DRD1

DRD1 EXTENDED R&D PROPOSAL
Development of Gaseous Detectors Technologies

Abstract

The document provides an overview of the state of the art and challenges for various detectors concepts and technologies, as well as a detailed list of R&D tasks grouped into Work Packages (WPs) that related to the strategic R&D programs to which funding agencies might commit, with related infrastructures and tools necessary to advance the technological goals, as outlined in the ECFA R&D roadmap. The main DRD1 document is structured into chapters, each describing the activity planned by the eight Working Groups (WG), which are the core of the future scientific organization. The current DRD1 proposal concentrates on the collaborative research program for the next 3 years.

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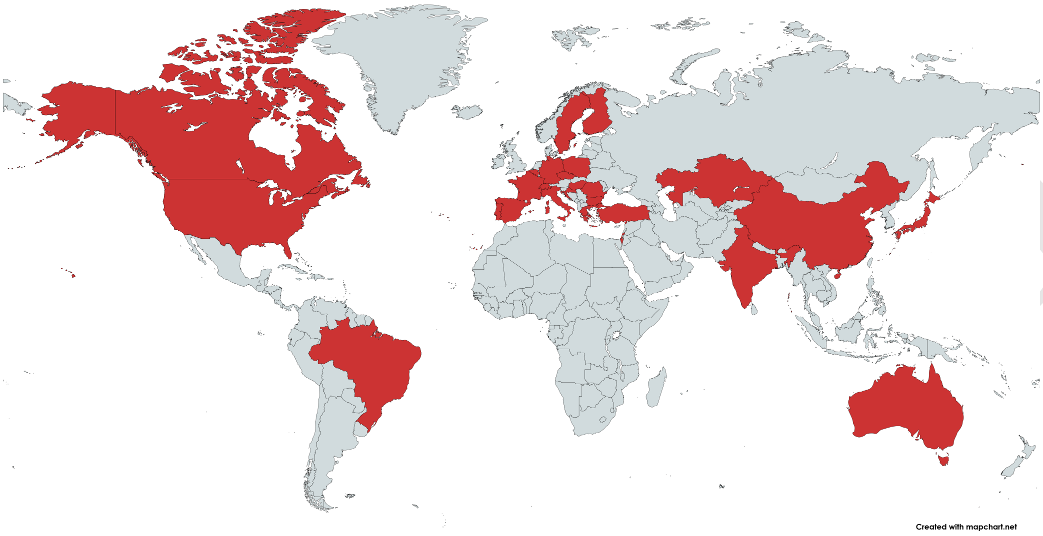

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Contents

1 Executive Summary

The Executive Summary will be prepared after the June 2023 DRD1 Community Meeting.

2 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 The pioneering Geiger counter (1908) has been replaced by parallel-plate avalanche chambers and various types of discharge detectors.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 In the new approaches, wires, typically used in MWPC, Drift Chambers and Time Projection Chambers (TPC), have been replaced by Micro-patterned structures created by photo-lithographic techniques on glass, thin polymer foils, and other thicker insulator substrates, etc.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 4.1. 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 somewhat 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 worldwide (KLOE-2 [6], CLAS12 [7], T2K [8], BELLE II [9], BESIII [10]) , which primarily use extended Gaseous Detector 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 Detector community and the Detector R&D Roadmap [11]. 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, and rare-event studies, 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 4.2, 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.

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

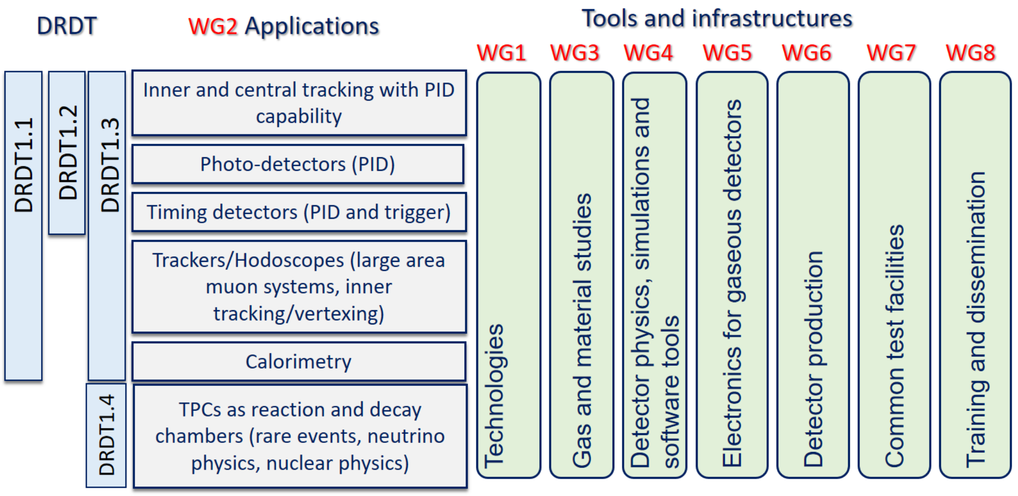

Figure 2: DRD1 Scientific Organization

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.

3 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 [12]. 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.

3.1 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.

3.1.1 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 as follows:

- WG1: Technological Aspects and Developments of New Detector Structures, Common Characterization and Physics Issues
- WG2: Applications
- WG3: Gas and Material Studies, and link to Novel Technologies
- WG4: Detector Physics, Modelling and Simulation frameworks
- WG5: Electronics for Gaseous Detectors
- WG6: Production and Technology Transfer
- WG7: Common Test Facilities and Infrastructures
- WG8: Knowledge Transfer, Training and Career

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

3.1.2 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.

3.1.3 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. The implementation of Work Packages respect with the ECFA themes and in the context of the Collaboration is shown in Fig. reffig:DRD1-WP-Schema

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 [12]. The involved Funding Agencies will be responsible for approving the WPs and overseeing their progress.

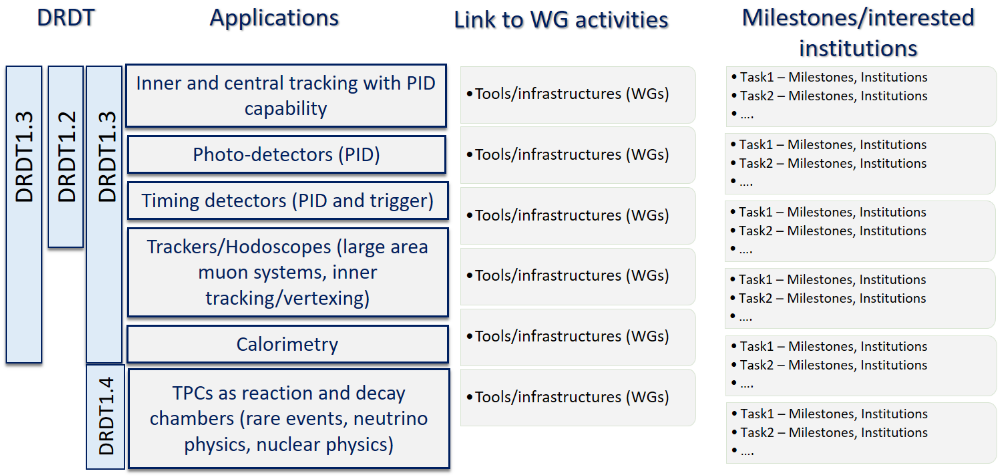

Figure 3: Implementation on Work Packages in the DRD1 Collaboration, with relations with ECFA themes and Working Groups

4 Research Topics and Work Plan

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

4.1.1 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) [13], 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 are provides less than 100ns. Examples of future wire-based detector concepts include: an ultra-low mass and large-volume drift chamber (35 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 [14], 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) [15] 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 demanding 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 [16]) 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 micro-electrodes (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 wide spread 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) [17] 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 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 neutrino-less 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.

4.1.2 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 at 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 MGPD 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.

4.2 Applications [WG2]

4.2.1 TRACKERS/HODOSCOPES (LARGE AREA MUON SYSTEMS, INNER TRACKING/VERTEXING)

Large area muon systems are often associated with gaseous detectors, representing one of the most successful technologies at combining the typical requirements for this application: the ability to easily instrument very large surfaces, good space-time resolutions, high efficiency and lightweight. In the future, muon systems, which in a collider environment are usually surrounding the experiment calorimeters, could be in some design partially or totally merged with them, sharing similar challenges. Moreover, such systems play a key role in tracking and time-tagging particles from rare-event decays and long-lived particles over large detection volumes.

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 ≈MHz/cm^2 with longevity compatible with decades of operation;
- enabling reliable and efficient operation with suitable low-GWP gas mixtures.

  Reaching the above objectives can be achieved through:
  - low-noise electronics integrated with a highly stable and noise shielding Faraday cage,
  - new detector materials and geometries increasing signal pick-up,
  - innovative materials with lower resistivity yet ensuring spark-quenching;
- time resolution ≈10-100 ps for applications aimed at extending the reconstruction power in very high-rate collider experiments (e.g., for identifying bunch-crossing, pile-up mitigation, and improved determination of the particle velocity).
- large-scale serial production;
- low-rate applications involving muon tracking in HEP as well as muon tomography over large areas will benefit from the development of robust, compact and low-power data acquisition systems, operating in highly autonomous conditions.

Besides 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 exploited. 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 are currently very different, they share many of the above challenges.

A work package (WP1) addressing the R&D needed for such genuine trackers/hodoscopes (large area muon systems, inner tracking/vertexing) is presented in Tables 1 and 2.

4.2.2 INNER AND CENTRAL TRACKING WITH PARTICLE IDENTIFICATION CAPABILITY (DRIFT CHAMBERS, STRAW CHAMBERS AND TIME PROJECTION CHAMBERS)

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 flavor 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 granularity resulting in a very large number of wires require novel feedthrough-less approaches to wiring (e.g., the DC of MEG2).
- new wire materials:
  - high gas gains (about 5×10^5) and electrostatic stability for long wires require lighter and more mechanically resistant wire materials. Carbon monofilaments might be good candidates, requiring developments in metal coating for increased wire conductivity and ease of soldering.

Electronics:

- front-end:
  - large bandwidth and high gain pre-amplifiers for efficient application of cluster counting techniques, together with low power consumption and low mass, demand the design and implementation of dedicated ASICs.
- Data Acquisition System (DAQ):
  - waveform digitizers at high sampling rates and without dead time, coupled to Field Programmable Gate Array (FPGA)-based data-processing systems, are needed for real-time signal processing, filtering, minimization of data throughput, event time-stamping, and triggering purposes.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3 y	Interested Institutes
T1	New resistive RPC materials and production techniques for resistive layers	- Develop low-cost resistive layers - Increase rate capability	WG3 (3.1C, 3.2D), WG6, WG7 (7.1-5)	1.1, 1.2	- HPL, low resistivity glass - Semiconductors - Printed resistive patterns - DLC-sputtered electrodes for surface-dissipation in RPCs	- Design, construction and test of prototypes with new production techniques	INFN-RM2, INFN-PD, INFN-BO, U Kobe, INFN-PV, WIS, INFN-LNF, CERN, IPPLM, U Bolu-Abant, U Cambridge, HYU, MPP.
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	WG3 (3.1C, 3.2D), WG4, WG6, WG7 (7.1-5)	1.2	- High-rate DLC layout for micro-RWELL	- Design, construction and test of prototypes with new resistive materials - Modelling and Simulation (signal induction) - MPGD prototypes based on resistive elements for tracking	USTC, INFN-PD, INFN-NA, INFN-RM3, INFN-LNF, INFN-FE, INFN-PV, INFN-BO, U Kobe,WIS, IRFU/CEA, IPPLM, LMU, U Bolu-Abant, CERN, MPP.
	2D readout optimization	- Development of low-granularity 2D-readout with high tracking performance			- Layouts based on low resistivity DLC film and charge sharing	- Design, construction and test of prototypes with low-granularity 2D-readout	INFN-LNF
T3	New front-end electronics	- 1 fC threshold - High-sensitivity electronics to help achieving stable and efficient operation up to ≈MHz/cm^2	WG5, WG7 (7.1,2)	1.1	- Integration of FEE in the detector Faraday cage - Integration of electronics and readout PCB	- Conceptual electronics design based on gas detector simulation and experimental measurements - Development and test of a front-end prototype - High throughput multichannel FE (peak time/amplitude based VMM3a): performance studies and optimization.	IFIN-HH, INFN-FE, INFN-BA, INFN-BO, INFN-TO, IRFU/CEA, IPPLM, INFN-RM2, U Cambridge, CERN, MPP.
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	WG5	1.1, 1.2	- FPGA-based architecture - FPGA with embedded processing for triggering and ML - Basic firmware and software can be bootstrapped from existing readout system	- First prototype by the end of 2024 for commissioning at test beam - SRS/VMM3a Readout: Continuous and trigger mode, distributed systems, synchronization with other DAQs.	IFIN-HH, INFN-BO, U Bonn, IPPLM, CIEMAT, CERN

Table 1: WP1 (Part I) - a work package on genuine trackers/hodoscopes (large area muon systems, inner tracking/vertexing). Applications: future electron colliders (ILC/C^3, FCC-ee, CEPC), Muon collider, Hadron Physics, FCC-hh, muography. Technologies: RPC, MICROMEGAS and GEM, micro-RWELL, GridPix, m-PIC, FTM, MWPC (DT, CSC, TGC). *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3 y	Interested Institutes
T5	Eco-friendly gases	- Guarantee long-term operation - Explore compatibility and optimized operation with low-GWP gases	WG3 (3.1A, 3.1B, 3.2C), WG4, WG7 (7.1-4)	1.1	- Ageing studies - Leak mitigation and maintenance of existing systems - Gas simulation: drift velocity, diffusion	- Test and characterization of gaseous-detection technologies with low-GWP gases (broadly)	U Oviedo, CERN, U Wurzburg, INFN-BA, INFN-LNF, INFN-BO, INFN-PV, IRFU/CEA, U Coimbra, VUB and UGent, IPPLM, LMU, U Aveiro, INFN-RM2, Istinye U, HYU, MPP.
T6	Manufacturing	- Construction of large-area detectors at low cost - Modular design - Technology transfer strategy and training center for production	WG3 (3.2E), WG6, WG8	1.3	- Optimization of the manufacturing procedure to minimize time-consuming or costly steps	- Design and manufacturing of large-area detector - Large-area DLC production - CERN: MPGD based manufacturing capabilities and large-area modules (design and prototyping). Note: MPT Workshop	U Heidelberg, USTC, WIS, GSI, INFN-NA, INFN-RM3, INFN-LNF, INFN-BO, UW–Madison, IPPLM, LMU, INFN-RM2, Istinye U, Wigner, CERN, MPP.
T7	Thinner layers and increased mechanical precision over large areas	- Test to experience the ultimate limits to thinning down the detector	WG3 (3.2E), WG5, WG7 (7.1,2)	1.3			INFN-BA, INFN-LNF, IPPLM, LMU, INFN-RM2, MPP.
T8	Longevity on large detector areas	- Study discharge rate and the impact of irradiation and transported charge (up to C/cm^2)	WG1, WG3 (3.1B, 3.1D, 3.2B), WG4, WG7 (7.1,3)	1.1	- Discharge probability - Ageing		WIS, INFN-NA, INFN-RM3, INFN-BA,INFN-LNF, IRFU/CEA, U Coimbra, IPPLM, LMU, INFN-RM2, INFN-BO, MPP.
T9	Low-mass MPGDs for inner-tracking at low-energy ee colliders	- development of low-mass planar cylindrical mechanics	WG5		- low-mass cylindrical micro-RWELL for Inner tracker	- Prototype test	INFN-LNF
T10	Develop robust, compact, and low power DAQ for low rates	- 256 channel readout - 100 W or less - 1200 cc DAQ volume - Rugged design for remote (<1 km), e.g. underground operations	WG5		- Muon rates from few Hz to few events per day	- Deployed and tested at depth	OXY

Table 2: WP1 (Part II) - a work package on genuine trackers/hodoscopes (large area muon systems, inner tracking/vertexing). Applications: 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 mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

Gas:

- hydrocarbon-free mixtures:

    - safety requirements on flammable gases demand the use of hydrocarbon-free gas mixtures, that should preserve a high quenching power and low Z number.
- recirculation systems:
    - the dramatic increase in the cost of noble gases, the large volumes, and the stringent purity requirements on the gas mixture demand sophisticated and complex purification and recirculation systems.

The main points are summarized in Table 3.

Straw Chambers

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 ($\mathrm{d}E/\mathrm{d}x$) can be used for PID or at least noise hit suppression and requires dedicated ASIC developments for the electronic signal readout. The WG1 section (4.1) lists examples and applications for straw detector systems currently in development or planned for the future.
For applications at 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), favor 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-

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Development of front-end ASICs for cluster counting	- High bandwidth - High gain - Low power - Low mass	WG5, WG7 (7.2)	1.1, 1.2	- Achieve efficient cluster counting and cluster timing performances	- Full design, construction and test of the first prototype of the front-end ASIC for cluster counting	IHEP CAS, CNRS-LSBB, INFN-RM1, INFN-LE, INFN-PD, INFN-BA, INFN-TO, SBU, IPPLM
T2	Develop scalable multichannel DAQ board	- High sampling rate - Dead-time-less - DSP + filtering - Time stamping - Track triggering	WG5, WG7 (7.2)	1.1, 1.2	- FPGA-based architecture - ML algorithms-based firmware	- A working prototype of a scalable multichannel DAQ board	IHEP CAS, INFN-LE, INFN-BA, UW–Madison, IPPLM, INFN-BO
T3	Mechanics: develop new wiring procedures and new end-plate concepts	- Feedthrough-less wiring - More transparent end-plates ($X < 5\% X_0$)	WG3 (3.1C)	1.1, 1.3	- Separate the wire support function from the gas containment function	- Conceptual designs of novel wiring procedures - Full design of innovative end-plate concepts	USTC, GANIL, CNRS-IN2P3/IJCLab, CNRS-LSBB, GSI, MPP, INFN-RM1, INFN-LE, INFN-BA, INFN-PD, CERN, PSI, U Manchester, SBU, Wigner
T4	Increase rate capability and granularity	- Smaller cell size and drift time - Higher field-to-sense wire ratio	WG3 (3.2E), WG7 (7.2)	1.3	- Higher field-to-sense wire ratio allows increasing the number of field wires, decreasing the wire contribution to multiple scattering	- Performance evaluation on drift-cell prototypes at different granularities and with different field configurations	USTC, CNRS-IN2P3/IJCLab, CNRS-LSBB, MPP, Bose, INFN-RM1, INFN-LE, INFN-BA, CERN, PSI, U Bursa, U Manchester, SBU, INFN-BO
T5	Consolidate new wire materials and wire metal coating	- Electrostatic stability - High YTS - Low mass, low Z - High conductivity - Low ageing	WG3 (3.1C)	1.1, 1.2	- Establish contacts with companies producing new wires - Develop metal coating of carbon wires	- Construction of a magnetron sputtering facility for metal coating of carbon wires	GSI, CNRS-IN2P3/IJCLab, CNRS-LSBB, INFN-RM1, INFN-LE, INFN-BA, CERN, PSI, U Manchester, SBU, INFN-BO
T6	Study ageing phenomena for new wire types	- Establish charge-collection limits for carbon wires as field and sense wires	WG3 (3.2B), WG7 (7.3,4)	1.1, 1.2	- Build prototypes with new wires as field and sense wires	- Prototype tests in-beam and at irradiation facilities - Measurement of performance and dependence on total integrated charge	CNRS-IN2P3/IJCLab, INFN-RM1, INFN-LE, INFN-BA, INFN-BO
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	WG3 (3.1B, 3.2C), WG4, WG7 (7.4)	1.3	- ATEX and safety requirements - Attention to the cost of gas - Hydrocarbon-free mixtures	- Study the performance of hydrocarbon-free gas mixtures - Implement a complete design of a recirculating system	MPP, INFN-RM1, INFN-LE, INFN-BA, PSI, U Bursa, SBU, IPPLM, U Aveiro, Wigner

Table 3: WP2 - a work package on inner and central tracking with PID (a. Drift Chambers). Applications: future electron colliders (FCC-ee, CEPC), flavor factories (SCTF). *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

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.

A work package with R&D tasks for straw chambers (WP3) is presented in Table 4 and 5.

Time Projection Chambers

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 × 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 presented in Table 6 and 7.

4.2.3 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

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Optimize straw materials and technology	- Develop thin films and metallization - Resistance to ageing - Low cross-talk - Establish material relaxation control - Gas leakage control - Compatible with operation in vacuum	WG1, WG3 (3.1C, 3.2B), WG6, WG7 (7.1-4)	1.1 1.2 1.3		- Design and production of materials - Production of straw tubes	MPP, CERN, JU-Krakow, U Manchester, U South Carolina, U Hamburg
T2	Develop small-diameter straw tubes (< 4 mm) for highest rate capability	- Rate capability >500 kHz/cm^2 - Fast timing (<50ns) - Charge load >10 C/cm	WG1, WG7 (7.1-3)	1.1 1.2 1.3	- Wire centering - Electrostatic stability - Establish assembly techniques and tools - Ultrasonic-welding PET - Straw tracker mechanics	- Straw materials and tube design - Film tube production - Establish the straw-tube assembly technique - Prototype setup with several channels	
	Develop straw tubes of 5 mm-diameter	- Faster timing (<100 ns) - High rate capability, $\mathcal{O}(100\ \mathrm{kHz/cm^2})$					MPP, HUJI, INFN-PV, AGH-Krakow, JU-Krakow, CERN, U Bursa, U Manchester, U South Carolina, KEK-IPNS
	Develop ultra-thin film walls	- < 20 μm thickness - $X/X_0 \sim 0.02\%$ per straw - Film metallization - New film materials and new technologies (e.g. nano-fibre)					INFN-PV, JU-Krakow, U Manchester, U South Carolina, KEK-IPNS
	Develop ultra-long straws (up to 4 m)	- Establish good mechanical properties					HUJI, INFN-PV, JU-Krakow, CERN, U Manchester, U South Carolina, INP-Almaty, U Hamburg
T3	Optimize straw tracker mechanics	- Develop self-supporting modules - Control relaxation - Develop a method for straw alignment	WG1, WG3 (3.2E), WG6, WG7 (7.1)	1.1 1.2 1.3	- Design of all mechanical tools - QA	- Develop assembly technique - Prototype construction	MPP, HUJI, JU-Krakow, CERN, U Bursa, U Manchester, FZJ-GSI-U Bochum, U Hamburg, U South Carolina, IFIN-HH

Table 4: WP3 (Part I) - a work package on inner and central tracking with PID (b. Straw Chambers). Applications: future electron colliders (FCC-ee, CEPC), FCC-hh, FAIR, Dark Matter, rare event searches, and neutrino physics. *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

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 com-

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T4	Optimization of electronic readout and ASIC development	- Time readout with sub-ns precision - Leading and trailing edge time readout	WG5, WG7 (7.1-2)	1.1	- Dedicated R&D on ASIC	- ASIC development - Development of readout system	INFN-PV, MPP, HUJI, JU-Krakow, AGH-Krakow, CERN, U Bursa, U Manchester, U South Carolina, INP-Almaty
T5	3D/4D-Tracking and PID via dE/dx	- Spatial resolution <150 µm - T_0-determination with ≈ns resolution - p/K/π-separation at p<1 GeV/c	WG1 WG4 WG7	1.1		- Development of SW algorithms - Analysis of (in-beam) test data	MPP, INFN-LE, INFN-PV, AGH-Krakow, JU-Krakow, CERN, U Manchester, Istinye U, FZJ-GSI-U Bochum, INP-Almaty, U Hamburg
T6	Longevity	- Ageing resistance > 1 C/cm for thin-wall straws - Ageing resistance > 10 C/cm for straws and highest particle rates	WG1, WG3 (3.2B), WG7 (7.2)	1.1	Test at various DRD1 test facilities	Prototype measurements	MPP, CERN, JU-Krakow
T7	Software	- Straw tube simulation and calibration - Event simulation - Pattern recognition - Tracking and PID - Tracker alignment	WG4	1.1, 1.2	- Garfield, Geant - Alignment, e.g. Millepede - Real-time processing	- Development of new analysis algorithms and applications to (in-beam) test data	FZJ-GSI-U Bochum, CERN, U South Carolina, INP-Almaty, U Hamburg, U Aveiro, Istinye U, IFIN-HH

Table 5: WP3 (Part II) - a work package on inner and central tracking with PID (b. Straw Chambers). Applications: future electron colliders (FCC-ee, CEPC), FCC-hh, FAIR, Dark Matter, rare event searches, and neutrino physics. *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

ponents.

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 as 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;
- introduce affordable techniques for the construction of large-area detectors;
- increase 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

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	IBF reduction	- Gain×IBF $\approx$ 1-2 - IBF optimization together with energy resolution and discharge stability	WG4, WG7 (7.1-2,5)	1.2	- Hybrid stacks - Gating GEM - Distortion corrections - Space-charge monitoring - Development of simulation tools - Operation in magnetic fields	- Provide a large-area prototype with a uniform IBF distribution of G*IBF=5 keeping the energy resolution at a tolerable level - Present a structure with stable settings for G×IBF of 1-2 - Determine the ion blocking power of a GEM-based gate - Provide systematic studies and simulations of IBF performance for the most common structures in (high) magnetic fields - Introduce an IBF calculator (Garfield-based) for optimization of the HV parameters	IFUSP, GSI, U Bonn, IRFU/CEA, USTC, KEK-IPNS, DESY, GANIL, RWTH Aachen, INFN-PD, IP-PLM, CERN, PSI, U Bursa, SBU, WIS, U Coimbra, U Aveiro, Wigner, SINP Kolkata, BNL.
T2	Pixel-TPC development	- Produce 50000-60000 GridPixes to read out a full TPC - Achieve $\mathrm{d}N/\mathrm{d}x$ counting-resolution $< 4\%$	WG5, WG7 (7.1-2,5)	1.1	- InGrids (grouping of channels) - Low-power FEE - Optimization of pixel size (>200 µm) or cost reduction	- Provide a large-area pixel-based (InGrid) readout module - Measuring IBF for GridPix. Reduction with double-mesh - Present $\mathrm{d}N/\mathrm{d}x$ measurements in beam - Small area prototypes of MPGD/TimePix hybridisation.	U Bonn, U Carleton, WIS, CERN
T3	Optimization of the amplification stage and its mechanical structure, and development of low X/X_0 field cages (FC)	- Uniform response across a readout unit-area. - Keep $\sigma_{dE/dx} \approx 4\%$ - Point resolution of <100 µm - Minimize static distortions by reducing insensitive areas - Minimize $E \times B$ - Achieve E-field homogeneity at $\sim 10^{-4}$ level	WG1, WG4, WG6, WG7 (7.1-2,5)	1.1 1.2	**Minimization of static distortions:** - Algorithms for distortion corrections - Field shaping wires - Minimize GEM frame area (use thicker GEMs) - Laser systems **Main ampl. stages:** - Encapsulated resistive-anode MMG - Multiple GEM - GridPix - Hybrids **FC:** - high-quality strips, suspended strips - module flatness	- Provide a solution for a large-volume TPC with $\mathcal{O}(10^6)$ pad-readout by means of pre-production of several readout modules of comparable quality	IRFU/CEA, U Bonn, IHEP CAS, USTC, GANIL, CNRS-IN2P3/IJCLab, GSI, RWTH Aachen, INFN-RM1, INFN-PD INFN-BA, IPPLM, PSI, U Bursa, SBU, BNL, WIS, IFAE, BNL.

Table 6: WP4 (Part I) - a work package on inner and central tracking with PID (c. Time Projection Chambers). Area of application: future electron colliders (ILC/C^3, FCC-ee, CEPC), heavy ion, neutrino facilities. *Institutes should be considered exclusively as a preliminary expression of interest or as potential involvement.*

of calorimeters for future facilities.

A work package summarising the main R&D tasks for calorimetry (WP5) is presented in Table 8.

4.2.4 PHOTO-DETECTORS (PID)

Advantages of employing a gaseous medium for photon detection are the low material budget, negligible sensitivity to magnetic fields, and cost-effectiveness,

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T4	Low-power FEE	- <5 mW/ch for >10^6 pad TPC - ASIC development in 65 nm CMOS	WG5	1.3	- Continuous vs. pulsed	- Present stable operation of a multi-channel TPC prototype with a low-power ASIC	IHEP CAS
T5	FEE cooling	- Operate 10^6 channels per end-plate	WG5	1.2	- Two-phase CO_2 cooling - Micro-channel cooling with 300 µm pipes in carbon fiber tubes - 3D printing: complex structures, performance optimization, material selection	- Present a prototype of a cooling system for the 10^6 pad TPC option	IRFU/CEA, U Lund, INFN-PI, INFN-LE, INFN-PD
T6	Gas mixture	Optimize: - Longevity - Ageing - Discharge probability - Drift velocity - Ion mobility	WG1, WG3 (3.1D, 3.2A, 3.2B), WG4, WG7 (7.1-3,5)	1.1	- Discharge probability, ageing, gas properties - Optimization of the HV working point - Optimization wrt. the expected resolution (aim for <100 µm) - Cluster ions	- Lower the discharge probability of readout units by 1-2 orders of magnitude down to $\sim 10^{-14}$ per hadron - Avoid secondary discharges in MPGD stacks	CERN, IFUSP, GSI, TUM, IHEP CAS, GANIL, USTC, CNRS-IN2P3/IJCLab, IRFU/CEA, CNRS-LSBB, RWTH Aachen, U Bonn, Bose, INFN-RM1, INFN-LE, INFN-PD, INFN-BA, IPPLM, USC/IGFAE, U Bursa, SBU, U Warwick, U Aveiro, U Bolu-Abant, BNL.

Table 7: WP4 (Part II) - a work package on inner and central tracking with PID (c. Time Projection Chambers). Area of application: future electron colliders (ILC/C^3, FCC-ee, CEPC), heavy ion, neutrino facilities. *Institutes should be considered exclusively as a preliminary expression of interest or as potential involvement.*

especially for large-area systems. The main R&D challenges for this application include:

- optimization of photocathodes efficiency by suppressing ion backflow and developing more robust photoconverters;
- stability of photocathodes in gas and noble-liquid media;
- development of very low noise, large dynamic range front-end electronics (FEE);
- improvement of the detector performance in terms of space and time resolution, along with a fast charge collection to maximize the rate capability;
- in addition, for TRD systems, a better separation between the transition radiation and the ionization process is desired.

A work package addressing the challenges for photo-detection (WP6) is presented

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Development of high-granularity demonstrators	- Cell size ≈1 cm^2 - Channel count ≈10k per m^2	WG5, WG7 (7.2)	1.1	- Innovative signal-induction structures to balance readout cost and performance - Front-end electronics	- Performance validation of a technology demonstrator in-beam	VUB and UGent, IP2I, MPP, WIS, INFN-RM2, CERN, INFN-NA, INFN-RM3, INFN-BA, INFN-LNF, CIEMAT, Istinye U, U Cambridge
T2	Gas Studies	- Gas mixture operation with low environmental impact (low-GWP)	WG3 (3.1B, 3.2C), WG4, WG7 (7.1-4)	1.1,1.3	- Improvement of recuperation and recirculation systems - Longevity studies - Ecological gas mixtures without F-gases	- Performance stability results with lower % of fresh gas - Identification of an eco-gas mixture with performance comparable to the standard one	VUB and UGent, IP2I, MPP, INFN-RM2, CERN, U Bursa, WIS, IPPLM, CIEMAT, U Aveiro, Istinye U
T3	Mechanics optimization	- Uniform response over large surface ≈1-2 m^2	WG3 (3.2E), WG7 (7.1-2)	1.1	- Optimization of detector structures to minimize dead area - Development of large-scale MPGD construction techniques - Production of high planarity, large-area PCBs for MPGDs - Mechanical fabrication of very thin High-Pressure Laminate and glass RPCs - Uniform resistivity - Uniform gas gain	- Construction of a first full-scale prototype and performance assessment - Establish QC and QA procedures for mass production	VUB and UGent, IP2I, MPP, INFN-RM2, IFIN-HH, USTC, INFN-RM3, WIS, CIEMAT, Istinye U

Table 8: 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. *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

in Table 9.

4.2.5 TIMING DETECTORS (PID AND TRIGGER)

Two main technologies are currently considered and developed in this area: timing RPCs based on the multi-gap technology and MPGDs sensing Cherenkov light (PICOSEC). Depending on the application, developments focus on timing capabilities of 20-50 ps and rate capabilities of 30-150 kHz/cm^2, where different technologies can be used to fulfill the most challenging requirements:

- Multi-gap timing RPCs: this can be achieved in principle by reducing the thickness of the gas gaps ≈100 μm and by increasing the number of gaps to ≈10, to maintain high efficiency provided good detector uniformity can be preserved over large areas. A rate capability up to 100 kHz/cm^2, necessary for systems under intense irradiation conditions, could be achieved by

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Increase photocathode efficiency and develop robust photoconverters	Improve: - Longevity - QE - Extend to the visible range - Rad-hardness up to 10^{11} n_{eq}/cm^2	WG3 (3.1C), WG6, WG7 (7.1-4)	1.1	- Study hydrogenated nanodiamonds - Study diamond-like carbon (DLC)	- Demonstrate the performance of nanodiamond-powder photocathodes in terms of their chemical reactivity and ageing - Provide a detailed characterization of QE of new photocathode materials, e.g. DLC	INFN-TS, CERN, HIP, IRFU/CEA, NISER Bhubaneswar, U Coimbra, LMU, U Aveiro, RBI, Wigner, BNL.
T2	IBF suppression, discharge protection	- IBF reduction down to 10^{-4} and below - Stable, high gain operation up to 10^5-10^6 - Operation in magnetic field	WG4, WG7 (7.1,5)	1.2	- Multi-MICROMEGAS detectors - Zero IBF detectors - New structures (Cobra, M-THGEM,) and coating materials (Mo) - Grids: bi-polar grids, gating GEM	- Demonstrate a small-area new structure or stack of structures providing stable operation at high gains and low IBF performance	USTC, INFN-TS, INFN-PD, INFN-PV, TUM, WIS, U Bonn, HIP, IRFU/CEA, NISER Bhubaneswar, CERN, MSU, SBU, JLab, BNL, U Coimbra, IPPLM, U Aveiro, RBI, BNL.
T3	Gas studies	- Develop eco-friendly gas radiators and, in particular, explore alternatives to CF_4	WG3 (3.2A), WG4, WG7 (7.2,4)	1.1, 1.3	- Identification of eco-friendly gas mixtures free from greenhouse gases - Alternatives to CF_4 for optical readout		CERN, NISER Bhubaneswar, HUJI, GSSI, INFN-PD, INFN-TS, AGH-Krakow, IPPLM, USC/IGFAE, U Aveiro
T4	FEE	- Stability at high input capacitance - Low noise - Large dynamic range	WG5	1.2		- Present an ASIC concept/prototype	IFUSP, NISER Bhubaneswar, INFN-PD, INFN-TS, AGH-Krakow, IPPLM, U Manchester, MSU, SBU, JLab, DIPC
T5	Enhance mechanics	- High-pressure operation - Improve gas tightness	WG6	1.3			NISER Bhubaneswar, HUJI, GSSI, USC/IGFAE, CERN, MSU, JLab, DIPC, IPPLM, RBI
T6	Precision measurements	- Time resolution $\leq$ 100 ps - Spatial resolution $\leq$ 1 mm	WG7.2		- MPGD: PICOSEC		CERN, IPPLM, BNL.

Table 9: WP6 - a work package on gaseous photon detectors. Area of application: nuclear physics, hadron physics, future ee, and eA machines. *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

thinner (better signal pick-up), and lower resistivity (to speed up the charge evacuation process) plates, down to the conventional-wisdom value at which spark-quenching tends to weaken $\approx 10^9$ Ωcm.

- PICOSEC and other precise-timing MPGDs: further developments require, in particular, identifying less expensive materials (e.g. fast radiation-hard Cherenkov radiators in the case of PICOSEC) and, similar to timing RPCs, achieve precise mechanical stability and uniformity for gas gaps at the level of $\approx$1-10 µm. The development of robust radiation-hard photocathodes through the exploration of novel materials and photo-converter protection, stable operation at high gain and IBF optimization are critical aspects for Cherenkov-based detectors. It will require considerable R&D, that is covered through synergies with WP6 (photo-detection). In general, an enhanced time response can be attained along these lines as well as optimized radiator and photocathode characteristics and, certainly, through the optimization of the gap geometry and gas properties.

Future R&D should concentrate on the following, major, points:

- uniform rate capability, time resolution, and efficiency over large detector areas;
- new materials for very high rate applications (low resistivity, radiation hardness);
- uniform gas distribution, spacer material and spacer geometry;
- thinner structures: mechanical stability and uniformity;
- eco-gas mixtures and gas recuperation systems;
- electronics: low noise, fast rise time, sensitive to small charges.

A work package addressing the challenges for timing (WP7) is presented in Table 10.

4.2.6 TPCS AS REACTION AND DECAY CHAMBERS (RARE EVENTS, NEUTRINO PHYSICS, NUCLEAR PHYSICS)

TPCs employed in the field of rare event searches (historically referring to research where natural radioactivity can limit experiment performance), as well as those used (or envisaged) for neutrino physics or as active targets (AT-TPC) for nuclear reaction/decay studies, share methodological and technological characteristics. In fact, contrary to tracking TPCs largely deployed at colliders, those used as reaction and decay chambers may not have necessarily external triggers, a condition stemming from the general aim of fully containing the reaction products down to the interaction vertex, with few or no ancillary detectors. The breadth of the associated research programs frequently forces them to detect low and highly ionizing tracks (sometimes simultaneously), displaying reconstruction capabilities down to tens of µm sampling and keV energies , case-dependant, much below their collider counterparts. Radioactive contamination might be critical in some instances. 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

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Optimize the amplification technology	- Uniformity over m^2 (time resolution, rate capability, efficiency)	WG1, WG6, WG7 (7.1-2,4)	1.1-1.3	- PICOSEC - Position-sensitive timing RPC - Ultra high-rate timing RPC development - DLC-based timing RPC - GaAs timing RPC – Resistive Cylindrical Chamber RCC	- Provide a large-area, multi-channel prototype of an MPGD-based timing detector	CERN, IRFU/CEA, U Sofia, USTC, HIP, GANIL, IP2I, MPP, U Heidelberg, NCSR Demokritos, INFN-BA, INFN-PD, INFN-PV, LIP-Coimbra, U Bursa, MSU, SBU, JLab, U Hamburg, RBI, U Tsinghua, INFN-RM2, BNL.
T2	Enhance timing	- Time resolution $< 20\,\text{ps}$ up to $30\,\text{kHz/cm}^2$	WG3 (3.2A, 3.2D), WG4, WG7 (7.2)	1.1	MPGD:PICOSEC	- Present large area MPGD timing detector capabilities in beam	CERN, IRFU/CEA, USTC, HIP, GANIL, IP2I, MPP, NCSR Demokritos, INFN-PD, INFN-PV, U Bursa, SBU, JLab, MSU, UW–Madison, U Hamburg, RBI, BNL.
T3	Enhance rate capability	- Time resolution $< 50\,\text{ps}$ up to 100-150 kHz/cm^2	WG3, WG4, WG7 (7.2)	1.3	RPC: - Gap thickness - Number of gaps - Thin, low-R glass - Single cell layout - GaAs timing RPC - Resistive Cylindrical Chamber RCC PICOSEC: use at high rate	- Provide a prototype for >100 kHz/cm^2 rate capability	CERN, IRFU/CEA, U Sofia, USTC, HIP, GANIL, IP2I, MPP, U Heidelberg, NCSR Demokritos, INFN-BA, INFN-PD, INFN-PV, LIP-Coimbra, U Bursa, U Manchester, MSU, SBU, JLab, CIEMAT, VUB and UGent, Istinye U, INFN-RM2, BNL.
T4	Material studies	- Rad-hardness - Longevity	WG3, WG7 (7.3,4)	1.1-1.3	- Low-resistivity glass - Spacers - Photocathodes - Photoconverters - GaAs - HPL or phenolic glass		INFN-PV, CERN, USTC, RBI, MPP, U Heidelberg, U Manchester, RBI, INFN-RM2
T5	Low-noise FEE	- High input capacitance - Large dynamic range - Fast rise time - Sensitivity to small charges - Low noise	WG5	1.2		- ASIC design - Full readout-chain for multichannel readout solutions for timing $\approx 10\,\text{ps}$ (discrete and ASICs)	USTC, IP2I, IRFU/CEA, GSI, MPP, INFN-PD, INFN-PV, LIP-Coimbra, CERN, U Manchester, MSU, SBU, JLab, INFN-TO, RBI, U Tsinghua, INFN-RM2
T6	Space charge effects, IBF and stability		WG4, WG7 (7.1-2,5)		- Simulations - High gain operation - Synergy with trackers and TPCs		CERN, GSI, U Aveiro, U Tsinghua
T7	Gas studies	- Eco-friendly mixtures - Recuperation - Ageing - CO_2 based mixture with geometrical quenching	WG3 (3.2A, 3.2B, 3.2C), WG7 (7.2-4)	1.3	- Low-GWP solutions for saturated-avalanche operation	- Gas mixtures for MPGD(PICOSEC) based timing detectors (replacement of Ne, CF_4, C_2H_6)	U Sofia, USTC, HIP, GANIL, IP2I, MPP, U Heidelberg, INFN-BA, INFN-PV, LIP-Coimbra, CERN, MSU, SBU, JLab, LMU, U Aveiro, INFN-RM2

Table 10: WP7 - a work package on gaseous timing detectors. *The mentioning of Institutes in the draft should be considered exclusively as a preliminary expression of interest or as potential involvement given the role of the institute in the field. Please contact us if your Institute should be added or removed from the table.*

spatial sampling or keV-tracking. As a result, the needed R&D can be hardly organized outside its own category and associated work package.

While the requirements of TPCs used as reaction/decay chambers are markedly distinct from those of the large-volume tracking chambers already discussed, there are notable exceptions. One is the need for high-rate compliance at present and future heavy ion facilities, and in particular space-charge suppression for the study of very-rare nuclear reactions. Next-generation neutrino TPCs, on the other hand, are also concerned with momentum reconstruction of uncontained tracks. Further along these lines, operation in magnetic fields can be also used on some nuclear reaction studies or even rare event TPCs to improve PID. The necessary R&D is already covered through WP4 tasks.

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 $\approx$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 $\approx$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:

  this is an asset for some active-target nuclear experiments, enabling detection schemes aimed at near-Fano energy resolution and single-electron detection in rare event searches. However different these performance metrics might seem, experiments have long popularized electroluminescent amplification on mm-scale gas gaps to achieve these. Only recently, alternative strategies based on hybrid GEM-mesh structures or RWELL/RPWELL joined the effort.
- increasing optical throughput (primary and secondary):

  as optical imaging extends over larger and larger areas, e.g. for low-energy WIMPs or double-beta decay, 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:

  this is generally critical and excludes many common techniques, for instance, those based on conventional glass fiber / epoxy-based printed-circuit boards and most ceramic materials.

Tables 11 and 12 provide a compilation of the main tasks that have been identified and that are proposed in order to execute this R&D (WP8). The tasks are highly independent, but some small overlap has been allowed. This is seemingly beneficial, as it increases the synergies between different scientific fields. On the other hand, identifying mutually exclusive tasks does not seem operative or even possible in many cases.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T1	Enhanced operation of optical readout across gas densities	- Achieve an ionization-energy threshold of at least ≈keV in the range 10 mbar to 10 bar (and, in the case of noble gases, to saturated vapours and even to the liquid state) with a scalable concept. - Reconstruction of MeV-nuclei of variable stopping power, with mm and sub-mm sampling.	WG1, WG6, WG7	1.2, 1.4	- High optical gain across gas densities in pure CF_4 and CF_4-based mixtures with keV-sensitivity. - Fine track sampling capabilities in the range of 10's of μm to few mm. - Adaptations in optics and camera readout to cover larger areas, at low granularity and with drift-time information (3D-readout). - Simultaneous detection of low and high ionization particles.	- Low-pressure nuclear track reconstruction at ≈10 keV. - Low-pressure electron-track reconstruction with the simultaneous reconstruction of nuclear tracks at ≈100 keV. - MIP tracking at 10 bar in argon-based gas mixture. - Reconstruction of MeV-nuclei with mm and sub-mm sampling at varying pressure and gas conditions. - Stability of reconstruction of nuclear-reaction byproducts over a large range of primary ionizations.	CERN, GANIL, ANU, IRFU/CEA, USC/IGFAE, GSSI, INFN-RM1, INFN-PD, INFN-BA, INFN-LNF, U New Mexico, STFC-RAL, IFIC, U Liverpool, U Genève, U Warwick, U Coimbra, Fermilab, MSU, HUJI, U Bursa, U Bolu-Abant, WIS, DIPC, U Hamburg, IFAE, AUTH
T2	Enhanced operation of charge readout across gas densities	- Achieve an ionization-energy threshold of at least ≈keV in the range 10 mbar to 10 bar (and, in the case of noble gases, to saturated vapours and even to the liquid state) with a scalable concept. - Reconstruction of MeV-nuclei of variable stopping power, with mm and sub-mm sampling.	WG1, WG5, WG6, WG7	1.2, 1.4	- High avalanche gain across gas densities in CF_4, H_2, He, Ar, Xe -based TPCs with keV-sensitivity. - Fine track sampling capabilities in the range of 10's of μm to few mm. - High-density and low-power electronics, with the ability to self-trigger. - TimePix-based charge readouts.	- Low-pressure nuclear track reconstruction at ≈10 keV. - 1 keV ionization-energy threshold at high pressure. - Few MeV's-proton tracking at 10 bar in argon-based gas. - Reconstruction of MeV-nuclei with mm and sub-mm sampling at varying pressure and gas conditions. - Stability of reconstruction of nuclear-reaction byproducts over a large range of primary ionizations.	IRFU/CEA, GANIL, U Bonn, ANU, U Zaragoza, U Colorado, Fermilab, UH Manoa, MSU, RWTH Aachen, HUJI, U Bursa, U Bolu-Abant, U Warwick, WIS, CNRS-IN2P3/UGA, ISNAP, U Coimbra, INFN-LNS, SINP Kolkata, U Hamburg, U Aveiro, U New Mexico, AUTH , U Kobe
T3	Enhanced operation of pure or trace-amount doped noble gases	- Operation of m^2 and ton-scale detectors with single-electron sensitivity and near-Fano level energy resolution	WG1, WG3 (3.2C) WG6, WG7	1.4 (and DRD2)	- Enhancement of electroluminescence (EL) yield in noble gases (scalability, light output). - Single-electron detection. - Near-Fano energy resolution. - Stabilization of trace-amount doping (mixing, purification). - Barium tagging. - Stable amplification in dual-phase detectors. - Develop novel amplification structures	- Developing large-area ($\geq m^2$-scale) EL amplification: keeping energy resolution and single-electron sensitivity. - Imaging in low-diffusion gas. - A viable concept for Barium tagging or a viable roadmap towards it. - Very large-area ($\geq 10 m^2$-scale) camara-based 3D imaging. - Operation of resistive-protected detectors.	DIPC, IFIC, U Manchester, U Liverpool, U Coimbra, LIP-Coimbra, AstroCeNT, Ben-Gurion U, WIS, U Aveiro, AUTH

Table 11: WP8 (Part I) - 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 / nuclear physics, neutrino physics. *The mentioning of Institutes in the draft should be considered exclusively as preliminary expression of interest or as potential involvement given the role of the institute in the field. There is no commitment and involvement has to be confirmed in a later stage. Please contact us if your Institute should be added or removed from the table.*

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Comments	Deliv. next 3y	Interested Institutes
T4	Ultra-low-energy reconstruction of highly ionizing tracks (including R&D on negative-ion readout)	- Tracking of $\approx$10keV nuclear tracks in a concept scalable to m^2 and beyond	WG1, WG5, WG6, WG7	1.2, 1.4	- Track reconstruction of nuclei down to 10 keV energies or below. - Simultaneous tracking of nuclei and electrons. - Accurate $\mathrm{d}E/\mathrm{d}x$-sampling for electron and nuclei identification. - ML for complex topologies. - Negative-ion TPCs for 3D-tracking on large areas, and associated electronics. - Optical readout in a negative ion TPC. - Track-reconstruction on spherical counters.	- A technology demonstrator in the m^2 scale, with $\approx$10keV tracking-threshold for nuclear tracks at $\approx$10's of μm sampling.	CERN, GANIL, ANU, IRFU/CEA, GSSI, INFN-RM1, INFN-PD, U New Mexico, STFC-RAL, MSU, UH Manoa, U Kobe, IHEP CAS, USTC, U Bolu-Abant, LIP-Coimbra, U Warwick, WIS, CNRS-IN2P3/UGA, ISNAP, U Coimbra, INFN-LNS, SINP Kolkata, U Hamburg, AUTH , U Kobe
T5	Determination of the interaction time (T_0)	- Achieve a viable timing signal while keeping low electron diffusion and high amplification of the ionization signal	WG3 (3.1A)	1.4 (and DRD2)	- T_0 sensitivity for accelerator-based neutrino TPCs. - T_0 sensitivity in the reconstruction of low-energy nuclear recoils, via scintillation light or minority carriers in case of negative-ion TPCs. - Explore the applicability of alternative methods (diffusion, positive ions) - T_0-determination on spherical counters.	- Demonstration of track reconstruction and T_0-tagging for minimum ionizing particles at $\approx$1MeV-threshold and high pressure.	IFIC, U Liverpool, AstroCeNT, Ben-Gurion U, U Zaragoza, GSSI, USC/IGFAE, Fermilab, DIPC, ANU, WIS, U Hamburg, U New Mexico
T6	Modelling	- Develop a microscopic framework for computing scintillation and negative-ion yields, and transport	WG3 (3.1A, 3.2A), WG4	1.3,1.4	- Modelling primary scintillation. - Modelling secondary scintillation. - Modelling ion transport and avalanche for electronegative mixtures. - Modelling space charge.	- Develop a framework for optical simulation that is integrated as part of the standard community tools, or develop a concrete implementation path towards it.	CERN, U Bursa, USC/IGFAE, IFIC, U Aveiro, AstroCeNT, GSSI, U Kobe, INFN-BA, WIS, DIPC, U Coimbra, SINP Kolkata, U Hamburg, U Aveiro, AUTH
T7	Gas mixtures and gas handling	Study new gas mixtures, operated in conditions of high purity	WG3 (3.1B, 3.2C), WG6, WG7	1.3, 1.4	- New gas mixtures for optical readout. - New gas mixtures for negative-ion readout. - Recirculation and recuperation systems. - Purification of low-quenched mixtures.	- Develop alternatives to CF_4-based mixtures operated in open loop, or a viable path towards it.	USC/IGFAE, DIPC, U Coimbra, CERN, U Liverpool, GSSI, INFN-RM1, U Zaragoza, Fermilab, RWTH Aachen, U Warwick, WIS, DIPC, ISNAP, U Hamburg, U Aveiro, U New Mexico, AUTH
T8	Radiopurity	- Improve manufacturing process and purification as well as material-selection standards	WG3		- Radon emanation studies - Mitigation of gaseous radioactive isotopes - Material selection - Develop radiopure amplification structures and radiopure optical cameras.	- Develop MPGDs and manufacturing techniques with high radiopurity.	USC/IGFAE, DIPC, U Liverpool, GSSI, U Zaragoza, U Hamburg, U Kobe

Table 12: WP8 (Part II) - a work package on TPCs used as reaction/decay chambers. Area of application: rare event searches (DM, solar axions, $\beta\beta 0\nu$-decay), active targets / nuclear physics, neutrino physics. *The mentioning of Institutes in the draft should be considered exclusively as preliminary expression of interest or as potential involvement given the role of the institute in the field. There is no commitment and involvement has to be confirmed in a later stage. Please contact us if your Institute should be added or removed from the table.*

4.2.7 BEYOND HEP

Gaseous-detection technologies are used in a wide range of fields. The main applications related to HEP have been listed above, and the main goals and necessary developments described in the tables corresponding to the eight work packages (WPs) identified. From a broad point of view these developments can be seen, ultimately, as focused on achieving: i) low-cost and mass production capabilities through collaboration with industries, ii) high space-time resolution for detecting photons or charged particles, iii) outstanding imaging capabilities and energy reconstruction, iv) enhanced sensitivity to low-energy deposits. It can therefore be expected that the technology enhancements achieved in the coming years will naturally permeate to disciplines outside HEP. Areas that will benefit from the accomplishments of the R&D tasks and goals listed in the aformentioned WPs include:

- muography and large area applications;
- dosimetry/beam monitoring and medical imaging applications (PET, CT, X-ray, SPECT, Gamma cameras, or X-ray fluorescence imaging));
- fast/thermal neutron imaging (MPGD-based readout with solid converter) for tomography and nuclear waste monitoring;
- X-ray polarimetry and space applications;

Finally, technology transfer between DRDs and industry is beneficial to both parties, thus expectedly expanding the range of future applications.

4.3 Gas and Materials [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 obtain high-performance gaseous detectors. 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.

4.3.1 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 characterization 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 enviromental concerns as well as in view of the future availability and costs of fluorinated gases (F-gases) , the search and characterization 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 system 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. In this context, the studies of solid converters and photocathodes need to be addressed for the improvement of spatial and time resolution but also for radiation hardness. 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, photocathodes, novel materials, 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 term of radiation. This can be achieved with dedicated studies of current and gas-induced ageing effects as well as on 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 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 characterization, 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 characterization 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. The common interest in resistive materials for MPGD and RPC, devoted in particular to very high-rate applications, as well as for low material budget 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 [12] as it will be described in the next Section.

Reference	Description	Deliverable Nature
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

4.3.2 COMMON RESEARCH INTERESTS

WG3's objective is to enhance our comprehension and knowledge regarding the properties of gas and materials utilized in our technologies. These studies aims to optimize 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 [18], 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 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, photocathodes 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 optimization 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 recognized 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 recognized 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 characterization studies and the development of common databases of gas properties.

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 and novel wire materials for drift chambers and the study of the radiation hardness of detector materials have been already recognized as specific subjects of interest.

c) **Gas Systems**: The purity of the gas mixtures is also recognized 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, 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 miniaturization is increasing, while new fabrication techniques like additive manufacturing, microfabrication 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.

4.3.3 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
- Aging/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
- Laboratories for examination and treatment of material surfaces
- Workshops for precision mechanics (wire chambers and large volume detectors)
- Chemical laboratory for material characterization and ageing studies
- Laboratories for detector characterization 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 are also the possibilities to profit from a database of gas properties (common to all the technologies), software for simulation of gas properties (WG4) and to make use of legacy from groups involved in eco gas studies for RPCs. Synergies with WG8 on databases, information and experience sharing will be estabilished.

4.4 Modelling and Simulations [WG4]

4.4.1 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.

4.4.2 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 [19, 20, 21], developed by Rob Veenhof. Garfield can calculate very efficiently analytically the electric field for 2D geometries using complex algebra. Interfaces are available for HEED [22] which is used for the simulation of the primary ionization of charged particles and Magboltz [23, 24] for the transport parameters of electrons. Primary ionization due to electrons and heavy ions can be calculated using Degrad [25] and SRIM [26], 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 [27, 28, 29, 30, 31]. 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 [32], of the order of few 10^7, close to Raether's breakdown criterion. Later improvements to a 1.5D [33] and 2D [34] 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 [31] 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 [35], 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 [36]. 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 [37], and an interesting approach is being explored using simplified hydrodynamic simulations implemented in COMSOL [38, 39].

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 [20] 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) [40] 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 [41] 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 [42]. 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 [43, 44, 45]. Recently the extension of the Ramo-Shockley theorem for conductive media [35] has allowed proof-of-principle numerical simulations of signal induction in MPGDs with resistive elements [46]. 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 [47]. 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 [48]. Lastly, the use of hydrodynamic simulations to understand the formation and propagation of streamers has also triggered the investigation of discharge simulations in MPGDs [49, 50].

4.4.3 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 is interested in contributing to the understanding of the detector physics and assessing the detector performance through simulations, while about 30% of them is 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 [51], but further testing and integration are needed. A continuous integration environment should be set up, through e.g., Jenkins [52], 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.

Improvement of Garfield++ Framework: The performance of the micro-

Reference	Description	Deliverable Nature
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 - Objectives 4.1-4.2: Overview

scopic tracking can be further enhanced by improved interpolation of the electric field map, which is currently a very time-consuming step [53]. 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++ [51]. 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 [54];
- 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 [55] and other Boltzman solvers such as Bolsig+ [56], pyMethes [57] and Betaboltz [58];
- 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 [39]. Furthermore, the modelling and simulation of space charge within this simplified hydrodynamic approach have proven to be effective to model gain variations in GEM detectors observed at high particle fluxes [59]. 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 [51] 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 [60] could be resolved by including space-charge effects [61]. 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 [35]. 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 [46, 62], 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 [63]. 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 [64], 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 4 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 simu-

lated 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.

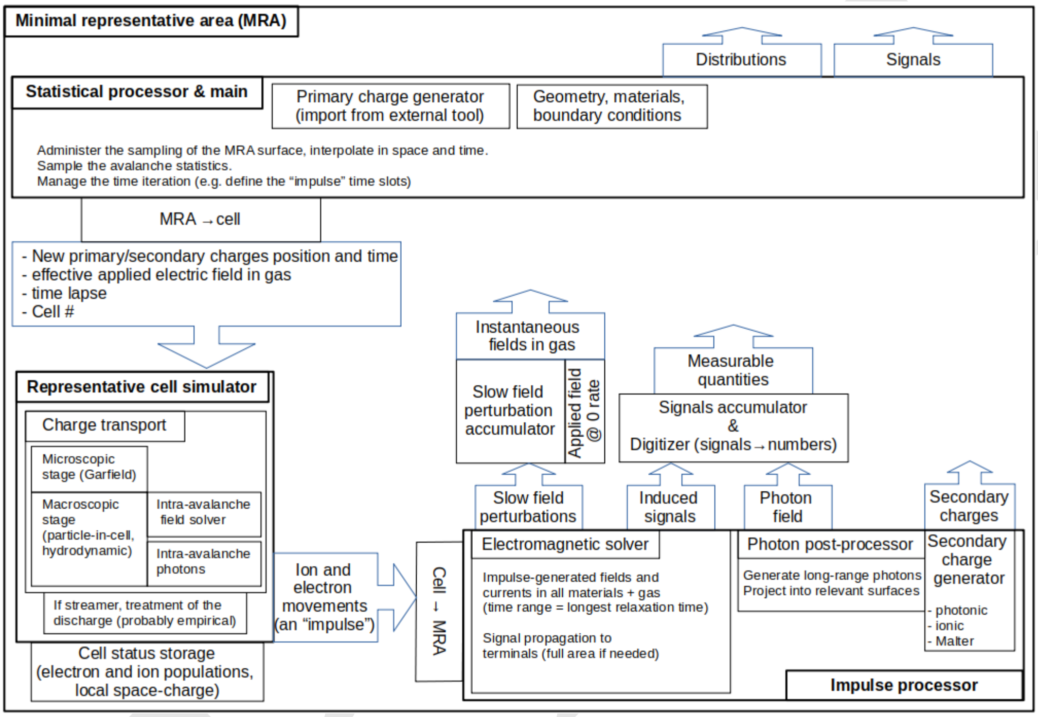

Figure 4: Scheme of an integrated simulation environment to simulate large-area resistive detectors. The representative cell simulator is called by the statistical processor to produce time lapses of the charge movements on sampling points (cells) within the minimal representative area (MRA). The impulses thus generated are processed to yield their MRA-wide physical effects, which are accumulated and will influence the subsequent steps.

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 features 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 [65]. 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 do already exist or are being developed (e.g. REST, LArSoft, GEMC, ATTPCROOT) 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 a 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 ternairy 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 behavior of a detector is studied as a whole with a complete simulation, after which a parametrized simulation can be used to extract the behavior. This method has the potential to significantly reduce the time needed for a single simulation [66] 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 [67], 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 to have a simulation for the diffusion in polyatomic gas mixtures using elastic and inelastic collision integrals

4.5 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 the e.g. detector amplification structures and enable their improvements. After the introduction in Section 4.5.1 and a summary of the state-of-the-art (Section 4.5.2) the major tasks are outlined in Sections 4.5.3 to 4.5.5 and summarised in Tables 16-18.

Reference	Description	Deliverable Nature
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 - Objectives 4.3-4.11: Overview

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.

4.5.1 INTRODUCTION

The development of dedicated GD electronics is of major relevance for the advancement of detectors, their operation, qualification and application in experiments. This is recognised and fully supported by large experiments, which in the past often profited from merging R&D electronics into their final DAQs as for the

DAQ of the European Spallation Source or the ATLAS New Small Wheel.

WG5 will, compared to DRD7, address the electronics need during the R&D phase, where e.g. radiation hardness, high-speed links, data reduction, dense integration and experiment-specific front-end ASICs with the highest performance play a subordinate role. The aims are to develop and provide well-suited service electronics in smaller quantities such as high- and low-voltage systems, monitoring equipment (Section 4.5.5) and in particular DAQs (Section 4.5.4) that are well-supported, can be maintained by the community with limited manpower and require a short training period until efficient use is reached. In a similar effort, the development of front-end ASICs for the specific needs of the different GD technologies (Section 4.5.3) could be supported. This working group, therefore, is concentrating on developing a platform for R&D detectors and introductory test systems for large experiments. A community survey has shown that the Scalable Readout System (SRS) [68] developed by the RD51 Collaboration was a huge success, and many groups familiar with the system have mentioned that continued support and development of new features are among the most important tasks of DRD1. The requests for additions reflect the increased diversity of the community and range from analogue and discrete readouts to multichannel integrated ASICs for multi-purpose data acquisition. Also, the application requirements mentioned in the survey show a large almost uniform distribution of pixel readout, strip readout and waveform digitization. Also, non-conventional features like high time resolutions (sub ns), FPGA-based pre-reconstruction and wide dynamic ranges are of interest for many groups. Finally, support for noise reduction, grounding, shielding and spark protection was mentioned with similarly high numbers as other future challenges.

4.5.2 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) with a number n_{chip} of ASICs. These integrate each a number n_{ch} of readout channels and, depending on technology and detector type, convert the primary charge into voltage signals that can be transmitted over front-end 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 configuration data together with common clocks and optional triggers and to all ASICs on the front-end. In return, the ASICs send triggered or untriggered serial channel data over front-end links to the FECs. A scalable system transmits and receives over one single front-end link per hybrid to make it a completely independent vertical readout slice with $n_{chip} \times n_{ch}$ channels connected to one of n_{link} link-ports of a FEC. In order to avoid a bandwidth limit in the front-end, the link bandwidth must be higher than the maximum output bandwidth that the ASIC output can provide. A single FEC can then seamlessly concentrate the stream of event fragments from all connected ASICs in a single transit buffer integrated inside an FPGA. Single FEC readout systems hence consist of n_{link} non-saturating, vertical slices with n_{link} front-end links, concentrating $n_{chip} \times n_{ch} \times n_{link}$ channels with transit lifetimes up to tens of microseconds before being transmitted to a very high-bandwidth network link connecting the online system. In general, an array of n_{FEC} FECs transmits over n_{FEC} network links to a non-blocking network switch to the network port(s) of the Online system. Small systems with typically a single FEC however can make use of a Laptop with 1 Gbit network ports controlled by standard DAQ and Control and data analysis software. Large systems require an online system running on computers with hundreds of Gigabit I/O capacity and disk arrays to cope with the incoming bandwidth. Scalable systems can use the same DAQ and control software both on large or small systems, starting with a single hybrid up to a number of hybrids at which the I/O capabilities of the connected Online system start to limit the scalability. Higher scalability can be reached by adding links, disks, switches and computers to the online system. On the FEC level, the scaling limit can also be reduced by implementing user-defined real-time triggers in the firmware in the FPGAs, to remove insignificant subevents from the transmission to the online links. Algorithms are detector specific and must be completed within the lifetime of the subevents in the FPGA-embedded buffers. The use of state-of-the-art FPGAs in the next generation of FECs is intended to concentrate an even higher number of channels to increase both the effective detector regions and trigger efficiencies.

Readout System for MPGDs: Within the RD51 collaboration, the community has agreed on a common effort to develop a central readout system: the SRS (Fig. 5 [69]). It is developed by the community for the community, which also maintains and further develops it as a system directly usable or adaptable to the needs of the R&D groups. Improvements and extensions by single or several groups together are fed back to the whole community. The success of SRS allows the R&D groups to focus primarily on detector developments. SRS is a scalable readout concept for MPGD detectors, consisting of a crate-resident SRS 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) with link adapter for analogue or digital front-ends. Small systems can get aggregated in units of 128 channels and operated with the same DAQ software as required for large systems. The addition of more 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. for ATLAS, ALICE and CMS.

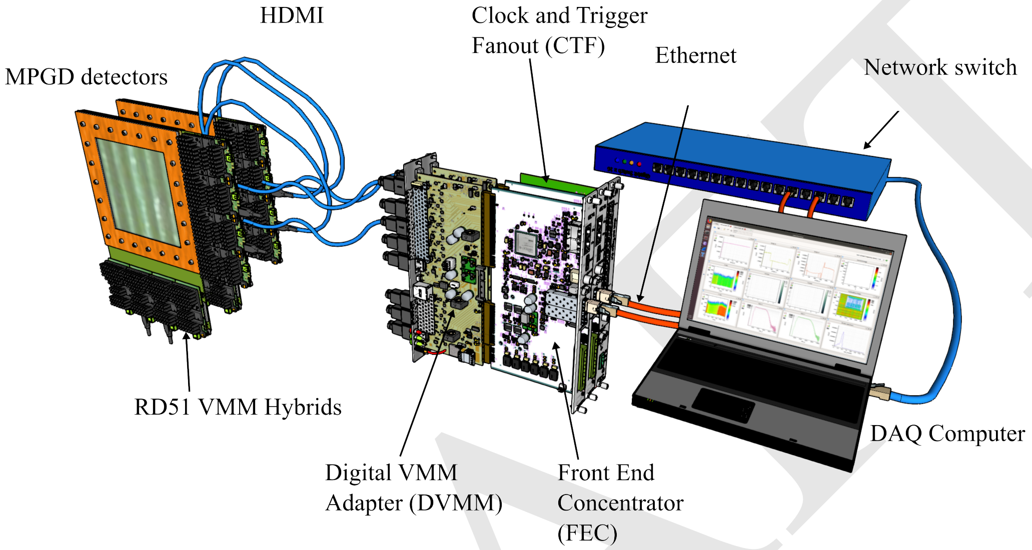

Figure 5: Schematic display of the SRS in the flavour with the VMM as front-end chip. Each of the two exemplary MPGD detectors is read out by eight VMM hybrids (each hybrid: $n_{ch} = 128$, $n_{chip} = 1$). All VMM hybrids of one detector can be connected with each one HDMI cable to the DVMM adapter card of one FEC ($n_{link} = 8$). Several FECs can be connected to a DAQ computer by an Ethernet network switch.

SRS is designed to work with different front-end ASIC technologies, initially implemented with the analogue APV-25, followed by Timepix and since 2019 via the digital VMM3a ASIC, allowing for higher rates, zero-suppression and a wide range of configuration settings to match a wider range of detectors. Further SRS front-ends in preparation are SAMPA and Timepix3. SRS hybrids plug directly onto detectors via connectors standardized for MPGDs. The VMM hybrid is by default equipped with general-purpose coolers, dissipating up to 4 Watts per 128 channel hybrid. The readout links are HDMI A-D cables, used for transmission of very high bandwidth, LVDS-encoded data, configuration, clock and trigger and, optionally power. With externally supplied power and a small Powerbox, HDMI links can be as long as 30 m. VMM hybrids transmit 2x 400 Mbps per HDMI cable, resulting 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 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 a 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 peculiar 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 elongation 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 requires 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.

4.5.3 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 sho be at least 1 ns and ADC few fC/mV and more.

uld 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. Novel detector readout technologies, like cluster counting, 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 than for 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 costs of such enterprises, smaller, blue-sky R&D developments on the other hand, which could not afford the expense of dedicated electronics development were 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.

4.5.4 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, other ASIC front-ends may work better for different applications, from the point of view of input coupling or dynamic range, whether they require triggerless, 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 dis-

Reference	Description	Deliverable Nature
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 - Objective 5.1: Front End Challenges

tance, 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 was 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 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 a 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 and 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 gasesous detectors. Either the fronend 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 or Dark Matter search physics. 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 environement 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 emulating the appropriate rate might be required. An example of such a facility is GIF++ [70] 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 [71] 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 readout of small gas detectors from inaccessible confined spaces and over long distance. Limited numbers of channels ($<$1k) per μSRS node eliminate the need for crate-based frontend concentrators if the bandwidth of a common network switch is sufficient to transfer the data from all connected nodes to the DAQ. Individual uSRS nodes can transmit self-triggered event data at high rates ($>$1MHz). The optional fibre interconnection between nodes provides clock synchronization and common control from a single, SoC-controlled master node. A first implementation is the uROC with two HDMI ports for readout of 256 VMM3a channels with 1Gbit/s ethernet uplink and 30 Watt USB-C power delivery.

4.5.5 TOPICS BEYOND THE READOUT SYSTEMS

In addition to the readout electronics described in the previous sections, many additional electronics 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 save 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 a lot of 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 ev-

Reference	Description	Deliverable Nature
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 front-end implementation(tbd)*
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 - Objective 5.2: Modernised Readout System

eryone 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 System on Chip (Soc) device to measure and correct for such comparably slowly changing parameters.

Reference	Description	Deliverable Nature
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 - Objective 5.3: Beyond Readout System

4.6 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.

4.6.1 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, that aim to identify needs, assess current capabilities, and identify required resources for potential upgrades, are listed in Table 19.

Reference	Description	Deliverable Nature
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 - Objective 6.1: Development and maintenance of common production facilities and equipment, list of tasks and deliverables

The need to produce large-area RPC detectors with high efficiency and homogeneity for 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[1], glass, etc.)
- Cutting and cleaning of electrode materials
- Silkscreen printing of electrodes
- 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

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[1] High Pressure Laminate

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.

4.6.2 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 has 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, medium quantities to large volumes, different equipment and facility organization may be required respect with to the ones of the common production facilities introduced in Section 4.6, 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	Deliverable Nature
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 - Objective 6.2: Quality controls and large volume productions, list of tasks and deliverables

4.6.3 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 exposure, 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 [72]. 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.
- 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	Deliverable Nature
D6.3.1	Technology transfer checklist	Report
D6.3.2	Technology transfer database (project, industrial partner)	Database

Table 21: WG6 - Objective 6.3: Collaboration with Industrial Partners

4.6.4 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	Deliverable Nature
D6.4.1	Establishment and support of a forum for sharing experiences, knowledge, and best practices on gaseous detectors	Online Forum

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

4.7 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 [12].

4.7.1 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 [73] 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.

Reference	Description	Deliverable Nature
D7.1.1	Estabilishment 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 - Objective 7.1: Detector Laboratories Network

4.7.2 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 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.

Reference	Description	Deliverable Nature
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 - Objective 7.2: Common Test Beam Facilities

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. As such, existing analysis framework repositories as REST-for-Physics [74] could be potentially explored.

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 periods that CERN beam facilities are not available (e.g. periods of long shutdowns) or (ii) in case of difficulty to bring their equipment to CERN and therefore prefer a local test beam site.

4.7.3 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

Reference	Description	Deliverable Nature
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 - Objective 7.3: Commmon Irradiation Facilities

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.

4.7.4 SPECIALISED LABORATORIES

This activity is strongly connected to the WG3 research lines (Sec. 4.3). 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 sig-

Reference	Description	Deliverable Nature
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

Table 26: WG7 - Objective 7.4: Specialised Laboratories

nal 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 gas chromatograph station is needed. For material (detector and infrastructures) studies, other analysers are available in the collaboration and a common effort will be done to classify them into a shared database.

4.7.5 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 27. 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 controls 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[2] 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 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 [74], 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

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

libraries that have been developed for special purposes will also be included in the repository.

Reference	Description	Deliverable Nature
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 flowmeter 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 - Objective 7.5: Instrumentation and software sharing

4.7.6 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.

D7.6.1 Test Facilities Database: Fill existing databases [75] and create new ones when required.

4.8 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 is fundamental for the development and advancement of detector R&D and in extension 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.

4.8.1 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 in 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	Deliverable Nature
D8.1.1	Organisation of topical workshops	Event
D8.1.2	Creation of repository for DRD1 notes	Online repository

Table 28: WG8 - Objective 8.1: Knowledge exchange and facilitating scientific collaboration

4.8.2 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 sharing of technical experiences. Schools, technical training courses and 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 development, 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 recent 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 development within the DRD1 community, where experienced researchers and technicians and senior staff can offer their support and guidance;

4.8.3 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

Reference	Description	Deliverable Nature
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 29: WG8 - Objective 8.2: Training and dissemination initiatives

positions for hardware-oriented profiles. A few general 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 RFD 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, 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	Deliverable Nature
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 30: WG8 - Objective 8.2: Career promotion

4.8.4 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. 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	Deliverable Nature
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 31: WG8 - Objective 8.4: Outreach and education

5 Collaboration Organization

5.1 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, 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.

6 Resources and Infrastructures

6.1 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.

6.1.1 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 representatives 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.

6.1.2 WORK PACKAGES

In addition to the Common Fund, the DRD1 Funding Framework incorporates the concept of Work Packages. These Work Packages – to be approved by the involved Funding Agencies - serve as detailed plans that outline the allocation of resources provided by the respective Funding Agencies to the participating institutes. 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. 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.

6.1.3 COMMON INVESTMENTS

Major common investments, such as raw materials and infrastructure, within the DRD1 Collaboration will follow a similar mechanism to Work Packages (WPs). Drawing inspiration from the RD51 Collaboration model[3], the participating parties in DRD1 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.

7 Partners and Their Fields of Contributions

7.1 Contributions of the DRD1 Institutes.

The active participation and contributions of each DRD1 Institute in the collaborative tasks undertaken within the Working Groups will be regularly updated and documented in the publicly accessible repositories of the DRD1 Collaboration. This transparent 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. Furthermore, the detailed contributions of the institutes to specific Work Packages will be clearly outlined in the relevant annexes of the Memorandum of Understanding (MoU).

7.2 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.

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

Acronyms

ALICE A Large Ion Collider Experiment.
ASIC Application Specific Integrated Circuits.
AT-TPC Active Target TPC.
ATLAS A Toroidal LHC ApparatuS.

BEM Boundary Element Method.
BESIII The Beijing Spectrometer III.

C^3 Cool Copper Collider.
CEPC Circular Electron Positron 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.
FCC-ee electron-positron Future Circular Collider.
FCC-hh proton-poton and heavy ions Future Circular Collider.

FEM Finite Element Method.
FPGA Field Programmable Gate Arrays.
FTM Fast Timing MPGD.

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.

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.
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.
SHiP	Search for Hidden Particles.
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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