required for a 4 MHz hit rate with RD51 VMM3a hybrids is 0.4 Gbps. FECs are designed for input bandwidth of 1 Gbps, hence the integration of further ASICs on FE hybrids should pay attention to their output bandwidth and if required, reduce the number of FE links to the FECs.

On the FEC layer and in particular, on a scalable backend layer, event fragments get concentrated in FPGA-resident event transit buffers with lifetimes up to tens of microseconds before being transmitted to the Online system. This allows for the implementation of real-time triggers over very large detector regions with user-defined FPGA algorithms in the backend layer.

Small systems with a single or a small number of FECs frequently make use of a laptop with 1 Gbit network ports controlled by standard DAQ and Control and data analysis software. Large systems, preferably connected via a scalable backend use the same online system running on performant computers with multi-gigabit networks and fast disk arrays to cope with the higher bandwidth. Scalable systems use the same DAQ and control software both on large and small systems, starting from a single hybrid. High-channel cunt systems beyond 4k ch may require scalable backends, more and faster links, faster disks, high bandwidth switches and computer arrays. On the backend level, the scaling limit can also be reduced by implementing user-defined real-time triggers in the FPGAs. These may remove insignificant subevents from the transmission to the online links or combine trigger events. Algorithms are detector-specific and must finish within the lifetime of the subevents in the FPGA-embedded buffers, calling for hardware-level algorithms using DSP and combinatorial logic. The use of state-of-the-art FPGA's (Ultrascale+ Zync) further comes with embedded real-time cores, providing a wide field of possibilities to implement intelligent triggers over complete detector regions.

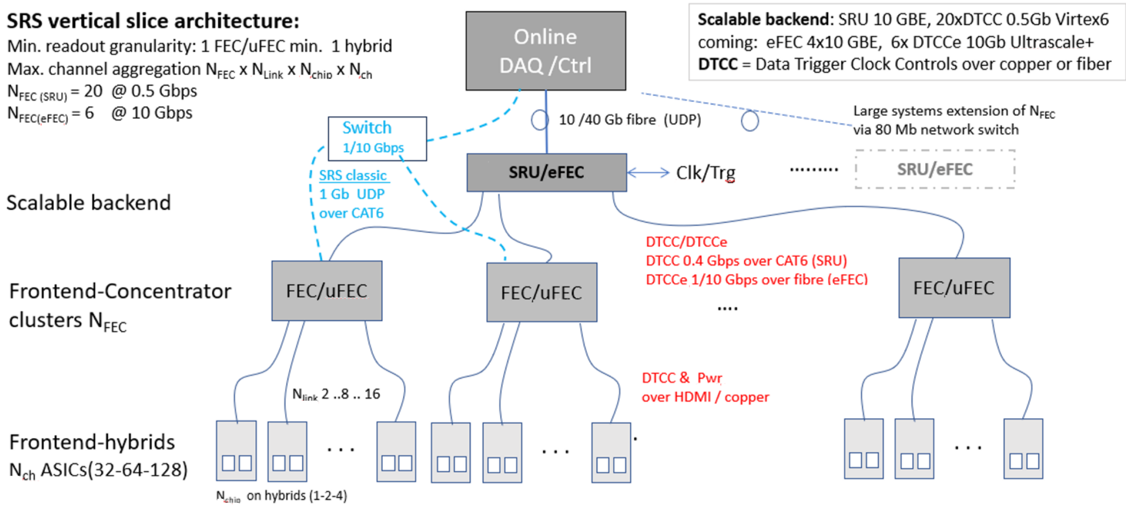

Figure 8: scalable SRS readout architecture showing both "SRS classic" with FECs connected via a network switch to the Online system and with a scalable backend, either the 2010 SRU (Scalable Readout Unit) or the 2023 eFEC with 4x higher bandwidth and a new FE link protocol over fiber optics (DTCCe) much superior to the classic DTCC protocol over CAT6 cables. The generalized FEC layer now ranges from μFECs for only 2 hybrids to FECs for up to 16 hybrids. The Frontend Power distribution, consisting of USB-C powered Powerboxes for groups of 8 hybrids is not shown for simplicity.

Readout System for MPGDs: Within the RD51 collaboration, the community agreed on an effort to develop a common readout system: the SRS (Fig. 9 [73]). Developed within the community for the community, SRS evolved as a system under direct feedback from many test beams followed by improvements and extensions available for the whole community. In 2023, SRS is a very mature readout system in terms of hardware, firmware and software. Its ease of use and organized training allowed the R&D groups to focus primarily on detector developments. SRS is a scalable readout concept for MPGD detectors, consisting of a crate-resident backend and a detector-resident front end. The SRS paradigm splits the SRS backend and front-end into fully functional, vertical DAQ slices allowing to start with a single, 128-channel front-end card (= hybrid, n_{ch} = 128) connected over an HDMI cable to a Front-End Concentrator Card (FEC) over specific link adapters for analogue or digital front ends. Small systems can get expanded in units of 128 channels and operated with the same DAQ software as required for large systems. The addition of 128-channel slices is native to SRS and the reason for the name "scalable". By 2023, the MPGD community deployed more than 100 small and large SRS systems internationally for different research purposes. At CERN, SRS helped to bootstrap readout and test of detectors of e.g. ATLAS, ALICE and CMS. SRS is designed to work with different front-end ASIC technologies, initially implemented with the analogue APV-25, followed by Timepix2 and since 2019 via the digital VMM3a ASIC enabling self-triggered detector readout at MHz rates with zero-suppressed data and a wide range of configuration settings to match a wide range of detectors. Further SRS front ends in preparation are SAMPA and Timepix3. SRS hybrids plug directly into MPGD detectors via low-impedance HRS connectors, standardized by RD51 for MPGDs. The VMM hybrid is by default equipped with general-purpose coolers for convection or flow cooling, for a nominal dissipation of 4 Watts per 128 ch. hybrid. The frontend link protocol of SRS for transmission of Data, Trigger, Clock and Control (DTCC) is implemented over commercial HDMI-AD cables with 4 differential Gbit sub-links and includes embedded power lines. AVP25 hybrids are fully powered over HMDI cables up to 20m whilst the digital VMM3a hybrids with high power requirements require extra power cables if the HDMI cable length exceeds 2m. A dedicated, USB-C-powered Powerbox for the SRS front end removes power drop issues over HDMI cables and enables link lengths beyond 20m. VMM hybrids transmit 2x 400 Mbps per HDMI cable, resulting

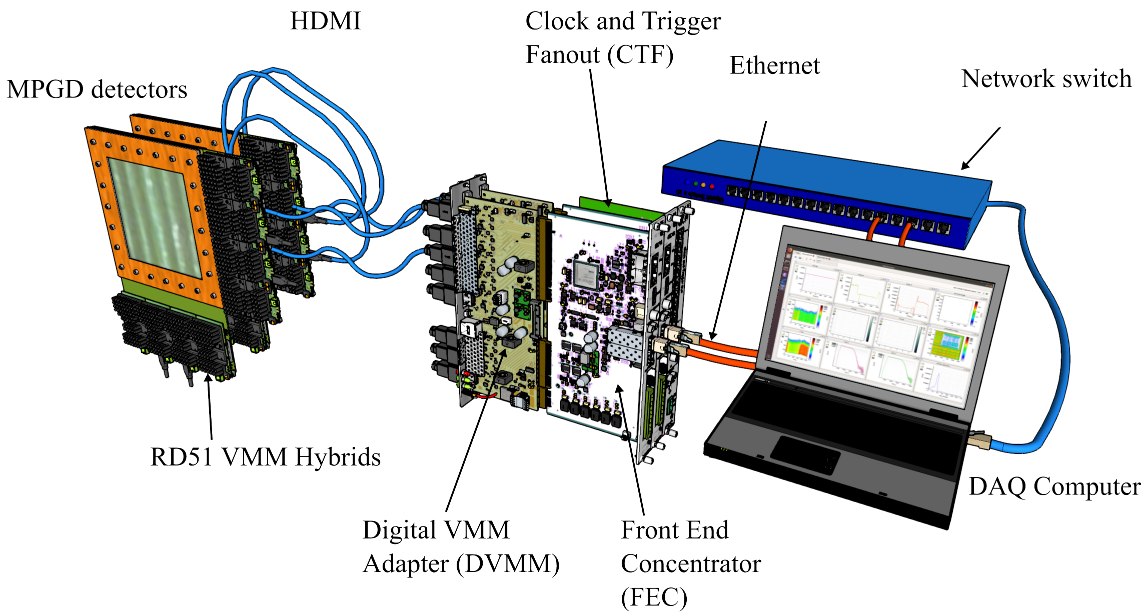

Figure 9: Schematic display of the SRS in the flavour with the VMM as front-end chip. Each of the two exemplary MPGD detectors is read out by eight VMM hybrids (each hybrid: $n_{ch} = 128$, $n_{chip} = 1$). All VMM hybrids of one detector can be connected with each HDMI cable to the DVMM adapter card of one FEC ($n_{link} = 8$). Several FECs can be connected to a DAQ computer by an Ethernet network switch.

in self-triggered hit rates of up to 8.9 Mhit/s per hybrid. With 8 connected hybrids per FEC, up to 1k channels can be read out per FEC. SRS Mini-crates can house 2 FEC/DVMM for up to 2k channels. Euro-crates provide slots and power for up to 8 FEC/DVMM slots for up to 8 k channels. SRS hardware is available for CERN users via the CERN store, or alternatively commercially from two producers. Detailed SRS documentation on HW, SW and FW with user FAQ is available on public drives and GitHub. SRS with the VMM comes with software for mid-size systems, data acquisition, online monitoring and data reconstruction as input to the dedicated analysis. The FEC-to-online links are so far implemented via 1 Gbit Ethernet UDP standard via copper or fibre, with a planned firmware upgrade for 2.5 Gbit Ethernet. Another firmware project plans to implement the ATLAS L0 trigger mode for the VMM front end to complement the triggerless readout mode preferred by most users.

Readout System for RPCs: The main feature of an RPC detector is high timing precision related to the fast rise time of the signal. The time resolution can go from a few ns for a large gas gap detector down to a few 10s of ps for a multi-gap detector. The charge produced in avalanche mode fluctuates from a few pC up to $\approx$100 pC). The pickup charge is significantly smaller than the avalanche charge and stays within a few 100 fC. The size of the pick-up strips or pads is kept at the centimetric range. Reducing it may improve the spatial resolution, but would reduce the charge amount per strip/pad. This feature defines the typical properties of RPC electronics:

- A pre-amplifier that can be coupled with a shaper
- A fast discriminator in a range from 1 to hundreds of fC. In some cases, like calorimetry applications, multiple discriminator levels can be used for a semi-digital readout.
- A TDC to tag the rising (*Tr*) (and possibly falling edge - *Tf*) with a precision significantly better than the time resolution of the detector to read. The Time-Over-Threshold (*TOT* = *Tf* - *Tr*) can be subsequently used to estimate the deposit charge by the particle.

As of today, there are numerous readout ASICs, discrete readout systems pairing a pre-amplifier and a discriminator, and Front-End-Boards in the RPC community, tailored to particular needs. The way the electronics are connected to the pickup system is also specific to each system: soldered coaxial or twisted-pair cables, commercial connectors, and direct bonding, among others. Most of the RPCs target a 2D readout. This can be achieved either using pads or using specific geometries of strips: partitions with short strips, x and y strips or long strips with double-sided readout, where the relative time of transition of the signal is used to define the position. Each strategy has its advantages and disadvantages, but it strongly impacts the design of the electronics.

Readout System for TPCs: Signals in TPCs often have a larger time duration because of the longer drift distances and thus larger longitudinal diffusion of the signals as compared to planar tracking detectors. Therefore, signals have a higher probability of overlapping. To be able to identify and reconstruct correctly two overlapping events, the signal is sampled with a Fast Analogue to Digital Converter (FADC). Pixel-TPCs, due to their low occupancy, are less affected. In general, TPCs require a trigger signal which starts the time measurement until the charges arrive at the readout for the correct reconstruction of the third coordinate of the track position. Currently, only very few ASICs fulfil the fast sampling requirements of traditional TPC readout, most of which have been developed exclusively for large experiments like ALICE. The backend electronics necessary to operate these chips is complicated and tailored for the corresponding experiments. Besides, the availability of ASICs can be very limited. Many smaller experiments cannot find well-suited electronics and are required to either operate ASICs with inadequate timing properties or have to resort to using electronics designed for planar tracking detectors. Pixel-TPC developments employ the Timepix ASIC implemented in the SRS and recently

Timepix3, for which the implementation in SRS is ongoing.

Readout System for Straw Detectors: For straw chambers, the main parameters to consider are the drift time and collected charge. The drift time t_d depends on straw diameter d_s and wire diameter d_w. For instance, d_s = 5 mm and d_w = 30 μm, results in a maximal drift time of $t_d \approx 50$ ns. For such a configuration, the produced charge could reach up to 50 fC in Ar/CO2 mixture. To reduce the drift time, d_w should increase and d_s decrease, reducing the amplification field and collected charge. This can be compensated by a larger applied HV, with an increased risk of discharge. Optimal electronics for a straw tube require a low threshold sensitivity of 5-20 fC and a good double pulse resolution, i.e. the ability to separate signals with a time difference of the order of t_d. This implies a dead time smaller than t_d of one given electronic channel. The electronic shall contain a TDC module to resolve the position of the fast signal with a resolution of 1 ns or better. This information is used to measure offline the impact parameter of the signal with respect to the wire (usually referred to as space resolution). A measurement of the position of the signal along the wire can be obtained in that case from a double-sided readout.

II.1.5.3 Front-End Challenges for Future Facilities, Experiments and Applications

In future, the electronics for **RPC** detectors will meet the challenge of high rates and faster timing. The usage of RPCs in experiments with a high rate of particles per cm² is becoming more and more frequent. The development of thinner electrodes with lower bulk resistivity leads to a faster charge evacuation from inside the gap. It also reduces the screening effect and increases the pick-up charge. A smaller gas gap allows for the reduction of the produced charge. Consequently, the discriminator threshold will be reduced to keep the same efficiency. The typical target for high-rate application is 1-10 fC. It implies excellent control over the detector and electronic noise via innovative grounding schemes. The new electronics have to cope with much higher transmission rates and the usage of optical gigabit transmission would become more and more common. The timing challenge is motivated by the common usage of single-gap and multi-gap RPC detectors such as TOF or VETO. The increased number of electrodes and gas gaps in multi-gap RPCs leads to a significant improvement of the timing resolution. This requires the development or application of higher-precision TDCs, synchronization and high-precision clock distribution.

For the **TPC** community, a flexible ASIC not adapted to specific operating conditions of a large experiment, implemented in a flexible, well-supported backend is much sought after and is highly desirable for numerous small experiments and R&D projects. For the Pixel-TPC with GridPix readout, Timepix3 with simultaneous charge and time measurement and an ASIC with optimised pixel size are key. In addition, TPCs for rare event searches have very diverging requirements. For example, some of these experiments have to run triggerless, while others need a continuous readout. For the latter, a trigger signal has to be synchronized to ASIC clocks. Negative ion TPCs have drift times in the order of milliseconds, with correspondingly long signal-shaping-time requirements.

Straw Chambers require a versatile ASIC including a TDC and an ADC for individual channels. It is also important to have at least one analogue multiplexed output channel for debugging and monitoring purposes. This condition implies two different frequencies to control the TDC ($\approx$ 1 GHz) and the ADC ($\approx$ 40 MHz). The TDC resolution should be at least 1 ns and ADC a few fC/mV and more.

In **general**, detector R&D programs require fast, low-noise, high-bandwidth and multi-channel ($\approx$100) front-end electronics, often including embedded digital online processing of data. Detector readout technologies, like cluster counting [74, 75, 76], may require the development of entirely novel front-end topologies as opposed to the classical charge-preamplifier-discriminator or ADC chain. In addition, gaseous detectors pose a specific set of challenges to the front-end electronics design that can be different from the challenges faced by other detector technologies, like high-current transient or spark tolerance, high dynamic range, high-rate capabilities or deadtime mitigation techniques. These requirements are often conflicting with each other, as emphasized previously, making the technological and architectural choices very difficult. As an example, the ADC design performance benefited greatly from technology scaling, while, on the other hand, the dynamic range capability of analog circuits has inherently suffered with scaling. Additionally, it was also observed that architectural innovation has played a significant role in the performance evolution of mixed-mode circuits like ADCs, thus signifying that more mature technological nodes may still benefit from this evolution. This entails a specific front-end electronics R&D effort tailored to the requirements of GDs, while, nevertheless, in line with the technological developments the broader high-energy physics scientific community is targeting. Historically, this effort was predominantly conducted on a project basis with the effort distributed among the community but essentially uncorrelated, supported mainly by the large research communities of large-scale high-energy physics experiments. Given the required resources to develop dedicated electronics, smaller and blue-sky R&D developments have been left often to search for available ASICs, many times only loosely adapted to their requirements, adding significant delays and overheads to their projects. As new large-scale experimental collaborations are yet to be formed, this effort may be conducted on a more general basis, directed towards a set of collaborative directions that can bring together a number of research teams with different targets, but with similar technological requirements. Modern design practices and tools favour the exchange of architectural blocks in a more collaborative design approach, also as a method to mitigate risks and, thus, reduce the costs of complex designs. In this way, a generic MPGD, TPC or RPC-oriented front-end can be designed and assembled with the requirements of the gaseous detectors community itself, but also leveraging developments of the broader high-energy physics community. Another important aspect is that a successful detector R&D is only possible while accompanied by adequate electronics able to demonstrate the performance evolution. This makes the electronics R&D for gaseous detectors a rather short- or medium-term target but also implies that resources need to be allocated accordingly.

Reference	Description	Common Objective
D5.1.1	High-rate RPC electronics	Survey on low-threshold discriminators
D5.1.2	Front-end ASIC for TPCs - WP4	Description of parameters
D5.1.3	Front-end ASIC for straw chambers - WP3	Description of VMM3/3a
D5.1.4	Front-end ASIC for straw chambers - WP3	VMM3b or new ASIC design
D5.1.5	Front-end ASIC for MPGDs - WP1	Community survey on chip requirements

Table 16: WG5 - Common Objective (5.1, Front End Challenges)

II.1.5.4 Plan for Modernized Readout Systems

Front-End: As described earlier, various technologies and applications have a wide range of specifications for front-end circuits. Some circuits like VMM3a or a future potential successor may serve the purpose of many MPGD applications, and other ASIC front-ends may work better for different applications, from the point of view of input coupling or dynamic range, whether they require trigger-less, data-driven, continuous or triggered readout architectures. As the sensitivity and rate capability increase, the data bandwidth of the front-end links increases accordingly. In this respect, copper links are only usable up to a rather short distance, even with the use of state-of-the-art equalisation techniques. Therefore, optical links remain the best choice. In addition to the increased data-rate capability, they also realise an electrical separation between the detector-coupled front-end and the readout system, which helps to reduce spurious system effects and simplifies the grounding scheme of the experimental apparatus. On the other hand, optical links bring several challenges to the front-end design, one is the increased power required, but also the real estate at the level of the detector front-end, where space is usually limited. Radiation hardness may also be a concern in many cases. Several developments are underway in the community to address these issues, with products already designed and used in the LHC experiments. In some cases, industrial partners are developing products tailored for specific scientific use together with the scientific community. This opens up opportunities for bidirectional technology transfer or common developments.

Backend: SRSe is the planned extension of SRS, providing significantly higher readout bandwidth with up to 20 Gbit per eFEC to the online computing system and adding FPGA-embedded trigger processing in the new extended FEC card, named e-FEC. This unified SRS backend card can be housed/powered in the existing SRS crates and combines a FEC and link adapter on a single card. For backward compatibility, the eFEC has 8 configurable HDMI ports, allowing to connect VMM hybrids. For upgrades, 12 new SFP link ports will connect new SRS hybrids, predominantly via optical fibres. Link protocols between the front-end and back-end will be implemented in firmware.

Firmware: While the dimensions and complexities of circuits have increased, programmable digital circuits have evolved a lot over the years, from relatively simple mesh-distributed computing elements to novel emerging architectures that employ more complex or specialized computing units linked by network backbones. This evolution has proven beneficial in many cases. This architectural evolution was accompanied by a hardware description language evolution, which almost aims for a unification of the hardware description language and the computer language paradigms. While this union is still not perfect in many aspects, it is of particular importance in our physics-driven scientific community. It allows applying computer programming skills to develop FPGA firmware. In the same optic, FPGA and CPUs are now more closely coupled together in local or remotely distributed acceleration systems. There are several ongoing efforts towards implementing common abstraction mechanisms or data transport technologies like Remote Direct Memory Access (RDMA) that may be successfully used in data acquisition systems and heterogeneous data processing systems that implement novel technologies such as machine learning online processing with e.g. neural networks. Building on top of these developments in synergy with DRD7, the aim is to develop firmware packages for the future SRS system that offer interchangeable and scalable processing libraries including protocol encoding and decoding which are community-driven and as much as possible application agnostic.

DAQ: In the first phase, the DAQ for SRSe needs to be bootstrapped from the existing DAQ software (including data acquisition, online monitoring and reconstruction), firmware and slow controls for FECs with VMM front-end. A generalized front-end link interface and a high-bandwidth online link upgrade are to be added. Taking advantage of the recent Xilinx Ultrascale FPGAs with embedded processors, DDR4 memory can be added and interfaced to the Linux operating system on the FPGA or an embedded CPU.

Testing (Radiation Hardness, Rate Compatibility): Until now, the radiation hardness of electronics was a second-order concern in the electronics design of gaseous detectors. Either the front-end boards were localized far away from the colliding beams being used as muon detectors, or they were used in low rate/low radiation experiments such as TPCs or wire chambers at LEP, neutrino physics or Dark Matter searches. The increasing usage of gas detectors in proton collisions, heavy ions, sometimes very close to the beam axis for increased acceptance, for calorimetry, or tracking in high luminosity fixed target experiments requires particular care for the design of on-detector electronics. Depending on the application, radiation-tolerant design and commercial components can be sufficient, or radiation-hard custom components might be required. Irradiation facilities to test electronics are located all around the world since they require secondary particle energies from a few keV to a few 100 MeV. Many of them (mainly in Europe) are clustered into the RADNEXT network (https://radnext.web.cern.ch/) pioneered by CERN, others such as CHARM are available at CERN. RADNEXT maintains a database of tested components. Many facilities designed for medical applications can also be used for electronics testing. Depending on the radiation environment of the experiment, gamma photons, thermal neutrons, or high-energy neutrons/hadrons can be required. For the high particle rate expected in muon detectors of future facilities, a dedicated irradiation infrastructure to test the detector itself and emulate the appropriate rate might be required. An example of such a facility is GIF++ [77] at CERN. In that case, the electronics are to be tested for deadtime generated by heavy data rates, and space-time resolution to separate Minimum Ionising Particles (MIPs) from background particles. Detector timing resolution can be tested in facilities with single particle guns and low jitter, such as HZDR [78] in Germany. Together with WG7, these new challenges and requirements for the electronics can be addressed.

Portable μSRS: There is interest (so far from the muography community) in small and portable frontend readout nodes for the readout of small gas detectors from inaccessible confined spaces and over long distances. Limited numbers of channels (<1k) per μSRS node eliminate the need for crate-based frontend concentrators if the bandwidth of a common network switch is sufficient to transfer the data from all connected nodes to the DAQ. Individual μSRS nodes can transmit self-triggered event data at high rates (>1MHz). The optional fibre interconnection between nodes provides clock synchronization and common control from a single, System on Chip (SoC) controlled master node. A first implementation is the μROC with two HDMI ports for readout of 256 VMM3a channels with 1Gbit/s ethernet uplink and 30 Watt USB-C power delivery.

Reference	Description	Common Objective
D5.2.1	SRSe WP1-8	eFEC
D5.2.2	SRSe WP1-8	VMM software and firmware migration
D5.2.3	SRSe - WP1-8	DAQ and reconstruction software
D5.2.4	SRSe	Testing and integration
D5.2.5	Common DAQ/SRS WP1,4	SAMPA implementation
D5.2.6	Common DAQ/SRS - WP4	Timepix3 implementation
D5.2.7	Common DAQ/SRS - RPC	RPC front-end implementation needs, potential and feasibility evaluation (report)
D5.2.8	SRS upgrades	2.5 Gbit Ethernet and L0 trigger ß
D5.2.9	Portable, Connected μSRS nodes	readout of distributed, small detectors over long distance

Table 17: WG5 - Common Objective (5.2, Modernised Readout System)

II.1.5.5 Topics Beyond the Readout Systems

In addition to the readout electronics described in the previous sections, many additional electronic devices are needed to operate a particle detector successfully. In particular, gaseous detectors require several high voltage stages, for which a fine current monitoring system is necessary to detect discharges and prevent any damage to the detector caused by increased currents. To protect the readout electronics in case of discharges, spark protection for each channel should be included to preserve the ASIC, which is generally laid out for much lower voltages than the gas amplification stage. Another large area of expertise necessary for operating gaseous detectors is noise reduction, which is based on correct grounding, shielding and low-noise power supplies. This requires considerable experience and knowledge, which has to be passed on to younger generations of researchers and extended with new techniques and materials available today. The working group's tasks would also include the dissemination of these concepts and introducing everyone interested in the art of a good experimental setup in synergy with WG8. Finally, gaseous detectors also require a good knowledge of the environmental parameters, which have a significant impact on the performance of the detectors. Therefore, monitoring systems to record a variety of parameters are needed to provide the data for corrections studied in WG3 and allow offline or potentially even online calibration of detector parameters. A new and interesting approach is the use of CPU within a SoC device to measure and correct for such comparably slowly changing parameters.

Reference	Description	Common Objective
D5.3.1	MPGD HV - WP1	Stabilised voltage divider
D5.3.2	MPGD LV - WP1-8	PBX
D5.3.3	Monitoring - WP1-8	SoC investigation

Table 18: WG5 - Common Objective (5.3, Beyond Readout System)

II.1.6 Production and Technology Transfer [WG6]

Working Group 6 focuses on the production aspects of gaseous detectors, covering all essential construction elements. Its goal is to strengthen the connection between production techniques and innovative solutions. The group supports the development of cost-effective industrial technology solutions by improving production processes and assisting the transfer to industry. The proposed objectives within Working Group 6 include:

- **Objective 6.1**: Development and maintenance of common production facilities and equipment.
- **Objective 6.2**: Quality control and large volume productions.
- **Objective 6.3**: Collaboration with industrial partners.
- **Objective 6.4**: Establishment and support of a forum for sharing experiences, knowledge, and best practices.

Through these objectives, Working Group 6 aims to enhance production techniques for gaseous detectors, enabling the realization of innovative solutions and efficient implementation of industrial technology.

II.1.6.1 Development and maintenance of common production facilities and equipment

The Collaboration recognizes the significance of production facilities in prototyping novel detectors and deploying them in future experiments through final production. With objective 6.1, we emphasize the importance of collaborative efforts to enhance the conditions and capabilities of these facilities.

In the context of MPGD technologies, the CERN's EP-DT Micro-Pattern Technologies

(MPT) Workshop has played a crucial role. It has enabled, initiated, and supported various developments, including the implementation of GEM, THGEM, MICROMEGAS, and μRWELL technologies, as well as novel readout concepts like resistive and capacitive sharing. The MPT Workshop has successfully produced detectors for R&D purposes, small-scale experiments (e.g., TOTEM GEM, T2K MICROMEGAS, LHCb-GEM, KLOE-CGEM), and large-scale experiments (such as CMS GEM muon system and ALICE GEM TPC). In addition, its experience in transferring production technologies to industry (GEM, MICROMEGAS, μRWELL) is important for the gaseous detectors community and the needs driven by future facilities and applications. The strong link between the MPT workshop and the RD51 Collaboration has led to the recognition of the MPT Workshop as a common production facility.
Within the DRD1 Collaboration, similar strategies will be employed to expand the support to other gaseous detectors technologies. The production facilities should develop technology-specific elements, accept orders from collaboration members, and ensure accessibility to production tools and consumables. To facilitate this expansion, a set of defined tasks has been established. These tasks, which aim to identify needs, assess current capabilities, and identify required resources for potential upgrades, are listed in Table 19.
The need to produce large-area RPC detectors with high efficiency and homogeneity for

Reference	Description	Common Objective
D6.1.1	Production Needs: detector type and size, production volumes and quality	Report with estimation for each technology
D6.1.2	Production Capabilities: detector type and size, production volumes and production quality	Report with inventory for each technology
D6.1.3	Needs and Capability Matching (costs)	Report with required resources in terms of equipment and personnel
D6.1.4	Identify Resource Pooling strategies for the creation or the upgrade of production facilities	Resource Requests

Table 19: WG6 - Common Objectives (6.1: Development and maintenance of common production facilities and equipment)

future experiments emphasizes the importance of establishing a common production facility. Currently, such a facility does not exist. This facility should provide the necessary tools for producing and qualifying the components required for constructing single-gap and multi-gap RPCs. The following is a non-exhaustive list of needs and requirements:

- Electrodes base material (HPL[3], glass, etc.)
- Cutting and cleaning of electrode materials
- Silkscreen printing of electrodes

[3] High Pressure Laminate

- Gluing tools for spacers and HV connections
- Oiling tools for the HPL-based RPC
- Gas tightness and HV validation tests
- Mechanical tools for assembling single-gap and multi-gap RPCs, including readout electronics, and conducting robustness validation tests

Regarding wire-based detectors, WG6 should focus on maintaining the production devices and tools (e.g., wiring machines) in working order. One major risk in these technologies is the potential interruption in production needs over time. Establishing databases of existing materials and available equipment within the community would be highly beneficial for this technology.

More generally, WG6 should help to identify and maintain in working order the equipment or infrastructure used for the construction or QC of completed projects. It will also need to keep track of the skills associated with these activities, in the form of procedures or reports, but also by establishing a directory of the competent people involved.

II.1.6.2 Quality controls and large volume productions

Once a detector type progresses beyond the prototyping phase, quality assurance (QA) and quality control (QC) become crucial in ensuring that the technical parameters meet the required specifications during the full production.
Gaseous detectors have specific QC requirements, such as measuring leakage current and determining the maximum operating voltage to avoid instabilities. Each detector technology may have its own distinct and precise requirements. In wire-based detectors, for instance, the wire plays a fundamental role. Ensuring the wires are of high quality is crucial for the detector to function successfully in the experiment. Specific tests, including evaluating cylindricity, the elastic domain, maximum charge capacity, and material purity, must be identified to assess the quality of the base material accurately. In some cases, the proper instrumentation is missing. This is the case for instance for tension-checking devices, that are used to check the mechanical tension once the wires are mounted. Developing portable or replicable devices for the required tests would greatly benefit future production efforts. Within the context of DRD1, the community will collaborate to identify required controls and validation criteria. Additionally, when necessary, the Collaboration will work toward the development of appropriate methodologies and instrumentation.
When transitioning to large-volume production, a stringent quality assurance plan with detailed manufacturing procedures and quality control measures will be essential and required. WG6 aims to identify quality control processes used in common production facilities. These QA/QC guidelines can be used and adapted for large-scale production. However, the final quality assurance protocols have to come from the specific large-scale project, taking into account the specificity of the project itself.
Along with appropriate QA/QC measures, when production moves from small, and medium quantities to large volumes, different equipment and facility organization may be required with respect to the ones of the common production facilities introduced in Section II.1.6. In some cases, this can be achieved through investment from the common production facility itself, while in others, involvement from industrial partners may be more suitable. The

decision will depend on various factors, including detector technology and size, materials used, production volumes, delivery times, and available budgets. The best path forward will depend on the project's unique requirements. WG6 will offer guidance and support to the community in this context. In table 20 two tasks associated with this objective are presented.

Reference	Description	Common Objective
D6.2.1	QA/QC protocols for each technology	Report
D6.2.2	Inventory of missing but required instrumentation for QA/QC	Report

Table 20: WG6 - Common Objectives (6.2, Quality controls and large volume productions)

II.1.6.3 Collaboration with Industrial Partners

The involvement of industrial partners is necessary or preferable in the following cases:

- When production volumes exceed the capabilities of the facility, whether it is a common production facility or local facilities in partner laboratories.
- When production volumes and/or industrial manufacturing methods allow for cost reductions.
- When ensuring availability for potential commercial applications is required.

For large-scale production in industry, technology transfer plays a crucial role, considering the specific and complex nature of the gaseous detectors technologies covered by DRD1. Technology transfer can be time-consuming, expensive, and complex due to the differences between the production technologies of these detectors and standard industrial methods. It should be noted that the involvement of an industrial partner can cover specific production steps (e.g., mesh or wire stretching, GEM UV exposure[4], resistive layer deposition) or the production of specific parts (e.g. new wires).
CERN has extensive experience in transferring production technologies to industry and has established contracts with commercial companies (e.g. GEM and large PCBs used in ATLAS New Small Wheels' MICROMEGAS modules). In these processes, the collaboration between the CERN MPT workshop and various companies has been supported by the CERN Knowledge Transfer group [79]. It is possible, based on this experience, to identify aspects that will affect the success of a technology transfer. A few examples are reported here:

- Identification of the market through appropriate market surveys.
- Relevance of the production volume to the industrial partner's typical production scale.
- Interest of the industrial partner in acquiring new methods to address niche markets.

[4]GEM manufacturing technology: metal-clad polymer foil (copper on kapton) is coated on both sides with a photosensitive layer and exposed to UV light through a mask reproducing the desired holes' pattern.

- Clarification of intellectual property licensing and contractual obligations.

Additionally, qualifying the company before initiating the technology transfer process is crucial and increases the likelihood of successful transfers.
The experience gained from the MPT workshop's technology transfer of MPGD technologies, combined with the collaboration with companies for various institutes in DRD1, is expected to be invaluable for other technology projects. In table 21 two tasks associated with this objective are presented.

Reference	Description	Common Objective
D6.3.1	Technology transfer checklist	Report
D6.3.2	Technology transfer database (project, industrial partner)	Database

Table 21: WG6 - Common Objectives (6.3, Collaboration with Industrial Partners)

II.1.6.4 Establishment and support of a forum for sharing experiences, knowledge, and best practices

To assist the community, especially newcomers, in locating experts who can provide guidance on issues related to the design and implementation of their detectors, an online forum (table 22) will be created in synergy with the laboratory handbook of WG7 and the resource sharing of WG8. This forum will enable any community member to post a question that can be viewed by the entire community, allowing individuals who have encountered and resolved similar problems to provide answers. The forum will be structured to minimize the need for ongoing maintenance while ensuring that the questions and answers remain accessible over an extended period of time to prevent redundancy. This will help avoid the repetition of common questions and facilitate efficient knowledge sharing within the community.

Reference	Description	Common Objective
D6.4.1	Establishment and support of a forum for sharing experiences, knowledge, and best practices on gaseous detectors	Online Forum

Table 22: WG6 - Common Objectives (6.4, Establishment and support of a forum for sharing experiences, knowledge, and best practices on gaseous detectors)

II.1.7 Collaboration Laboratories and Facilities [WG7]

Developing robust and efficient GDs requires a thorough understanding of their fundamental properties and performance at every stage of their development. This means investing significantly in detector testing activities, which involve testing prototypes and qualifying final detector-system designs. Collaborative efforts in this direction are justified given the large number of groups involved and the efficiency that can be gained by making common investments, thus avoiding duplication of efforts. WG7 activities are covering General Strategic Recommendation GSR1 and GSR5 of the ECFA Detector R&D Roadmap [14].

II.1.7.1 DETECTOR LABORATORIES NETWORK

We propose the establishment of a strategic worldwide distributed network of research laboratories to meet the needs of the scientific community. The network would serve as an entry point for the community, providing support and disseminating methodology and instrumentation to facilitate the work of detector scientists. The laboratories in the network would work collaboratively to share expertise, resulting in greater efficiency and cost-effectiveness. The development of this network would also help to increase the value of the laboratories at the national level, showcasing their contributions to cutting-edge research and innovation. Table 23 summarizes milestones and deliverables specific to this objective.

Network Establishment: The goal of this task is to establish a network of laboratories that can support the scientific community in conducting detector characterization studies, providing access to specialised instrumentation and test setups that might otherwise be difficult to obtain. The task will involve identifying potential laboratories and evaluating their capabilities and resources. Required agreements and protocols for accepting groups will be specified.

Characterization Methods and Techniques: The second task of this proposal is to discern techniques and methods for detector characterization. Existing solutions will be spread in the community and new ones introduced when required. The task will cover the development and dissemination of appropriate instrumentation, including sensors, electronics, and data acquisition systems, to support detector studies. Collaboration with industrial partners will be pursued for technological and dissemination aspects.This task will be carried on in synergy with WG8 Training and Dissemination Initiatives.

Laboratory Handbook: The third task of this proposal is to keep up-to-date an open-access laboratory handbook. The handbook will serve as a comprehensive resource for the network of laboratories, providing detailed documentation on techniques, methods, instrumentation, and other relevant topics. The *The Gaseous Detectors Handbook* by F. Sauli [80] will be used. The task will involve reviewing and updating the handbook on a regular basis to ensure that it remains cutting-edge and relevant to the needs of the scientific community. This task will be carried on in synergy with WG6 (D6.4.1) and WG8 Training and Dissemination Initiatives.

II.1.7.2 COMMON TEST BEAMS

Measurements in test beam facilities cover all the critical performance parameters for new detector systems like efficiency, noise, time/position/energy resolutions etc. As members of the DRD1 collaboration, research groups will get easier access to the test beams and irradiation facilities by making common requests and grouping the test campaigns. The

Reference	Description	Common Objective
D7.1.1	Establishment of a Detector Laboratories Network	Network and Webpage
D7.1.2	Identify and define available and required characterization techniques and methods	Report
D7.1.3	Update and review laboratory handbook	Handbook

Table 23: WG7 - Common Objectives (7.1, Detector Laboratories Network)

Reference	Description	Common Objective
D7.2.1	Design and Upgrade the gas system for the test beams	Gas system
D7.2.2	Tracking and Timing Beam Telescopes with different GD technologies	Telescopes
D7.2.3	Develop a DCS for power supplies, environmental parameter monitoring	Control system
D7.2.4	Support the development of a common DAQ for Test Beam	Common Test Beam DAQ
D7.2.5	Identify test beam facilities with potential local support from DRD1 members	Database of facilities

Table 24: WG7 - Common Objectives (7.2, Common Test Beam Facilities)

main test beam facility will be at CERN's North Area SPS extraction lines but the possibility of using other test beam facilities will also be explored. The collaboration will develop common infrastructures (including gas systems), DAQ/controls, as well as test beam analysis software that can easily integrate additional detector systems (ref. to objective 5). It will serve as a vehicle for community building and will address individual component performance, as well as combined performance and integration issues whenever appropriate. Milestones and deliverables will be summarised in table 24.

Common Test Beam at the CERN/SPS/NA: CERN's PS and SPS can provide a variety of particle species with a wide momentum range. The collaboration plans to request common test beam time periods at the SPS. The H4/PPE134 experimental area in EHN1 is identified as the best location given the available beams, the space and the presence of a 1.5T Magnet with a large enough opening. The area has been used in the past by the RD51 Collaboration for regular common test beam campaigns.

Tracking and Timing Telescopes: Based on different (gaseous) detector technologies, the collaboration is aiming to build tracking and timing telescopes that can be made available for collaborators coming to the common test beam. Though remote support will not be provided, the hardware can be shared to be used outside of the common test beam campaigns at the SPS/NA.

Common DAQ(s) and Software: The DAQ software developed in the context of common electronics will be made available to the community. A repository of analysis software will be created to allow the exchange of developments between groups. Existing analysis framework repositories, such as REST-for-Physics[5] [81], are readily available within the community for detector data processing, event reconstruction and analysis.

Identify Other Test Beam Facilities: The aim of this task is to identify other test beam facilities that have a local support group that could be accessed by members of the collaboration. This way DRD1 collaborators may have alternative testing sites: (i)for different beam requirements or (ii) for periods when CERN beam facilities are not available (e.g. periods of long shutdowns) or (iii) in case of difficulty in bringing equipment to CERN. One example is the DESY II Test Beam Facility[6] that provides a highly available electron beam from 1 to 6 GeV with rates up to the 10 kHz range. Each beamline is fully controlled by the user group and infrastructure for gases is installed in several beamlines. Pre-mixed gases can be provided and many infrastructures including beam telescopes are available. In beam area TB24/1, a large bore solenoid is installed on a movable stage including a full setup for gas detector tests. Local support is available from the DESY test beam team.

II.1.7.3 Irradiation Facilities

Reference	Description	Common Objective
D7.3.1	Irradiation facility gas system: Identify the gas system for the irradiation test	Design of an upgraded Gas system
D7.3.2	Equip Beam Telescopes using different GD technologies	Beam Telescope
D7.3.3	Develop a DCS for power supplies, environmental parameter monitoring	Control system
D7.3.4	Support the development of a common DAQ	Common DAQ
D7.3.5	Identify irradiation facilities with potential local support from DRD1 members	Database

Table 25: WG7 - Common Objectives (7.3, Common Irradiation Facilities)

The DRD1 irradiation program will focus on using available facilities to optimize the development and selection of the most suitable radiation hard technologies for the various gaseous detectors components and, at a later stage, assess and monitor the radiation hardness of the qualified components during production. Moreover, the characterization of specific detectors designed for prolonged operation under a large particle background requires targeted ageing tests. Research groups will get easier access to irradiation facilities by making common requests for facility space and irradiation time.

[5] https://rest-for-physics.github.io/
[6] Web page: https://testbeam.desy.de, Contact:testbeam-coor@desy.de

II.1.7.4 SPECIALISED LABORATORIES

This activity is strongly connected to the WG3 research lines (Sec. II.1.3). It is intended to supply the collaboration with the tools used for the research, give value to local realities for global purposes (as well as valorise each interested laboratory at the national level), and identify possibilities (with in-kind contributions from local support). Milestones and deliverables are summarised in table 26.

Outgassing and Ageing Laboratories: Any permanent or semi-permanent degradation of detector performance is classified as an ageing effect. The first check to be performed when a material/component is used for the assembly of a gaseous detector is to certify its compatibility with the gas mixture. Indeed, the use of new material/components can bring into the gas mixture unwanted volatile chemical species that can poison the gas mixture and finally compromise the detector's performance. This check should be applied to all materials that will be in contact with the gas mixture. The ATLAS-TRT team developed a setup used to check the outgassing from materials or equipment. This setup is still used by them and by the CERN EP-DT Gas Team to certify any component used for the gas systems built at CERN. Other similar setups exist in the collaboration, they will be identified and classified.

Gas Analyzers: The gas mixture is the sensitive media where the detectable signal is produced. A correct and stable mixture composition is a basic requirement for good and stable long-term operation of any gaseous detectors. The presence of contaminants or a wrong composition not only can affect the immediate performance of a detector but can potentially accelerate ageing processes. The development of standardised and easy-to-use gas analysis modules is of paramount importance for the understanding of detector performance and, finally, detector test results. Typical impurities that indicate that the mixture is not under control are O_2 and H_2O. For monitoring the concentration of the main mixture components or the presence of other impurities, a GC (Gas Chromatograph) or an RGA(Residual Gas Analyzer) station is needed. For material (detector and infrastructures) studies, other analysers are available in the collaboration and a common effort will be made to classify them into a shared database.

Photocathodes: the use of photocathodes is required in different applications using gaseous detectors as amplification stage. Qualification of deposition of well-known photocathodes, as well as the exploration of novel materials, require a set of infrastructures and instrumentation not always accessible to all groups. Within the DRD1 community laboratories with setups for deposition and photocathode characterization (Quantum Efficiency, stability, longevity) exist. WG7, in synergy with WG3, will support the establishment of a network between the existing realities and will promote cooperation and try to facilitate access to these facilities.

Reference	Description	Common Objective
D7.4.1	Consolidation and maintenance of the existing ATLAS-TRT outgassing test setup	Outgassing Test Setup
D7.4.2	Identify ageing study setups available in the collaboration and prepare a database	Report Webpage
D7.4.3	Database for outgassing and ageing effect of the material tested	Report Webpage
D7.4.4	Development of standardised and easy-to-use gas analysis modules	Design and construction of prototypes
D7.4.5	Network of deposition and characterization facilities for photocathodes	Network of laboratories

Table 26: WG7 - Common Objectives (7.4, Specialised Laboratories)

II.1.7.5 Instrumentation and software sharing

The scope of this objective is the dissemination of tools and instrumentation in order to offer the possibility to the groups to share their developments. Milestones and deliverables are summarised in table 28. For this objective, we set the following tasks:

Gas Mixture Supply Systems and Monitoring Tools: It has been demonstrated by the experience accumulated during the preparation and operation of the gas systems for the CERN LHC experiments, that the definition of standard modules can facilitate the construction, operation, and maintenance of the gas systems. Moreover, the design and the resulting use of standardised gas modules can facilitate the characterization of gaseous detectors. The control software for the gas system can run either locally in a standard PC or, for more complex installation, in a PLC. The user interface will make use of standard software provided by the suppliers or SIMATIC WinCC Open Architecture[7] applications in case of more complex systems.

Laboratory Instrumentation: Standard laboratory instrumentation is important to facilitate the work of experimental groups in detector characterization both with cosmic rays and particle beams. Although some of these instruments may be dependent on the kind of detector technology under test, nevertheless, most instruments are general purpose and can be shared by different groups at different times. Therefore, we aim to establish a common store of standard equipment for remote detector control, readout electronics, data acquisition based on NIM, VME and standard high-voltage supply equipment. We intend to compile an online catalogue of available modules at the various common DRD1 infrastructure locations and also facilitate the search and the possible rent of additional equipment at the CERN store. This should be extended also to non-standard and custom equipment available at various sites so that in case of particular needs, a group could first address the request to the community before embarking on new developments. In parallel, we aim to form a group of experts who could help newcomers with the correct use of the equipment

[7] SIMATIC WinCC Open Architecture, a software package designed for the use in automation technology.

and/or the understanding of possible failures.

Laboratory and Test Beam Software: Software infrastructure is more dependent than the hardware on detector technology and front-end electronics. However many tasks are common and could be standardised with only minor modifications for different detector types. There exist software efforts in the community, such as REST-for-Physics [81], leading towards common detector data processing using a unified data format for the different stages of detector event processing, such as detector response, event reconstruction, waveform analysis, etc. The unified data format provided by REST-for-Physics links appropriately between detector data processing and analysis, simulation packages and electronic readouts. The community plans to explore the potential use of and contribution to the software readily available.
Software for remote detector control, data acquisition, HV and gas system monitor/control are general-purpose libraries that can be of common use. We propose to develop and maintain these common libraries producing also the corresponding documentation. A proper repository with updated libraries and manuals will be available and a TWiki page will be updated with all the important information. Again we would like to make available a group of experts for problem-solving in case of software failure. As for the hardware infrastructure, custom software libraries that have been developed for special purposes will also be included in the repository.

Reference	Description	Common Objective
D7.5.1	HW&SW Development of standardised gas mixing and distribution units for detector under test	Design and construction of prototypes
D7.5.2	Development of standardised flow-meter setups to monitor the supply and/or return flow mixture	Design and construction of prototypes
D7.5.3	Survey of existing hardware equipment at common infrastructure	Online documentation
D7.5.4	TWIKI page with module manuals and schematics	Online documentation
D7.5.5	Survey of need for common libraries	Online documentation
D7.5.3	Development of general purpose libraries for data taking	Software libraries

Table 27: WG7 - Common Objectives (7.5, Instrumentation and software sharing)

II.1.7.6 DETECTOR TEST FACILITIES DATABASES

An updated list of facilities that are available for detector tests will be created. It will cover test beams, irradiation, and other useful specific measurements.

When possible, this list will be integrated into the existing databases. One example is the Irradiation Facilities Database[8] [82] developed in the AIDA-2020 [83]. This website hosts information about facilities for radiation testing at CERN, in EU, and worldwide. Technical descriptions of the facilities are given, together with a contact person and access conditions.

Reference	Description	Common Objective
D7.6.1	Test Facilities Database	Database

Table 28: WG7 - Common Objectives (7.6, Testing Facilities Database)

II.1.8 Knowledge Transfer, Training, Career [WG8]

Recognizing the importance of knowledge exchange, training opportunities and promoting researcher careers in a collaborative framework, Working Group 8: Training and Dissemination aims at facilitating scientific exchanges in the gaseous detectors community and educating as well as retaining experts in the field of gaseous detectors development. Training and Dissemination are fundamental for the development and advancement of detector R&D and in the design of the next-generation particle physics experiments. In this context, WG8 will build upon and expand on established methods within gaseous detectors communities, and exploit synergies between gaseous detectors technologies and among DRD1 Working Groups. To this goal, the scope of this working group contains:

- Knowledge exchange and facilitating scientific collaboration.
- Training and dissemination initiatives.
- Career promotion.
- Outreach and education.

The shared interests and common challenges of different Gaseous Detectors Technologies offer great potential for the exploitation of synergies within the collaboration. Through regular knowledge-sharing and training events, WG8 will offer opportunities for scientific exchange and help to identify areas of shared interests between members of DRD1. Close ties to other working groups will be instrumental to identify areas of topical focus and facilitate inter-technology exchanges and collaboration. In line with the General Strategic Recommendation 8 in the ECFA Detector R&D Roadmap, WG8 will interface with ECFA TF9: "Training" with a focus on training events and on initiatives to promote a positive environment for early career researchers which are not limited to a specific detector technology but aim towards a better recognition of detector R&D and career opportunities for instrumentalists. Following the strong expression of interest to participate as well as organise training, knowledge sharing and dissemination activities by the gaseous detectors community, WG8 aims at establishing and strengthening communication between members of the collaboration and to promote participation in common activities.

[8] https://irradiation-facilities.web.cern.ch/

II.1.8.1 KNOWLEDGE EXCHANGE AND FACILITATING SCIENTIFIC COLLABORATION

The exchange of acquired knowledge and experience is an essential collaborative aspect in view of accelerating learning and development processes and focuses the attention and participation of the community on relevant technological challenges. DRD1 will organise open workshops on topics of particular interest either at regular intervals or according to specific interests and needs. Topics for workshops can be suggested by any member of the DRD1 collaboration and WG convenors are encouraged to propose topics of particular interest to be considered by the DRD1 management. Workshops can be specific to a Work Package and associated applications, a certain detector technology or address specific cross-technological interests (e.g. ecological gases, simulation techniques, electronics, advanced materials). Topical workshops can be attached to other community meetings such as DRD1 collaboration meetings and will be typically organised in a hybrid format (in person + remotely) to optimise participation recognising the international nature of DRD1. In addition to organising topical workshops, DRD1 supports and encourages the organisation of and participation of members in instrumentation conferences and workshops. To facilitate scientific collaboration, DRD1 undertakes to strengthen the recognition of original contributions of individuals and groups, through the sharing of work presentations, the dissemination of significant published articles on topics of interest and the publication of internal notes to the DRD1 collaboration.

Reference	Description	Common Objective
D8.1.1	Organisation of topical workshops	Event
D8.1.2	Creation of repository for DRD1 notes	Online repository

Table 29: WG8 - Common Objectives (8.1, Knowledge exchange and facilitating scientific collaboration)

II.1.8.2 TRAINING AND DISSEMINATION INITIATIVES

It is important to recognise the value and relevance of training and dissemination not only for students and early career researchers but for the entire gaseous detectors community. Training events expressly dedicated to experienced researchers can expose them to Gaseous Detectors Technologies they are not necessarily familiar with, resulting in cross-fertilization among neighbouring techniques and an exchange of experiences. Training and dissemination events for technicians will be organised with a focus on the physics goals of Gaseous Detectors Technologies to motivate and inform the detector design processes and result in the sharing of technical experiences. Schools, technical training courses and the sharing of resources will be described as envisioned training and dissemination initiatives.

Schools: We propose the organisation of dedicated schools with a specific focus on Gaseous Detectors Technologies.

- General schools providing an overview of gas detector physics and science cases, gas amplification technologies, readout approaches, simulation and data analysis, with hands-on exercises on detector assembly, detector operation and characterisation, and data processing;

- Topic-specific schools in synergy with other WGs, examples of which may include a Simulation School on relevant modelling tools and approaches (with WG4) or an Electronics School with a focus on readout electronics systems for gaseous detectors and hands-on activities (with WG5).

In addition to schools directly organised by DRD1, WG8 will actively contribute to and support internships and summer school programmes organised at universities and institutes.

Technical Training Courses and Events: Building on past experiences, technical training courses and events, with the goal of exchanging experience on topics of common interest (gases and materials, simulation techniques, electronics, detector design and assembly) will be organised. In addition to academic training events, WG8 recognises in this context the interest in establishing synergies with other DRD1 WGs. Training periods may take place in DRD1 laboratories, especially when detector production or commissioning is ongoing in synergy with WG6 “Production”. A particular focus will also be given to the opportunities for scientific exchange and training inherent to common facilities in synergy with WG7 “Common test facilities”.

Sharing of Resources: A fundamental part of training and dissemination within DRD1 resides in the possibility of sharing resources and knowledge. To this goal, we propose to create a collection of online resources on gaseous detectors developments, in particular:

- A compilation of documentation on gas detector physics and operation, technical drawings, materials and gases specifications, and technical resources in general (also gathered from past workshops, conferences and events), periodically updated with state-of-the-art contributions from DRD1 members and recently published material;
- The creation of online forums and/or a technical Wiki to exchange knowledge and experiences, where DRD1 members can submit explicit questions and/or requests for help on common challenges and specific subjects; This could be realised possibly through the use of a Wiki software interface, in order to gather in a simple, user-friendly and common environment all the above-mentioned resources.
- The realisation of a database of expert contacts on specific topics of gaseous detectors developments within the DRD1 community, where experienced researchers, technicians and senior staff can offer their support and guidance;

II.1.8.3 Career promotion

Detector R&D plays an essential role in experimental particle physics and the promotion of the careers of young physicists engaged in hardware activities and R&D is critical to the success of particle physics research, as they bring new ideas and new approaches to physics and detector development. However, their career development can be hindered by a number of factors, including the low recognition of instrumentalist work and the reluctance in academic institutions to promote positions for hardware-oriented profiles. A few general

Reference	Description	Common Objective
D8.2.1	Organisation of gaseous detectors school	Event
D8.2.2	Identification of technical training interests and opportunities	List of possible activities
D8.2.3	Organisation of technical training course	Training event
D8.2.4	Creation of expert database	Web resource

Table 30: WG8 - Common Objectives (8.2, Training and dissemination initiatives)

remarks should be considered to implement strategies to promote the career of R&D experts. For a detector physicist reaching a good level of maturity could be a long path. R&D work is intrinsically long and risky: a lot is invested but results can be drastically negative, and discovering the causes (whether of concept or method) to re-complete the exploratory path is not obvious. Moreover, often linked to R&D there are needs from the experiments: construction, quality control, commissioning, all activities that are very time-consuming, with high levels of responsibility but poor visibility. In this context, the following strategies should be pursued within the scope of DRD1 applicable to young detector physicists:

- Invite young researchers to leadership roles within the collaboration (e.g. WG (co-)convenorship, organising topical workshops).
- Awards for young (as well as experienced) researchers presented during the collaboration meeting.
- Visibility through presentations in collaboration meetings and topical workshops.
- Promote opportunities through blue-sky R&D in Common Projects with dedicated funding for young researchers.
- Favour new career development opportunities through expanded collaborative networks, training events such as summer schools and workshops, and DRD1 visiting scientist programs.
- Monitor the work related to experiments needs, associate stimulating and innovative detector physics R&D aspects to, sometimes unavoidable, repetitive work which often does not require intellectual effort and, therefore scarcely considered.

Moreover, opportunities must be advertised on DRD1 web pages:

- Share information about job opportunities.
- Availability of training periods in the DRD1 common facilities and laboratories.

In addition to the actions under the direct control of DRD1, attention must be given to promoting the implementation of longer-term measures at research institutes and universities including the following:

- Increase the availability of high-level PhD thesis fully dedicated to detector developments.
- Include gas detector activities in university courses.
- Engaging trainee students in the development of detectors, as they evolve to achieve their undergraduate/diploma/PhD degree.

- Academic positions or longer term contracts for courses on detector developments.
- Correct evaluation of detector-dedicated activities in CVs.
- Responsibility roles for R&D within collaborations.

Reference	Description	Common Objective
D8.3.1	Create job opportunities listing	Web resource
D8.3.2	Initiate DRD1 award for young researchers	Event
D8.3.3	Promote young researcher participation in collaboration activities	Participation in events

Table 31: WG8 - Common Objectives (8.3, Career promotion)

II.1.8.4 Outreach and education

Outreach and education are crucial activities for attracting students to physics research and ensuring that the field remains diverse and inclusive. Both outreach and education, are transversal to all R&D projects and should be considered within the scopes of all DRDs.

Outreach must help to dispel misconceptions about physics being too difficult or abstract and must show the practical applications of physics research. By providing opportunities for students to learn about and engage with physics research, outreach programs can help to inspire the next generation of physicists. Outreach activities can also provide opportunities for students to engage with researchers, ask questions, and get hands-on experience with physics concepts and tools and may use social media channels to make detector research more accessible. Nowadays there is a huge variety of outreach projects all around the world. A few, excellent examples are Masterclass, laboratory visits, open days (a rich experience at CERN), European researchers' night, experiences in virtual reality, and many others.

Education programs can help to engage, inspire and educate students on particle physics and detector R&D, essential for developing the next generation of physics researchers. These programs could be tailored to different age groups and could include activities such as lectures, workshops, and laboratory visits and could also be designed to align with educational standards to provide an academic benefit to students. Laboratory activities are crucial parts of physics education for young students and as such should be sustained and promoted. They help in learning experimental techniques and build teamwork and collaboration skills. These skills are essential for success in physics and other scientific fields. The specificity of R&D in gaseous detectors (DRD1) should be expressed by:

- Sharing the knowledge, tools, methods, and gaseous detector-based experimental setups.
- Promoting events and hands-on experience. Conduct seminars and tutorials.
- Building common demonstrator setups; construction of portable or closed gas systems.

- Participating in outreach activities for the general public or at the high-school level to attract newcomers to the field of gaseous detectors.
- Promoting gas detector lectures and laboratory activities in university courses as well as external schools and training events.
- Ensuring high-quality educational lab activities focusing on gaseous detectors are encouraged.

Reference	Description	Common Objective
D8.4.1	Identify outreach activities and promote participation	Report on webpage
D8.4.2	Identify existing education setups and resources	Report on webpage
D8.4.3	Provide resources for educational setup	Description, technical plans, documentation

Table 32: WG8 - Common Objectives (8.4, Outreach and education)

Acronyms

ALICE A Large Ion Collider Experiment.

ASIC Application Specific Integrated Circuits.

ATLAS A Toroidal LHC ApparatuS.

BEM Boundary Element Method.

BESIII The Beijing Spectrometer III.

C^3 Cool Copper Collider.

CERN Conseil Européen pour la Recherche Nucléaire.

CLIC Compact Linear Collider.

CMS Compact Muon Solenoid.

COMPASS Common Muon and Proton Apparatus for Structure and Spectroscopy.

CP Common Projects.

CPU Central Processing Unit.

CSC Cathode Strip Chamber.

DAQ Data Acquisition.

DC Drift Chamber.

DHCAL Digital Hadronic Calorimeter.

DLC Diamond-like Carbon.

DRDT Detector R&D Theme.

DT Drift Tube.

DUNE Deep Underground Neutrino Experiment.

ECFA European Committee for Future Accelerators.

EIC Electron Ion Collider.

FAIR Facility for Antiproton and Ion Research.

FCC Future Circular Collider.

FEC Front End Concentrator.

FEM Finite Element Method.

FPGA Field Programmable Gate Arrays.

FTM Fast Timing MPGD.

GC Gas Chromatography.

GD Gaseous Detector.

GEANT GEometry ANd Tracking.

GEM Gas Electron Multiplier.

GPU Graphics Processing Unit.

GridPix Timepix3 chip with integrated amplification grid.

GWP Global Warming Potential.

HEP High Energy Physics.

HL-LHC High Lumi LHC.

HPL High-Pressure Laminate.

IBF Ion Back Flow.

ILC International Linear Collider.

InGrid Integrated Grid Detector.

KLOE K_L^0 LOng Experiment.

LEM Large Electron Multiplier.

LHC Large Hadron Collider.

LHCb Large Hadron Collider beauty.

LVD Large Volume Detector.

micro-PIC micro PIxel Chamber.

micro-RWELL micro Resistive WELL Detector.

MICROMEGAS MICRO MEsh GAseous Structure.

MIP Minimum Ionizing Particle.

MPGD Micro Pattern Gas Detector.

MRPC Multi Gaps Resistive Plate Chamber.

MSC Multi-Step Avalanche Chambers.

MSGC Micro Strip Gas Chamber.

MWPC Multi Wire Proportional Chamber.

neBEM nearly exact Boundary Element Method.

PET Positron Emission Tomography.

PID Particle Identification.

QE Quantum Efficiency.

RGA Residual Gas Analyzer.

RICH Ring Imaging Cherenkov Counter.

RPC Resistive Plate Chamber.

RPWELL Resistive Plate WELL Detector.

RWELL Resistive WELL Detector.

SCTF Slab Core Test Facility.

SDHCAL Semi-Digital Hadronic Calorimeter.

SFP Small Form-factor Pluggable.

SHiP Search for Hidden Particles.

SoC System on Chip.

SPS Super Proton Synchrotron.

SRS Scalable Readout System.

T2K Tokai to Kamioka.

TGC Thin Gap Chamber.

THGEM THick Gaseous Electron Multiplier.

TPC Time Projection Chamber.

TRD Transition Radiation Detector.

WG Working Group.

WinCC-OA SIMATIC WinCC Open Architecture.

WP Work Package.

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