arXiv:1806.09955v1 [physics.ins-det] 26 Jun 2018

May 2018

R&D PROPOSAL
RD51 EXTENSION BEYOND 2018

EDITORS:
S. Dalla Torre (INFN Trieste), E. Oliveri (CERN),
L. Ropelewski (CERN), M. Titov (CEA Saclay)

Abstract

The RD51 Collaboration, in charge of the development and dissemination of MicroPattern Gaseous Detectors (MPGD) since 2008, proposes to extend its activity, after 2018, for a further five-year term. Since the RD51 initial years, the community of MPGD developers and users has grown considerably. It is reflected by the many MPGD-based applications in high energy and nuclear physics experiments as well as in other basic and applied-research fields. They rely on the parallel progress of detector concepts and associated technologies. The cultural, infrastructure and networking support offered by RD51 has been essential in this process. The rich portfolio of MPGD projects, under constant expansion, is accompanied by novel ideas on further developments and applications.

The proposed next term of RD51 activities aims at bringing a number of detector concepts to maturity, initiating new projects and continuing the support to the community. Among leading proposed projects are ultrafast, high-rate MPGDs; discharge-free, high-resolution imaging detectors with resistive elements and high-granularity integrated electronics; novel noble-liquid detector concepts, including electroluminescence in gas bubbles; studies of environment-friendly counting gases and long-term sealed-mode operation; optical-readout detectors with radiation-hard imagers for fundamental research experiments, radiography and other domains.

The proposed R&D program is also expected to enrich our basic knowledge in detector physics, to form a generation of young detector experts - paving the way to new detector concepts and applications. The vast R&D program requires acquiring additional, up-to-date expertise in advanced technologies.

Geneva, Switzerland
June 27, 2018

List of collaborating Institutes:

Albuquerque, NM, USA, Department of Physics and Astronomy, University of New Mexico
Alessandria, Italy, University of Piemonte Orientale and INFN Torino
Amsterdam, Netherlands, NIKHEF
Annecy le Vieux, France, LAPP
Arlington, TX, USA, University of Texas, Arlington
Athens, Greece, INP NCSR "Demokritos"
Athens, Greece, National Technical University of Athens
Athens, Greece, University of Athens
Aveiro, Portugal, University of Aveiro
Barcelona, Spain, CNM-IMB (CSIC)
Bari, Italy, INFN and University Aldo Moro of Bari
Beijing, China, Lab. of Radiation Physics, Tsinghua University
Bellaterra, Spain, IFAE Barcelona
Bhubaneswar, India, National Institute of Science Education and Research
Bogota, Colombia, Centro de Investigaciones, Universidad Antonio Narina
Bogota, Colombia, National University of Colombia, Physics Department
Bonn, Germany, Rheinische Friedrich-Wilhelms Universität
Braunschweig, Germany, Physikalisch-Technische Bundesanstalt
Budapest, Hungary, Wigner RCP
Bursa, Turkey, Department of Physics, Uludag University
Cambridge, MA, USA, MIT
Charlottesville, VA, USA, Dept of Physics, University of Virginia
Coimbra, Portugal, Laboratorio de Instrumentacao Instrumentacao e Fisica Experimental de Particulas
Coimbra, Portugal, University of Coimbra
Daejeon, Republic of Korea, Center for Axion and Precision CAPP, Institute for Basic Science
Darmstadt, Germany, GSI
Dubna, Russia, JINR
Ferrara, Italy, INFN Ferrara and University of Ferrara
Frascati, Italy, INFN Laboratori nazionali di Frascati
Freiburg, Germany, Physikalisches Institut
Albrecht-Ludwigs Universität
Garching, Germany, Physik Department E18
Technische Universität München
Gatchina, Russia, St Petersburg Nuclear Physics Institute
Geneva, Switzerland, CERN

Geneva, Switzerland, DPNC, section de physique, Université de Genève
Gent, Belgium, Dept of Physics and Astronomy, University Gent
Gif sur Yvette, France, CEA IRFU (Saclay)
Grenoble, France, Institut Max von Laue - Paul Langevin (ILL)
Hamburg, Germany, DESY
Hefei, China, State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China
Helsinki, Finland, Helsinki Institute of Physics
Kobe, Japan, Kobe University
Kolkata, India, Saha Institute of Nuclear Physics
Kolkata, India, Variable Energy Cyclotron Centre, VECC
Krakow, Poland, AGH University
Lanzhou, China, Institute of Nuclear Research, Lanzhou University
Lund, Sweden, European Spallation Source
Magurele, Romania, IFIN-HH
Mainz, Germany, University of Mainz
Melbourne, FL, USA, Florida Institute of Technology
Mexico City, Mexico, Universidad National Autonoma de Mexico
Milano, Italy, University of Milano Biococca
Cagliari, Italy, INFN Cagliari and University of Cagliari
Moscow, Russia, Institute for Nuclear ResearchResearch, Russian Academy of Sciences
Mumbai, India, Nuclear Physics Division, Bhabha Atomic Research Centre
München, Germany, Max-Planck-Institut für Physik
Nantes, France, SUBATECH
Napoli, Italy, INFN Napoli and University Federico II of Napoli
Novara, Italy, TERA Foundation
Novosibirsk, Russia, Budker Institute of Nuclear Physics and Novosibirsk State University
Orsay, France, Laboratoire d'Acclelerateur Lineaire (LAL)
Palaiseau, France, Laboratoire Leprince-Ringuet
Philadelphia, USA, Temple University
Siena, Italy, University of Siena and INFN Pisa
Rehovot, Israel, Weizmann Institute of Science
Roma, Italy, INFN Roma La Sapienza and University La Sapienza of Roma
Roma, Italy, INFN and University Roma 3
Roma, Italy, Istituto Superiore di Sanità and INFN Roma La Sapienza
Rustrel, France, Low background noise interdisciplinary underground laboratory, LSBB, CNRS
Santiago, Spain, Instituto Galego de Fisica de Altas Energias
Sao Paolo, Brazil, University of Sao Paolo

Seoul, Korea, Republic of, Korea Detector Laboratory, Korea University
Shanghai, China, Jiao Tong University
Stony Brook, USA, Physics Department
Thessaloniki, Greece, Aristotle University of Thessaloniki
Tokyo, Japan, University of Tokyo
Tomsk, Russia, Tomsk Polytechnical University
Torino, Italy, INFN Torino and University of Torino
Trieste, Italy, INFN Trieste and University of Trieste
Tsukuba, Japan, Tsukuba University of Tsukuba
Tucson, AZ, USA, Dept. of Physics, University of Arizona
Tunis, Tunisia, Centre National des Sciences et Technologies Nucleaire
Upton, NY, USA, Brookhaven National Laboratory
Valencia, Spain, Instituto de Fisica Corpuscular (IFIC)
Valetta, Malta, University of Malta
Valparaiso, Chili, Departamento de Fisica, Universita’ Tecnica Federico Santa Maria
Wako, Japan, Nishina Center for Accelerator-Based Science, RIKEN
Warsaw, Poland, Institute of Plasma Physics and Laser Microfusion
Wuhan, China, Huazhong Normal University
Zagreb, Croatia, Zagreb University
Zaragoza, Spain, University of Zaragoza
Zurich, Switzerland, Institute for Particle Physics, ETH Zurich

Contents

1 Executive Summary

The RD51 Collaboration, in charge of the development and dissemination of Micro-Pattern Gaseous Detectors (MPGD) since 2008, proposes to extend its activity, after 2018, for a further five-year term. This proposal, where the Collaboration community expresses firm interest, is based on the analysis of the progress in the MPGD sector during the RD51 years and the Collaboration contribution to the present state-of-the-art; on the legacy in terms of expertize and infrastructures that RD51 has built-up over the years; on the perspectives for future R&D projects and the wide dissemination of MPGD usage, where the Collaboration can continue offering relevant cultural and infrastructural support. Therefore, the scope and activities for the RD51 extension cluster around two main missions: novel R&D developments towards reaching or overcoming performance limits and the continuation and reinforcement of the support actions for the community and MPGD dissemination.

Highlights of the future R&D scenario based on the ongoing projects are central elements of the present proposal. A clear direction for future developments is that of the resistive materials and related detector architectures. Their usage improves detector stability, making possible higher gain in a single multiplication layer, a remarkable advantage for assembly, mass production and cost. Single layer architectures represent also a preferential approach in hadron sampling calorimetry.

The frontier of fast and precise timing is moved forward by novel developments. Very encouraging trends are obtained by coupling gaseous detectors and Cherenkov radiators to take advantage from the prompt radiation emission. Correspondingly novel electronics and front-end circuits are being developed.

A variety of novel opportunities is offered by MPGD hybridization, a strategy aiming to strengthen the detector performance combining the advantages offered by a variety of approaches. It is obtained both by combining MPGD technologies and by coupling gaseous detectors to different detection technologies, as is the case for optical read-out of gaseous detectors.

Contributions to the detector concepts from up-to-date material science are required for several domains: resistive materials, solid-state photon and neutron converters, innovative nanotechnology components. Material studies can contribute to requirements related to low out-gassing, radiation hardness, radio purity, converter robustness and eco-friendly gases.

The support actions towards the community are aimed to preserve and enrich the present scenario, including: networking activity, with focus on training and education, further development of dedicated simulation tools, advances in electronics tools, continuation of the collaborative interactions with strategic CERN workshops. The need for new materials and technologies will result in an RD51 action of stimulus to the whole community of detector developers towards the creation of common networking and infrastructures.

The collaboration plans to maintain the current organization, characterized by a simple and effective management, and the existing structure based on the working groups.

The Collaboration requests to CERN are moderate, at a level similar to the present one, with emphasis to the support of the Gaseous Detector Development (GDD) laboratory, the collaborative access to the EP-DT-EF Micro Pattern Technology (MPT) Workshop and to the EP-DT-EF Thin Film and Glass (TFG) Laboratory, as well as access to other CERN technical facilities.

2 Introduction

2.1 Motivations and mission of the RD51 Collaboration

The modern photo-lithographic technology on flexible and standard PCB substrates has favored the invention, in the last years of the 20th century, of novel Micro-Pattern Gas Detectors (MPGD); among them: the Micro-Strip Gas Chamber (MSGC) [1], the Gas Electron Multiplier [2] (GEM) and the MicroMegas (MM) [3]. Since the very beginning, the goal was the development of novel detectors with very high spatial ($\sim$50 μm) and time (ns) resolution, large dynamic range, high rate capability (up to $\sim 10^6$ Hz/mm^2), large sensitive area and radiation hardness - making them an invaluable tool to confront future detector challenges at the frontiers of research. The dedication of several groups of MPGD developers has led to rapid progress, crowned by new inventions and understanding of the underlying operation mechanisms of the different detector concepts. MPGDs promised to fill a gap between the high-performance but expensive solid-state detectors, and cheap but rate-limited traditional wire chambers. Nevertheless, the integration of MPGDs in large experiments was not rapid, in spite of the first large-scale application within the COMPASS experiment [4] at CERN SPS in the early days of the 21st century. In COMPASS, telescopes of MMs and GEM trackers demonstrated reference performance at particle fluxes of 25 kHz/mm^2, with space resolution better than 100 μm and time resolution around 10 ns. Thus, the potentiality of MPGD technologies became evident and the interest in their applications has started growing in the High Energy Physics (HEP) and nuclear physics domains, and beyond. Consequently, it was crucial to consolidate and enlarge the dedicated community to foster further developments and dissemination of MPGD applications in the HEP sector and other fields. The RD51 CERN-based technological Collaboration [5], promoted by L. Ropelewski and M. Titov, was established to pursue these goals.

RD51 activities started in 2009; the collaboration comprised 57 Institutions in 21 Countries. Nowadays, the number participating Institutions is 90 in 25 Countries (Fig. 1). Initially, the participation was mainly limited to Europe and nearby countries. Over the years, the number of collaborating Institutes from other continents, like from China, India, Japan, USA, has greatly increased - reinforcing the RD51 world-wide vocation and enhancing the geographical diversity and expertise of the MPGD community [6].

Since its foundation, the RD51 collaboration has provided important stimulus for the development of MPGDs. While a number of the MPGD technologies were introduced before RD51 was founded, with more techniques becoming available or affordable, new detection concepts are still being introduced, and existing ones

Figure 1: *Worldwide dissemination of the RD51 collaboration.*

are substantially improved. The nature and extent of the Collaboration activities is reflected in the seven Working Groups (WG), transversal to the RD51 activities, covering all relevant R&D topics: MPGD technologies and novel structures, detector characterization, study of the physical phenomena and detector simulations, dedicated electronics tools for read-out and laboratory studies, production and engineering aspects, common test facilities, and dissemination beyond the HEP community - including dedicated education and training. Since the very beginning, RD51 focused on a broad networking effort to share and disseminate the know-how and the technologies, and the promotion of generic R&D: a seminal activity for the enlargement of the application portfolio. Originally created for a five-year term, RD51 was prolonged for a second five years term beyond 2013, following the LHCC recommendation stating: "RD51 is a successful R&D Collaboration with well-defined and important future plans." [7].

2.2 MPGD progress during the RD51 years: the consolidation of the existing technologies

Important consolidation of the some better-established MPGD technologies has been reached within the RD51 collaboration, often driven by the working conditions of large collider experiments.

One of the breakthroughs came with the development of MM with resistive anodes for discharge mitigation [8], in the context of the ATLAS New Small Wheel (NSW) project [9]. Figure 2 shows the Saclay clean room used for the assembly of the large area final detector. This concept allows limiting the energy of occasional discharges and results in a protection of both the detector and its front-end electronics and, equally relevant, in a substantial dead-time reduction (time required to re-establish the operational voltage). The resistive anodes have been obtained by a variety of approaches: photo-lithography, screen-printing technologies and sputtering.

The construction of GEM-detectors implies two main issues: GEM-foil production and preservation of the correct spacing between successive GEMs in multilayer configurations. Initially GEM foils were produced using a double-mask approach with the chemical etching performed from both foil faces. The difficulty of aligning the two masks, limiting the achievable lateral size to 50 cm, has led to the development of a single-mask production protocol. It was initially developed for the upgrade of the TOTEM experiment [10], further used to produce GEM foils for the KLOE2 cylindrical GEM-detector [11] and that of the CMS forward muon spectrometer [12]. The requirement to preserve the constant inter-foil spacing in multilayer GEM detectors of large-size was first fulfilled successfully, though with small dead-zones, by adequate spacers; e.g. in COMPASS [13] and TOTEM [14] trackers. Later, the INFN groups involved in the construction of the GEM-based trackers for LHCb experiment introduced an alternative approach: GEM-foil stretching prior to gluing on support frames [15]. This concept also paved the way to the construction of a cylindrical-GEM detector [11]. Further extension of the stretching technique has been introduced for the CMS forward muon spectrometer [12]: to save a relevant fraction of the assembly time the foils are mechanically fixed onto the frames, where they are mechanically stretched and kept at the correct tension without gluing. This NS2 technique, no-stretch no-spacer method, presented by R. de Olivera at MPGD2013 [16], has become the basis of the GEM-detector construction for the CMS upgrade. Nowadays, the single-mask GEM technology, together with the NS2 technique, simplifies the fabrication process, resulting in an important minimization of the production time - particularly relevant for large-volume production (Fig. 3). So far, the largest GEM foil production is the one ongoing for the upgrade of the ALICE Time Projection Chamber (TPC) [17] (Fig. 4). The demanding requirements of a TPC, where fine resolution tracking and good dE/dx accuracy are equally relevant, has imposed a detailed and stringent quality assessment protocol. Therefore, this construction effort represents the first fully-engineered large mass-production of MPGDs.

THick GEMs (THGEM), also referred to in the literature as Large Electron Multipliers (LEM), have been introduced in parallel by several groups at the beginning of the 21^{st} century [18]. They are derived from the GEM design, scaling-up $\sim$ 10-fold the geometrical parameters and changing the production technology. The Cu-coated polyimide foil of the GEM multipliers is replaced by that of standard PCBs (e.g. FR4) and mechanical drilling produces the holes (Fig. 5). They

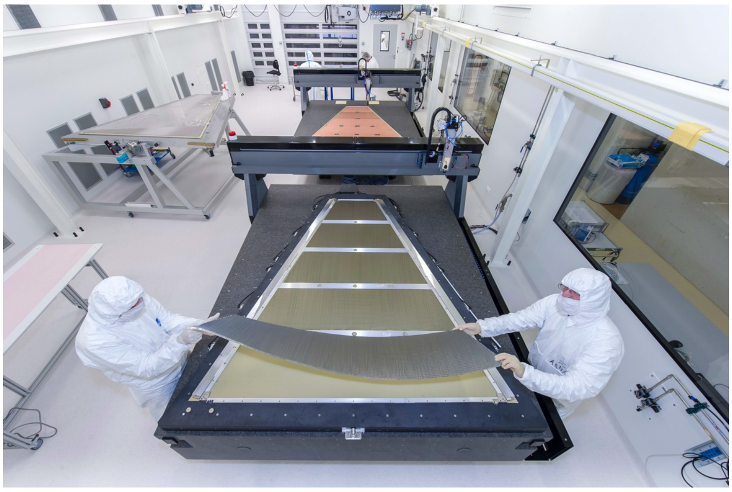

Figure 2: *The ATLAS team in the Saclay clean room building a large area resistive micromegas module for the ATLAS New Small Wheel Upgrade [19].*

give access to large avalanche gains and good rate capabilities. THGEM electrodes can be mass-produced in large sizes with standard PCB technology, in spite of the large number of holes: some millions per square meter. They have intrinsic mechanical stiffness, and are robust against damages produced by occasional electrical discharges. Efforts have resulted in improved electrical stability by using a dedicated polishing protocol applied to the industrially-produced THGEM electrodes; an increased gain uniformity in large-size multiplier is reached by careful control of the electrode-thickness uniformity [20].

Advances have been also achieved on the algorithm side. Exploiting the ability of Micromegas and GEM detectors to measure both the position and arrival time of the charge deposited in the drift gap, a novel method for MM-trackers [21] and later for GEM trackers [22] has been developed. It allows preserving the space resolution also for inclined particle trajectories: the information collected by thin anode strips is treated as that of a μTPC. This approach combined with a more traditional centroid algorithm permits reaching nearly constant resolution of $\sim 100\ \mu$m for trajectory inclinations up to 40^o.

2.3 MPGD progress during the RD51 years: novel technologies

The consolidation of the better-established technologies has been accompanied by the flourishing of novel ones, often specific to well-defined applications. Novel technologies have been derived from MM and GEM concepts, hybrid approaches combining different MPGDs technologies, gaseous with non-gaseous multipliers;

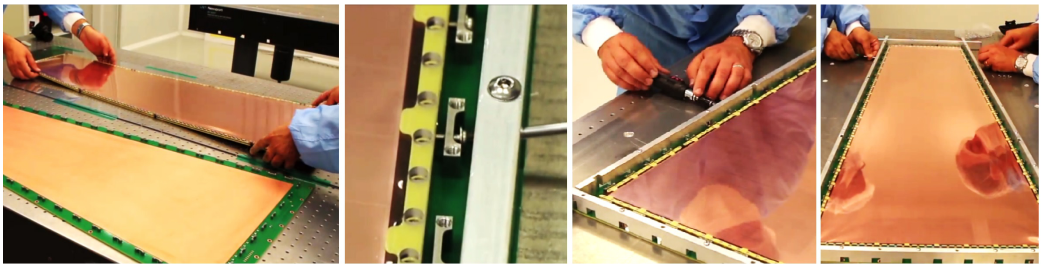

Figure 3: *Left and centre: The NS2 technique, no-stretch no-spacer GEM, developed for the CMS GEM upgrade of the GE1/1 forward muon station [23]. Right: stretching of the stack of GEM foils during the assembly. Courtesy of the CMS GEM group.*

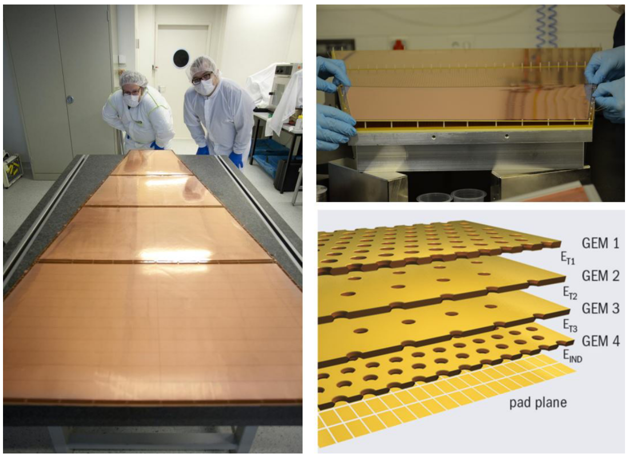

Figure 4: *Left: single mask large-size GEMs of a detector segment for the upgrade of the Time Projection Chamber of the ALICE experiment at CERN [24]. Right top: assembly of a framed GEM on top of the pad readout plane. Right Bottom: Schematic view of the stack of four GEM layer with different pitches optimized for Ions Back Flow suppression [25]. Courtesy of the ALICE TPC Upgrade group.*

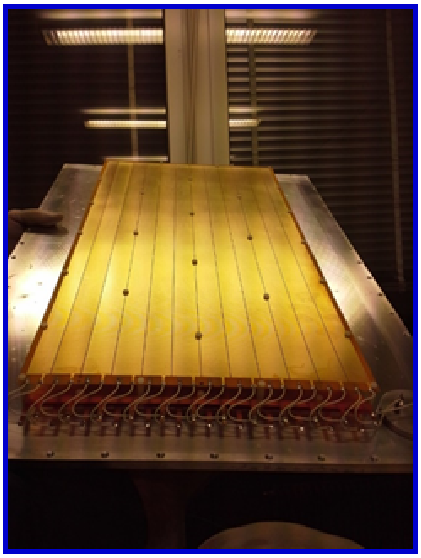

Figure 5: *Picture of a large-size THGEM produced for the gaseous photon detectors of COMPASS RICH. Courtesy of the COMPASS RICH group.*

others are based entirely on new concepts and architectures. Novel technologies are illustrated by the several selected examples:

- Coupling the microelectronics industry and advanced PCB technology has been important for the development of gas detectors with increasingly smaller pitch size. An elegant solution is the use of a CMOS pixel ASIC, assembled directly below the GEM or MM amplification structure. Modern "wafer post-processing technology" allows for the integration of a small-scale micromesh grid directly onto a fine-granularity Timepix chip [26], thus forming integrated read-out of a gaseous detector (InGrid) [27]. Such a concept allows reconstructing 3D-space points of individual primary electron clusters and serves as an “electronic bubble chamber”. A breakthrough here is the development of the ILC TPC prototype with a total of 160 InGrid detectors, each 2 cm^2, corresponding to 10.5 million pixels [28], read-out with the RD51 Scalable Readout System (SRS) (Sec. 3.3). New structures, where a GEM foil is facing the Medipix chip [29], thus forming the GEMpix detector [30], is in use for medical applications as well as for treatment of radioactive wastes [31].
- GEM geometries with extra electrodes added onto one of the two GEM-foil faces in multi-layer configurations aim at obtaining a breakthrough in ion-blocking capability - a feature required in gaseous photon detectors. Micro Hole and Strip Plates [32] and Cobra [33] architectures have been designed

and characterized.

- A promising GEM-derived architecture is that of the μ-RWELL [34], where the anode is directly placed at the hole bottom, forming the well structure, in order to maximize the collection of the avalanche electrons; this single-element structure comprises a resistive layer for spark protection. Several THGEM-based detectors have been proposed, including WELL structures, with the THGEM electrode being coupled to a readout anode, directly or via resistive film or plate for discharge damping [35].
- Initially, GEMs were introduced to act as preamplifier in gaseous detectors [36] and, therefore, the concept of the hybrid approach was present since the very beginning in MPGD concepts. More recently, electron multipliers have been coupled to devices capable of detecting the luminescent light produced in the amplification process: in GEM TPC with optical read-out [37] and THGEM-based read-out for double-phase liquid Ar detectors [38]. A final MM multiplication stage is added to GEM or THGEM multipliers in order to control the ion back-flow making use of the intrinsic ion trapping capability of the MM principle; GEM and MM schemes have been proposed as read-out sensor of the ALICE TPC [17], while THGEMs and MM are the basis structure of novel gaseous photon detectors in COMPASS RICH [39].
- The μPIC [40] is a fully industrially produced PCB including anode strips on one face and orthogonal cathode strips on the other one. A regular pattern of uncoated zones is present along the cathode strips; an electric conductor buried in the thin PCB substrate transfers the anode voltage to a "dot" at the center of each of the uncoated cathode zones: charge multiplication occurs there, under the electric field established between the cathode strips and the anode dots. A resistive coating of the cathode strips ensures tolerance to occasional discharges. This technology is easily extensible for the production of large areas up to a few square meters.

2.4 MPGD progress during the RD51 years: MPGD applications

The choice of MPGDs for relevant upgrades of CERN experiments indicates the degree of maturity of given detector technologies for constructing large-size detectors, the level of dissemination within the HEP community and their reliability. During the last five years, there have been major MPGDs developments for ATLAS, CMS, ALICE and COMPASS upgrades, towards establishing technology goals and technical requirements, and addressing engineering and integration challenges. In parallel, the portfolio of MPGD applications in fundamental research has been enlarged in HEP and also in other science sectors, as illustrated by the following non-exhaustive list of examples.

ATLAS and CMS are building large-area MPGD trackers to equip the forward regions, capable of contributing already at the trigger level. Large size, about 1×2.5 m^2, resistive MM will cover a total surface of 1200 m^2 in the ATLAS NSW upgrade [9], while triple GEM detectors with size up to 1.2×0.45 m^2 are being produced for a total GEM-foil surface of about 250 m^2 in the CMS GE1/1 upgrade [12]. The construction of novel four-layer GEM counters designed to upgrade the ALICE TPC read-out system [17], for a total GEM-foil surface of about 500 m^2, is well advanced. In 2016, wire-chamber based photon detectors of COMPASS RICH-1 have been replaced by hybrid MPGDs. These include two layers of staggered THGEM and a MM multiplication stage, with CsI photocathodes, equipping a total surface of 1.5 m^2; they accomplish the delicate mission of single photon detection [39]. RD51 has continuously offered to these projects consultancy support, contributions by dedicated studies on demand; e.g. studies of etching processes in GEMs and discharges studies in triple-GEM detectors focused to the GEMs for the ALICE TPC upgrade. RD51 made also available its common test-beam facility at the H4 line at SPS and the permanent cosmic ray stand in the Gaseous Detector Development (GDD) laboratory, dedicated to R&D studies of the MM for the ATLAS NSW project.

MPGDs are currently being used in a variety of nuclear physics experiments and also fulfill the most stringent constraints imposed by the future collider facilities, from FAIR and EIC to ILC and FCC. At Jlab, GEM detectors are deployed in the HallA experiment [41, 42], Super BigBite spectrometer [43], PRad experiment [44] and in the TPC of the BoNuS experiment [45]. At BNL, the PHENIX-Cherenkov counter has been equipped with CsI-coated cascaded-GEM UV detectors in the Hadron-Blind Detector (HBD) [46] and four GEM trackers in the forward direction; moreover GEMs are considered for the read-out of the sPHENIX TPC [47].

MSGC trackers have been operated at the DIRAC [48] and at HERA-B experiment [49]. A MM detector has been operated at the axion experiment CAST [50]. A triple GEM cylindrical detector instruments the vertex region of the KLOE2 experiment [11] and a second cylindrical detector is under construction for BESSIII in Beijing [51]. Cylindrical MMs have been developed for the experiment CLAS12 [52] at JLab and are now one of the options for tracking at the future Electron Ion Collider (EIC) [53]. A variety of MPGD approaches are being considered for TPC read-out at ILC: GEMs [54], MMs [55] and InGrids [56]. MM [57], GEM [58] and Resistive plate WELL (RPWELL) detectors [59] are considered as potential sensing elements in Digital Hadron Calorimetry at ILC. MPGDs are developed for low-energy nuclear physics experiments. GEMs will read-out a TPC operated at low pressure using light gases at the National Superconducting Cyclotron Facility (NSCL) in Michigan [60], MM detectors are the read-out sensors of the double-sided TPC of the Neutron Induced Fission Fragment Tracking Experiment

(NIFFTE) at Los Alamos Neutron Science CEnter (LANSCE) [61].

Working at cryogenic temperatures - or even within the cryogenic liquid itself - requires optimization to achieve simultaneously high gas gain and long-term stability. THGEMs are at the base of different developments aiming at novel read-out detectors for large-volume noble-liquid TPCs in rare-event experiments. Dual-phase liquid Ar TPCs employ LEM/THGEM elements in the gas phase as one charge-readout option proposed for the DUNE experiment [62]; they are also being investigated in LBNO-DEMO at CERN [63]. An alternative, charge read-out concept via avalanche-induced electroluminescence in the THGEM holes is considered, using Geiger Avalanche Photo Diodes (GAPD), in the so-called CRyogenic Avalanche Detector (CRAD) [64]. Electroluminescence-photon recording with a gaseous PM (GPM) has been recently demonstrated in a dual-phase Xe detector, as a potential solution for dark-matter detectors [65]. THGEMs have been successfully operated in a dual-phase Xe detector detecting by PMTs the light produced by electroluminescence [66]; moreover, coating the THGEM with a CsI film, it is possible to detect both the ionization and the scintillation signal produced in the liquid Xe.

For the field of rare-event searches, Micro-bulk MMs, built making use of radiopure materials, are studied for the neutrino-less double beta decay experiment PANDAX-III [67] at the Jinping Underground Laboratory, China. The NEWAGE0.3b Detector at the Kamioka mine, Japan, is developing a negative-ion TPC [68], using a μ-PIC [40] detector coupled to a pre-amplifying GEM foil. MMs are foreseen for axion search in the experiment IAXO [69], for WIMPs search at TREX-DM [70] and for a dark-photon search at P348 [71]; the experiment PADME [72], also dedicated to a dark photon search, will use GEM detectors.

There are number of applications of the MPGDs in the neutron detection domain, which include neutron beam diagnostics and neutron detection at spallation sources, fusion experiments, neutron tomography, and many others. Neutron imaging by MPGDs has been effectively performed by the MSGC-based D20 reflectometer at the Institut Laue Langevin (ILL) [73]. More recently, neutrons have been detected using GEM detectors and polyethylene converter [74] at Frascati ENEA Tokamak. High-efficiency n-detectors based on GEMs where the neutrons are converted in a set of $^{10}B_4C$-coated lamellas orthogonal to the GEM planes [75] are under development for applications at the European Spallation Source (ESS).

Beyond fundamental research, MPGDs are in use and considered for applications of scientific, social and industrial interest; this includes the fields of medical imaging, non-destructive tests and large-size object inspection, homeland security, nuclear plant and radioactive-waste monitoring, micro-dosimetry, medical-beam monitoring, tokamak diagnostic, geological studies by muon radiography and X-ray imaging, as illustrated by two recent applications. A telescope of MM trackers has been used for the muography of the Khufu's pyramid in Egypt, contributing to the discovery of a previously not-identified large void [76]. A novel method has been proposed for measuring by the GEMPix detector the ^{55}Fe content in samples of metallic material activated during operation of CERN accelerators and experimental facilities [31].

2.5 MPGD progress during the RD51 years: dissemination

The RD51 collaboration has been also advancing the MPGD domain with scientific, technological and educational initiatives. The dissemination of MPGDs beyond fundamental research was one of the major new vectors when the continuation of the RD51 was approved in 2013. A series of Academy-Industry matching events [77], organized by the RD51 in collaboration with HEPTECH [78], was dedicated to neutron detection in 2013 [79] and 2015 [80] and to photon detection in 2015 [81]. These events provided a platform where academic institutions, potential users and industry could meet to foster collaboration with people interested in MPGD technology. Specific R&D programs are dedicated to applications as, for instance, the development of the optical read-out of fluorescence light produced by electron multiplication in GEM detectors [37], also communicated via a CERN Technology Brief [82]. More in general, RD51 has contributed to the broad scientific and technological "know-how" in the MPGD field by networking activity providing financial support to the general-interest collaborative efforts and to the specific common facilities and tools. Concerning RD51 networking, it is based on the frequent periodical meetings of the community: two yearly collaboration meetings, inter-spaced by two working mini-weeks. Given the ever-growing interest in MPGDs, RD51 re-established an international conference series on the detectors [83–87] every second year and organizes the schools [88–92] and specialized workshops [93–96]. The know-how dissemination is also supported via the series of the RD51 Internal Notes [97].

In addition to the support mechanisms and facilities tools, further discussed in Sec. 3, the portfolio is rich and diversified, including: maintenance and development of simulation software dedicated to gaseous detectors, development of a complete read-out chain designed to operate in a laboratory context, also expandable to large read-out systems, realization of affordable laboratory instruments dedicated to MPGD developments, and more. Last, but not least, the RD51 community has open access to the instrumentation, services and infrastructures of the large and well-equipped Gas Detector Development (GDD) laboratory at CERN, continuously hosting several parallel R&D activities. In addition, the common test beam infrastructure at the H4 test-beam area at SPS, available usually three times a year during the periods of beam availability for RD51, allows several groups to investigate in parallel their R&D projects. It is largely maintained by the GDD

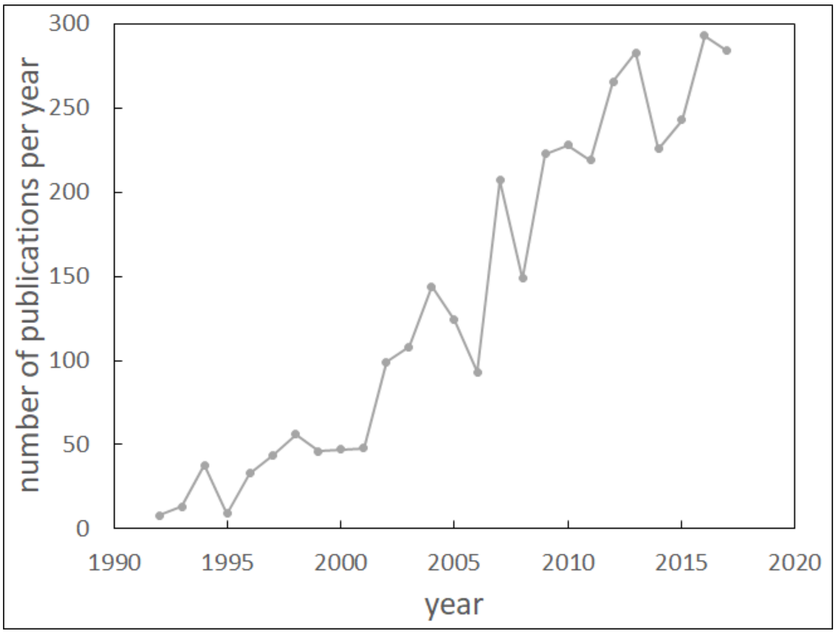

Figure 6: *Number of publications dedicated to MPGDs per year; data source: Scopus; estimated error at the 20% level.*

Team.

An indicator of the level of interest for MPGDs, of the corresponding development effort and the wide dissemination of these detectors is the increasing number of publications dedicated to MPGDs, as illustrated in Fig. 6.

3 RD51 Legacy, Expertize and Infrastructures

The main objective of the RD51 R&D program is to advance technological development and application of MPGDs [98]. Since its early stages, the RD51 collaboration has paid attention to building a proper environment for performing high-quality advanced R&D on MPGDs; it continues to advance the MPGD domain with scientific, technological, and educational initiatives. It is a worldwide open scientific and technological forum on MPGDs, and RD51 has invested resources during ten years in forming expertise, organizing common infrastructures and developing common research tools [5]. Starting new generic research projects to explore innovative ideas has been strongly boosted by fruitful discussions and exchanges within the broad MPGD community and associated experts. The progress in various R&D projects has been made possible by open access to facilities and research tools. The RD51 Common Fund has supported the networking activities, projects of common interest. In particular maintenance and development of simulation software, developments in the electronics sector and novel concepts at their starting phase.

In several cases, the presence of a trustworthy collaboration behind a given proposal has been also beneficial in proposal submissions to funding agencies. Over the ten RD51 years, many of the achieved results went, in some cases, beyond original expectations. The collaboration is firmly interested in another five-year period extension - to preserve and adapt the existing scenario of successful operation and achievements to future needs. The collaboration is moreover keeping alive, with a programmed and coherent evolution and with a continuous development, several fundamental tools otherwise lost or left to less powerful efficient, isolated individual efforts. This section summarizes the RD51 legacy, expertize and infrastructures available to the community; a few examples representing the current RD51 collaboration patrimony are also discussed.

3.1 Community and Expertise

The international RD51 community is primarily involved in the development for fundamental-research application and in generic R&D; activities focused on applications beyond basic research are also continuously growing. The collaboration is widely distributed in terms of institutes and countries. The variety of expertise and the full coverage of all the MPGD concepts and associated techniques is securing a proper balance to address future R&D challenges, allowing for an open and unbiased exchange of knowledge and information. There is no similar detector R&D consortium, world-wide, relying on such freedom and diversity of research groups and their interests. In this context, every RD51 member is contributing with his (her) own knowledge and acquires, in exchange, all available knowhow and expertise in the community. It has been proven to be an enriching dynamic process for everyone, and especially for the young generation of scientists. Common events (conferences, meetings, workshops, schools, lectures, trainings - Fig. 7) and common spaces (laboratory and test beam) have been playing an essential role in this fruitful exchange. Envisaging the needs for R&D activities on MPGD, RD51 has been structured in several working groups. Each of them is focusing on various aspects of gas-detector technologies: detector physics and measurements, new technologies, simulations and modeling, electronics, production techniques and common testing facilities. This structure facilitates interactions within the community and effectively focuses efforts and resources. The Spokespersons, the RD51 Management Board members and the working-group Leaders have the role of linking effectively needs and available expertize and resources; their role is vital for keeping the community together. The aim of the requested extension is to

Figure 7: First Academy-Industry Matching Event organized by RD51: *Special Workshop on Neutron Detection with MPGDs [79].*

preserve this effective and successful working environment, to support and enrich the existing framework and to form together new important areas of expertise in the context of novel and future detector technologies.

3.2 Detector physics, simulations and software tools

Fast and accurate detector-physics simulations activities have gained considerable importance, with the increase of the complexity of novel instrumentation. Developed by Rob Veenhof many years ago and continuously updated, Garfield [99] represents a unique software package for microscopic modeling of detector response. Garfield, together with HEED [100], Degrad [101] and Magboltz [102], represents the core of MPGDs simulation tools. They are all common and open-access to the community. In most of the new MPGD R&D projects, the suggested concepts are corroborated by these simulation studies; they permit better understanding of the operation mechanisms and expected detector performances. Simulating MPGDs requires an integrated approach of field calculations and charged particle transport, since the field changes substantially over the free path between collisions. Within RD51, an open-source, nearly exact boundary element solver (neBEM) was developed to overcome problems often related to finite-element methods of approximating electrostatic fields in the proximity of electrodes [104].

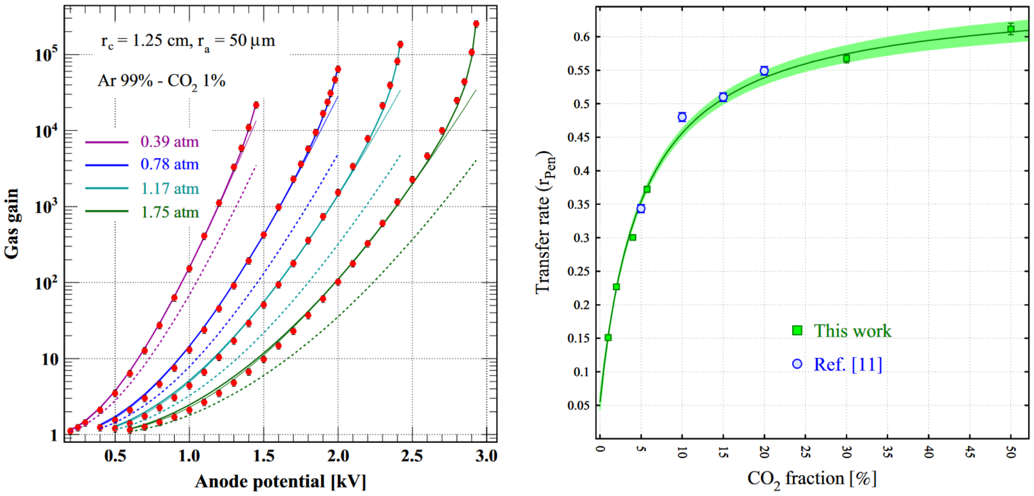

Figure 8: *Left plot: Calculated and measured gas gain curves: calculated without corrections (dashed lines), with Penning transfer included (thin straight lines), with Penning transfer and photon feedback included (thick straight lines) and measured data (points). Right plot: Transfer rate in Ar-CO_2 as a function of CO_2 concentration at mixture pressure of 1070 hPa [103].*

RD51 is supporting and encouraging maintenance and new developments of invaluable simulation tools. It is important to mention that any model simulations require validations by experimental measurements. One example is the dedicated measurement campaign and data analysis program that was undertaken to understand avalanche statistics and determine the Penning transfer-rates in numerous gas mixtures (Fig. 8). Significant efforts were also devoted towards modeling of MPGD performances for particular applications; e.g. studies of electron losses in MM with different mesh specifications for the ATLAS NSW, and GEM electron transparency, charging-up and ion-backflow processes for the ALICE TPC upgrades, and their comparison with experimental data. Individual groups are very often motivated to engage themselves in accurate and, in some cases, very difficult measurements because of the presence of the large RD51 community as the end-user of their efforts.

3.3 Electronics

In the front-end electronics and data acquisition systems for MPGDs, detector-electronics integration (e.g. modern gaseous detectors with CMOS pixel readout), and discharge-protection strategies have been among the core missions of RD51.

Developments very specific to our technologies, easier access to otherwise very expensive instrumentation and a large community working with common hardware and software tools are part of motivations behind the RD51 electronics activities. The most prominent RD51 development is a basic multichannel readout system for MPGDs, the so-called Scalable Read-out System (SRS) [105](Fig. 9). It is an "easy-to-use" portable system from detector to data analysis, with read-out software that can be installed on a laptop for small laboratory setups. Its scalability principle allows systems of 100,000 channels and more to be built through the simple addition of more electronic SRS slices, and operated at very high bandwidth using the on-line software of the LHC experiments. The number of SRS systems deployed so far already exceeds 100, with more than 250,000 APV25 front-end channels. It is available through the CERN store or via the CERN Knowledge Transfer office, which also granted SRS reproduction licenses to several companies. Since 2013, SRS has been re-designed in the ATCA industry standard, allowing for much higher channel density and output bandwidth.

The LHC experiments - ATLAS, TOTEM and CMS - have been using SRS in-house prototypes in laboratory tests in the course of their upgrade projects. The front-end adapter concept of SRS represents another degree of freedom, because any sensor technology typically implemented in multichannel ASICs may be used. Originally designed to operate with APV25, nowadays, the system has been extended allowing implementation of three different ASICs on SRS hybrids as plug-ins for MPGDs: APV25, Timepix and VMM. Following this encouraging experience, SRS has been ported for the readout of photon detectors (ex. SiPMs of NEXT TPC) and tracking detectors (e.g. "InGrid" arrays for ILC TPC). The latter represents a real break-through development of a large-area MPGD with CMOS pixel ASIC allowing reaching the level of integration, compactness and resolving power typical of solid-state pixel devices.

The realization of customized and affordable laboratory instruments dedicated to MPGD developments is an additional support R&D tool. A number of instruments have been developed and are presently at different maturity stages; several of these projects have been supported by the EU AIDA 2020 project [106]. Among them:

- active power supply system, namely Active Voltage Divider (AVD), designed to match the requirements of MPGD architectures including multiple multiplication stages, presently available at prototype level;
- femto-ammeter, available in an initial version, while faster readout O(MHz), floating operation and bipolar capability are the planned further improvements;

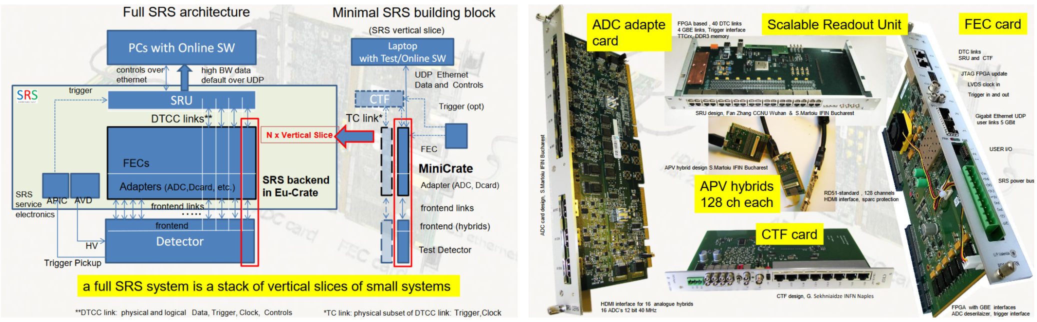

Figure 9: *Left: RD51 Scalable Readout System Architecture. Right: SRS Hardware components. [107].*

- RHIP system [108], where an array of cheap, fully floating pico-ammeters is read-out via radio connection;
- the APIC unit, a single channel readout unit including pre-amplification, shaper, discriminator, trigger options, presently a mature device ready for commercialization;
- a monitoring unit for environmental parameters (pressure, temperature, humidity), developed first in an Arduino-based version and, later, in a Raspberry-Pi-based version;
- a dedicated high voltage system under development to match MPGD requirements, presently not satisfied by commercial devices; it makes use of commercially available DC-to-DC converters and local intelligence, its design includes a sophisticated control allowing for a real-time voltage monitoring and current monitoring at the nA level, and performs voltage corrections for temperature and pressure changes.

3.4 Workshops

MPGD workshops: For nearly 20 years, the CERN Micro Pattern Technology (MPT) workshop has been a unique facility, where generic R&D, detector-components production and quality control take place; these allow advancing cost-effective MPGDs manufacturing and their production by industrial processes. Following trends in the large detector units, the RD51 collaboration, representing the needs of the community, proposed an extension of the workshop infrastructure, necessary to manufacture detectors with dimensions up to 2×1 m^2, more than doubling the maximum size of MPGDs produced at that time. Approved in 2009 by the CERN management, and promoted within AIDA [110] and by synergies between CERN and the RD51 community, the installation of new equipment

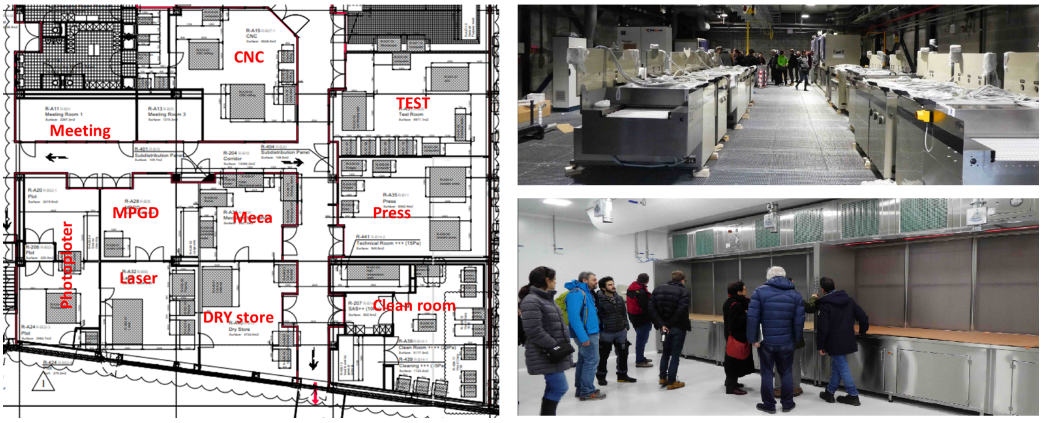

Figure 10: *New Micro Pattern Technology (MPT) workshop (building 107) of CERN EP-DT. [109]*

has been completed in 2012 in the old workshop premises. The new, high-tech equipped and up-to-date building will be fully used starting from the fall of 2018 (Fig. 10). This upgrade paved the road to very promising R&D on the large-area MPGD-based detectors, in a view of large-scale production in industry at a later stage. The current technological status has been attained thanks to the formidable competencies developed over the years, available in the workshop, and to the important support coming from the collaboration and the community. The available expertise is offering the possibility of producing application-tailored detectors and prototypes with a large variety of configurations and complexities, matching a broad range of physics requirements. Scaling up MPGD detectors, while preserving the typical properties of small prototypes, allowed the use of major MPGD technologies in the current upgrades of large experiments, e.g. that of the LHC. More robust solutions, implementing resistive materials and thin films in single-stage detectors, extended the range of possible applications. The expertise acquired in the past allowed the workshop to move to full detector production and assembly. With such a widespread dissemination, a technological transfer became essential. Different approaches have been followed, but in all the cases, the RD51 collaboration has been open to provide support when needed and whenever it had the necessary competencies. Nowadays, the CERN MPT workshop, in collaboration with RD51 and experiments that are using MPGDs on a large scale, serves as a reference point of contact for companies interested in MPGD manufacturing and helps them to reach the required level of competencies. Contacts with some have strengthened to the extent that they have signed license agreements and engaged in a technology-transfer program; more than 10 companies are already producing GEM, MM and THGEMs of reasonable sizes. While, the CERN MPT represents

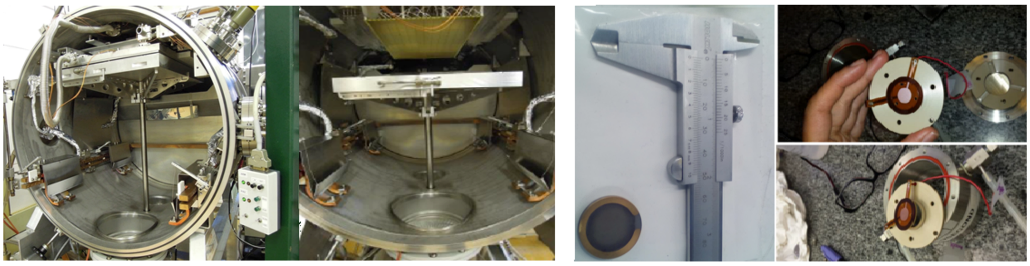

Figure 11: *Left: Large Area CsI Evaporator at the Thin Film and Glass (TFG) EP-DT workshop. The setup has bees used for CsI coating of ALICE HMPID RICH Detector and for the COMPASS THGEM based Upgrade. Right: CsI coating for precise and fast timing R&D with MPGD (PICOSEC project). [111]*

the major infrastructure used by the collaborators for technology advances, several other facilities have also been built. The MPGD workshop at IRFU/CEA Saclay represents another prominent example.

Thin-film and Glass laboratory at CERN: [112] In our community, more specifically in the context of gaseous photodetectors, an important role is played by thin-film coating laboratories capable of depositing photocathodes on detector electrodes. The EP-DT Thin-film and Glass laboratory at CERN (Fig. 11) is a good example. Large-area CsI photocathodes have been successfully produced for RICH detectors currently deployed at CERN (ALICE HMPID, COMPASS RICH-1 MPGD). A recent R&D project in RD51 requires CsI deposition for the development of fast and precise timing detectors. Successful results have been achieved in a short time [113] thanks to the availability of this facility and its long-standing expertise.

3.5 Common space and common test facilities

Common spaces have been prioritized by the collaboration because of their important role in the process of sharing knowledge and expertise. The CERN EP-DT Gaseous Detector Development (GDD) laboratory has been enlarged and modernized and is accessible to the whole RD51 community (Fig. 12). It is equipped with infrastructures, instrumentation and electronics needed for gaseous detector R&D, such as radioactive sources, X-rays generators, gas-mixing units, standard and flammable gases, etc. Clean rooms are accessible for assembly, modification and inspection of the detectors. It is the place where some common R&D activities are carried out by different groups and institutions, making use of both, permanent and dedicated temporary installations. All three major LHC upgrades, incorporating MPGDs, started their R&D in close contact with RD51, using dedicated setups at the GDD/RD51 laboratory.

A semi-permanent common test-beam infrastructure has been installed at the H4 test beam area at CERN's SPS for the needs of the RD51 community (see Fig. 13). The H4 area has the advantage that there is the "Goliath" magnet (around 1.5 T over a large area), allowing tests of MPGDs in a magnetic field. Collaboration members extensively use this facility for studying the performance of their new detectors. Three yearly periods, of two weeks each, have been always granted to RD51, with an average presence of four groups per period. It represents an efficient way of using the beam line. The presence of common test-beam infrastructure (e.g. high-precision beam telescopes, trigger detectors, HV control, DAQ, fiber optics lines, signal and Ethernet cables, stainless steel pipes, gas-distribution systems, etc.), eases installation and permits groups to rapidly start their experiments. Experience sharing and exchanges between groups is probably one of the most important and invaluable aspects of this common activity. The common GDD-RD51 laboratory provides important additional support, because it is located close to the test-beam area. Prototypes can be thoroughly scrutinized and tested before, during and after the beam campaign. The same argument is valid for the proximity of the Micro Pattern Technology Workshop. While the CERN common test facilities are the most valuable within the RD51 framework, each participating institute is willing to share facilities - thus creating a worldwide network of invaluable infrastructures. The extension of the collaboration will allow us to preserve the current framework and to enlarge possibly the existing support and network.

Figure 12: *CERN EP-DT-DD Gaseous Detector Developments (GDD) laboratory.*

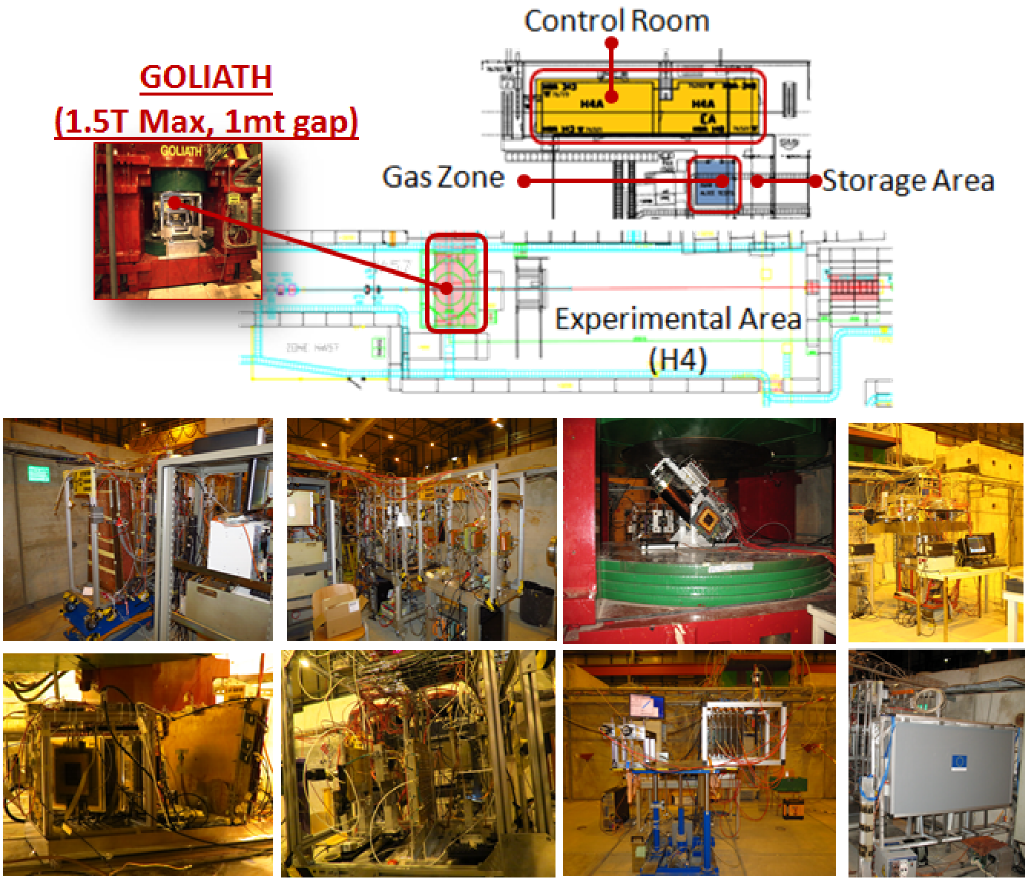

Figure 13: *Top: Layout of the semi-permanent test beam installation for RD51 in the SPS Extraction Lines of the North Area . Bottom: Several setups equipped in the H4 line during a test beam campaign.*

4 RD51 extension beyond 2018: the overall scope and objectives

Numerous MPGD developments and applications summarized above, carried within the framework of RD51, have demonstrated that the collaborative R&D and exchanges made within a large community of experts have led to a significant progress on all fronts over the past decade. Technological and scientific advances have led to improved detector performances - also when scaling up the new technologies to large-area detectors. This progress has been particularly crucial in HEP-experiments upgrades worldwide; examples were described above on the incorporation of GEM, MM, THGEM and their hybrid combinations in several large experiments. Also in the next years, a collaborative R&D phase and the right environment will have a strong impact on project-oriented activities - similarly to the current scenario where three of the major upgrades for the LHC experiments benefited from the RD51 framework. The RD51 collaboration has been playing a crucial role in this progress - boosting exchanges and cooperation within the community on both scientific and technological matters. Common facilities and availability of experts and expertise have greatly contributed to the very noticeable progress. Frequent meetings, workshops and conferences permitted educating a young generation of detector experts - in laboratories situated all over the world. It is of a prime importance to preserve the expertise that can be applied to other future detectors concepts. RD51 extension will permit further educational activities - paving the way towards a new, highly-motivated generation of young detector scientists. Moreover, the collaboration will play a crucial role in attracting diversified resources. CERN, collaborating institutions and projects contributions, industry, EU projects, project synergies are a few examples of possibilities for the community.

The better understanding of the physics processes, originating from experiment-validated model simulations, paved the way towards novel detector concepts. For example, higher granularities and rate capabilities, thinner detectors with embedded electronics, are expected to advance particle-flow based calorimetry (ILC-DHCAL) or high-precision tracking systems in high fluence environments. Fast and precise timing MPGDs are being developed for time tagging or filtering measurements, e.g. for high-luminosity colliders. Robust single-stage MPGD may pave the road to very large detection systems and civil imaging applications (e.g. radiography, homeland security); their industrial production would simplify the detector assembly procedures and possibly reduce the costs. High data-transfer bandwidth readout systems or optical readout can advance some potential applications. Hybrids detectors of combined technologies, e.g. gaseous and silicon, or gas and solid converter, can reach unprecedented performances. New concepts of charge and light sensing in noble-liquid detectors, may lead to progress in neutrino experiments and rare-event searches (e.g. Dark matter). Portable or sealed detectors would be obvious solutions to medical, cultural heritage, safety and security applications. Advanced materials and techniques can evolve into new sensitive or amplifying structures, extending the current detection sensitivities. This is just a partial list of fascinating R&D lines that MPGDs will see in the years to come.

4.1 R&D Program on Advanced MPGD Concepts

Resistive materials and architectures: originally introduced to improve space resolution, resistive materials and structures are another example where material science is very relevant to our field. Already used in several MPGD projects, resistive electrodes offer significant improvement in detector stability (discharge damping). It was shown that detectors with resistive anodes have led to several new structures incorporating single amplifying-stage MPGDs. Efforts will focus on the search for new resistive materials, with the right properties, radiation hardness and also the capability of operation under specific conditions (e.g. in dual-phase Ar and Xe detectors). New detector architectures will be investigated for efficiently damping eventual-discharge energy. DLC coating, originally introduced for the MSGC, is for instance at the base of the ongoing RWELL project: a single stage MPGD with single detector element. While different resistive-electrode architectures have been investigated, the proposed novelty is in design of more robust, easily-assembled and industrially-produced detector elements directly coming from the production process. The effects on large-area detector systems or for possible commercial use would be invaluable. For example, in the context of precision tracking at high rates, the ongoing Small-Pad MM project is proposing DLC coatings for resistive MM, with high-granularity pads (few square mm) readout. The proposed solution has been inspired by R&D activities of the ongoing RD51 SCREAM project with a goal to construct the first MPGD-based sampling calorimeter prototype using resistive MM and RPWELL (THGEM-based) as active elements. Resistive structures like the embedded resistor and the RPWELL have the unique features that the resistive layer can be segmented into pads (no crosstalk due to surface diffusion) and the avalanche charge is evacuated to ground over short distances and therefore quickly (short RC time-constant). Fast charge clearance prevents charge buildup in the avalanche region and preserves the intrinsic proportional response of MPGDs at high rate and/or to high energy deposits.

Fast and precise timing: Timing performances are often combined with other requirements, e.g. radiation hardness, spatial resolution and rate capabilities - imposing limits to technological choices. The PICOSEC project [113], supported by RD51, has recently achieved, in its prototype version, time resolutions of $\sim$25psec for MIPs; the detector combines Cherenkov radiator, CsI photocathode and a MM sensor. The interest expressed by the community and the spectrum of potential applications makes this project an excellent candidate for further R&D. It contains many aspects, common also to other detector concepts: among them, new converter and photosensitive materials, new fast-multiplier concepts, electronics, radiation hardness etc. This challenging project requires close interactions and synergies with other communities. Among them are Large Area Picosecond Photo-Detectors (LAPPD) [114] or FAST Fast Advanced Scintillator Timing [115]. Novel fast electronics will get high priority in this project. The current RD51 activities on electronics are proving how much a collaboration environment can make the difference (resources, teamed-up needs, exchange of information and competencies). Radiation-hard fast scintillators and adequate photocathodes will require interactions with experts in the fields. Common interests of course would be with gaseous-based photon detectors for RICH counters and more generally with developments of Gaseous-Photo-Multipliers (GPM). The R&D would necessitate the development of new strategies, new materials, new techniques and new architectures - expected to reduce, if not completely eliminate, the existing limitations. Entering such new fields of research will benefit from the existence of knowhow and expertise within our large collaboration.

New materials and technologies: material science is entering strongly in our field and can provide alternative MPGD materials, new structures, protection layers, etc. RD51 intends investigating MicroElectroMechanical Systems(MEMS)-like, nano-production techniques and 3D printing with conductive and insulating materials. The latter one could speed up particularly detector prototyping. The collaboration will create the proper environment for this type of developments, linking all members to the adequate infrastructures. Material studies for low out-gassing (contamination and aging), for longevity (radiation hardness), radio purity (rare events), efficiency (neutrons, photons), robust converters (single photons, UV), gas studies (eco-gases) will be a mandatory step to face. Previous experience (back to wires and MSGC) shows how in these kinds of studies a collaborative effort can offer good results in an efficient way. New knowledge has to be accumulated and the requested extension provides important support in this context. Low out-gassing materials would have impact on sealed detectors operation and that incorporating chemically unstable converters and photocathodes. Examples are: flame detection, radio protection, n-detection, medical applications, homeland security, space and cultural heritage (paintings, pyramids). The community's good background will be extended to cope with all the new possibilities.

Hybrid detectors: one characteristic property of current MPGDs is the hybridization capability, namely the combination of different multiplication concepts, where RD51 members have investigated a variety of hybrid solutions. Such hybridizations are linked to specific technological competencies acquired along the development phases. Hybrid detectors can offer improved avalanche-ion blocking: COMPASS-RICH as an example where CsI-coated photocathode, THGEM is followed by a MM multiplier. InGrid with the integration of MM on Timepix is another important example; it represents an ultimate performance for the ILC TPC: large MM signal, low noise, and extreme chip granularity. In the area of hybridization, several successful ongoing R&D projects are related to optical readout of gaseous detectors; among them - optical avalanche imaging, beam monitoring fluorescence, CT tomography, Compton camera and neutron detection, sensors for dual-phase TPCs. Current advances in digital cameras (CCD and CMOS in particular) are opening new possibilities of applications of low-cost, performing and ready to-use highly-pixelated readout systems. Even though high-resolution integrated imaging represents the most common case, event-by-event and energy-resolved acquisitions are important in some cases; an example is major interest

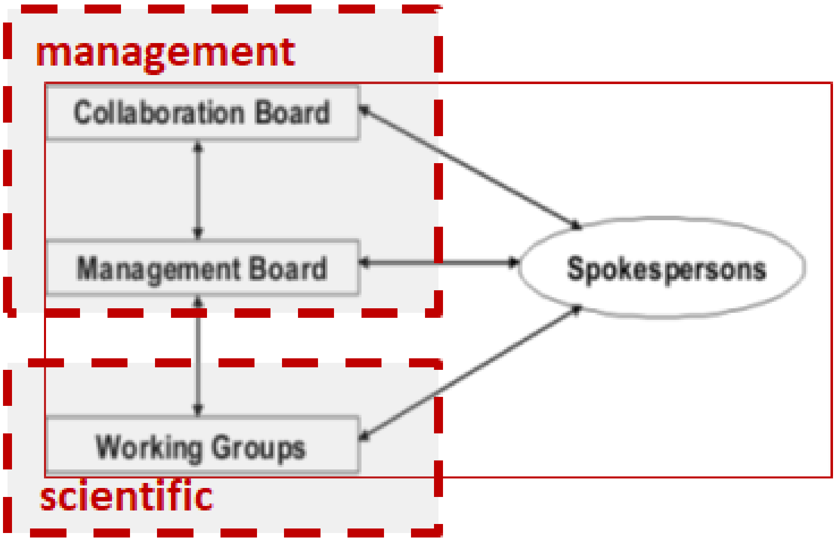

Figure 14: The internal organization of the RD51 Collaboration is schematically illustrated.

in TPC readout (rare events, nuclear physics). Here, hybrid design (charge and light detection) can be implemented, combining the time evolution of the induced signal with high-resolution 2D projection. In this application, future R&D will clearly follow new cameras developments, with improved sensitivity, faster acquisition and hopefully radiation-hard imagers - thus paving the way to a large number of possible new applications.

4.2 Support and Infrastructures

The collaboration is firmly interested on its extension for another five-year period to preserve and enrich the scenario presented in Sec. 3. The wide and international collaboration, built in the last ten years of activity, is eager to continue contributing to the community. Support to generic R&D, wide expertise in MPGD technologies, unbiased exchange of knowledge and information, sharing of efforts are a few example of natural motivation towards future activities of the existing community.

The collaboration plans to maintain the current organization (Fig. 14) and the existing structure based on the working groups (Fig. 15):

- WG1 - Technological Aspects and Development of New Detector Structures
- WG2 - Common Characterization and Physics Issues
- WG3 - Applications

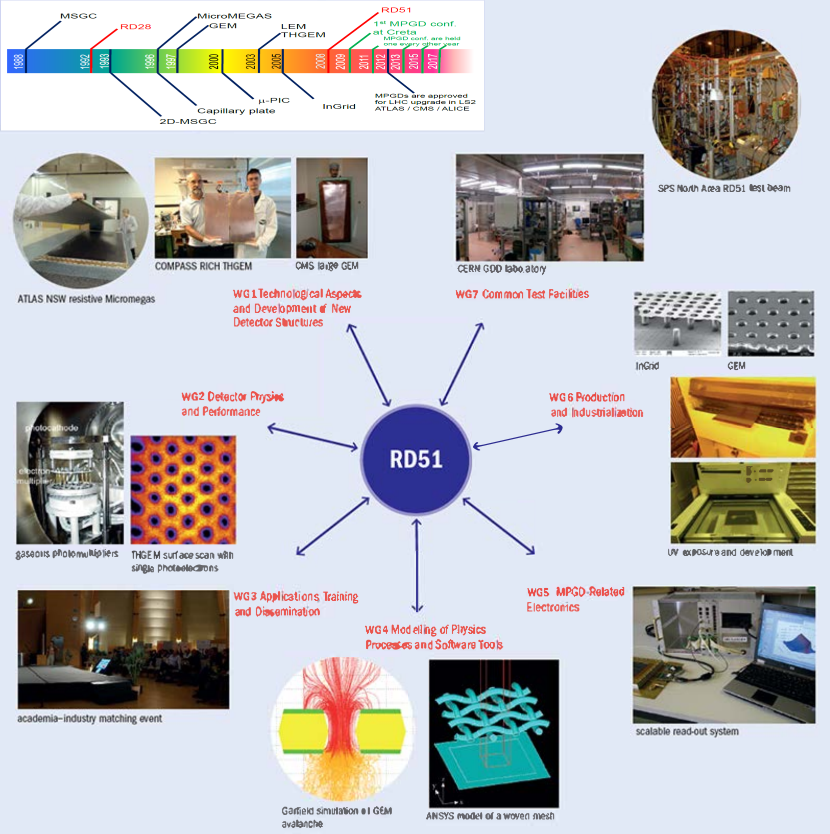

Figure 15: The seven working groups of RD51, with illustrations of just a few examples of the different kinds of work involved. Top left: the 20-year pre-history of RD51. Image credits: RD51 Collaboration. [6]

- WG4 - Simulations and Software Tools
- WG5 - MPGD Related Electronics
- WG6 - Production
- WG7 - Common Test Facilities

New important areas of expertise will be covered, in particular in the field of novel and future technologies. The current status of support and infrastructures described in section 3 will be discussed in this section looking forward to the extension of the collaboration.

Detector physics, simulations and software tools: have been introduced in section 3.2. Support of Garfield++ package, which allows detailed simulation of small-scale structures, represents an important patrimony of RD51; it is an invaluable tool not only for MPGDs, but also for gaseous and silicon detectors, in general. The RD51 prolongation will allow extending present modeling efforts to new and complex processes useful for the community. It will permit extending the existing network of developers and users, forming a new generation of young experts and thus strengthening the portfolio of available tools. The collaboration also aims at supporting emerging developments to provide better simulation methods to describe the physics processes in MPGD detectors. For example, microscopic tracking algorithms in Garfield++ were devised and have shed light on the effects of surface and space charge in GEMs, as well as on the transparency of MM meshes. The collaboration will support ongoing efforts on interfacing between different modeling tools, started since a few years within the RD51 community. The aim is to address properly and efficiently most of the involved processes at the microscopic level: primary ionization, transport and avalanche, ions and ions clustering, charging up and space charge, signal induction and discharges. GEANT4 [116], COMSOL [117] and SPICE [118] are just a few examples. Note that these complete simulation platforms are of invaluable importance in the process of reaching the limit of a technology and detector performances. Last, but not least, the extension will strongly support the presence of a core of experts available for developing, maintaining and transferring the existing knowledge.

Electronics: developments and detector-electronics integration advances have been described in section 3.3. RD51 has been strengthening its expertise in the electronics domain for MPGDs since its origin. The extension will allow us to move forward toward novel exciting activities, to maintain and enhance existing support and to keep active the existing community. The major success of the RD51 collaboration - the SRS architecture - will continue to be used as a non-expensive and open platform for small and medium-sized systems. Many groups continue contributing to the SRS hardware, firmware and software maintenance and the system has already extended beyond RD51. It will be upgraded with new additional features to satisfy the needs of new challenging applications and projects. Within the Horizon2020 projects BrightnESS and AIDA2020, RD51 has decided to implement the VMM ASIC developed by BNL for the ATLAS NSW upgrade. The SRS-VMM will become the backbone of R&D in MPGDs for the next decade and replace the successful, but discontinued, APV25-based readout, which drove the research within RD51 in the last eight years. The interface process, facilitated by the original SRS design and by the acquired expertise with the APV25, is ongoing. Input protection circuit, noise reduction, reading configuration and powering schemes are a few examples of the available know-how existing in RD51. Several groups have signed up to apply SRS-VMM in their experiments; e.g. for GEM-based readout at the NMX macromolecular diffractometer at the European Spallation Source. Another example originates from large-area, high granularity, pad readout detectors requiring proper readout solutions, where embedded electronics is an attractive possibility. This solution is feasible only if the know-how of properly integrating electronics and detector exists in the community. Challenging new developments will be also supported, such as the readout electronics for precise timing (tens of picoseconds) detection with MPGD. Front-end ASICs and SRS are clearly part of the new trends and there will be other developments and applications. RD51 will support these activities, improve testing capabilities, and contribute to reinvent mainstream technologies under a new paradigm of integration of electronics and detectors, as well as integration of functionality. The extension of the collaboration will allow our community to consolidate expertise, sustain the close interaction between electronics and detector experts, boost new developments and guarantee a general approach to satisfy a wider broader set of requests on detector-electronics integration, for a general use.

Workshops, novel technologies and material: The extension of the collaboration for the next term will allow strengthening ongoing collaborative partnerships between RD51 and Workshops; multidisciplinary collaboration is the stew in which creativity and innovation thrive. Synergies with the upgraded *MPT workshop* at CERN will continue to be further enhanced. One has to highlight the role played by the community to advance MPGD production, in view of not only the LHC upgrades, but also for the benefit of other physics programs performed worldwide and potential commercial applications that may arise. Novel detector structures, stimulated by the needs and inspired by the community, are produced on the basis of acquired technological and scientific knowhow. The outcome of performance studies, quality control, and rapid feedback to production-process tuning, are just a few examples of contributions. The latter provides proper evaluation of the maturity of the technology. The possibility of rapid prototyping to access new solutions and production processes, in conjunction with the possibility to go for small, if not single production, facilitates the transfer of new detector technologies towards applications. An extension of the RD51 collaboration will secure an open, mutually reviewed, widespread and unbiased exchange of information and play a crucial role for application of new techniques, processes and materials. *Thin-film Deposition Laboratories* : a large interest in new techniques and materials is growing in the community. The extension of RD51 for another five-years term would give an important support for preserving and possibly enlarging this expertise ; it will motivate other new challenging activities (e.g. improvement of photocathode lifetime in gaseous detectors). New and more robust photocathodes, secondary electron emitter, thin resistive or protection layers - are just a few examples of future activities of interest in our community. In this context, existing infrastructures and expertise are expected to grow in the field of material science and thin-film deposition, will play an important role for the new developments.*Material Science*: a prolongation of RD51 collaboration will allow directing efforts towards understanding and studying new detector-related materials and concepts. With sometimes unique and very peculiar properties, they might be good candidates for new and maybe exotic future developments in detection techniques. A wide range of possibilities can arise from these studies. For example, new types of radiation converters could enhance detection efficiencies; new amplifying structures could be eventually optimized (e.g. GEM made out of crystallized glass [119] or glass piggyback Micromegas [120]). Nanotechnologies are daily entering in various fields of science; one of the novel approaches is the study of the charge transfer properties through graphene deposited on electrodes in gaseous detectors [121]. Some research activities in the collaboration have been already directed into this new R&D. The collaboration would like to direct efforts in bringing and facilitating the flow of knowledge and expertise from other communities to ours.

Common space and common test facilities: the development of robust and efficient MPGDs entails the understanding of their performance and implies a significant investment for laboratory measurements and detector test-beam activities to study prototypes and qualify final designs, including integrated system tests. Therefore, maintenance of the GDD (CERN PH/DT) lab at CERN and test-beam facilities at H4 SPS extraction line plays a key role among the objectives of RD51. The extension of the collaboration will allow us to preserve the current framework and possibly enlarge the existing support and scientific network.

5 Requests to CERN

Since the initial period of RD51, namely since 2009, the support offered by CERN facilities has substantially contributed to the collaboration activities and achievements - without major impact on CERN resources. A similar support is requested for the next term; it consists of:

- access to the GDD lab space, infrastructure and maintenance support;
- office space and administrative support;
- maintenance of the semi-permanent setup at the SPS H4 test beam line and, correspondingly, access to the beams over several time periods for a total of six weeks per year;
- continuation of the collaborative access to the:
  - the EP-DT-EF MPT (Micro Pattern Technology) Workshop;
  - the EP-DT-EF TFG (Thin Film and Glass) Laboratory;

- access to other CERN technical facilities, in particular:
  - EP-DT-DD Bond Laboratory
  - TS-DEM-WS Electronics Assembly Workshop
  - EN-MME-MM Materials, Metrology & NDT
  - TE-VSC Surface treatment, coating and chemical analysis
  - the central computing resources for MPGD simulations.

The development of the next generation of MPGDs and, more in general, of ionizing particle detectors can largely profit of novel emerging technologies as those related to nanomaterials, MicroElectroMechanical Systems (MEMS), sputtering, novel photoconverters, 3-D printing options, as also tested within our planning for future R&D discussed in Sec. 4.1. It is expected that, both at CERN and within the R&D community, these new needs will result in the formation of synergies and networks between scientists devoted to detector R&D and groups and institutions mastering the novel technologies. In selected sectors, this process can also result in novel infrastructural resources at CERN. Therefore, RD51, while stimulating the community of the detector developers towards the exploration of the emerging technologies, require accessing the dedicated networks and possible future infrastructures. Furthermore, in a context of constructive synergies, RD51 is willing to offer support to the actions towards the dissemination of emerging technologies for detector developments and assembly.

References

[1] Oed, A. Position-sensitive detector with microstrip anode for electron multiplication with gases. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 263, 351-359 (1988).

[2] Sauli, F. GEM: A new concept for electron amplification in gas detectors. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 386, 531-534 (1997).

[3] Giomataris, Y. et al. MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environments. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 376, 29-35 (1996).

[4] Abbon, P. et al. The COMPASS experiment at CERN. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 577, 455-518 (2007).

[5] Alfonsi, M. et al. R&D Proposal, Development of Micro-Pattern Gas Detectors Technologies, CERN-LHCC-2008-011 / LHCC-P-001, 14 August 2008, `http://rd51-public.web.cern.ch/rd51-public/Documents/RD51Proposal\_21082008.pdf`

[6] Ropelewski, L. and Titov, M. RD51 and the rise of micro-pattern gas detectors, CERN Courier, 25 September 2015, `http://cerncourier.com/cws/article/cern/62507`.

[7] LARGE HADRON COLLIDER COMMITTEE, Minutes of the one-hundredth-and-fourteenth meeting held on Wednesday and Thursday, 12-13 June 2013, CERN/LHCC-2013-012 LHCC-114 12 June 2013.

[8] Alexopoulos, T. et al. A spark-resistant bulk-micromegas chamber for high-rate applications. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 640, 110-118 (2011).

[9] Kawamoto, T. et al. New Small Wheel Technical Design Report, 2013, CERN-LHCC-2013-006, ATLAS-TDR-020

[10] Villa, M. et al. Progress on large area GEMs. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 628, 182-186 (2011).

[11] Balla, A. et al. Construction and test of the cylindrical-GEM detectors for the KLOE-2 Inner Tracker. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 732, 221-224 (2013).

[12] Colaleo, A. et al. CMS Technical Design Report for the Muon Endcap GEM Upgrade, Jun 3, 2015, CERN-LHCC-2015-012, CMS-TDR-013.

[13] Ketzer, B. et al. Performance of triple GEM tracking detectors in the COMPASS experiment. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 535, 314-318 (2004).

[14] Bagliesi, M. G. et al. The TOTEM T2 telescope based on triple-GEM chambers. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 617, 134-137 (2010).

[15] Alfonsi, M. et al. High-rate particle triggering with triple-GEM detector. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 518, 106-112 (2004);
Alfonsi, M. et al. Status of triple GEM muon chambers for the LHCb experiment. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 581, 283-286 (2007).

[16] De Olivera,R. Fabrication techniques and industrialization of MPGDs, invited talk at Third Conference on Micro-Pattern Gaseous Detectors (MPGD2013), Zaragoza, Spain, 1-4 July 2013.

[17] ALICE Collaboration, Upgrade of the ALICE Time Projection Chamber, CERN-LHCC-2013-020 / ALICE-TDR-016, March 3, 2014.

[18] Periale, L. et al. Detection of the primary scintillation light from dense Ar, Kr and Xe with novel photosensitive gaseous detectors. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 478, 377-383 (2002);
Jeanneret, P. PhD thesis, Neuchatel University, 2001;
Barbeau, P. S. et al. Toward coherent neutrino detection using low-background micropattern gas detectors. IEEE Trans. Nucl. Sci. 50, 1285-1289 (2003);
Chechik, R. et al. GEM-like hole multipliers: properties and possible applications. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 535, 303-308 (2004).

[19] Peyaud, A. et al. ATLAS-NSW : sortie du premier prototype et début des tests sur banc cosmique 23 August 2017, `http://irfu.cea.fr/Phocea/Vie_des_labos/News/index.php?id_news=3563`

[20] Alexeev, M. et al. Status and progress of novel photon detectors based on THGEM and hybrid MPGD architectures. J. Instrum. 8, C12005-C12005 (2013).

[21] Alexopoulos, T. et al. Development of large size Micromegas detector for the upgrade of the ATLAS Muon system. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 617, 161-165 (2010).

[22] Garzia, I. et al. GEM detector performance with innovative micro-TPC readout in high magnetic field. EPJ Web Conf. 170, 01009 (2018).

[23] Merlin, J. Status of the GE1/1 production for CMS, RD51 mini week, 19-22 Feb 2018, CERN. `https://indico.cern.ch/event/702782/contributions/2894896/attachments/1603190/2542368/JMerlin\GE11\Production\Overview_20022018.pdf`

[24] Gasik, P. et al. School of ROC: A Workshop on Readout Chambers,27 May 2015, ALICE MATTERS `http://alicematters.web.cern.ch/?q=ALICE_TPC_GEMdetector`

[25] The upgrade of the largest gas detector in the world: the ALICE GEM-TPC project, Dense and Strange Hadronic Matter Physik-Department Technische Universität München. `https://www.denseandstrange.ph.tum.de/index.php?id=82`

[26] Llopart, X.et al. Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 581, 485-494 (2007).

[27] Chefdeville, M. et al. An electron-multiplying Micromegas grid made in silicon wafer post-processing technology. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 556, 490-494 (2006).

[28] Koppert, W. J. C. et al. GridPix detectors: Production and beam test results. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 732, 245-249 (2013).

[29] Llopart, X. et al. First test measurements of a 64k pixel readout chip working in single photon counting mode. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 509, 157-163 (2003).

[30] Murtas, F. GEMPIX Detector `https://web2.infn.it/GEMINI/index.php/gempix-detector`.

[31] Curioni, A. et al. Measurements of 55 Fe activity in activated steel samples with GEMPix. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 849, 60-71 (2017).

[32] Veloso, J. F. C. A. et al. A proposed new microstructure for gas radiation detectors: The microhole and strip plate. Rev. Sci. Instrum. 71, 2371-2376 (2000);
Lyashenko, A. V et al. Further progress in ion back-flow reduction with patterned gaseous hole-multipliers. J. Instrum. 2, P08004-P08004 (2007).

[33] Lyashenko, A. et al. Efficient ion blocking in gaseous detectors and its application to gas-avalanche photomultipliers sensitive in the visible-light range. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 598, 116-120 (2009).

[34] Bencivenni, G. et al. The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD. J. Instrum. 10, P02008-P02008 (2015).

[35] Bressler, S. et al. Beam studies of novel THGEM-based potential sampling elements for Digital Hadron Calorimetry. J. Instrum. 8, P07017-P07017 (2013).

[36] Bouclier, R. et al. New observations with the gas electron multiplier (GEM). Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 396, 50-66 (1997).

[37] Brunbauer, F. M. et al. Live event reconstruction in an optically read out GEM-based TPC. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 886, 24-29 (2018).

[38] Bondar, A. et al. Geiger mode APD performance in a cryogenic two-phase Ar avalanche detector based on THGEMs. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 628, 364-368 (2011).

[39] Alexeev, M. et al. The MPGD-based photon detectors for the upgrade of COMPASS RICH-1. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 876, 96-100 (2017).

[40] Ochi, A. et al. A new design of the gaseous imaging detector: Micro Pixel Chamber. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 471, 264-267 (2001).

[41] Bellini, V. et al. GEM tracker for high luminosity experiments at the JLab Hall A. J. Instrum. 7, C05013-C05013 (2012)..

[42] Basile, E. et al. Production status of the JLAB Hall-A GEM and Si μ strip Tracker. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 718, 429-431 (2013).

[43] BigBite Spectrometer Web Page, Jefferson Lab. `http://hallaweb.jlab.org/equipment/BigBite/`.

[44] Gasparian, A. et al., High Precision Measurement of the Proton Charge Radius, July 5, 2011, Proposal to Jefferson Lab PAC-38.

[45] Amarian, M. et al. The Structure of the Free Neutron at Large x-Bjorken, 2006, Research Proposal to Jefferson Lab (PAC 36).

[46] Anderson, W. et al. Design, construction, operation and performance of a Hadron Blind Detector for the PHENIX experiment. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 646, 35-58 (2011).

[47] sPHENIX Collaboration, sPHENIX preConceptual Design Report, Oct 27, 2015. `http://inspirehep.net/record/1500630/files/access.pdf`.

[48] Adeva, B. et al. DIRAC: A high resolution spectrometer for pionium detection. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 515, 467-496 (2003).

[49] Hott, T. MSGC development for the Inner Tracker of HERA-B. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 408, 258-265 (1998).

[50] Aune, S. et al. Performance of the micromegas detector in the CAST experiment. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 573, 38-40 (2007).

[51] Amoroso, A. et al. A cylindrical GEM detector with analog readout for the BESIII experiment. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 824, 515-517 (2016).

[52] Aune, S. et al. Micromegas tracker project for CLAS12. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 604, 53-55 (2009).

[53] Posik, M. et al. Barrel MicroMegas and Forward Triple-GEM, EIC User's Meeting, Stony Brook, New York, USA, 2014.

[54] Behnke, T. et al. A novel self-supporting GEM-based amplification structure for a Time Projection Chamber at the ILC. J. Instrum. 8, P12009-P12009 (2013).

[55] Colas, P. et al., Tests of a new anode resistive coating for a Micromegas TPC, MPGD2015, Trieste.

[56] Hartjes, F. et al. Test beam studies of the GasPixel transition radiation detectorprototype. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 706, 59-64 (2013).

[57] Adloff, C. et al. Test in a beam of large-area Micromegas chambers for sampling calorimetry. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 763, 221-231 (2014).

[58] White, A. Development of GEM-based Digital Hadron Calorimetry using the SLAC KPiX chip. J. Instrum. 5, P01005-P01005 (2010).

[59] Moleri, L. et al. The Resistive-Plate WELL with Argon mixtures âĂŞ A robust gaseous radiation detector. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 845, 262-265 (2017).

[60] Cortesi, M. et al. Operation of a THGEM-based detector in low-pressure Helium. J. Instrum. 10, P02012-P02012 (2015).

[61] Heffner, M. et al. A time projection chamber for high accuracy and precision fission cross-section measurements. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 759, 50-64 (2014).

[62] Cantini, C. et al. Recent R&D results on LAr LEM TPC and plans for LBNO demonstrators. J. Phys. Conf. Ser. 650, 012011 (2015).

[63] Trzaska, W. H. et WA105-Collaboration, LBNO-DEMO (WA105): a large demonstrator of the Liquid Argon double phase TPC, PhotoDet2015, 4th International Conference on New Photo-detectors (pp. 054).

[64] Bondar, A. et al. Two-phase Cryogenic Avalanche Detectors with THGEM and hybrid THGEM/GEM multipliers operated in Ar and Ar+N 2. J. Instrum. 8, P02008-P02008 (2013).

[65] L. Arazi et al., First results of a large-area cryogenic gaseous photomultiplier coupled to a dual-phase liquid xenon TPC, JINST 10, P10020 (2015).

[66] Erdal, E. et al. First demonstration of VUV-photon detection in liquid xenon with THGEM and GEM-based Liquid Hole Multipliers. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 845, 218-221 (2017).

[67] Chen, X. et al. PandaX-III: Searching for neutrinoless double beta decay with high pressure 136Xe gas time projection chambers. Sci. China Physics, Mech. Astron. 60, 061011 (2017).

[68] Ikeda, T. et al. Study of Negative-Ion TPC Using μ-PIC for Directional Dark Matter Search. EPJ Web Conf. 174, 02006 (2018).

[69] Armengaud, E. et al. Conceptual design of the International Axion Observatory (IAXO). J. Instrum. 9, T05002-T05002 (2014).

[70] Iguaz, F. J. et al. TREX-DM: a low-background Micromegas-based TPC for low-mass WIMP detection. Eur. Phys. J. C 76, 529 (2016).

[71] Andreas, S. et al. Proposal for an Experiment to Search for Light Dark Matter at the SPS, arXiv:1312.3309 [hep-ex].

[72] Raggi, M. et al. The PADME experiment at LNF. EPJ Web Conf. 96, 01025 (2015).

[73] Hansen, T. C. et al. The D20 instrument at the ILL: a versatile high-intensity two-axis neutron diffractometer. Meas. Sci. Technol. 19, 034001 (2008).

[74] Esposito, B. et al. Design of a GEM-based detector for the measurement of fast neutrons. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 617, 155-157 (2010).

[75] Albani, G. et al. Evolution in boron-based GEM detectors for diffraction measurements: from planar to 3D converters. Meas. Sci. Technol. 27, 115902 (2016).

[76] Morishima, K. et al. Discovery of a big void in KhufuâĂŹs Pyramid by observation of cosmic-ray muons. Nature 552, 386-390 (2017).

[77] Academy Industry Matching Events
https://indico.cern.ch/category/3634/

[78] http://heptech.web.cern.ch/.

[79] Neutron Detection with Micro-Pattern Gaseous Detectors, 14-15 October 2013, CERN https://indico.cern.ch/event/265187/.

[80] Second Special Workshop on Neutron Detection with MPGDs, 16-17 March 2015, CERN, https://indico.cern.ch/event/365840/

[81] Special Workshop on Photon Detection with MPGDs, 10-11 June 2015, CERN, https://indico.cern.ch/event/392833/

[82] CERN Technology brief: Optical readout system for gas-based detectors.

[83] MPGD2009, Crete, Greece, https://indico.cern.ch/event/51279/.

[84] MPGD2011, Kobe, Japan, http://ppwww.phys.sci.kobe-u.ac.jp/~upic/mpgd2011/.

[85] MPGD2013, Zaragoza, Spain, http://gifna.unizar.es/mpgd13/index.php/component/content/?view=featured.

[86] MPGD2015, Trieste, Italy, http://mpgd2015.ts.infn.it/.

[87] MPGD2017, Philadelphia, USA, https://indico.cern.ch/event/581417/ .

[88] RD51 Training
`http://rd51-public.web.cern.ch/RD51-Public/Meetings/TrainingSessions.html`

[89] RD51 Open Lectures: Signal generation, modelling and processing, 11-15 December 2017, CERN `https://indico.cern.ch/event/676702/`

[90] RD51 Electronics School, Feb 3-5, 2014, CERN `https://home.cern/images/2014/02/rd51-electronics-school`, `https://indico.cern.ch/event/283113/`

[91] RD51 Simulation School, Jan. 19-21, 2011, CERN, `http://indico.cern.ch/conferenceDisplay.py?confId=110634`

[92] GEM and Micromegas detector design and assembly training, Feb. 17-20, 2009, CERN `http://indico.cern.ch/conferenceDisplay.py?confId=50797`, `http://indico.cern.ch/conferenceDisplay.py?confId=52462`

[93] RD51 Precise Timing Workshop, RD51 Topical Workshop, 22-23 Feb 2017, CERN, `https://indico.cern.ch/event/607147/timetable/`

[94] Resistive electrodes, RD51 Topical Workshop, RD51 Mini-Week 7-9 Dec 2015, CERN, `https://indico.cern.ch/event/457639/`

[95] Calorimetry with MPGD (WG1 session), RD51 Topical Workshop, RD51 mini week 8-11 Dec 2014, CERN, `https://indico.cern.ch/event/356113/timetable/?view=standard`

[96] RD51/ALICE-TPC workshop, RD51 Topical Workshop, 18 June 2014, CERN, `https://indico.cern.ch/event/323839/timetable/?view=standard`

[97] RD51 Internal Notes, `https://espace.cern.ch/test-RD51/RD51\%20internal\%20notes/Forms/AllItems.aspx`

[98] RD51 Collaboration, Development of Micro-Pattern Gas Detectors Technologies. `http://rd51-public.web.cern.ch/RD51-Public`

[99] Veenhof, R. Garfield - simulation of gaseous detectors,
`http://garfield.web.cern.ch/garfield/`

[100] Smirnov, I. HEED - High Energy Electro Dynamics, `http://ismirnov.web.cern.ch/ismirnov/heed/`

[101] Biagi, S. Degrad - cluster size distribution and primary cluster distribution in gas mixtures for minimum ionising particles and X-rays, `http://magboltz.web.cern.ch/magboltz/`

[102] Biagi, S. Magboltz - Boltzmann transport equations for electrons in gas mixtures under the influence of electric and magnetic fields, `http://magboltz.web.cern.ch/magboltz/`

[103] Şahin, Ö. et al. High-precision gas gain and energy transfer measurements in Ar-CO 2 mixtures. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 768, 104-111 (2014).

[104] Mukhopadhay, S. et al. neBEM - A nearly exact Boundary Element Method, `http://nebem.web.cern.ch/nebem/`

[105] Martoiu, S. et al. Development of the scalable readout system for micro-pattern gas detectors and other applications. J. Instrum. 8, C03015-C03015 (2013).

[106] AIDA-2020, Advanced European Infrastructures for Detectors at Accelerators, `http://aida2020.web.cern.ch/`

[107] Muller, H. SRS systems from APV to VMM, RD51 mini week, 19-22 Feb 2018, `https://indico.cern.ch/event/676702/contributions/2818988/attachments/1575628/2488041/From_APV_to_VMM_frontends.pdf`

[108] Bari, M. et al. RHIP, a Radio-controlled High-Voltage Insulated Picoammeter and its usage in studying ion backflow in MPGD-based photon detectors, 5th International Conference on MPGDs, MPGD2017, Philadelphia, USA, 22-26 July 2017.

[109] De Oliveira, R. RD51 mini week, 19-22 Feb 2018, CERN, `https://indico.cern.ch/event/702782/contributions/2898910/attachments/1604103/2544241/2018-RD51-Building_107.pdf`

[110] AIDA, Advanced European Infrastructures for Detectors at Accelerators, `https://aida-old.web.cern.ch/aida-old/index.html`

[111] Danielsson, H. EF Section, DT Group Meeting, 1 Nov 2016, CERN. `https://indico.cern.ch/event/569467/contributions/2302612/attachments/1364146/2065846/meeting_1_11_20162.pdf`

[112] CERN EP-DT-EF Detector Technologies Thin Film and Glass (TFG) Laboratory, `https://ep-dep-dt.web.cern.ch/thin-film-glass-service/thin-film-lab`

[113] Bortfeldt, J. et al. PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector, arXiv:1712.05256 [physics.ins-det] `https://arxiv.org/abs/1712.05256`.

[114] Large-Area Picosecond Photo-Detectors Project `https://psec.uchicago.edu/`

[115] Fast Advanced Scintillator Timing `http://fast-cost.web.cern.ch/fast-cost/`

[116] GEANT4, `http://geant4.web.cern.ch/`

[117] COMSOL Multiphysics - finite element analysis, solver and multiphysics simulation software, `https://www.comsol.com/`

[118] SPICE - Simulation Program with Integrated Circuit Emphasis, `https://en.wikipedia.org/wiki/SPICE`

[119] Takahashi, H. et al. Development of a glass GEM. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 724, 1-4 (2013).

[120] Attié, D. et al. A Piggyback resistive Micromegas. J. Instrum. 8, P05019-P05019 (2013).

[121] Franchino, S. et al. Charge transfer properties through graphene for applications in gaseous detectors. Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 824, 571-574 (2016).