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R & D Proposal

Development of Micro-Pattern Gas Detectors Technologies

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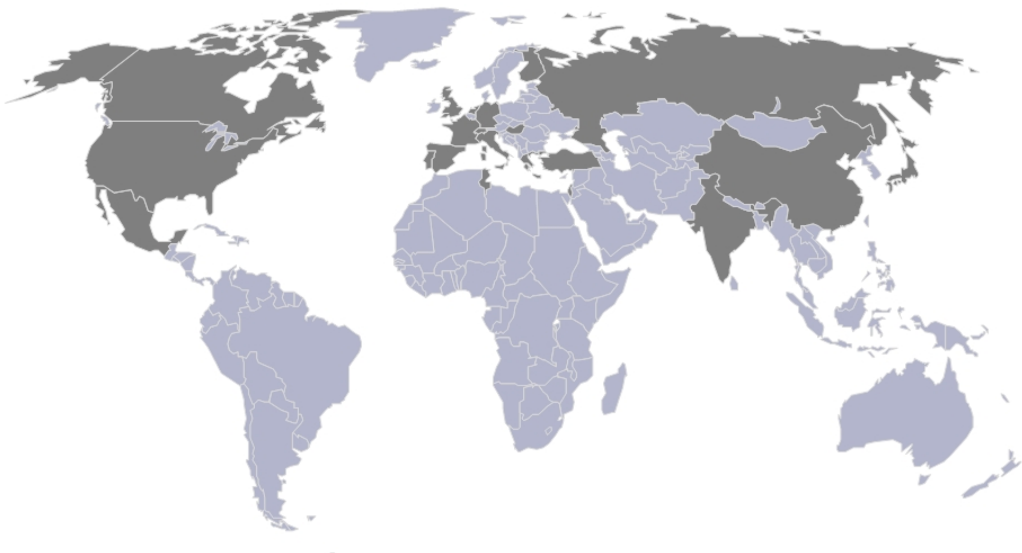

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I. Executive Summary

The proposed R&D collaboration, RD51, aims at facilitating the development of advanced gas-avalanche detector technologies and associated electronic-readout systems, for applications in basic and applied research.

Advances in particle physics have always been enabled by parallel advances in radiation-detector technology. Radiation detection and imaging with gas-avalanche detectors, capable of economically covering large detection volumes with a low material budget, have been playing an important role in many fields. Besides their widespread use in particle-physics and nuclear-physics experiments, gaseous detectors are employed in many other fields: astro-particle research and applications such as medical imaging, material science, and security inspection.

While extensively employed at the LHC, RHIC, and other advanced HEP experiments, present gaseous detectors (wire-chambers, drift-tubes, resistive-plate chambers and others) have limitations which may prevent their use in future experiments. Present techniques will not be capable of coping with the expected high-flux and high-repetition rates, and often will not provide the needed space point resolution. For example, point resolution in large-volume TPCs based on wire read-out will suffer from high fluxes of back-flowing ions and from the limited granularity of the readout; particle-trackers will not withstand the high fluxes and will require large-area high-resolution localization; calorimeters will need better and faster sampling elements; Cherenkov detectors in particle and astro-particle experiments will require more efficient and robust large-area photon detectors; rare-event cryogenic noble-liquid detectors for dark-matter, neutrino-physics double-beta decay and other searches will require large-volume detectors with adequate economic low-radioactivity readout elements. Besides resolutions - radiation hardness, rate capability and economic aspects related to production costs are of major concern.

The possibility of producing micro-structured semi-conductor devices (with structure sizes of tens of microns) and corresponding highly integrated readout electronics led to the success of semi-conductor (in particular silicon) detectors to achieve unprecedented space-point resolution. Micro-structured gas-amplification structures now open the possibility to apply the same technology to gaseous detectors and enable a plethora of new detector concepts and applications.

The invention of Micro-Pattern Gas Detectors (MPGD), in particular the Gas Electron Multiplier (GEM), the Micro-Mesh Gaseous Structure (Micromegas), and more recently other micro pattern detector schemes, offers the potential to develop new gaseous detectors with unprecedented spatial resolution, high rate capability, large sensitive area, operational stability and radiation hardness. In some applications, requiring very large-area coverage with moderate spatial resolutions, more coarse Macro-patterned detectors, e.g. Thick-GEMs (THGEM) or patterned resistive-plate devices could offer an interesting and economic solution. The design of the new micro-pattern devices appears suitable for industrial production. In addition, the availability of highly integrated amplification and readout electronics allows for the design of gas-detector systems with channel densities comparable to that of modern silicon detectors. Modern wafer post-processing allows for the integration of gas-amplification structures directly on top of a pixelized readout chip. Thanks to these recent developments, particle detection through the *ionization of gas* has large fields of application in future particle, nuclear and astro-particle physics experiments with and without accelerators.

We propose the formation of a world-wide collaboration, RD51, for R&D on MPGDs aiming at efficient coordinated effort to advance the development of MPGDs and associated technologies. The RD51 collaboration involves 298 authors, 57 Universities and Research Laboratories from 21 countries in Europe, America, Asia and Africa. All partners are already actively pursuing either basic- or application-oriented R&D involving a variety of MPGD concepts. The collaboration will establish common goals, like experimental and simulation tools, characterization concepts and methods, common infrastructures at test beams and irradiation facilities, and methods and infrastructures for MPGD production. An intensified communication between the cooperating teams will be fostered in order to better understand and solve basic and technical issues and to solve common problems connected e.g. to detector optimization, discharge protection, ageing and radiation hardness, optimal choice and characterization of gas mixtures and component materials, availability of adequate simulation tools, optimized readout electronics and readout integration with detectors, as well as detector production aspects.

Summarizing, the main objective of the R&D programme is to advance technological development and application of Micropattern Gas Detectors.

The proposed research is organized in 7 working groups (WG) each being structured through a set of tasks. Working-group conveners will coordinate the R&D tasks of the respective working groups. They will nominate responsible persons for each individual task; they will be also responsible for proper communication between their working-group members and with other working groups.

The 7 working groups are shown in Table 1. Their overall objectives and tasks are summarized below.

Technological Aspects and Development of New Detector Structures (WG1): The objectives of this WG are both the optimization of fabrication methods for MPGDs and the development of new multiplier geometries and techniques. These objectives are pursued via selected tasks: (1) Development of techniques to manufacture large area modules with reduced material budget and minimum dead regions; new materials, including low-radioactivity ones for rare-event detectors; (2) Design optimization including fabrication procedures and the development of new MPGD geometries for bulk Micromegas, micro bulk Micromegas and single-mask GEMs, Thick GEMs (THGEM), Resistive Electrode Thick GEMs (RETGEM), Micro-Patterned Resistive Plate Chambers (MPRPC), Micro Hole And Strip Plates (MHSP), charge-dispersive readout and integration of gas-amplification structures on top of a CMOS readout chip by wafer post-processing (InGrid); (3) Development of radiation-hard detectors; and (4) Design of portable sealed detectors.

Common Characterization and Physics Issues (WG2): In this WG, a common effort towards the development of common standards for the characterization and comparison of different technologies will be made. The collective knowledge on the physics of discharges in MPGD detectors will be bundled and solutions towards more efficient prevention of and protection against discharge will be made. Systematic studies on ageing and radiation hardness of MPGDs will be performed and a common database on radiation hardness and ageing properties of materials will be created in order to arrive at radiation-hard detectors capable of operating beyond the limits of present devices. The tasks in the WG are: (1) Development of common test standards (comparison of different technologies in different laboratories); (2) Discharge studies and spark-protection developments for MPGDs; (3) Generic aging and material radiation-hardness studies (creation of database of "radiation-hard" materials & detectors depending on application, commercially available materials, cleanliness requirements, validation tests for final detector modules, gas system construction, working remedies); (4) Charging up (gain stability issues) and rate capability; (5) Study of avalanche statistics: exponential versus Polya (saturated-avalanche mode).

RD51 – Micropattern Gas Detectors	WG1 MPGD Technology & New Structures	WG2 Characterization	WG3 Applications	WG4 Software & Simulation	WG5 Electronics	WG6 Production	WG7 Common Test Facilitites
Objectives	Design optimization Development of new geometries and techniques	Common test standards Characterization and understanding of physical phenomena in MPGD	Evaluation and optimization for specific applications	Development of common software and documentation for MPGD simulations	Readout electronics optimization and integration with MPGD detectors	Development of cost-effective technologies and industrialization	Sharing of common infrastructure for detector characterization
Tasks	Large Area MPGDs Design Optimization New Geometries Fabrication Development of Rad-Hard Detectors Development of Portable Detectors	Common Test Standards Discharge Protection Ageing & Radiation Hardness Charging up and Rate Capability Study of Avalanche Statistics	Tracking and Triggering Photon Detection Calorimetry Cryogenic Detectors X-Ray and Neutron Imaging Astroparticle Physics Appl. Medical Applications Synchrotron Rad. Plasma Diagn. Homeland Sec.	Algorithms Simulation Improvements Common Platform (Root, Geant4) Electronics Modeling	FE electronics requirements definition General Purpose Pixel Chip Large Area Systems with Pixel Readout Portable Multi-Channel System Discharge Protection Strategies	Common Production Facility Industrialization Collaboration with Industrial Partners	Testbeam Facility Irradiation Facility

Tab.1: Working groups of RD51.

Applications (WG3): Several applications impose specific new requirements and challenges on the production and properties of MPGDs. While the development of the applications itself is carried out in the individual laboratories, the collaboration will collect the requirements coming from these specific applications. The individual tasks are structured according to these applications: (1) MPGD based detectors for tracking and triggering; (2) MPGD based Photon Detectors (e.g. for RICH); (3) Applications of MPGD based detectors in Calorimetry; (4) Cryogenic Detectors for rare events; (5) X-ray and neutron imaging (6) Astroparticle physics applications; (7) Medical imaging and diagnostics applications; (8) Synchrotron Radiation, Plasma Diagnostics and Homeland Security applications.

Simulations and Software Tools (WG4): In this WG, a common, open-access, maintainable software suite for the simulation of MPGD detectors will be developed. The existing tools for the simulation of primary ionization, transport and gas amplification will be extended, in particular to improve the modeling at very small scales. An effort will be made in order to integrate the tools into the Geant 4 package to make them easier to maintain and directly applicable within arbitrary geometry and field configurations. Also the modeling of the electronics response to the detector signals has to be improved. This will also make the simulation applicable to systems with very high granularity such as CMOS pixel readout. The tasks are: (1) Development of algorithms (in particular in the domain of very small scale structures); (2) Simulation improvements; (3) Development of common platform for detector simulations (integration of gas-based detector simulation tools to Geant 4, interface to ROOT); and (4) Development of simplified electronics modeling tools.

MPGD related electronics (WG5): The availability of highly integrated electronics systems for the charge readout of high granularity MPGD systems poses a non-trivial problem to many of the modern MPGD applications. The specifications of such systems for the different fields of application will be collected. For the classical configuration of charge collecting pads or strips an easy-to-use portable readout solution will be developed. Ultimate granularity is achieved by using the inputs of a CMOS pixel readout chip directly as a charge collecting anode. The specifications of such a readout chip will be worked out and a common effort will be made towards a next-generation pixel chip for MPGD readout. The tasks are: (1) Definition of front end electronics requirements for MPGDs; (2) Development of general purpose pixel chip for active anode readout; (3) Development of large area detectors with pixel readout; (4) Development of portable multichannel data acquisition systems for detector studies; and (5) Discharge protection strategies.

Production (WG6): In this working group cost-effective, industrial technology solutions will be developed and transferred to industry. A common "production facility" based on the MPGD workshop at CERN will be developed and maintained and procedures for industrialization will be set up. The tasks are: (1) Development and maintenance of a common production facility; (2) MPGD production industrialization (quality control, cost-effective production, and large-volume production), (3) Collaboration with Industrial Partners.

Common Test Facilities (WG7): The development of robust and efficient MPGDs entails the understanding of their fundamental properties and performance at several stages of their development. This implies a significant investment for detector test beam activities to perform the R&D needed, to test prototypes and to qualify final detector system designs, including integrated system tests. The measurements in test-beam facilities cover efficiencies, noise, time, position and energy resolutions - basically all the critical performance parameters for new detector systems. Additionally, characterization of specific detector behaviors operated in large particle background demands some targeted aging tests in irradiation facilities. A common effort in this direction is needed because the number of groups involved in MPGD development has grown very significantly and will still do so during the coming years. As members of the RD-51 collaboration, research groups will get easier access to the facilities inside RD-51 collaborating institutes and at CERN, and, most important, share resources, make common requests and group experiments. The two tasks are (1) Development and maintenance of common "Test-Beam Facility"; and (2) Development and maintenance of common "Irradiation Facility".

Organizational Issues: The deciding body for all organizational and scientific matters of the RD51 collaboration is the collaboration board (CB). It will be formed of representatives of all cooperating institutions. The CB will elect its Management Board (MB), its chair and deputy and the spokesperson and his/her deputy. The MB and Spokespersons will nominate the working-group conveners. Details of the collaboration organization will be defined by the CB.
The conveners of the working groups will initiate frequent electronic communications and regular meetings with their respective task-leaders, group members and other WG conveners. Common matters will be regularly discussed among conveners and members of the RD51 Management Board (MB). General communication and discussion of the results and of future plans will be maintained through annual meetings.

A common website for collection and information of both organizational and scientific matters is set up (https://espace.cern.ch/test-RD51/default.aspx). The initial work plan of the collaboration is estimated to cover 5 years.

A common fund will be created by small annual contributions of the partners; it will be devoted mainly to organizational matters. Larger investments, however, will remain with the individual collaboration partners and their funding agencies. Sub-groups of the collaboration may make common investments to achieve their scientific goals.

This proposal is structured as follows: In Section 2, an overview about the state-of-the-art of MPGDs and their fields of application is provided. In Section 3, the work plan within the 7 working groups is outlined. Section 4 deals with organizational issues and Section 5 describes the resources and infrastructures. Section 6 provides an overview of the collaboration partners, their fields of expertise, and contribution to the collaboration.

II. Current Trends in Micro-Pattern Gas Detectors

II-A. Summary of MPGD Technologies and Experimental Results (introduction, design principles and outline of MPGD performances)

Modern photo-lithographic technology has enabled series of inventions of novel MPGD concepts: Micro-Strip Gas Chamber (MSGC), GEM, Micromegas and many others [1], revolutionizing cell size limits for many gas detector applications. The MSGC, a concept invented in 1988 by A. Oed [2], was the first of the microstructure gas detectors. Consisting of a set of tiny metal strips laid on a thin insulating substrate, and alternatively connected as anodes and cathodes, the MSGC turned out to be easily damaged by discharges induced by heavily ionizing particles and destroying the fragile electrode structure [3]. The more powerful GEM and Micromegas concepts fulfill the needs of high-luminosity colliders with increased reliability in harsh radiation environments. By using smaller basic cell size compared to classical gas counters, these detectors offer intrinsic high rate capability (fine pitch and fast collection of positive ions) [4], [5], excellent spatial resolution (~30 µm) [6], [7], and single photoelectron time resolution in the nanosecond range [8], [9].

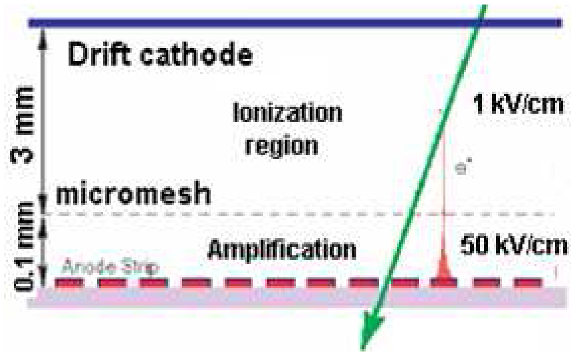
Micromegas

Micromegas (Micromesh gaseous detector) detector was invented in 1995 by I. Giomataris et al.[10]. The gas volume is split in two regions by a thin micromesh, held at a negative potential of a few hundred volts and sustained at a distance of a few tens to one or two hundred microns from an anode. To preserve a distance between the anode and the grid mesh, spacers from insulating material are used. In the region above the mesh, called the conversion or ionization region, the primary electrons are produced by the conversion of x-rays or by ionization from a charged track. The field in this region ranges generally between 10 V/cm and one or two kV/cm, fixed by the voltage imposed on a drift cathode closing this volume. The thickness of this region ranges from a few mm for detection of normally incident tracks, to a few meters in the case of a TPC. The liberated electrons drift towards the mesh, which they pass with a high efficiency thanks to the funnel shape of the field lines. In the lower region, between the mesh and the anode, high fields of several tens of kV/cm provide multiplication to these ionization electrons. The electric field is homogeneous both in the drift and amplification gaps. Due to the narrow amplification region in Micromegas, locally small variations of the amplification gap are compensated by an inverse variation of the amplification coefficient and therefore do not induce gain fluctuations.

This very simple concept has many advantages: a very low material budget, only two moderate-voltages suffice to operate it, a very fast electron signal and an efficient and fast ion collection due to the small gap size, high rate capabilities and low space charge build-up, as well as the absence of ballistic deficit. The small amplification gap is a key element in Micromegas operation, giving rise to excellent spatial resolution: 12 µm (RMS) accuracy (limited by the pitch of micromesh) is achieved for MIPs with a strip pitch of 100 µm and low diffusion CF_4/iC_4H_{10} (80:20) mixture (see Fig. 2a) [7] and very good energy resolution (~12 % FWHM at 6 keV, as shown in Fig. 2b) [11]. A time resolution of 600 ps (RMS) was achieved by the KABES beam spectrometer of the NA48 experiment. Micromegas studies with fast CF4-based gases are described in [12].

A big step in the direction of the industrial manufacturing of large-size detectors is the development of the "Bulk" Micromegas technology [13]. The basic idea is to build the whole detector in a single process: the anode plane with copper strips, a photo-image-able polyamide film and the woven mesh are laminated together at a high temperature forming a single object. At the end, the micromesh is sandwiched between

2 layers of insulating material, which is removed after UV exposure and chemical development. Several large “Bulk” Micromegas (27×26 cm^2) have been produced (see Fig. 1b) and successfully tested.

a) 

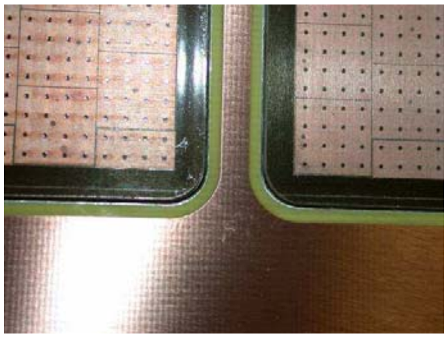
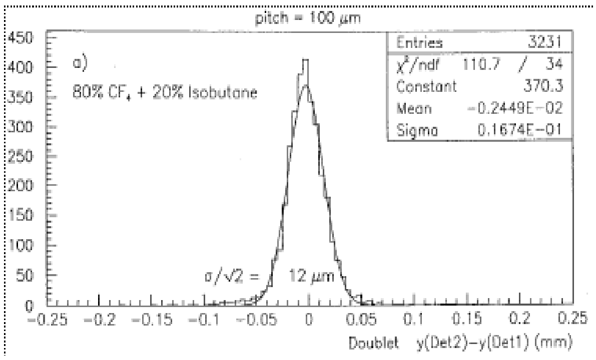
b) 

Fig. 1. a) Schematic drawing of the Micromegas detector. b) Photograph of the “Bulk” Micromegas detectors. Pillars of 400 µm diameter every 2 mm are visible.

a) 

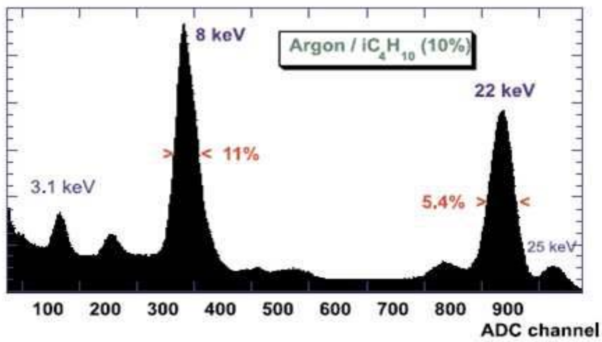
b) 

Fig. 2. a) Micromegas spatial resolution obtained with 100 µm readout strips and CF_4/iC_4H_{10} (80:20) mixture. b) ^{109}CD source spectrum obtained with Micromegas in an Ar/iC_4H_{10} (90:10) mixture.

GEM

Introduced in 1996 by F. Sauli [14], a GEM consists of a set of holes, arranged in a hexagonal pattern (typically 70 µm diameter at 140 µm pitch), chemically etched through copper-kapton-copper thin-foil composite (see Fig. 3a). Application of a potential difference between the two sides of GEM generates the field map shown in Fig. 3b: electrons released by the ionization in the gas drift into the holes and multiply in the high electric field (50-70 kV/cm). Sharing the avalanche multiplication between several cascaded electrodes (see Fig. 3c), allows to operate triple-GEM detectors at overall gains above 10^4 in the presence of highly ionizing particles, while eliminating the risk of hazardous discharges (<10^{-12} per hadron) - the major advantage of the GEM technology [15], [16]. Fig. 4a shows the discharge probability measured as a function of total effective gain, in the single-, double- and triple-GEM, exposed to alpha particles. The use of fast Ar/CF_4-based gas mixtures resulted in a time resolution better than 5 ns RMS (see Fig. 4b). A unique property of GEM detector is a full decoupling of the amplification stage (GEM) and the readout electrode (PCB), which operates at unity gain and serves only as a charge collector. This offers a freedom in the optimization of the anode readout structure, which can be made of pads or strips of arbitrary pattern [17]. GEMs can be also easily bent to form cylindrically curved ultra-light detectors, as preferred for inner tracker applications [18], [19]. Cascaded GEMs reach gains above 10^5 with single-electrons; this permitted conceiving gaseous imaging photomultipliers (GPM) with single-photon sensitivity [20].

Controlled etching of GEM foils (decreasing the thickness of the copper layer from 5 to 1 μm) allows reducing material budget in triple-GEM to 1.5×10^{-3}, which is about one half of a 300-μm-thick Si-microstrip detector [21].

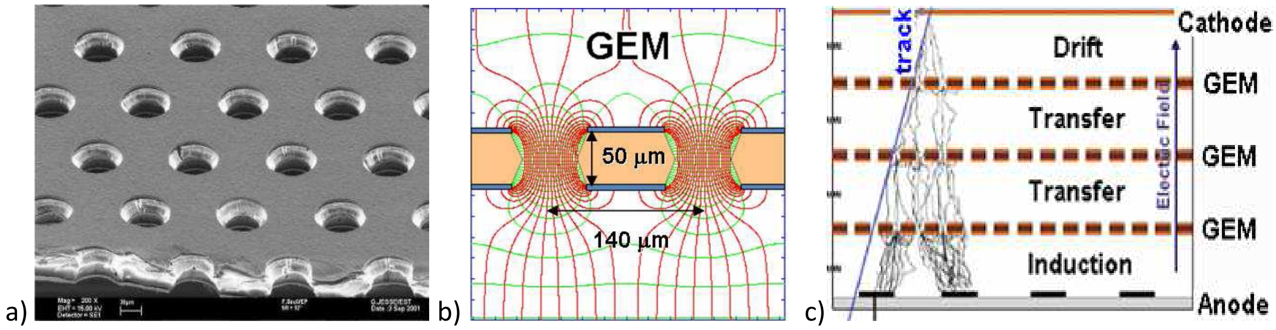


Fig. 3. a) Close view of a GEM electrode, etched on a metal-clad, 50 μm thick polymer foil. The hole's diameter and distance are 70 μm and 140 μm. b) Schematics and electric field map of the GEM amplification cell. c) Schematic drawing of the triple-GEM detector.

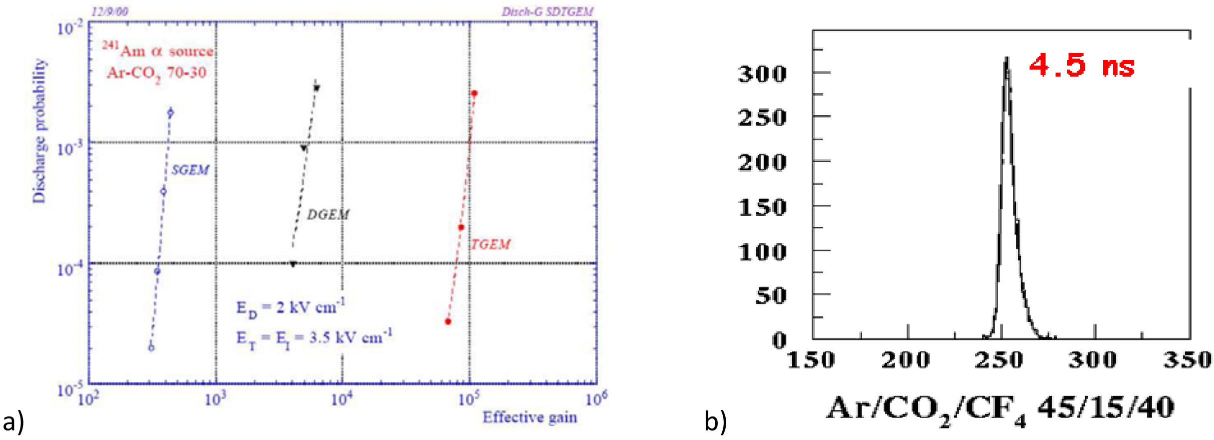


Fig. 4. a) Discharge probability as a function of total effective gain for single (SGEM), double (DGEM) and triple (TGEM) detectors. b) Time distribution in triple-GEM detector with $Ar/CO_2/CF_4$ (45:15:40). The RMS of the distribution is 4.5 ns.

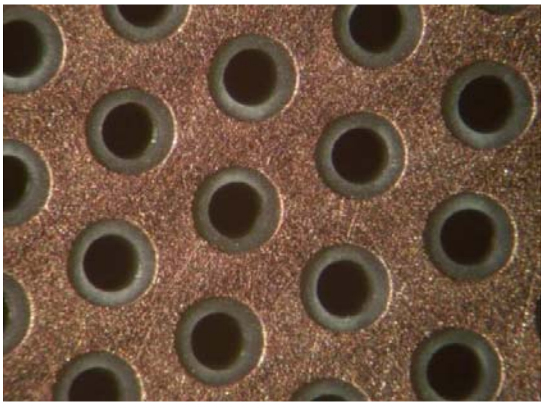
Thick-GEM, Hole-Type Detectors and RETGEM

The success of GEMs and glass capillary plates triggered the development of coarse and more robust structures, "optimized GEM" [22], [23], LEM [24] followed by thick-GEM (THGEM) [25], [26] gaseous multiplier. These are produced by standard printed circuit technology: mechanical drilling of 0.3-1mm diameter holes, etched at their rims to enhance high-voltage stability, thus increasing gain (see Fig. 5a); different PCB materials can be used, of typical thicknesses of 0.4-1mm and hole spacing of about 0.7-1.2mm. Detectors formed by single and multiple THGEM foils have been studied in laboratory, also in gaseous-photomultiplier configurations - coupled to semitransparent or reflecting CsI photocathodes [27].

Effective gas amplification factors of 10^5 and 10^7 and fast pulses of a few nanosecond rise-times were reached in single and cascaded double-THGEM elements [26]. Stable operation with high single-photoelectron detection efficiency was recorded at fluxes exceeding MHz/mm^2. This technology looks pretty adequate for the needs of a new generation of photon detectors for Cherenkov imaging devices:

namely good spatial and time resolutions, large gains (single photoelectron sensitivity), possible industrial production of large surfaces, and easy construction - thanks to the intrinsic robustness of the PCB electrodes.

A novel spark-protected version of thick GEM with electrodes made of resistive kapton (RETGEM) has been recently developed [28]. Sheets of resistive kapton 50 µm thick were glued onto both surfaces of the PCB to form resistive-electrode structure; holes 0.3 mm in diameter with a pitch of 0.6 mm were mechanically drilled (see Fig. 5b). At low counting rates, the detector operates as a conventional THGEM with metallic electrodes, while at high intensities and in case of discharges the behavior is similar to a resistive-plate chamber. Recent studies of photosensitive RETGEMs with CsI deposited directly on the dielectric kapton (without metallic substrate) have shown rather high quantum efficiency (34 % at 120 nm) [29]. Application of THGEM and RETGEM concepts to RICH technology promises to advance particle identification capabilities. Cascaded GEM, THGEM and RETHGEM were successfully operated in noble gases, at cryogenic temperatures, in two-phase mode [30,31].

a) 

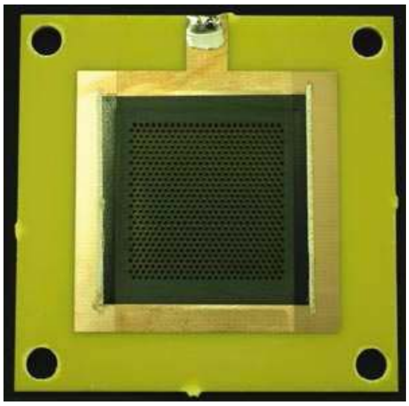
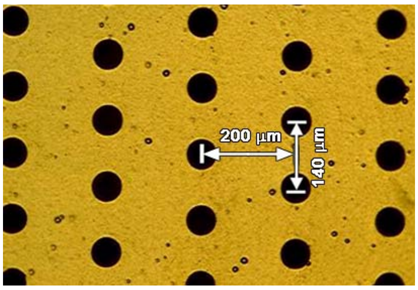
b) 

Fig. 5. a) Photo of the THGEM-multiplier. A rim of 0.1 mm is chemically etched around each hole to reduce discharges. b) Photo of the RETGEM detector with resistive-Kapton electrodes.

In cascaded micropattern detectors coupled to solid state photocathodes the backflow of the positive ions to the photocathodes is reduced, as a large fraction of the ions are collected in the intermediate elements [32]. Specific development activities are ongoing with the aim of further reducing the ion feedback flow, to pave the way to photon detectors with chemically-unstable photoconverters, e.g. Bialkali photocathodes with visible-light sensitivity. A proof of principle of visible-sensitive cascaded gaseous photomultipliers was demonstrated with GEM and various Micro-Hole and Strip Plates (MHSP [33]) elements [34].

The MHSP is a GEM-like hole-electrode with anode- and cathode-strips etched on its bottom face (see Fig. 6); the avalanche developed inside the hole is further multiplied on the anode-strips [33] . The anode-strip extra electrode permits efficient electron extraction from the holes, allowing for high gains even at high-pressure operation (e.g. gain~500 at 5 bar Xe) [35]. In addition, when operating the MHSP, biasing the strip in reverse mode, i.e. using the extra electrode to attract positive ions, a breakthrough in ion blocking has been achieved in MHSP/GEM cascaded multipliers [32,34]. The required low IBF values for TPCs and GPMs were reached with these cascaded MPGDs.

a) 

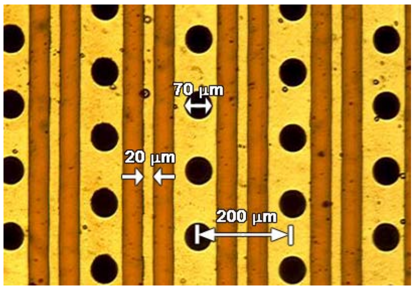
b) 

Fig. 6 - Photomicrograph of the MHSP, top a) and bottom b) sides. The thin strips can be used either for charge multiplication or for ion trapping.

Charge dispersive readout in MPGDs with a resistive anode.

MPGDs typically achieve 40-50 µm resolution but require a high density sub-millimeter width anode structure for the readout. A modified form of MPGD with a resistive anode can achieve comparable resolution using much wider pads. A thin high surface resistivity film is used for the MPGD anode and is laminated to a separate readout pad plane with an intermediate insulating spacer [36]. The resistive anode film forms a distributed two-dimensional RC network with respect to the readout plane. A localized charge arriving at the anode surface will disperse with the system RC time constant determined by the anode surface resistivity and the capacitance density determined by the anode-readout plane spacing. With the initial charge dispersing and covering a larger area with time, wider pads can be used for position centroid determination without sacrificing resolution.

MPDG with CMOS pixel ASICs

Advances in micro-electronics industry and advanced PCB technology have been very important for the development of modern gas detectors with increasingly smaller pitch size. The fine granularity and high-rate capability of micro-pattern devices can be fully exploited using high-density pixel readout with a size corresponding to the intrinsic width of the detected avalanche charge. However, for a pixel pitch of the order of 100 µm, technological constraints severely limit the maximum number of channels that can be brought to the external front-end electronics. An elegant solution is to use a CMOS pixel chip, assembled directly below the GEM or Micromegas amplification structure and serving as an integrated charge collecting anode. With this arrangement avalanche electrons are collected on the top metal layer of the CMOS ASIC; every input pixel is then directly connected to the amplification, digitization and sparcification circuits, integrated in the underlying active layers of the CMOS technology. Using this approach, gas detectors can reach the level of integration typical of solid-state pixel devices.

Particle detectors are designed to achieve sensitivity required to study physics processes of interest. The multi-pixel anode readout of micro-pattern gas detectors allows a true 2D image reconstruction and opens novel detection opportunities in:

- Astronomical X-ray polarimetry (2-10 keV energy range);
- Position-sensitive single electron detection;
- Time Projection Chamber readout;
- High-rate particle tracking;
- Advanced Compton Telescopes (0.4-50 MeV energy range);
- Low-energy nuclear recoil reconstruction (WIMP interactions).

The advent of finely segmented MPGD with pixel read-out can lead to the appearance of a highly efficient X-ray polarimeter in the 2-10 keV energy bands, which allows measuring simultaneously position and energy-resolved linear polarization. For this, an analog, low-noise and high granularity (50 µm pitch) multi-pixel ASIC was developed [37] - [40], shown in Fig. 7a, so that the initial direction and dynamics of X-Ray energy loss in the gas can be accurately tracked before it is distorted by Coulomb scattering.

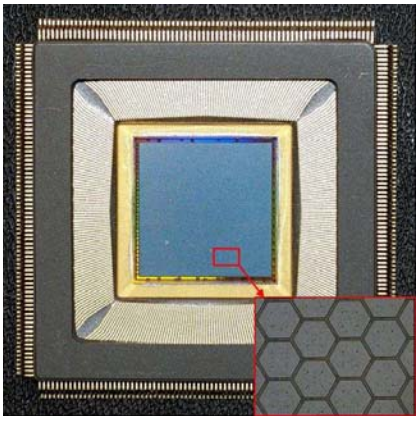
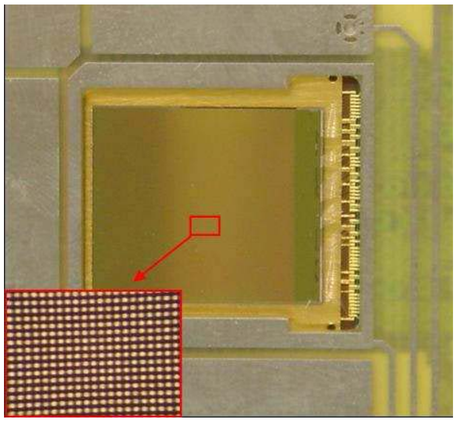
a)  b) 

Fig. 7. a) Photo of the analog CMOS ASIC with hexagonal pixels, bonded to the ceramic package [40]. b) Photo of the Medipix2 chip [41]; the 25 µm wide conductive bump bond openings, used for electron collection, are seen as a matrix of dots [44].

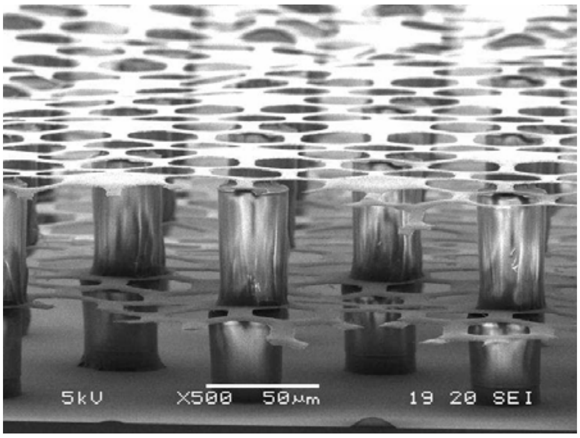
A binary multi-pixel CMOS chip ("Medipix2"), originally developed for X-ray imaging [41], has been shown to work with Micromegas and GEM detectors [42] - [44]. Approximately 75 % of every pixel in the Medipix2 matrix is covered with an insulating passivation layer. Hence, the avalanche electrons are collected on the conductive bump-bonding pads, exposed to the gas (see Fig. 7b). A modification of the Medipix2 chip ("Timepix" [45]), which allows to measure the drift time information of primary electrons, has been designed, produced and already tested with GEM and Micromegas gas amplification systems for the TPC readout at the future Linear Collider.

Ingrid Technology

An attractive solution for the construction of MPGD with pixel anode readout is the integration of the Micromegas amplification and CMOS chip by means of 'wafer post-processing' technique [46]. With this technology, the structure of thin (1 µm) aluminum grid is fabricated on top of an array of insulating (SU-8) pillars of typically 50 µm height, which stand above the CMOS chip, forming an integrated readout of the gaseous detector. This technology is called InGrid and provides an accurate control of alignment and grid geometry. The process uses standard photolithography and wet etching techniques and is CMOS compatible. It can be used to equip both single chips and chip wafers with Micromegas grids. The sub-µm precision of the grid dimensions and avalanche gap size results in a uniform gas gain; the grid hole-size, pitch and pattern can be easily adapted to match the geometry of any pixel readout chip. Ingrid detectors can also be used to measure X-ray energies with an unprecedented resolution (closed to the Fano limit). Several InGrids have been fabricated on dummy silicon substrates, showing an energy resolution of 5 % RMS at 5.9 keV. Many basics quantities of gas physics like (Fano factors, diffusion constants, and cluster size distributions) can be measured with this detector. Recently, TwinGrid and TripleGrid structures have been developed and tested (see Fig. 8).

The protection against sparks is provided by a 10 to 20 µm thin layer of highly resistive material (hydrogenated amorphous silicon) deposited directly over the chip surface. This protection is called

“SiProt” and its optimal thickness is being investigated. Several Medipix2/Timepix chips were equipped with “SiProt” and InGrids and were found to function normally after the post-processing.

a) 

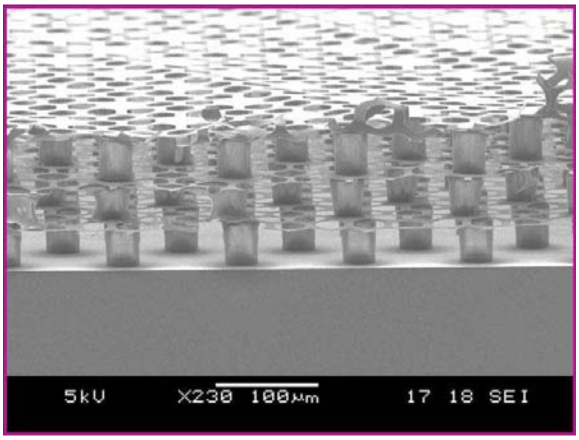
b) 

Fig. 8. a) Photo of the TwinGrid Structure. b) Photo of the TripleGrid Structure.

II-B. Fields of Applications (HEP, Astrophysics, Nuclear Physics, Industrial and Medical Applications)

The performance, robustness and radiation hardness of the MPGD have encouraged their applications in many other fields; a short summary of the most recent results is given below.

High-Rate Particle Tracking and Triggering

COMPASS is a first high-luminosity experiment at CERN, which pioneered the use of GEM and Micromegas detectors for high-rate particle tracking, reaching 25 kHz/mm^2, in the near-beam area. Both technologies have achieved tracking efficiency of close to 100 %, a spatial resolution of the order of 70 - 100 µm (RMS) and a time resolution of ~ 10 ns (RMS) [47], [48]. The excellent performance and radiation hardness of 22 large size triple-GEM (30×30 cm^2) and 12 Micromegas (40×40 cm^2) detectors after several years of successful operation has demonstrated the large-scale reliability and robustness of the MPGD concept [49]. Fig. 9a shows a 2D-efficiency map of one COMPASS GEM triple detector; while 2D-efficiency for one Micromegas plane is shown in Fig. 9b. An average efficiency of ~95% was achieved for both technologies. No degradation of performance was observed in COMPASS detectors after an accumulated charge of a few mC/mm^2, corresponding to an equivalent flux of ~10^{11} MIPs/mm^2. For the COMPASS physics program in 2007, a set of triple-GEM trackers with pixel readout (1×1 mm^2) in the central region and 2D strip readout in the periphery is built [50].

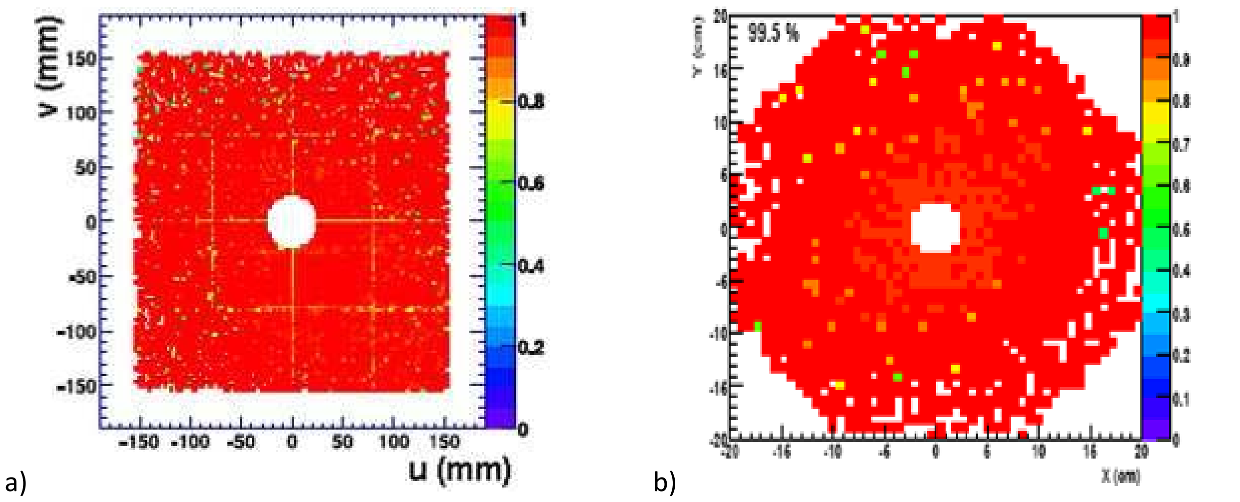


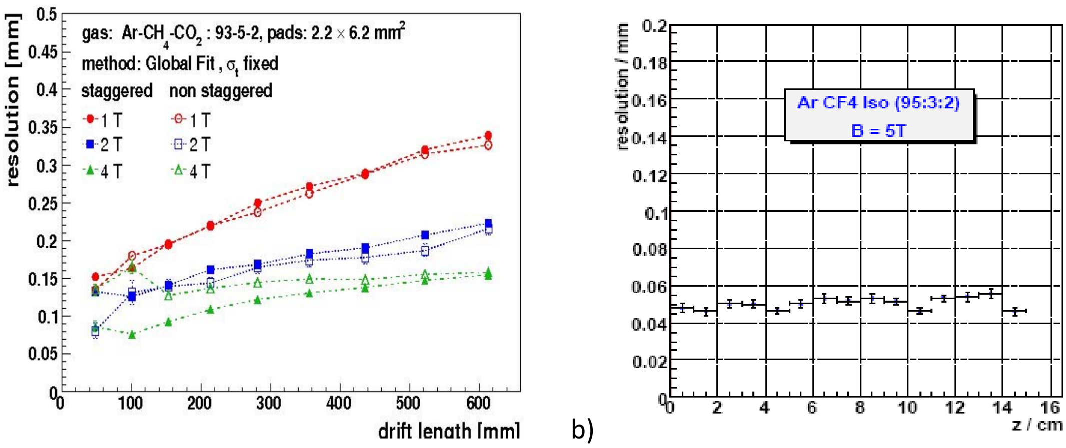
Fig. 9. COMPASS high intensity physics runs: a) 2D-efficiency map of one COMPASS triple-GEM detector; b) 2D-efficiency map of one COMPASS Micromegas plane.

Time Projection Chamber Readout

R&D for a high precision Time Projection Chamber (TPC) readout is ongoing in the international ILC-TPC collaboration [51]. A Time Projection Chamber (TPC) using MPGDs as a gas amplification device is one of the main options for charged-particle tracking. The main topics are the construction of low material budget field-cage and the development of gas amplification end-plates using GEM or Micromegas. In the context of the particle flow concept at the ILC, the requirements for charged-particle tracking are mainly high efficiency and double track resolution. In addition, in order to achieve a momentum resolution of $\sigma(1/pt) \sim 5\times10^{-5}$/GeV for the combined (vertex detector and TPC) system, at least 200 space points with an average transverse resolution of 100 µm have to be measured over a maximal drift length of 250 cm in 4 T field. These requirements are beyond the limits of MWPCs, but can be fulfilled with GEM or Micromegas readout, which offer number of advantages: negligible E×B track distortion effects, the narrow pad response function (PRF) and the intrinsic ion feedback suppression. A new TPC readout possibility is with cascaded GEM/MHSP elements with high ion-blocking capability [32].

The future MPGD-TPC developments are not limited to the R&D for the linear collider; in fact they will be used in a variety of applications. Employing the “Bulk” technology, 72 large Micromegas (34×36 cm2) will be built for the T2K/TPC detector to instrument an area of almost 10 m^2. Reading out large volume TPCs with highly segmented anode plane is also a key point for high resolution track imagers, proposed for an advanced Compton Telescope [52] and for the detection of possible signatures of WIMP elastic interactions [53], [54]. The primary advantage of a pixelized gas tracker is that the direction of the Compton recoil electron or the low energy nuclear recoil can be reconstructed far more accurately than in any other detection medium.

TPC Readout for the Linear Collider: The principle of the ILC-TPC MPGD concept has been successfully validated over the last years. The single-point resolution of $\sigma \sim 140$ µm (RMS) has been achieved with GEM-TPC prototype after 60 cm of drift in 4 T field (see Fig. 10a). The spatial resolution for low magnetic fields shows the expected dependence from the drift length, which is caused by diffusion. For high fields the GEM-TPC resolution is dominated by the PRF [55]. Recent studies with Micromegas-TPC, using charge-dispersive readout technique, demonstrated excellent single-point resolution of 50 µm (RMS) over the 15 cm drift length in 5 T field, as shown in Fig. 10b [36]. In this case a high surface-resistivity thin film is laminated to the readout PCB with an intermediate insulating spacer substitutes the conventional MPGD anode plane.



a) b)

Fig. 10. Transverse spatial resolution vs drift distance for 2×6 mm^2 pads: a) GEM-TPC with the $Ar/CH_4/CO_2$(93:5:3) mixture at 1 T, 2 T and 4 T fields [55]; b) Micromegas-TPC, using charge dispersive readout, with the $Ar/CF_4/iC_4H_{10}$(95:3:2) mixture at 5 T field [36].

The resistive surface forms a distributed two-dimensional RC network with respect to the pad plane [56]. The arriving avalanche charge at the anode disperses with the RC system time-constant (determined by the anode surface resistivity and capacitance per unit area). With the avalanche charge dispersing and covering a larger area with time, wider pads can be used without losing accuracy in charge-centroid determination. This also avoids degradation of the point-resolution due to single-pad hits at short drift distances. A fractional ion back-flow into the drift volume down to 0.2 % is measured both with GEM and Micromegas, which in combination with modern low-noise electronics might allow avoiding the use of gating grid. An attractive approach to use GEM foil for gating, if needed, has been proposed in [57]. However, the effect of electron transmission losses on the spatial resolution (at low GEM voltages used for gating) has still to be experimentally measured. Ten-fold better ion blocking with full electron collection was recently reached with cascaded GEM/MHSP elements, which will be further investigated in this work [32].

CMOS-based Readout for the Linear Collider: While the standard approach to readout the signals is a segmented pad-plane with front-end electronics attached through connectors from the backside, an attractive possibility is the use of PixelASICs to serve as integrated device hosting the pad, the preamplification and the digitization and sparsification of the signals. Earlier studies using GEM and Micromegas mounted on the Medipix2 chip provided two-dimensional images of minimum ionizing track clusters [42] - [44]. The Timepix chip can reconstruct the 3D-space points of individual electron clusters and thus count the number of ionization clusters per unit length for particle discrimination. Each pixel in the chip matrix can be programmed to record either the electron arrival time with respect to an external shutter ("TIME" mode) or the time-over-threshold ("TOT" mode) information, providing pulse-height measurement.
Initial 'proof-of-principle' studies using Micromegas foils equipped with Medipix2 chip provided 2D images of minimum ionizing track clusters [42], [43]. The CMOS chip was also demonstrated to function perfectly with Micromegas; the Timepix chip equipped with "SiProt" and InGrid have been operated for several months in He and Ar based mixtures. The protection against sparks was established by introducing alpha-emitters in the chamber gas. The resulting very large amount of charge triggered gas discharges in Micromegas that were sustained by the chip (without destruction) and even recorded. The combination of InGrid with the Timepix chip has demonstrated to collect the complete information from charges particle tracks, left in the form of primary ionization electrons in the gas volume.

a) b)

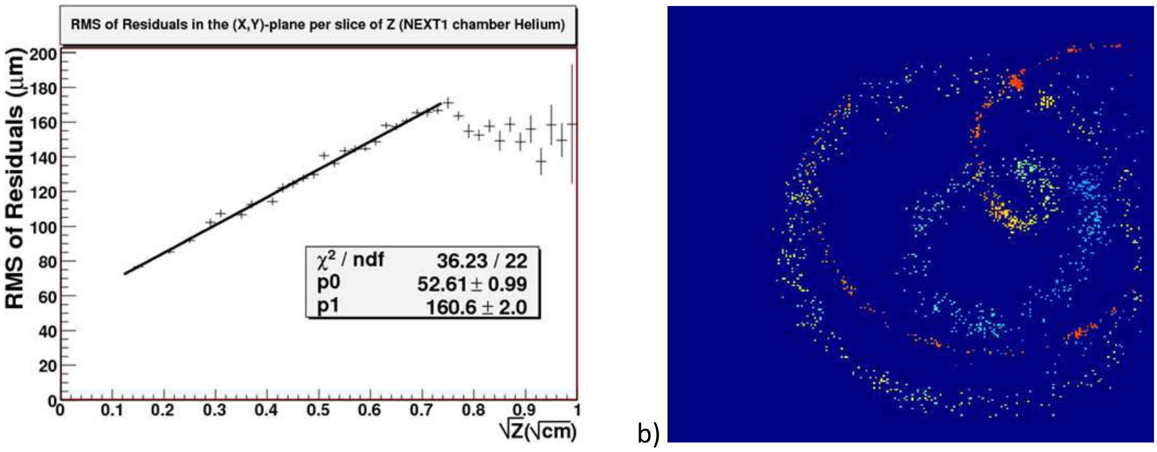


Fig. 11. a) Residuals as a function of the square root of the drift distance in He/iC_4H_{10} (80:20) measured with Micromegas/Timepix detector. b) Tracks of electrons from a Sr^{90} source, measured in Ar/iC_4H_{10} (80:20) and in a magnetic field of 1 T. The picture shows the projections of the tracks on the pixel plane with the various colors corresponding to various arrival times. The x, y-axis represent chip sensitive area, arranged as a square matrix of 256×256 pixels of 55×55 μm^2 size.

The tracking capabilities were investigated by recording tracks of cosmic particles. The hit residuals with respect to the fitted projected tracks are plotted as a function of the square root of the drift distance in Fig.

11a. Later, the detector was also operated in a 1 T field produced by a dipole magnet. The chamber was oriented such that the electric and magnetic fields were parallel and irradiated with few MeV alpha-source from a ^{90}Sr source. The electrons entering into the chamber through the cathode produced ionization while spiraling in the gas volume. In Fig. 11b, two-dimensional projection of two electrons of different momentum is shown. Thanks to the fine granularity readout, double track separation capabilities look very promising even for tracks overlapping on the pixel plane.

The triple-GEM detector with Medipix2 chip has been initially studied with ^{55}Fe X-Rays and ^{106}Ru electrons [44]. Stable operation at the gas gain of up to several 10^5 has been achieved with Ar(He)/CO2 (70:30) mixtures. The device allows to perform moderate-resolution energy spectroscopy measurements (20 % FWHM at 5.9 keV X-rays) using only digital readout and two discriminator thresholds. Later, the GEM/Medipix2 detector has been exposed to 5 GeV electron beam at DESY (see Fig. 12a). The dependence of the spatial resolution from the drift length (y-coordinate of the track inside the 6 mm GEM drift volume) was measured using external Si-telescope planes [58,59]. The deviations of “center of gravity” of individual cluster avalanches from the straight line fit can be parameterized as:

$$\sigma^2_{mean}(y) = \sigma^2_0 + \sigma^2_{dif}(y) = \sigma^2_0 + D^2_T \cdot y / n_{el}^{cl} \qquad (1)$$

where, σ_0 is the GEM “defocusing” term (depends on diffusion of amplified electrons in the triple-GEM structure and GEM hole/pitch size), D_T is a transverse diffusion coefficient, n_{el}^{cl} is an effective number of primary electrons per cluster contributing to resolution, and y is a drift distance from the surface of the first GEM. The triple-GEM device has been also operated with Timepix readout (both in “TIME” and “TOT” modes) in the same setup at the DESY beam. Fig. 12b shows an electron track recorded in the “TIME” mode; the color denotes the arrival time of electrons in a pixel. Diffusion of primary ionization clusters as a function of the drift distance was clearly observed, as shown in Fig. 12c. The intrinsic spatial resolution, extrapolated to zero drift length (y=0), of $\sigma_0 \sim 23 - 32$ µm was measured both for different GEM/Medipix2 and GEM/Timepix stack configurations.

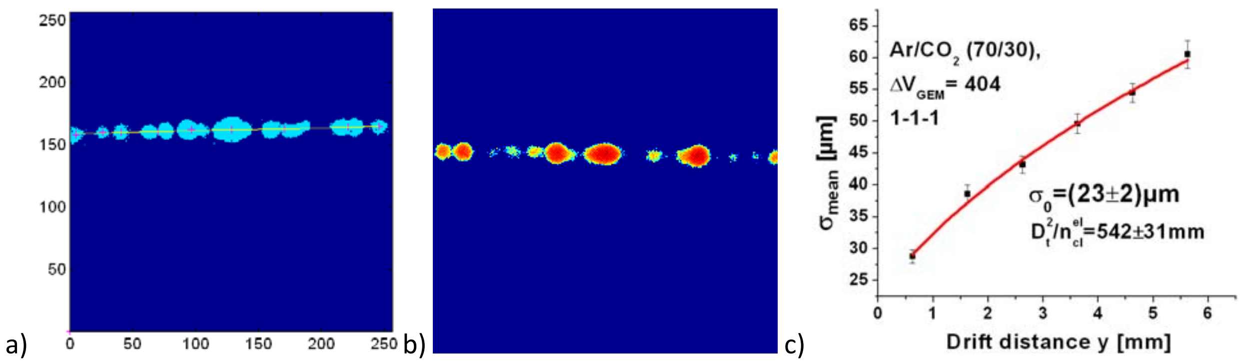


Fig. 12. a) and b) Images of 5 GeV electron tracks in Ar/CO_2(70:30) recorded with triple-GEM coupled to Medipix2 and Timepix (“TIME” mode) readout, respectively. The x, y-axis represent chip sensitive area, arranged as a square matrix of 256×256 pixels of 55×55 μm^2 size. c) Spatial resolution (σ_{mean}) as a function of drift distance in Ar/CO_2 (70:30) mixture and triple-GEM/Medipix2 detector.

These results demonstrate that the CMOS readout of MPGD meets requirements for tracking detectors in the next generation of high energy colliders. Significant progress has been also made in the development of simulation tools and comparison with data recorded with Medipix2 and Timepix chips [60].

Photon Detectors for Cherenkov Imaging Counters

Large-area RICH gaseous detectors with a thin photosensitive CsI-layer deposited on the cathodes of a MWPC, developed in the context of RD26 [61], are currently employed for particle identification in many high energy physics experiments [62], [63]. This innovative technology, presently fully established, is affected by limitations related to the presence of the CsI photo-converter: aging [64] and electrical stability issues [65]. Aging of the photo-converting layer, resulting in a reduced QE, takes place after accumulated charge densities larger than 1 mC/cm^2, and it is caused by the ion bombardment by the positive ions created in the multiplication process. Ion bombardment is also the source of the electrical instabilities exhibited by MWPCs, when a CsI photocathode is used; the instabilities depend on the particle-induced ionization background level and the supply voltage value. The microscopic details of the phenomenon are not known: mechanisms considered are CsI activation or the accumulation of a large amount of charge on the surface of the CsI layer, slowly neutralized through the dielectric layer formed by the CsI film itself. Both the limitations mentioned above impose to operate the photon detectors at low gain (substantially lower than 10^5). It is therefore necessary to integrate the detector signal over long time intervals (at least 200 ns), preventing to build fast detector systems with good time resolution. The challenges of the future precision experiments, very demanding in terms of high rates, time resolution and detector performance seem hardly to be compatible with this generation of gaseous photon detectors. Ion bombarding is at the origin of the aging process and gain limitations of MWPC coupled to CsI photocathodes. It is therefore very natural to consider detector architectures for which this bombardment is naturally suppressed, namely detectors with "closed geometry" gaseous electron multipliers. In the recent years there has been a considerable progress in the field of photon detection by combining gaseous detectors formed by multiple GEM foils with semi-transparent or reflective CsI photocathodes (PC) to localize single photoelectrons [66]; for example a good summary of most of the work in the field is in [67]. These detectors offers high gain, even in noble gases, sub-nanosecond time response, excellent localization properties and are able to operate at high magnetic fields and cryogenic temperatures. Using triple-GEM detector with a hexagonal readout, a position accuracy of 55 µm (RMS) and a two-photon separation of around 1 mm has been achieved [68]. A Micromegas filled with He/iC_4H_{10} mixture at atmospheric pressure allows to achieve time resolution of ~700 ps for single photoelectrons [9].

The hole-type gaseous structures: GEMs, Cappillary Plates and TGEMs coupled to CsI-PC can operate stably down to 80 K [69] - [72]. The operation of MPGD-based photomultipliers in CF_4 with CsI-PC [73] could form the basis of new generation windowless Cherenkov detectors, where both the radiator and the photosensor operate in the same gas. Exploiting this scheme a Hadron Blind Detector (originally proposed for Parallel Plate Avalanche Chamber [74] - [76]) was recently developed and constructed using triple-GEM amplification system with CsI PC deposited on the top GEM, as a part of the upgrade program for the PHENIX experiment at RHIC [77], [78]. A hadron-blindness property is achieved by reversing the direction of the drift field E_D, therefore pushing primary ionization produced by charged particles towards the mesh. In this configuration photoelectrons released from the CsI surface are still effectively collected into the GEM holes and multiplied. The avalanche confinement within the GEM holes strongly reduces photon-mediated secondary processes in CF_4 (CsI is sensitive to the CF_4 scintillation peak at 170 nm) [73]. To advance in the development of GEM-based photon detectors, one of the key ingredients is represented by the possibility to produce, with good production quality and yield, GEM-like foils of large surface, a goal common to other applications of these detectors. Another way is to build large-area cascaded THGEM or RETHGEM detectors with reflective CsI photocathodes [79]; these have sub-mm resolutions (FWHM) [80].

Recently, a UV photo-detector based on a semitransparent CsI photocathode followed by the fine-pitch GEM foil, that matches the pitch of a pixel ASIC (50 µm), has shown excellent imaging capabilities [81]. The photoelectron emitted from CsI layer drifts into a single GEM hole and initiates an avalanche, which is then collected on the pixel CMOS analog chip. Due to the high granularity and large S/N of the read-out system, the "center of gravity" of the single electron avalanche corresponds to the center of GEM hole. Accumulating thousands of such events produces "self-portrait" of the GEM amplification structure, shown in Fig. 13 (a). The peaks, corresponding to GEM holes, are well resolved in the barycenters distribution on Fig. 13 (b) allowing achieving superior single electron avalanche reconstruction accuracy of 4 µm (RMS). Thanks to the very low pixel capacitance at the preamplifier input (noise ~ 50e$^-$ ENC), detector has significant sensitivity to a single primary electron even at gas gain of a few thousands. The position resolution of the device is currently limited by the 50 µm GEM pitch. The symmetric shape of a single electron charge cloud at the readout plane demonstrates that the spatial resolution is not degraded by the avalanche spread inside the GEM, and is independent from the direction of entrance of electron into the hole. One of the most exciting future applications of GEM and Micromegas devices with CMOS multi-pixel readout could be position sensitive single-photon detection. The excellent spatial and time resolution, ambiguity-free reconstruction of multi-photon events and non-negligible single-electron sensitivity, makes them a suitable candidate for fast gas photo-multipliers.

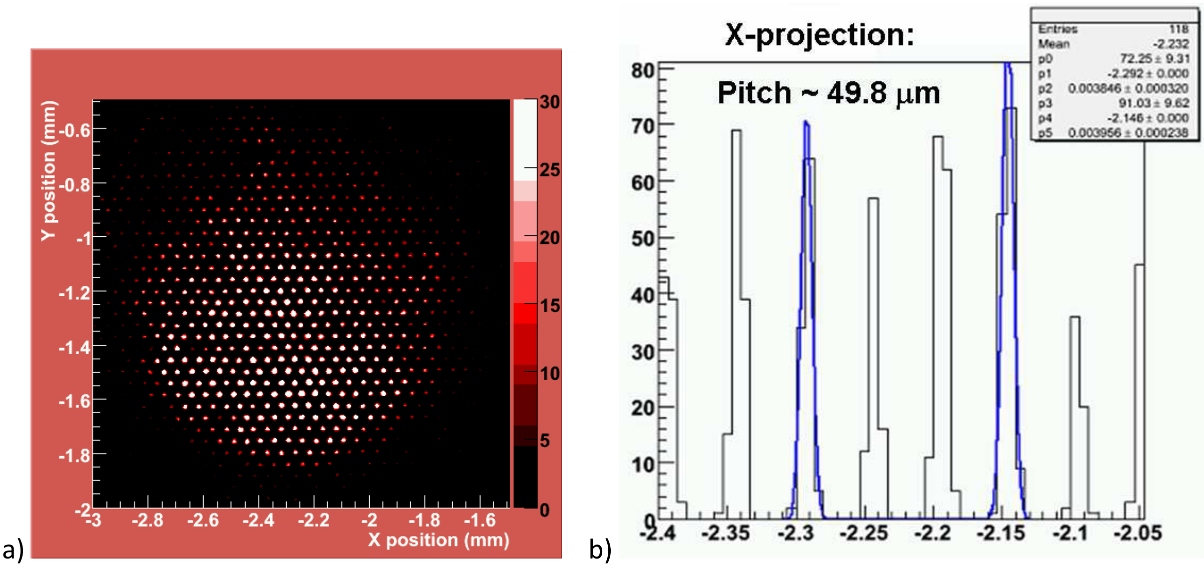


Fig. 13. a) "Self-portrait" of the GEM amplification structure obtained with a CMOS analog pixel chip. b) A horizontal cut through the 2D image of barycenter positions ("centre of gravity" of the single electron avalanche). The peak to peak distance corresponds to the GEM pitch. The gaussian fit gives ~ 4 µm (RMS) width [81].

X-Ray Astronomy

A GEM detector coupled to a VLSI analog pixel chip, comprising pixelized charge collecting electrode and readout electronics, can bring great improvement in sensitivity, at least 2 orders of magnitude, compared to traditional X-ray polarimeters (based on Bragg crystals or Compton scattering) [37]. The novel device allows reconstructing individual photoelectron tracks with a length as short as few hundred microns; the total charge collected in the pixels is proportional to photon energy. The degree of X-ray polarization is computed from the distribution of reconstructed track angles, since the photoelectron is emitted mainly in the direction of photon electric field. Three ASIC generations of increased complexity and size, reduced pitch and improved functionality have been recently designed and built [38]-[40]. The third ASIC version, realized in 0.18 µm CMOS technology, includes self-triggering capability and has 105600 hexagonal pixels with a 50 µm pitch, corresponding to an active area of 15×15 mm^2. A GEM coupled to such a CMOS pixel array is able to simultaneously produce high resolution images (50 µm RMS), moderate spectroscopy (15% FWHM at 6 keV) as well as fast timing (30 ns RMS) in the 2-10 keV X-ray energy range. At the focal plane of the large area mirror of the XEUS telescope, a single 15×15 mm^2 ASIC will cover a field of view of 5 arcmin, large enough to image extended objects like Crab Nebula. Because of the high detector sensitivity, polarization of Active Galactic Nuclei down to few % level can be measured for 1 mCrab sources in one day [40]. A sealed gas pixel detector for X-ray astronomy is currently under development [81].

Neutron Detection and Low Background Experiments

There are many applications of the Micromegas concept in the neutron detection domain, which include neutron beam diagnostics [82], inertial fusion experiments [83], thermal neutron tomography [84] and a novel compact sealed Picollo-Micromegas detector, designed to provide in-core measurements of the neutron flux and energy (from thermal to several MeV) in the nuclear reactor [85]. Neutrons can be converted into charged particles to detect ionization in Micromegas by two means: either using the detector gas filling or target with appropriate deposition on its entrance window. Micromegas detectors are also used in searching for solar axions (CAST) [86] or under development for low energy neutrino experiments (HELLAZ, NOSTOS) [87], [88], including neutrino oscillations and neutrino magnetic moment measurements. In particular, in the CAST experiment at CERN, the expected signal comes from solar axion conversions into low-energy photons of 1-10 keV energy. Micromegas detector with high granularity anode elements can largely reduce the background event rate down to $5\times10^{-5}keV^{-1}cm^{-2}s^{-1}$, exploiting its stability, good energy and spatial resolution [89]. Cascaded-GEM multipliers with polyethylene neutron-converter foils were developed for fast-neutron imaging [90]. The largest devices, with simple 2D double-sided PCB boards, have 30×30 cm^2 dimensions. Fast-neutron imaging detectors based on the THGEM concept are under development.

Cryogenic Detectors

The GEM-based cryogenic avalanche detectors can be used in the field of coherent neutrino-nucleus scattering using two-phase Ne and Ar [91], [92], solar neutrino detection using two-phase or high-pressure He and Ne [93], dark matter searches using two-phase Ar and Xe [94], Positron Emission Tomography (PET) using two-phase Xe [95], and digital radiography using two-phase Ar and Kr [96].

The operation principle of the cryogenic two-phase avalanche detector with GEM readout is the following (see Fig. 14): the ionization produced in the noble liquid by radiation is extracted from the liquid into the gas phase by an electric field. Then it is detected with the help of a multi-GEM multiplier operated at cryogenic temperatures, in saturated vapor above the liquid phase. The recently obtained results [97]-[102] indicate that the GEM structures can operate at low temperatures at high gains exceeding 10000 in all noble gases: in He and Ne at above 20 K and in Ar, Kr and Xe in the range of 78-295 K. Moreover, a stable operation of the triple-GEM multiplier in Ar, Kr and Xe in the two-phase mode has been demonstrated at gains reaching 10000, 1000 and 200 respectively. That means that the GEM structures can be successfully incorporated into cryogenic avalanche detectors. It was also shown that the multi-GEM multiplier can provide the detection of both the ionization signal, extracted from the liquid, and the scintillation signal, generated in the noble liquid by a particle [102]. The latter is achieved by depositing an UV-sensitive photocathode, namely CsI, on top of the first GEM (Fig. 14). The ionization signal is used to measure the position and energy. The scintillation signal would provide the trigger to readout the ionization signal and to measure the position in depth, like in Time Projection Chamber. It would be also used to reject the background in low background experiments, such as coherent neutrino scattering, dark matter search and solar neutrino detection, by comparing to ionization signal. In addition, the fast scintillation signal in liquid Xe would provide the trigger for coincidences of two collinear gamma-quanta in PET. Successful high-gain operation of a double-THGEM in a two-phase LAr detector was recently demonstrated [103]. It paves the way towards THGEM-based cryogenic Gamma Cameras.

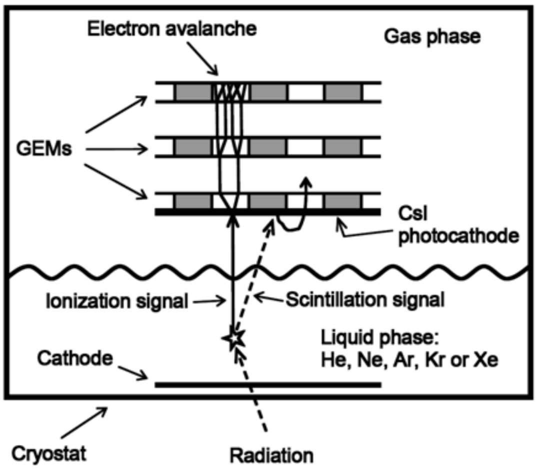


Fig. 14. Principles of operation of the GEM-based cryogenic two-phase avalanche detector with the detection of both ionization and scintillation signals [98].

Medical applications

There were many attempts to use GEM detectors for medical applications and portal imaging. In particular, GEM-based prototype was used to detect simultaneously the position of the therapeutic radiation beam (gammas or electrons) and the position of the patient tumor in order to provide feedback to the cancer treatment machine and correct (on line) position of the beam with respect to the patient [104,105]. In this device the x-ray image was obtained by using a gas converter and the gamma image of the beam by using solid converters placed in between several GEM detectors. Both detectors were integrated in a common gas chamber and GEMs served as amplification structure. The main advantage of this detector compared to other advanced designs, for example solid state detectors, is simplicity and low cost.

Independently a prototype of the GEM-based portal imaging device was developed in [106]. This group exploited a scintillation light produced inside GEM’s holes and integrated this light amplifier to the existing commercial portal imaging device. Another development was a mammographic scanner based on microgap micrppattern RPC [107] - [109]. In this device the cathode of the RPC was made of a medium resistivity GaAs and the anode was a readout plate with metallic strips having pitch of 30-50 µm. The gap between two electrodes was typically 3 mm. The detector has a position resolution of 30-50 µm in a digital form and was fully spark protected. Due to the high efficiency, single photon counting and efficient suppression of the scattered X-rays, the detector allowed obtaining high quality images at delivered dose of 10 times less than with the commercial devices. The same group also developed an improved version of this device in which a glass capillary plate was used as an X-ray converter [110].

Homeland security and prevention of planetary disasters

A unique property of RETGEM to operate at high gas gains in air was exploited to develop prototypes of Po detector and detectors of dangerous gases for homeland security applications. Both detectors have simple designs and very low production costs; however can compete with commercially available devices in sensitivity. For example detectors of dangerous gases are 10-100 times more sensitive than any commercial devices [111], [112].

Each year various planetary disasters take thousand of lives. Among them the most common and often happening are the earthquakes and forest fires. It was observed that before earthquakes a sharp increase of the Rn concentration in air regions associate to rocks and caves appears. This can be used for early earthquakes warning. The RETGEM-based device capable to operate in the air and to continuously monitor the Rn concentration is currently under development [112]. A network of such detectors can be developed and installed in “sensitive“ regions to provide daily assessment of the situation with the Rn gas. The same group is also developing a GEM and RETGEM based forest fire detectors which are 1000 time more sensitive than any commercial device [113].

III. Research Topics and Work Plan
III-A. Technological Aspects and Developments of New Detector Structures (WG1)

OBJECTIVE

Detector design optimization, development of new multiplier geometries and techniques.

Micropattern gaseous detectors are being developed for an ever growing domain of applications. These applications concern various operation conditions and each of these implies different requirements. Muon chambers for SLHC detectors as well as neutrino long-baseline oscillation experiments require large-area detectors. For various applications, especially in nuclear physics and in vertexing for collider experiments, the material budget has to be kept as low as possible. In the forward region of SLHC detectors, radiation hardness is an issue that will require special designs. Many applications will require the development of portable detectors, sealed and with compact light high voltage supplies, for applications out of the laboratory. Some applications will require high-rate to be sustained or on the contrary low-radioactivity for low-energy rare-event detection. Some will require high-pressure operation (dark matter search), others low pressure (low-energy Nuclear Physics). Special materials and geometries will be necessary for high magnetic-field operation. Some experiments will require high granularity, others high stability. Minimization of the ion backflow is essential for a Linear Collider TPC, as well as in photo-detection. Clearly, these operation and design issues will require strong connections with Working Groups 2 and 6.

To organize the R&D in Working Group 1 in these respects, a number of tasks have been singled out and are described in this section.

TASK 1

Development of large-area Micro-Pattern Gas Detectors (large-area modules, material-budget reduction)

Large Bulk Micromegas

Recent advances in Micromegas technology allowed increasing the size of detectors by a large factor. The fact that a robust stainless steel mesh is used as the amplifying grid opens the possibility to build detectors up to one meter long. The fabrication of bulk Micromegas consists of the following steps: 2 layers of photosensitive cover lay are laminated directly on top of the readout board, the thickness of these layers is defining amplifying gap. On top of them a stretched stainless steel mesh is laid and attached to the board by lamination of another closing photosensitive cover lay. 3 layers are then exposed to UV light through the desired mask to polymerize the cover lay in places, where spacers are needed. The pitch can vary from 1 to 4 mm, while spacer diameter from 0.2 to a few millimeters. The board is then developed with a defined sprayed chemistry to remove the unwanted cover lay, followed by thermal curing and cleaning, which effectively reduces dark current between mesh and readout electrode. The limiting factors of this technology are:

- Laminator opening: 0.6m - 1m in some companies.
- Development machine opening: 0.6m - 1m in some companies.
- Readout-board size: 50cm x 50cm for complex boards.
- Curing Ovens: 1m.

The stainless-steel mesh is available in 1.2 m wide rolls and is not a limiting factor. 60cm x 50cm detectors can be built using this technology. The possibility of segmenting the mesh has to be exploited to lower the detector capacitance and to provide an additional coordinate readout for large detectors with strips. CERN TS-DEM-PMT workshop is planning to build detectors of 100cm x 50cm size during the year 2008. One of the limiting factors is the readout board of this size. Possibility of merging smaller boards (easy to manufacture) is under investigation.

Also "wall-paper" flexible detectors can now be envisaged.

Single-mask GEM

The technology of GEM foils fabrication is fully established. Only a few improvements have been implemented in the last ten years. GEM foil is produced from an adhesiveless copper polyimide clad, with typical 50 µm polyimide thickness and 5 µm thick copper layers. The copper layer on either side is patterned by photolithography and chemically etched. The images on both faces should be perfectly aligned with a precision of 10 µm. This requirement prevents to extend effective GEM foil size beyond 60 cm x 40 cm. The standard pattern is defined by 70 µm diameter holes in a hexagonal matrix of 140 µm pitch. Smaller dimensions are feasible limiting though the size of the foil due to the fabrication difficulties. After copper patterning, followed by cleaning, exposed polyimide is chemically dissolved in an anisotropic way. The foil is then cleaned and electrically tested. Two methods to overcome the size limitation given by the requirement of precise mask alignment were proposed. In the first one, laser direct imaging machines were used to pattern the copper layers on both sides of the foil. This method was abandoned due to its complexity and lack of reproducibility. The second approach is to use a single mask process, where patterning of one of the copper layers is done using polyimide previously etched as a mask. This method gave promising results and first test prototypes of large size GEM foils (60cm x 40cm) are under test; the production of the 100cm x 35 cm size foils is foreseen later in 2008.

New materials and material budget reduction

Specific applications pose stringent requirements on the materials used in the MPGD construction. This is illustrated below by a non-exhaustive list of different requirements to the construction materials, depending on application:

- Materials with low out-gassing properties
- Radiation hard materials
- Low-radioactivity materials for rare-event detectors
- Converters for high energy photon detection
- Materials for low detector mass application
- Materials for low cost detectors
- Materials for large size detectors.

In particular, the material budget reduction is common to several applications and some approaches have already been considered.

The simplest idea is to decrease the thickness of electrode material. Recently, GEM foils have been produced, where the electrode thickness of 5 µm Cu have been reduced to 2 µm. Correspondingly, also the read-out boards should be lightened; this is even more necessary taking into account that the electric circuits are getting more and more complex, thus requiring more layers, which results in increased mass.

The second idea is to replace heavy metals by lighter ones, like Aluminum. At the present state of the art, it seems difficult to swap copper with aluminum in GEM detectors. Bulk Micromegas detectors using stainless steel meshes could be lightened by using aluminum vacuum plated polyester mesh. Read-out boards can be produced using aluminum for the conductive pattern.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG1-1/Development of large-area Micro-Pattern Gas Detectors - Micromegas	CEA Saclay, Demokritos, Napoli, Bari, Athens Tech. U., Athens U., Lanzhou, Geneva, PNPI, Thessaloniki, Ottawa/Carleton	Development of large area Micromegas with segmented mesh and resistive anodes	First prototype (1x0.5m^2)	m1/m12
			SLHC full size	m13/m60
	CEA Saclay, Ottawa/Carleton Demokritos, Athens Tech. U., Athens U.		ILC full size	m13/m36
WG1-1/Development of large-area Micro-Pattern Gas Detectors - GEM	Bari, CERN, Pisa-Siena, Roma, Arlington, Melbourne, TERA, PNPI, MPI Munich, Argonne	R&D	Report, small size prototypes	m1/m18
	Bari, CERN, Pisa-Siena		Full scale prototype	m6/m18
			Development completed	m19/m30
	Arlington		Medium-size prototype	m1/m6
			1 m^2 prototype	m13/m18
			1 m^3 stack	m19/m30
	Roma, Bari		JLab HallA full scale prototype	m18/m30

TASK 2

Detector design optimization including fabrication methods and new geometries (Bulk Micromegas, Microbulk Micromegas, single-mask GEM, THGEM, RETGEM, MHSP, charge-dispersive readout, Ingrid).

The MPGD structures can be grouped in two large families: Micromesh-based detectors and hole-type structures, both groups including rather mature technologies and novel approaches. The micromesh-based structures include: Micromegas, Bulk Micromegas, Microbulk Micromegas and Ingrid. The Hole-type structures are: GEMs, micro GEMs, thick GEMs (LEMs or THGEM), Resistive thick GEMs (RTHGEM) and MSHPs.

New geometries of the hole-type structures

They are derived from the GEM structure and they aim at specific applications. Within RD51 the following structures will be studied and developed:

micro GEMs, thick GEMs (LEMs or THGEM), Resistive thick GEMs (RTHGEM) and MSHPs.

In **thick-GEMs**, the GEM structure is scaled to larger values of the geometrical parameters. This is obtained replacing the kapton foil with a PCB; holes are produced by standard drilling techniques; the conical shape of the GEM holes is replaced by a clearance ring around the hole, the rim, obtained by PCB etching. Typical figures for the geometrical parameters range between 0.4 and 1 mm for the thickness, between 0.3 and 1 mm for the hole diameter, between 0.6 and 1.2 mm for the pitch; the rim varies between 0 and 0.1 mm. These electron multipliers exhibit specific features: the geometrical parameters can be scaled from GEM ones, but the microscopic behavior of the electrons, in particular diffusion in the gas, does not scale. As a consequence specific study and parameter optimization are needed. Thick GEMs are robust, mechanically stiff and can take advantage of a production technology widely used: they are well suited to instrument large surfaces. The space resolution that can be obtained is in the sub-mm range and the material budget is not particularly increased. These characteristics are fully compatible with the two main applications considered: the usage of THGEMs for the sensitive elements of digital hadron calorimetry and the design of THGEM-based single-photon detectors for Cherenkov imaging counters. In the latter application, THGEMs have CsI photocathodes deposited on their surface; the advantage of an architecture based on multiple layers of multipliers (cascaded multipliers), with respect to the presently used MWPCs, is the possibility to limit the ion feedback bombarding and damaging the photocathode.

In order to reduce or to eliminate discharges, **resistive THGEM**-like (RETGEM) structures have been studied, namely thick GEMs where the metal conductive electrodes are replaced by resistive materials, exhibiting surface resistivity in the range 0.1-1 MΩ/square. The main goal pursued introducing the resistive elements is to increase the electrical stability of the multipliers, making them stable at higher voltages so to obtain increased gains. Resistive structures have been produced either using resistive carbon loaded Kapton or screen-printed resistive technique. Preliminary tests indicate that the resistive-kapton material behaves better than the screen-printed version: the Kapton version is more robust against discharges and shows a better stability in time. In 2008, some material samples will be available from DuPont (US) allowing for studies of large size detectors, up to 500×500 mm^2. On the other hand, the advantage of the screen-printed technology is the possibility to easily change the value of the resistivity; studies of the sparking limit in these detectors have still to be performed.

The effectiveness of RETGEMs in low-rate applications has been demonstrated. More recently new geometries, where the resistive electrodes are coupled to conductive lines for fast voltage compensation have been proposed. The RETGEMs share several advantages and features of the THGEMs and the domain of applications is largely overlapping.

In the **MSHP structure**, also derived from the GEM geometry, the holes required to obtain electron multiplication are coupled to strip electrodes: the electric field configuration is set either to multiply avalanche electrons originating from hole-multiplication or to trap the positive ions produced in the avalanche process, in order to reduce the ion back-flow towards the cathode. Ion back-flow values below 10^{-3} have been reported. These structures have been developed to detect single photons in visible-sensitive gaseous photomultipliers or for Cherenkov imaging applications. The ultimate goal of this R&D program is the development of gaseous photon detectors: the photoconverters sensible to visible light are extremely fragile and they require the recently reached ion suppression in the range 10^{-4}.

Charge-Dispersive Readout Technique

The main idea of the charge-dispersive readout technique is to cover the read out pads with a thin dielectric layer and then cover this layer with a resistive sheet. This technology gives the possibility to increase the size of the read out pads and consequentially reduce the number of electronic channels for the same spatial resolution.

Charge dispersion readout techniques developed so far have been adequate for small 10×10 cm prototypes but they are inadequate for large detectors. The anode readout structure shall have uniform RC response over its area since any non-uniformity results in systematic bias in the measured position. Although the bias can be removed by calibration, for large detectors the calibration will be cumbersome and therefore the bias errors must be minimized. This will require: a) a high quality film with homogeneous surface resistivity and uniform thickness; and also b) excellent quality of lamination and of the intermediate insulating layer of dielectric should minimize the variation of spacing between the resistive layer and the readout pads. The resistive films used so far have the required uniformity of surface resistivity - within 5%. However, at present, there is no reliable supplier for high-quality resistive film. Non-uniform dielectric gap is presently the major weakness. Contacts were made with industry to investigate if spin coating or techniques used in fabricating multilayer PCBs or lamination techniques used in preparing thin silicon wafers for processing could be adapted for our needs. The CERN TS-DEM workshop has the expertise and the resources to help here.

Developments underway include improvement of resistive coatings for improving the space resolution by charge spreading and protection against sparks. There, new photovoltaic techniques and screen printing are tracks to be explored. The resistive-anode techniques have to be made compatible with the "bulk" technology, to combine the advantages of both.

PixelGEM detectors

PixelGEM detectors join the well established GEM technique, characterized by its remarkable space and time resolution, to a new architecture of the read-out elements: strips are replaced by pixels of 1 mm^2 typical size. This approach makes it possible to effectively extend the rate capability of the GEM-based detectors, by overcoming the limits related to the read-out channel occupancy. The first prototypes exist and demand for a complete characterization and optimization.

Ingrid Developments

With the InGrid technology, a grid is constructed onto a CMOS chip, resulting in an integrated and monolithic readout sensor. The InGrid technology is now being transferred to industry and is expected to become widely available in the future. New R&D is required for the production of highly-resistive grid material. At present, the CMOS chips are protected against gas discharges by a 20 µm thick highly-resistive layer, fully covering the chip. With a highly-resistive grid, this protection layer could be much thinner, or even completely removed, if circuitry in each pixel provides adequate dissipative charge drain.

Another R&D project is the development of multigrid structures. A first TwinGrid, in which a second InGrid is placed on top of the first one, has been constructed and already tested (see section II). With two grids, the gains in the two gaps can be chosen and optimized. In this mode of operation, only a modest extracting field is required in the bottom gap, avoiding discharges onto the pixel chip. Many parameters like ion feedback, energy resolution and single-electron efficiency can be optimized by variation of the geometrical parameters: the grid holes (shape and diameter), which can be different for both grids, and the gap sizes. In the next step, a third grid was added, providing new degrees of freedom, like the possibility to serve as a 'gating grid'. The misalignment of grid holes in this Triple-Grid may reduce or eliminate ion feedback. It should be mentioned that in order to optimize design of multigrid systems, extensive and detailed 3D simulations will be required in the future.

The 'wafer post-processing' technology can also be used if the readout CMOS matrix does not exactly match the required detector granularity. "Through-wafer vias" connections with variable re-routing lines allows to use detector elements with slightly smaller readout chips and space left over for external connections [114].

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG1-2/Further developments of new multiplier techniques – THGEM	CERN, Coimbra/Aveiro, Mexico, Trieste, Rehovot, Alessandria, Torino	Optimization of the THGEM technology for high gain, stable operation understanding the role of the geometrical and production parameters	Report	m1/m18
WG1-2/Further developments of new multiplier techniques – THGEM	Coimbra/Aveiro, Rehovot, Barcelona, Trieste	Development of large area THGEM, improvement of production techniques; search for optimal electrode materials, incl. low-radioactivity ones	Production techniques and new materials; prototype	m1/m24
WG1-2/Further developments of new multiplier techniques – THGEM	CERN, Trieste, Rehovot, Alessandria, Torino	Optimization of the THGEM technology for single photon detection	Report	m1/m18
WG1-2/ Further developments of new multiplier techniques – RETGEM	St. Etienne, St Petersburg	Development and optimization of RETGEM architectures and design	Report, small size prototype	m1/m30
WG1-2/ Further developments of new multiplier techniques –	Munich TUM	Optimization and characterization of	Prototype	m1/m12

PixelGEMs		PixelGEM counters		
WG1-2/Further developments of new multiplier techniques – INGRID	Bonn, NIKHEF	Postprocessing of the Timepix chip, present version	Report, small size prototypes	m1/m30
WG1-2/Further developments of new multiplier techniques - MHSP	Coimbra/Aveiro, Rehovot	Development and optimization of large-area MHSP detectors with 2D resistive readout	Report	m1/m18
	Coimbra/Aveiro, Rehovot		Full-scale prototype	m19/m30
WG1-2/Further developments of new multiplier techniques – COBRA	Coimbra/Aveiro, Rehovot	Development of two-sided MHSP and other patterned devices (e.g. COBRA) for ion trapping	Development report	m1/m24
WG1-2/Further developments of new multiplier techniques - bulk Micromegas with embedded digital FE electronics	Annecy, CEA Saclay	Development of large size units with reduced material budget	Mechanical prototype ($1m^2$)	m1/m6
			Bulk assembly	m7/m18
			Bulk assembly equipped with electronics	m19/m30
			Cubic meter prototype	m31/m60
WG1-2/Further developments of new multiplier techniques - GEM-based microvertex	Frascati, Bari	Development of cylindrical high space resolution GEM detectors	Prototype	m1/m30
WG1-2/Further developments of new multiplier techniques - INGRID-based microvertex	Nikhef	Development of Ingrid-based sensors for microvertex application	Report, small-size prototype	m1/m30

TASK 3

Development of Radiation-Hard and High Radiopurity Detectors

Radiation hardness of gaseous detectors has been a challenging and controversial topic since the beginning of their operation, and particularly for the high-energy physics experiments in view of the expected particle rates that these detectors will have to cope during their operation at the LHC. In the last 30 years a multitude of tests carried out in laboratory under conditions as stable and controlled as possible, have resulted in a set of good practices and recommendations that, when followed carefully, extend the lifetime of gas detectors by orders of magnitude [115] - [118]. Among them, a careful selection of detector assembly materials, gas mixtures and operating parameters are fundamental. It has yet to be proven if those gas detectors will cope with the expected doses in the real experimental environments.

Among all available gaseous detectors technologies, the Micro-Pattern Gas Detectors have emerged as the most robust ones. Lifetimes in excess of mC/mm^2, corresponding to a total particle flux of 10^{12} $MIPs/mm^2$, have been repeatedly reported with a variety of gases and obtained under different test conditions [119], [120]. The separation of gas amplification and the readout stages and a possible smaller effect of polymerization deposits on the electric field of MPGD are the main causes that would explain such immunity to aging, as compared to traditional wire chambers.

To advance in the field of radiation hardness and optimized materials, irradiation tests, specific aging studies and material out-gassing measurements are foreseen. MPGDs production and tests with radio-clean electrodes will be done, e.g. with Cirlex (a polyamide) [121].

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG1-3/Development of low-radioactivity materials	Zaragoza, CEA Saclay, Demokritos, Ottawa/Carleton	Development and upgrade of the manufacturing process of Micromegas for high radio purity applications	Report, small size prototypes	m1/m36
			Full-scale prototype	m37/m60
	Rehovot	THGEM production of radio-clean materials for rare-events	Prototype	m1/m20
WG1-3 / Development of radiation-hard detector concepts for future hadron colliders and fixed-target experiments	CERN, CEA Saclay, Demokritos, Napoli, Bari, Athens Tech. U., Athens U., Lanzhou, Geneva, St Petersburg , Thessaloniki, Ottawa/Carleton	Study and optimization of radiation hard MPGDs and optimized materials	Report, small size prototypes	m1/m36
		Aging studies at GIF	large prototype	m37/m60

TASK 4
Design of portable sealed detectors

Some applications (safety, solar-blind detection of flares, on-site radio-activity control in mines or in nuclear plants) require that detectors can be autonomous and easily transported to the site of use. This calls for sealed detectors, with portable high voltage supplies and portable electronics. Materials have to be chosen for low outgassing and gas-tightness, gas studies are necessary to find mixtures less sensitive to contamination, and special processing of the parts must be defined to allow a detector to work several months autonomously.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG1-4/ Design of portable detectors	CEA Saclay, CERN, St Etienne	Development of portable MPGD detector system	Report, Small size prototypes	m1/m12 m13/m24

III-B. Common Characterization and Physics Issues (WG2)

OBJECTIVE
Development of common standards and comparison of different technologies, performance evaluation of different MPGD detectors.

OBJECTIVE
Development of radiation-hard gaseous detectors operating beyond the limits of present devices.

TASK 1
Development of common test standards (comparison of different technologies in different laboratories)

The activities of groups can be subdivided as follows:

- (Large) area GEMs
- (Bulk) Micromegas & InGrid
- RETGEM
- THGEM, MHSP
- Other MPGDs

Operating test chambers can be done by means of cosmic rays, X-rays, radio-active sources, charged particles and from neutrons test beams, and by UV light (photo effect). Evaluation parameters are specific to particular application, but in general include:

- MPGD Geometry
- Detector dimensions and gas gain uniformity over the active area
- Gas mixture composition
- Detection efficiency
- Maximum gas gain and rate capability
- Energy, spatial and time resolution
- Gas gain calibration (charge pulse injection, ^{55}Fe signal monitoring, current measurements)
- Discharge probability
- If relevant: track position resolution per unit track length

In some cases results of the evaluation strongly depend on the experimental conditions and parameters definition. Development of common testing protocols and standards allows direct comparison of the results obtained with different technologies in different laboratories.

A database will be set up containing these evaluation parameters.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG2-1/Development of common test standards	CERN, CEA Saclay	Large GEM & Micromegas	Report	m1/m36
WG2-1/Development of common test standards	Freiburg	UV-laser probing, Pixel readout		
WG2-1/Development of common test standards	Hamburg/DESY	GEM characterization (electrical & mechanical)	Report	m1/m60
WG2-1/Development of common test standards	Univ. Geneva	GEM test bench		
WG2-1/Development of common test standards	Grenoble	1-100 keV source		
WG2-1/Development of common test standards	Nikhef, CEA Saclay, Bonn	GridPix/Gossip tests. Test beam experiments	GridPix, Gossip, InGrid detectors	m1/m60
WG2-1/Development of common test standards	Aristotle Univ. Thessaloniki NTU Athens, CEA Saclay, INP Demokritos Univ. of Athens, Ottawa/Carleton Hefei USTC, Napoli INFN	Micromegas studies, development of tracker detectors	Definition of operational parameters Prototypes construction	m1/m24 m1/m60
WG2-1/Development of common test standards	ICN UNAM Mexico	Large area photosensitive THGEM and RETGEM tests	Prototypes, operational parameters, construction, quantum efficiency	m1/m60
WG2-1/Development of common test standards	Rehovot	Setups for detector tests under high-purity conditions (monitoring with mass spectrometer)	Experimental setups	m1/m60
WG2-1/Development of common test standards	PTB Braunschweig	Calibrated and well specified neutron beams (few 10 keV - 20 MeV in house), thermal and fast up to 200 MeV externally.	Experimental setups. Full series of specified ISO energies (thermal epithermal, fast). Spectrum: white, monochromatic or quasi-monochromatic,	m1/m60

			pulsed and unpulsed.	
WG2-1/Development of common test standards	St Petersburg			

TASK 2
Discharge studies and spark-protection developments for MPGDs

Although discharges can be reduced or eliminated in special chambers, robustness is very important factor for the development of discharge-proof detector concepts. Discharges occur within the electrodes of MPGDs themselves, or between the electrodes and the pixels of CMOS chips, applied as active anode.

It is important to distinguish between (avoidable) discharges in edge areas like feedthroughs or electrode boundaries, and MPGD-intrinsic areas such as GEM or Micromegas hole rims. Indications of a dependence of the discharge limit on detector geometry (including cascaded detectors) suggest that a more detailed investigation on each device may lead to small, and hopefully cumulative, improvements. The effect of the gas composition should also be examined.

The comfortable margin between the gain needed for full efficiency detection of fast particles (~2000) and the maximum gain before discharge in the double devices (> 10^4) suggest that the recently introduced MPGD family is the most suited for reliable use in high-rate experimental set-ups, with simultaneous presence of a high flux of relativistic charged particles to be detected, and of a considerable background of unwanted, highly ionizing events, as for example proton knock-off by neutrons conversions and production of nuclear fragments. More experimental work and a careful analysis to the operational safety margins should be made before the adoption of particular detector geometry for the experiment.

Solutions are possible in applying (high resistivity) protection layers and in (dissipative) circuits in (pixel) front-end electronics. In order to study robustness of gas detectors, discharges can be provoked in a controlled way, with known intensity, by means of Thorium in the gas volume. The (exponential) relation between the applied electric field and discharge rate is an important quantity, determined by the MPGD geometry, the gas mixture and the HV.

One of the goals is to develop a more accurate model for discharge (streamer) development.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG2-2/ Discharge studies and spark-protection	St Etienne	Discharges, Rate effects	Resistive strip design of RETGEM	m1/m36
WG2-2/ Discharge studies and spark-protection	Budapest Eotvos Lorand	Sparks, Charging up		
WG2-2/ Discharge studies and spark-protection	Annecy	Spark protection	Bulk-Micromegas with resistive protection	m1/m18

			protection chip	m1/m24
WG2-2/ Discharge studies and spark-protection	Nikhef	Discharge studies GridPix, protection layers, discharge modeling	Dissipation circuitry, protection layers	m1/m60
WG2-2/ Discharge studies and spark-protection	St Petersburg			
WG2-2/ Discharge studies and spark-protection	CEA Saclay, NTU Athens, Demokritos	Micromegas discharge studies	prototype	m1/m18
WG2-2/ Discharge studies and spark-protection	TU-Munich	Radiation hardness tests		
WG2-2/ Discharge studies and spark-protection	ICN UNAM Mexico	Discharges	Spark-protected photosensitive THGEM and RETGEM	m1/m36
WG2-2/ Discharge studies and spark-protection	Univ. Athens	Bulk Micromegas Atlas Muon Update		
WG2-2/ Discharge studies and spark-protection	NTU Athens	Micromegas discharge studies and spark protection		
WG2-2/Development of common test standards	INP Demokritos	Micromegas, discharge studies, spark protection	Protection methods	m1/m18
WG2-2/ Discharge studies and spark-protection	Arlington	GEM Discharge studies		
WG2-2/ Discharge studies and spark-protection	Rehovot	Spark protection, resistive films	Methods, report	m6/m24

TASK 3

Generic aging and material radiation-hardness studies (creation of database of "radiation-hard" materials & detectors depending on application, commercially available materials, cleanliness requirements, validation tests for final detector modules, gas system construction, working remedies)

Amongst the most critical items that affect the lifetime of gas detectors are the materials used in the construction of the detector itself, and in the gas system that supplies the gas mixture [119],[122]. This is because many non-metallic materials outgas vapors, which transported with the gas flow may end up on the electrodes and insulators of the chamber, and/or favor polymerization processes that would lead to the growth of deposits in the irradiated regions. Therefore a careful selection of materials that are in contact with the gas is mandatory to screen those that would spontaneously outgas, even before verifying additional outgassing effects caused by the exposure of material samples to ionizing radiation.

Traditionally, such systematic studies have been carried out by introducing material samples in the gas flow stream of a non-prone to aging gas counter that was irradiated under controlled conditions [117]. The performance of the detector (typically its gas gain) was monitored and the gas analyzed in order to establish correlations between detector degradation and detection of pollutants in the mixture. The method is time consuming but allows establishing a list of materials suited for the assembly of rad-hard detectors. A swifter approach is possible by testing material samples, either searching for outgassing components in samples that are put in contact with gas by means of a gas chromatography/mass spectrometry, or for instance performing infrared analysis of a given material sample. Such analytical methods permit establishing a wide pre-selection of potential assembly materials that can be used as starting point to build complete detectors; the most promising candidate materials would need to be fully validated in dedicated aging set-ups.

By means of several sources of ionization radiation, MPGDs are tested on radiation hardness. Reports include figures on collected charge per unit surface, and collected dose in standard units. The applied sources of irradiation are stated.

E.g., at NIKHEF, an ultra clean system with some 25 InGrid MPGDs, placed in (gas) series, will be irradiated with UV light. The primary (photo-electric) current is amplified by gas amplification, resulting in a high current density (~ 1 µA/cm2).

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG2-3/ Generic aging and material radiation-hardness studies	CERN	Generic ageing Rad-hard materials	Report	m1/m36
WG2-3/ Generic aging and material radiation-hardness studies	Coimbra/Aveiro	Stability, rate effects, scintillating gases, CF_4	MHSP and THGEM aging results	m1/m60
WG2-3/ Generic aging and material radiation-hardness studies	Athens Aristotle Univ.	Ageing: strong ionization	Report	m6/m30
WG2-3/ Generic aging and material radiation-hardness studies	Bari INFN			
WG2-3/ Generic aging and material radiation-hardness studies	Cagliari INFN	(Triple) GEM Generic ageing CF4 in situ LHCB Muon Chambers	Reports	Start : m12 m18 first m30 final
WG2-3/ Generic aging and material radiation-hardness studies	Demokritos	5 MV source, Co source, Nucl. Reactor	Micromegas ageing results, improvements	m1/m18

WG2-3/ Generic aging and material radiation-hardness studies	Helsinki	Generic Ageing	Reports	m1/m60
WG2-3/ Generic aging and material radiation-hardness studies	Valencia IFIC	Outgassing		
WG2-3/ Generic aging and material radiation-hardness studies	LIP-Coimbra	Generic ageing		
WG2-3/ Generic aging and material radiation-hardness studies	Nikhef	Ageing of Gossip, 5 GBq 90Sr fac. Fundaments of ageing, UV light photoelectron source	Ageing-associated compounds, active filters	m1/m60
WG2-3/ Generic aging and material radiation-hardness studies	NTU Athens	5 MV source, Co source, Nucl. Reactor		
WG2-3/ Generic aging and material radiation-hardness studies	CEA Saclay	Micromegas aging studies with X-ray gun (cm^2 areas)	Report	m1/m60
WG2-3/Development of common test standards	ICN UNAM Mexico	Ageing studies of photosensitive RETGEM with several gases, especially in C_4F_{10}	Ageing results, improvements	m12/m60

TASK 4

Charging up (gain stability issues) and rate capability

MPGDs can exhibit an increase in gain after the high voltage is initially applied, and a certain time is required to reach a stable operating plateau [123]. This effect could be due to the polarization of the dielectric or the accumulation of charge on the dielectric surfaces [124], and it can therefore depend on a number of parameters of both the used foils and the operating environment of the detector. For example, in GEM-based detectors, the amount of increase and the time required to reach equilibrium can vary from foil to foil and may also depend on the rate of ionization. It has also been measured that GEM foils which exhibit a large charge up effect appear to be more susceptible to rate effects and to the water content of the operating gas. The amount of exposed polyimide in the holes of the GEM also appears to be a contributing factor to the amount of charge up effect observed. The same effect was recently observed in the case of THGEMs. Probably an even more complicated situation will exist in the case of RETGEMs. More studies of the insulating properties of the pillars used to support mesh in Micromegas should be also foreseen.

The RD-51 collaboration needs to define and carry out a set of tests to determine the principle causes of the increase in gain observed in certain MPGDs, and to try to understand if the parameters involved can be controlled in order to minimize or eliminate these effects and reach a stable operation. Reports are explicit on the parameters of the gas mixtures, gas gain and irradiation rate and water content. This becomes especially relevant for the development of large area MPGDs, where the amount of insulator material in the assembly can be important.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG2-4/ Charging up and rate capability	CERN	Stability studies	Report	m1/m36
WG2-4/ Charging up and rate capability	Coimbra/Aveiro	Stability, rate effects, scintillating gases, CF_4	MHSP and THGEM charging up results	m1/m60
WG2-4/ Charging up and rate capability	Rehovot	Gain stability and rate capability studies in ultra pure vs normal conditions	Report	m1/m24
WG2-4/ Charging up and rate capability	St Etienne	Discharges, Rate effects, Long-term stability tests	Optimization of the design and the construction materials	m1/m60
WG2-4/ Charging up and rate capability	Budapest Eotvos Lorand	Sparks, charging up,		
WG2-4/ Charging up and rate capability	Nikhef	Rate studies with InGrid & GridPix	Parameter sets	m1/m60
WG2-4/Development of common test standards	NTU Athens, INP Demokritos Univ of Athens	Micromegas rate issues Bulk Micromegas Atlas Muon Update	Rate improvement requirements	m1/m18
WG2-4/ Charging up and rate capability	CEA Saclay	Micromegas studies for COMPASS experiment	Prototype	m1/m24
WG2-4/ Charging up and rate capability	TERA-Pavia	GEM: rate effects		
WG2-4/ Charging up and rate capability	INFN-Trieste	THGEM charge up		
WG2-4/ Charging up and rate capability	TU-Munchen	Rate tests		
WG2-4/ Charging up and rate capability	ICN UNAM Mexico	Stability tests of large area photosensitive TGEMs and RETGEMs	Optimization of the design and the construction materials	m1/m60

TASK 5

Study of avalanche statistics: exponential versus Polya (saturated-avalanche mode)

The single electron response (Polya distribution) is relevant for the efficiency studies of MPGDs. The efficiency, Fano factor, Penning effects are to be known in order to obtain values for dE/dX and cluster content distribution with sufficient precision.

Other processes like the limited streamer mode, self quenching streamer mode, and discharge quenching are to be studied and reported.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG2-5/ Study of avalanche statistics	Nikhef, CEA Saclay	Micromegas and InGrid studies: single electron response, Polya distributions, Fano factors	Data + Simulations	m1/m24
WG2-5/ Study of avalanche statistics	NTUA Athens	Micromegas simulations		
WG2-5/ Study of avalanche statistics	Rehovot	Polya in THGEM and RETGEM in different gases	Report	m1/m18
WG2-5/ Study of avalanche statistics	Uludag Univ.	Simulation of avalanche gain statistics	Report or paper	m6/m18

III-C. Applications (WG3)

OBJECTIVE
Evaluation and optimization of MPGD technologies for specific applications.

The members of the new RD51 collaboration are engaged in a wide variety of projects using MPGDs. In this section we give summaries of those project application areas, which will, of course, benefit from the technical development work proposed. However, the responsibility for the completion of the application projects lies with the institutes themselves.

TASK 1
MPGD-based detectors for tracking and triggering (including Muon Systems)

Due to their wide variety of geometries and flexible operating parameters MPGDs are a common choice for tracking and triggering detectors in nuclear- and particle-physics. Consequently a large variety of different projects using these devices for tracking and triggering applications are currently under way or are being studied. Common themes for future applications are low mass, large active areas, high spatial resolution, high rate capabilities and high radiation tolerance.

Classical MPGD tracking detectors use thin *O*(mm) gas gaps from which the primary ionization from through-going ionizing radiation is collected. These electrons are then amplified by the amplification structure of choice. The amplified charge is collected on patterned readout structures with a large variety of possible patterning and routed to the readout electronics.

Micromegas are being considered for the SLHC upgrades of the ATLAS and CMS muon systems. With the luminosity increase at the SLHC, the particle fluxes in ATLAS Muon Spectrometer at pseudo-rapidities $\eta > 2$ will be of the order of few kHz/cm^2 at luminosity L = 10^{35}cm^{-2}s^{-1}. It is expected that forward muon tracking and trigger chambers of the ATLAS Muon Spectrometer with the highest counting rates will have to be replaced. Taking into account that several detector layers are needed, areas of more then 1000 m^2 will have to be instrumented with detectors that offer a spatial resolution of ~100 μm (RMS) and a time resolution of ~ 5 ns (RMS) and have high radiation tolerance. The “bulk Micromegas” technology is currently pursued to address these requirements, since it allows the production of very large area detectors. THGEM technology, which promises highly robust, high-rate devices and cost effective production, is also studied for these applications, as well as resistive plate chambers based on MPGDs. For LHCb, large-area planar detectors based on triple-GEM technology with a size of ~200 x 250 mm^2 with highly-granular pad readout have been developed for muon tracking and triggering in the high rate environment of SLHC.

For the PANDA experiment at the future FAIR facility thin large-area planar triple-GEM detectors are being developed, based on the experience from the triple-GEM trackers with 2D strip readout and the light-weight triple-GEM beam trackers with hybrid pixel/strip readout for the COMPASS experiment. For Hall A at Jefferson lab, a high resolution tracking system using triple-GEM chambers with an active area of 400 x 800 mm^2 and a spatial resolution of ~ 70 μm (RMS) as well as a large-area tracker with 1000 x 2000 mm^2 acceptance and a spatial resolution of better than 300 μm (RMS), both with 2D strip readout, is being planned. The STAR experiment at RHIC is currently designing and constructing a forward tracker based on 6 triple-GEM disks with a radius of ~ 400 mm and a 2D orthogonal (r-ϕ) strip readout based on GEM foils produced at Tech-Etch (supported by a US DOE SBIR grant), with an anticipated spatial resolution of better than 80 µm (RMS). In addition, the use of several small-area (~ 100 x 100 mm^2) triple-GEM trackers outside the main TPC of STAR is being studied as a means of improving TPC distortion corrections for high luminosity running. These two projects also involve the development of GEMs for tracking detectors and other applications at Tech-Etch. An ultra-light, fully sensitive cylindrical GEM detector has been proposed for the inner tracker of the upgraded KLOE experiment at DAFNE. The detector will provide a spatial resolution of $\sigma_{r\text{-}\phi}$ ~ 200 µm (RMS) and σ_z ~500 µm (RMS), with very low material budget.

MPGDs are also widely studied for the use in Time Projection Chambers (TPCs). They offer an improved spatial resolution, and some of the recent developments have a significant reduction of ion back-flow, relaxing the requirements on gating of the devices and, depending on the design, possibly allowing non-gated operation of TPCs. An additional requirement is low mass in the detector endplates. GEM and Micromegas with classical pad readout are investigated. The use of a GEM foil as a gating device, or as passive device to further suppress ion feed-back into the main drift volume are also subjects of studies; combined MHSP/GEM multipliers with unsurpassed ion blocking will be investigated. In addition, the readout with GEMs or Micromegas on top of ASICs with pixel readout that handle the charge collection as well as preamplification, digitization and sparsification of the signals, is studied. First proof of principles have been achieved with the Medipix2 and the Timepix chips, as well as with Timepix chips with an integrated Micromegas made from Si, the InGrid (see section II for detailes).

In addition to the large TPC project for the linear collider, TPCs can be used in directionally sensitive dark-matter searches and TPCs for high-multiplicity hadron experiments are studied. For the planned dEDM experiment at BNL, which will study the electric dipole moment of the neutron through studies of the deuteron, a TPC with Micromegas readout is being developed. A TPC based on GEM readout has been proposed for the inner tracker at the PANDA experiment. In order to cope with the high data rate of the experiment, this TPC will be operated without gating as a continuously sampling detector. A prototype detector, currently under construction, will be tested in the FOPI experiment at GSI and the Crystal Barrel at ELSA.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG3-1/ Detectors for Tracking and Triggering	INP/NCSR Athens, NTU Athens, U Athens, BNL, CERN, INFN Naples, U Thessaloniki, CEA Saclay	Bulk Micromegas for ATLAS and CMS SLHC muon system	First prototype Prototype studies to achieve 100 µm resolution	m1/m3 m4/m24
WG3-1/ Detectors for Tracking and Triggering	MPI Munich, Rehovot	THGEMs for ATLAS SLHC muon System	First studies, small prototypes	m1/m24
WG3-1/ Detectors for Tracking and Triggering	LIP Coimbra	Position sensitive timing RPCs for time-tagged muon tracking	Detailed project First prototype test Second prototype test	m1/m12 m13/m24 m25/m36

WG3-1/ Detectors for Tracking and Triggering	INFN Cagliari, INFN Frascati	Large triple-GEM tracking for LHCb	Detectors ready for installation First detectors installed, First tests with beam or cosmics Full installation and commissioning	m1/m3 m1/m3 m3/m12
WG3-1/ Detectors for Tracking and Triggering	TU Munich	Large-area triple-GEM tracking for PANDA		
WG3-1/ Detectors for Tracking and Triggering	INFN Rome	GEM-based tracking system for JLab Hall A	Conceptual design Detailed design Small area tracking Full scale prototype Revised design Electronics design Tracking modules Full integration Full calibration	m1/m3 m4/m6 m7/m12 m7/m12 m13/m18 m13/m18 m19/m36 m36/m48 m48/m60
WG3-1/ Detectors for Tracking and Triggering	BNL, Yale	Forward GEM tracker of STAR	Detector installation	m1/m24
WG3-1/ Detectors for Tracking and Triggering	Yale	Small-area triple GEM tracking outside STAR TPC	Detector installation	m1/m24
WG3-1/ Detectors for Tracking and Triggering	NIKHEF, CEA Saclay, Bonn, Freiburg, Ottawa/Carleton, Hamburg/DESY	LCTPC	Prototypes	m1/m60
WG3-1/ Detectors for Tracking and Triggering	TU Munich	GEM-TPC for PANDA		
WG3-1/ Detectors for Tracking and Triggering	INFN Frascati	Cylindrical GEM tracker for KLOE	Full scale prototype Final project Detector construction Full integration and Installation	m1/m3 m3/m12 m12/m24 m12/m24

TASK 2
MPGD based Photon Detectors (e.g. for RICH)

The use of gaseous detectors coupled with CsI photocathodes for large-area Ring Imaging Cherenkov Counters (RICH) is a well-established technique in nuclear and particle physics. The present devices, based on MWPCs, suffer from limitations in the achievable gain due to aging of the photo-cathodes from ion bombardment and due to ion-induced instabilities in the MWPCs. These gain limitations also lead to the need for long integration times and consequently limits on rates and time resolution. MPGDs, in particular GEM-like devices, are a very promising technology in this field due to the intrinsic ion feedback suppression, the cascadability of the multipliers to reach high gain and the possibility to directly deposit CsI photocathodes on the multiplier's surface.

For the application in RICH detectors, a rather coarse spatial resolution is usually sufficient, thus THGEMs are currently actively studied as photo-detectors. They offer a large area that can be coated with CsI, leading to high quantum efficiency, and their stiffness facilitates detector construction. Photosensitive THGEMs and RETGEMs are studied for an upgrade of the ALICE RICH, the VHMPID. Others are under R&D for COMPASS.

The operation of MPGDs with CsI photo-cathodes in CF_4 gas opens up the possibility for windowless Cherenkov detectors, where both the radiator and the charge detectors share the same gas volume. This principle was successfully applied in the PHENIX Hadron Blind Detector using a triple-GEM system with reversed drift field.

Recent advances in GEM/MHSP cascaded multipliers for single photon, UV and visible-sensitive photosensors, envisage high performance operation of such devices. Further studies are important to proceed with, namely in large-area detection with CsI or bialkali photocathodes. Also, preliminary results on a new micropatterned microstructure, the COBRA [34], indicate excellent ion back-flow reduction capability in cascaded electron multipliers. Since this device is still in its infancy, systematic studies are needed to evaluate its full potential.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG3-2/ Photon Detectors	Rehovot, INFN Trieste, Coimbra/Aveiro	Development of RICH detectors using THGEMs	Report Basic studies Prototypes Beam tests	m1/m36
WG3-2/ Photon Detectors	Coimbra/Aveiro, Rehovot	Study of MHSP, COBRA, and new patterned multipliers for photon detection and ion backflow reduction	Report Basic studies Prototype results	m1/m60
WG3-2/ Photon Detectors	Coimbra/Aveiro, Rehovot	Development of PACEMs and other high pressure photon detection devices	Report Basic studies Prototype results	m1/m24
WG3-2/ Photon Detectors	UNA Mexico	THGEMs, RETGEMs for ALICE VHMPID	Laboratory tests RICH prototype beam tests	m1/m3 m4/m12 m13/m24
WG3-2/Photon Detectors	Rehovot, Subatech-Nantes	THGEM gas PMTs for LXe Gamma Cameras	Basic studies, small prototypes	M3/m27

WG3-2/Photon Detectors	Rehovot, Coimbra/Aveiro	Gaseous PMTs for visible light with hole multipliers	Basic studies, small prototypes	M1/m48

TASK 3

Applications of MPGD based detectors in Calorimetry

Large-area MPGD systems are being studied as potential solutions for digital hadron calorimeters of future Linear Colliders. Implementations in GEM, THGEM, Micromegas, MHSPs, and RPCs, have been proposed.

Physics at a future linear collider demands unprecedented jet energy and di-jet mass resolutions. The Particle Flow Algorithm (PFA) approach is a promising avenue for realizing these resolutions. PFA's require as input very detailed information on shower development. This can be provided through the use of high granularity calorimeters, with small, O(1cm^2), cells readout in digital mode (DHCAL). The challenge then is to produce several thousand square meters of detector planes having good hit efficiency, low hit multiplicity, small dead boundary regions, and robustness against discharges or sparking. High density readout will also be required for the large channel count, O(10^8). Large area, O(1m^2), GEM planes are being developed for a DHCAL with high density readout via the SLAC KPiX chip. A commercial source of GEMs is also being developed in collaboration with industry.

MPGD-based digital hadron calorimetry is also being studied using Micromegas. Both analog and digital readout are pursued using the GASSIPLEX and HARDROC chips respectively. The use of THGEMs for large-area calorimeter applications is being studied as THGEMs offer the potential for low-cost large-area devices that are mechanically robust and can operate at high gains.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG3-3/Application of MPGD based detectors in Calorimetry	LAPP	Understand Micromegas for digital hadron calorimetry with PFA	Test beam results from prototype(s)	m1/m12
WG3-3/Application of MPGD based detectors in Calorimetry	UTA,UNAM	Develop and test large area GEM planes for calorimetry with PFA	1)Source/test beam results 2)Construct 1m^2 plane	m1/m3 m4/m12
WG3-3/Application of MPGD based detectors in Calorimetry	Columbia U. South Carolina	Micromegas/ electronics for calorimeter applications	Readout for bulk Micromegas	
WG3-3/Application of MPGD based detectors in Calorimetry	Rehovot, MPI-Munich, Coimbra/Aveiro	Use of THGEMs for calorimeter applications	first studies	m1/m12
WG3-3/Application of MPGD based detectors in	INP-Demokritos	Long term interest in Micromegas for		

Calorimetry		calorimetry		

TASK 4
Cryogenic Detectors for rare events

GEM, THGEM, RETGEM and MHSP systems are being developed for applications in cryogenic detectors for dark matter searches, neutrino physics (neutrino beams, superbeams, and astrophysical neutrino detection), double-beta decay, axion searches, and PET.

For instance, two-phase cryogenic detectors are being developed, based on GEMs and THGEMs, operating in argon and xenon for coherent neutrino-nucleus scattering, dark matter searches and PET. They will detect both ionization and scintillation signals in two-phase Ar and Xe detectors using multipliers with CsI photocathodes. The final goal is to provide results that can be used for the development of a 100 l detector, large enough to be used for full-scale neutrino-nucleus and dark matter experiments.

For applications in neutrino physics THGEM hybrid devices are being developed in combination with new generation silicon photosensors for operation in or above cryogenic liquids, notably liquid xenon. The objective is to demonstrate robustness and reliability of MPGDs, particularly with liquids, and studies of gain issues. Neutrino physics applications are being studied for use in detecting Super-Novae explosions, solar neutrinos, and double-beta decay.

Finally, MPGDs are also being applied to axion searches (CAST).

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG3-4/Application of MPGD based cryogenic detectors for rare events	Novosibirsk	GEM and THGEM detectors for coherent ν-nucleus scattering, dark matter search and PET	1) 10 l two-phase detector 2) Detection of nuclear recoils 3) Detector with ionization and scintillation	m1/m12 m13/m24 m25/m36
WG3-4/Application of MPGD based cryogenic detectors for rare events	Rehovot, UNAM, Sheffield, Coimbra/Aveiro	Development of dark matter search detectors using THGEM, RETGEM, and Micromegas.	Report, laboratory results, small prototypes	m1/m24-m60
WG3-4/Application of MPGD based cryogenic detectors for rare events	Sheffield	THGEM + cryo liquids for neutrino beam, superbeams	1) LAr test of photosensor readout 2) LAr rig for n-beam	m1/m3 m1/m3

			3) Completion of readout for 5x5 cm2 TGEM/LEM strip 4) Design of 200kg LAr rig 5) First operation of 200kg rig	m1/m2 m1/m9 m20/m24
WG3-4/Application of MPGD based cryogenic detectors for rare events	Rehovot, Novosibirsk, Coimbra/Aveiro	THGEM and other MPGD detectors for Super-Novae explosions, Solar neutrinos, Double-beta decay.	Report, basic results, prototypes	m1/m12-60

TASK 5

X-ray and neutron imaging

Gaseous detectors are used for neutron detection, usually by means of a hydrogenous converter. Detectors for thermal neutron as well as fast neutron (1 - 10 MeV) detection based on triple-GEM readout with a neutron converter are being studied, as well as Micromegas with a thin polyethylene film on the drift cathode.

MPGDs are also used in X-ray detectors. A particularly interesting application is the possibility to measure X-ray polarization by tracking individual photo-electrons, emitted perpendicular to the X-ray direction, in the detector gas, whose spatial distribution is determined by the polarization of the incoming photon. This is possible with a high-resolution readout of the signals on a pad plane below a MPGD.

X-ray detectors are also being developed for diffraction experiments at synchrotron radiation facilities based on triple GEMs structures. For the CAST solar axion experiment at CERN, X-ray detectors with 2D readout using Micromegas were designed and are operated with further developments ongoing. THGEMs and other related device such as MHSPs are investigated for their use in X-ray detection and polarization measurements. Also, the combination of MPGDs with Medipix2 and Timepix CMOS pixel chips is studied for the use in X-ray and neutron detection.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG3-5/ Neutron Imaging	PTB Braunschweig, Rehovot	Cascaded-GEM/THGEM for thermal and fast neutron imaging	Prototype detectors, tested in fast n-beams	m1/m24
WG3-5/ Neutron Imaging	Lanzhou, CEA Saclay	Micromegas for neutron detection	Prototype studies	m1/m36

WG3-5/X-ray Imaging	Novosibirsk	X-ray detectors for synchrotron radiation facilities	Prototype full detector	m1/m3 m4/m12
WG3-5/X-ray Imaging	INP/NCSR Athens, NTU Athens, U Zaragoza, CEA Saclay	Micromegas for X-ray detection at CAST		m1/m12
WG3-5/X-ray Imaging	Rehovot, Coimbra/Aveiro	THGEMs and related devices (e.g. MHSP) for X-ray detection and polarization measurement	Report, basic results, small prototypes	m1/m12-m60
WG3-5/X-ray Imaging	U Montreal	Medipix2 / Timepix with MPGDs for X-ray and neutron detection		

TASK 6

Astroparticle physics applications

MPGDs also offer interesting possibilities for astro-particle physics applications. In many cases, this overlaps with the use of such devices in areas discussed above, since these astro-particle physics applications often demand tracking, photon or X-ray detection or cryogenic devices.

Common applications are X-ray detection, possibly with polarization measurement, cryogenic detectors for neutrino and dark matter detection, and time projection chambers. A micro-TPC (MIMAC) is being developed for direct detection of non-baryonic dark matter by accurately measuring the track of recoil nuclei in the detector gas, and a TPC with Micromegas readout for rare event detection, such as dark matter studies and the search for neutrinoless double beta decay is under study.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG3-6/Astroparticle Physics	Zaragoza, Ottawa/Carleton	High Pressure Xe TPC with Micromegas readout	First tests improved Radiopurity of Micromegas	m1/m12 m13/m24
WG3-6/Astroparticle Physics	Barcelona/IFAE, Zaragoza, Ottawa/Carleton	Xe TPC with MPGD readout for NEXT or EXO	Small prototype Full detector (100 - 200 kg)	m1/m36 m37/m48
WG3-6/Astroparticle Physics	INP/NCSR Athens, NTU Athens, Zaragoza	X-ray detection / polarization measurement		

WG3-6/Astroparticle Physics	Novosibirsk, Sheffield, Rehovot	Cryogenic GEM/ ThickGEM detectors for neutrino and dark matter detection	Prototype (10 kg) Full Detector (100 kg)	m1/m15 m15/m48
WG3-6/Astroparticle Physics	LPSC Grenoble	Micro-TPC for dark matter detection	Bi-chamber module	m1/m36

TASK 7
Medical applications

MPGDs offer a number of possibilities for high resolution medical imaging at lower radiation doses, and potentially lower cost, than traditional techniques.

Proposed medical applications for MPGDs include Positron Emission Tomography, Mini SPECT/PET, and Nuclear Scattering Tomography for hadron therapy, X-ray imaging, and cancer diagnostics, and nanodosimetry.

The use of THGEMs is being studied for medical imaging, cancer diagnostics, and nanodosimetry. The imaging projects include the use of noble-liquid detectors. Cryogenic two-phase detectors based on GEMs and THGEMs operating in xenon are being used for PET applications. Very high rate GEM detectors are also being developed for medical imaging.

GEM detectors are being applied to Nuclear Scattering Tomography/Radiography. Work is also underway on a new method for the position calibration of the outgoing proton beam of a cyclotron used to produce radioactive tracers for PET, and a mini SPECT/PET cylindrical detector based on GEM technology.

Micromegas are also being used for medical applications. For example, a small gamma camera for nuclear medicine is being developed using Micromegas to obtain information about the position of interaction of the gamma rays. Micromegas are also being used in the areas of neutron and muon imaging.

Another gamma camera project will use scintillation from high pressure xenon and two MPGD position sensitive VUV photosensors operating face to face, in order to evaluate the gamma ray interaction position.

Finally, a small animal PET scanner based on RPCs is being developed, combining time measurements (<100 ps) with sub-millimetric position resolution.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG3-7/Medical applications of MPGD based.	Rehovot (with Nantes)	THGEMs for medical imaging, cancer diagnostics, and nanodosimetry	Report, basics results, prototypes,	m1/m36
WG3-7/Medical applications of MPGD based.	Novosibirsk	Cryogenic two-phase detectors based on GEMs and THGEMs for PET	1) Practical two-phase Xe avalanche detector 2) Detection of ionization	m1/m12

		applications	and scintillation from Na22 3) Study of 3-D position sensitivity in two-phase Xe avalanche detector	m1/m24 m1/m36
WG3-7/Medical applications of MPGD based.	University of Sienna, INFN Pisa, TERA Foundation	Development of high rate GEM detectors for Medical Imaging, Nuclear Scattering Tomography/Radio graphy	Prototype and electronics	m6/m30
WG3-7/Medical applications of MPGD based.	The University of Athens, Athens NTU, Aristotle University of Thessaloniki, CNSTN (Tunis)	Medical applications of Micromegas	Prototype, software development for image processing	m1/m24
WG3-7/Medical applications of MPGD based.	Coimbra/Aveiro	Gamma camera for animals/small tumors – high pressure Xe. Energy resolved X-ray tomography. Single photon counting X-ray imaging. Nuclear medical imaging.	Prototype camera using CsI-MHSP and Xe Small prototype arc-shaped MHSP detector -1 slice -multi-slices 5x5 cm2 and 10x10cm2 prototypes Dual phase detector for gamma detection	m1/m24 m1/m16 m12/36 m1/m24 m6/m36
WG3-7/Medical applications of MPGD based.	Coimbra/Aveiro, Rehovot	Nuclear medical imaging.	Visible and position sensitive hole based GPMs coupled to scintillation crystals	m12/m60
WG3-7/Medical applications of MPGD based.	Lanzhou	X-ray, neutron, muon imaging	Small Micromegas prototypes for imaging	m1/m36
WG3-7/Medical applications of MPGD based.	LIP-Coimbra	RPC-PET small animal scanner	1) Detailed project description 2) 2-head system 3) 4-head PET scanner for	m1/m12 m13/m24 m25/m36

			mice	

TASK 8

Synchrotron Radiation, Plasma Diagnostics and Homeland Security applications

MPGDs can be used for a variety of security related applications ranging from the detection of illegal and/or dangerous cargo, through population protection from advance warning of earthquake and forest fires.

Searching for illegal nuclear material in cargo presents a major security challenge due to the vast number of containers transiting through ports on a daily basis. A GEM application is being developed for cargo scanning. The goal is to take advantage of the superior spatial resolution of GEMs to perform muon tomography on cargo to detect hidden nuclear contraband using cosmic ray muons. GEM detectors will provide precise tracking of the muons allowing measurement of the muon deflection due to multiple scattering by high-Z materials in the cargo. This will require the development of large area GEMs in combination with affordable front-end electronics.

RETGEMs are being developed for application to radon detection in the air as an early warning of earthquakes, and for UV visualization including remote forest fire detection. They also were used for detection of dangerous gases.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start/Delivery Date**
WG3-8/Homeland Security applications of MPGD based detectors	Melbourne Florida Institute of Technology	GEM application for cargo scanning (cosmic ray muon tomography)	Prototype (1mx1m)	m1/m24
WG3-8/Homeland Security applications of MPGD based detectors	Athens NTU	Micromegas for remote forest fire detection	Prototype	m1/m24
WG3-8/Homeland Security applications of MPGD based detectors	St Etienne	RETGEMs for earthquake early warning, and remote forest fire detection	Prototype	m1/m24

III-C. Simulation and Software Tools (WG4)

OBJECTIVE

Development of common, open access software and documentation for MPGD simulations

Currently existing programs (Heed, Garfield, Magboltz, finite element programs) are capable of predicting with good precision the performance of gas-based detectors with characteristic dimensions of the order of a millimeter or larger. This includes detectors such as TPCs, Cathode Strip Chambers, Multi-Wire Proportional Chambers and Muon Drift Tubes. Calculations for these detectors rely mostly on analytic solutions of the fields and a statistical treatment of electron transport processes in a gas mixture.

The situation is different for the small-scale detectors that are being developed, e.g. GEM, Micromegas and MPGD detectors coupled to pixel readout. Many of these devices have complex electrode shapes, contain dielectrics as significant field shaping elements and have characteristic dimensions at the micron level. The fields in these detectors can not be solved by analytic means and statistical transport methods are not applicable since the mean free path of electrons is of the same magnitude as the electrode size.

Small-scale detectors therefore call for major improvements in the techniques used to compute fields and to simulate electron transport. Other areas where progress can be made within the RD51 collaboration are the simulation of ionization processes, handling of Penning transfers and the modeling of RPCs.

Work is also planned on the user interface. In particular, we intend to ensure that detector specific calculations can be combined with the statistical methods and the graphics provided by ROOT; as well as with the geometry extension and visualization of Geant 4.

TASK 1

Development of algorithms (in particular in the domain of very small scale structures)

Finite Elements Method:

The fields in small-scale devices are currently computed with the help of the finite element method. This technique, widely used for stress-strain analysis in engineering, starts by subdividing the problem domain into a patchwork of elements: triangles, tetrahedra, hexahedra etc. Inside the elements, the field is usually approximated by polynomials.

The method is not really satisfactory for electrostatic calculations for several reasons. In the case of the finite element program most widely used for detector studies, the polynomials are linear functions. Harmless for most purposes, but perhaps surprising, these are as a rule not solutions of the Maxwell equations. Much more serious is that they are a particularly poor approximation of the 1/r or $1/r^2$ fields encountered in the vicinity of electrodes, which is where most of the signal is produced. Furthermore, the field is discontinuous across element boundaries.

Integral Equations:

A promising alternative to the finite element method seems to be the Boundary Element Model (BEM). This method approximates the field as a sum over sources distributed on device boundaries and various dielectric interfaces, using the point-, line- or area-source fields. The elemental areas at the present level of development can be either rectangular or triangular that can suitably model any arbitrary three dimensional geometry. It leads to plausible field variations in the vicinity of the electrodes and to fields that are continuous. The technique is not widely available in commercial form, but open-source implementations are starting to emerge. One of these is specifically designed for the kind of elements frequently encountered in small-scale detectors and we intend to interface this program with other simulation frameworks.

TASK 2
Simulation improvements

<u>Electron Transport:</u>

The Magboltz program computes its statistical transport parameters from a microscopic simulation assuming constant fields. When tracing electrons through non-uniform fields, it is assumed that the field variations are small compared to the mean free path. This is not necessarily true in small-scale devices: the mean free path in commonly used gas mixtures is of the order of 1 µm (see Fig. 15), comparable to the thickness of e.g. GEM electrodes.

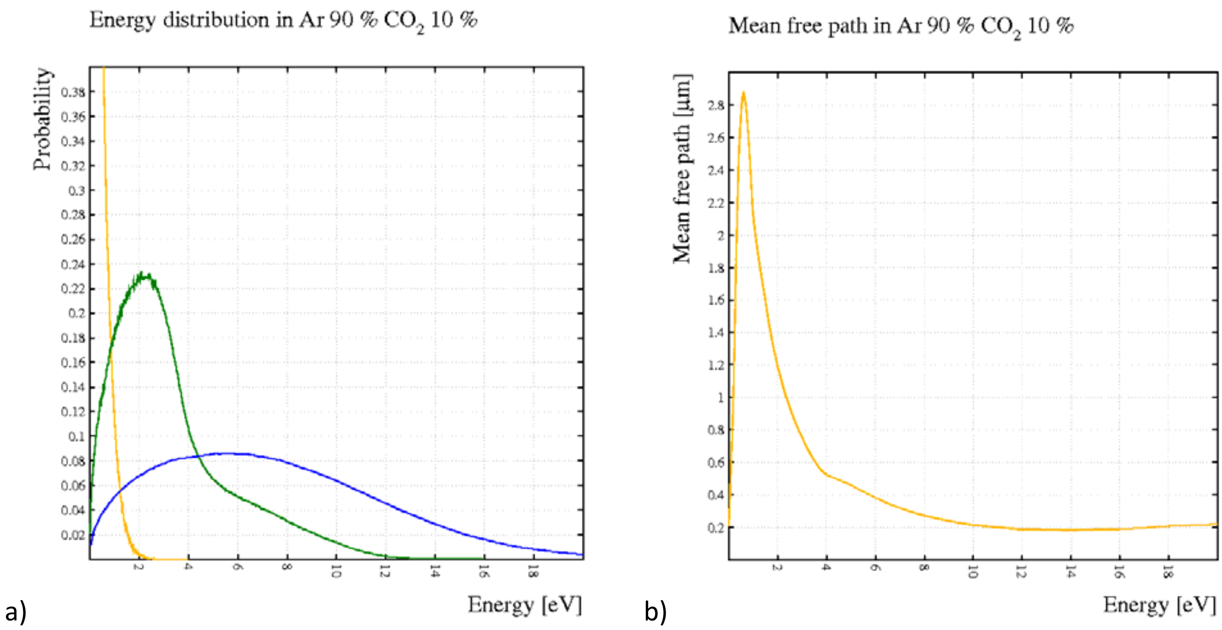


Fig. 15. a) The energy distribution of electrons in Ar/CO_2 (90:10) at an electric field strength of E = 500 V/cm (orange), E = 5000 V/cm (green) and E = 50000 V/cm (blue). Folding these distributions with the electron mean free path in this mixture shown in b), one finds average mean free paths of λ = 1.3, 1.0, 0.5 µm for E = 500, 5000, 50000 V/cm.

For transport over distances of 1 µm and larger, the most viable approach seems to be a Monte Carlo simulation using the uniform-field transport coefficients. This method is non-trivial because the positional probability distributions are in general non-Gaussian. Significant progress in this area has been made recently.

For transport over distances less than 1 µm in areas where the field changes over distances comparable to the mean free path, the only reasonable approach is a full microscopic simulation of the scattering process. Since the velocity and diffusion coefficients computed with Magboltz have proven accurate for a wide range of gases, the logical approach seems to be to use this program as basis. An additional benefit of such an approach is that the avalanche fluctuations can be simulated with much more precision.

Examples of successful simulation of small scale structures is shown in Fig. 16 for the case of CSC-like chamber (30 µm anode wires at 3000 V with pitch of 2 mm, cathodes at 3 mm on either side, Ar/CO_2 (80:20) mixture). Here, a trajectory of 10 GeV muon, simulated using Heed, is shown in yellow; green circles represent isolated ionization electrons, small green lines are photo-ionization electrons, purple lines are Auger electrons, blue shows attachment losses and in red are points where ionization occurs. The electron trajectories, tracked between individual collisions with the gas molecules (taking all molecular levels into account), show the electron position every 100 collisions.

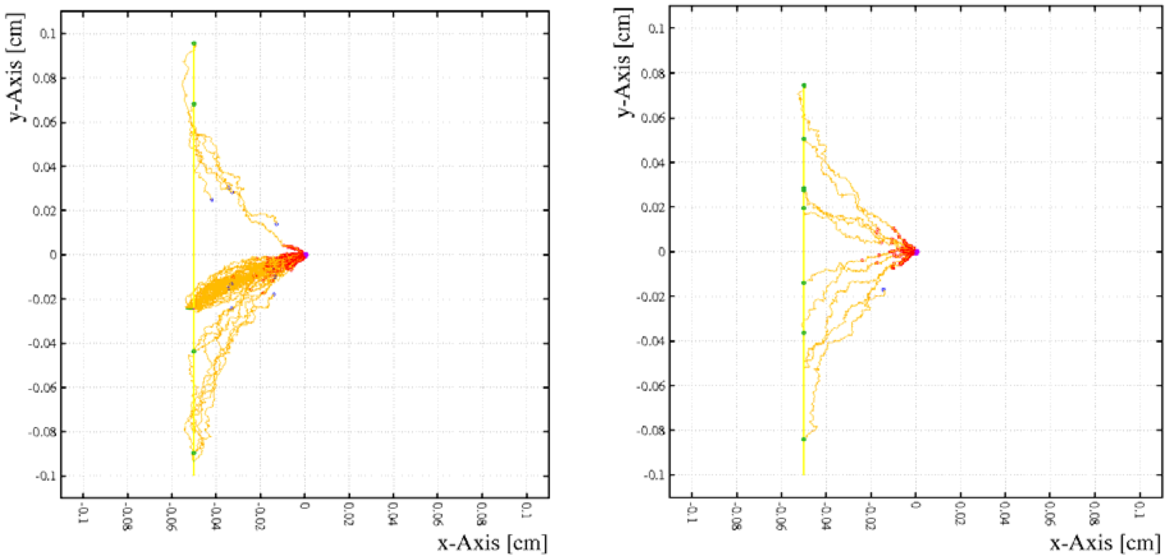


Fig. 16. Example of "microscopic tracking" for CSC-like chamber (30 µm anode wires at 3000 V with pitch of 2 mm, cathodes at 3 mm on either side filled with Ar/CO_2 (80:20) mixture). Trajectory of 10 GeV muon is shown in yellow. See text for details.

<u>Penning Transfers:</u>

Gas gain calculations using Townsend coefficients underestimate the gain in mixtures where so-called Penning-transfers occur. The mismatch reaches a factor of 10 in some mixtures. Although this process is qualitatively understood in the sense that the absence or existence of the effect in a given gas mixture can be predicted, sound theoretical estimates of the transfer probabilities are lacking. Pending theoretical predictions of the transfer rates, the user should be given the possibility to enter transfer rates that reproduce the observed gain.

<u>Ionization Processes:</u>

A new version of the Heed program, which simulates ionization patterns in nearly arbitrary gas mixtures, has become available. Implementation of this version awaits the move to a new simulation framework in which programming language compatibility is less of an issue.

The prediction of accurate cluster-size distributions, primary-cluster distributions and electron range for ionization clusters induced by charged particles in counting gases is of special interest now that the era of micropixel counters is starting in earnest. The ability of these counters to measure the parameters of clusters is so far unmatched by the ability to give accurate simulations of the cluster properties.

In particular, the program Heed relies on the photo-absorption ionization model that predicts significant shell effects that are part of this model. Unfortunately measurements have shown that these shell effects are very small [125].

The author of Magboltz is developing a model-independent approach that uses only experimental electron scattering data to predict the cluster properties. This data base already partly exists in Magboltz and will be extended to overlap the minimum ionizing energy region. Preliminary results already show good agreement with the data of [125] for argon. The results will be extended to all gases in the Magboltz database.

Resistive Plate Chambers (RPC): Resistive Plate Chambers are finally understood at a level that allows the inclusion of their simulation into the Garfield framework. Analytic solutions for electric fields and weighting fields for RPC geometries with presence of dielectric materials exist and can be implemented. Space charge effects, which in contrast to wire chambers and micro pattern detectors are extremely prominent in RPCs can be treated by simplified assumptions that are by now well established.

TASK 3

Development of common platform for detector simulations (integration of gas-based detector simulation tools to Geant 4, interface to ROOT)

Interface to ROOT:

At present, simulations are driven by scripts in a Rexx-inspired format. Large numbers of such files exist and they continue to be used. It seems clear therefore that the current command line interface needs to be maintained. In contrast, the graphics interface, currently based on HIGZ, can be greatly improved, e.g. by using ROOT libraries. This would permit restoring the capabilities that were present in the days when graphics was based on GKS, but which were lost while moving to HIGZ. The move to ROOT would present other major advantages:

• access to the superior statistical methods available in this package;

• possibility to use the more powerful C++ interpreter which is part of ROOT, as an alternative to the existing command line of Garfield since both interfaces could co-exist.

Interface to Geant 4:

The current plan is to attempt to do the change of framework in such a manner that it also becomes possible to interface the gas-based detector simulation programs with Geant 4. The Geant 4 toolkit provides flexible detector and physics modeling capabilities embedded in an object-oriented structure. Integrating gas-based detector simulation with Geant 4 would enable the accurate simulation of the detector in its environment, while allowing geometry description and navigation, particle tracking, visualization, abstract interface to physics processes and management of events. For example, secondary particles produced in the walls of the detector would be taken into account. Many of the pieces of information needed to simulate a gaseous detector are present in the Geant 4 models - but not all. For instance, while the gas composition will be known, there is currently no electrostatic potential attribute for the electrodes. The first step towards the development of Geant 4 for gas detector is to benchmark applications like drift chambers, TPCs and then MPGDs.

Exploratory talks with the Geant 4 team have been held and the approach to be taken seems fairly clear on the Magboltz, Heed and Garfield side. The approach taken would be identical to what is needed to run these programs in the context of ROOT, with interface classes to transfer the data. For electromagnetic fields, Geant 4 interface should rely on pre-calculated field maps. For the gas mixture, one could envisage an extensive public library of gas tables, to be generated through the existing Boinc and Grid interfaces. Electron and ion transport can be done either via native Geant 4 procedures or, in more specialized cases, via the procedures from Garfield. Induction of signals is a straightforward application of transport and field calculations and should therefore not pose problems. Clustering and ionization pattern of the newest Heed program could also be interfaced to Geant 4 since its default ionization loss is done in fixed intervals.

Software platform for DAQ, Reconstruction and Data Analysis

Generic code development for common DAQ tools, as well as general pattern recognition and track fitter algorithm would be a part of future RD51 collaboration sharing. The ROOT analysis package seems to be the logical choice for data analysis.

TASK 4
Explore possibilities to further integrate detector and electronics simulation.

In gas-based detectors, the signal usually results from the movement of charges (electrons and ions) produced through ionization and amplified in high field regions. These signals, which have both slow (kHz) and fast components (GHz and up), are modified by the signal propagation properties of the detector before being filtered, shaped and discriminated by the read-out electronics. Noise is added throughout this process.

The current simulation programs estimate the induced charges on all electrodes in the device, convolute the signals with nearly arbitrary transfer functions and add noise of all kinds. The programs can also output the signals for further processing by dedicated electronics simulation programs such as Spice. This functionality has been tested extensively for the Atlas MDTs and for the Alice TPC.

These features are to be carried over to the ROOT and Geant 4 classes. Signal output for other electronics simulation programs such as gEDA are to be added. Closer integration of detector and electronics simulation is to be investigated.

We also plan to give a lecture series on transfer functions.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG4-1/Developments of algorithms	SINP	Implement a Boundary Element Model (BEM) to perform field calculations.	Software and documentation	m1/m12
WG4-2/Simulation Improvements	CERN	Model refinements for electron transport by introducing electron and avalanche tracking on the molecular level.	Software and documentation	m1/m3
WG4-2/ Simulation improvements	Uludag, CERN	Extract Penning transfer probabilities from published experimental data.	Report or paper	m1/m3
WG4-3/Development of common platform for detector simulation	CERN	Create an interface with ROOT to take advantage of its data analysis methods.	Software and documentation	m3/m12
WG4-3/Development of common platform for detector simulation	Ottawa/ Carleton, TRIUMF, Geant 4-CERN	Create interface classes for use of Garfield components in Geant 4.	Software and documentation	m3/m12
WG4-4/Development of electronics modeling tools	RD51 electronics group	Explore possibilities to further integrate detector and electronics simulation	Lecture series, software and documentation	m1/m12

III-E. MPGD Related Electronics (WG5)

OBJECTIVE
Readout electronics optimization and integration with detectors

A first step in the RD51 electronics effort will be to collect the requirements from various groups of detector developers and try to synthesize those requirements into a small number of readout approaches. Although the signal shapes of MPGDs differ significantly from signals in wire chambers, frontend electronics developed for wire chambers can be directly used for MPGDs in many applications. Due to the lower ballistic deficit, the gas gain of micro-pattern detectors can typically be a factor 10 lower than in wire chambers in order to achieve the same pulse-height signals.

It is fairly clear that groups who aim to use large granularity will need a more conventional readout system derived from wire-chamber applications (GASSIPLEX, ASDQ, CARIOCA, and ALTRO) or already developed for MPGD applications like the VFAT chip. On the other hand there are many exciting developments which could come from pushing further the functionality of highly segmented pixel readout (GOSSIP, Timepix). Both classes of development will be able to benefit from the extreme component density provided by the latest deep sub micron CMOS processes. Given the prototyping costs however compromises will have to be reached in order to limit to a strict minimum the number of chip developments. A large fraction of the challenge will be in fact in the definition of the chips to be produced.

In order to set the proper basis for discussions within the MPGD community, a proper review of MPGD signal characteristics is needed. At the same time the possible use of existing readout electronics must be reviewed. A document on these issues is planned for fall of 2008.

TASK 1
Definition of front-end electronics requirements for MPGDs

The requirements for the electronics for gas detector readout are usually specified as a function of a large set of parameters including the detector geometry, gas gain technology choice and channel occupancy. In general the conventional way of reading out gaseous detectors uses a preamplifier followed by some kind of noise shaping stage. Ion tail cancelation can be included either as part of the shaping stage or as a separate functional block, if needed.

When thinking about the specifications for a general purpose chip for the MPGD community, two categories of applications have to be distinguished. The first category is TPC type readout, where the requirements of the different existing and planned TPC projects have to be reviewed. The second category covers tracking application of MPGDs as done in COMPASS or TOTEM.

There is a current activity on the so-called SUPER ALTRO chip in 0.13um CMOS technology, which would contain a frontend, ADC and digital signal processing. The goal is to find common specifications from the different MPGD developments in order to develop a general purpose chip that can be used by a large fraction of the community working on TPC and high rate tracking applications. Benchmarks will be the ATLAS muon system upgrade and the Linear Collider TPC project.

TASK 2
Development of general-purpose pixel chip for active anode readout

There has been a continuous trend towards higher channel count and smaller readout pitches over the last decades. The most modern examples of high granularity gas detector readout can be found in the developments at Pisa and in the Timepix development (for more details, see section II-A and II-B). In both cases a GEM foil can be placed above a pixelized readout chip and the charge cloud is read out directly. Alternatively a Micromegas foil may be integrated on top of the readout chip to provide the required gain. First versions of the Pisa chips required an external trigger to Sample and Hold the analogue hit information of the entire matrix. The most recent version has a segmented self-triggering which initiates the Sample and Hold within the 3-10 μs shaping time of the preamp [40]. The Timepix chip is based on the Medipix2 imaging device and requires an external shutter. In this case each pixel may be programmed to record particle arrival time using a 100MHz Clock or Time over Threshold to provide rough pulse-height information. The high level of segmentation of both developments has permitted measurements of X-ray polarization and particle track position with unprecedented precision. It is fairly clear that a significant component of the further developments in the gas detector field will be linked with those of the readout electronics.

Following the same principle, a new gas detector - GOSSIP (Gas On Slimmed Si Pixels) is under development, which consists of a thin gas layer of only 1 mm thickness read out by CMOS pixel array on a thinned silicon substrate. Gossip, with gas as detection medium instead of depleted Si, has certain advantages: the detector charge signals can be relatively large, and the input pixel capacitance can be extremely small, thus reducing the power dissipation and preamplifier noise. The pixel chips can be slimmed down to 50 μm, reducing the material budget. Due to its low power dissipation only modest cooling could be required. A first prototype of the front-end readout circuit of a GOSSIP chip has been developed in 0.13 μm CMOS technology and benefits from the low detector parasitic capacitance and the absence of leakage current. It includes a few channels equipped with preamplifier, discriminator and digital circuit to study the feasibility of the TDC-per-pixel concept. The design demonstrates very low input refereed noise (60 e^- (RMS)) in combination with a fast peaking time (40 ns) and analog power dissipation as low as 2 μW per pixel. Switching activity on the clock bus (up to 100 MHz) in the close vicinity of pixel input pads does not cause noticeable extra noise. The GOSSIP detector may become a complimentary development to the present Si-strip tracking systems; they can be produced cheaper and lighter than the current Si-based detectors.

A significant number of groups have expressed interest in continuing to explore the potential of pixel readout of gas detectors. At the same time there is interest in the semiconductor tracking community and in the Medipix3 Collaboration for a general purpose readout chip with similar characteristics. All users require a pixel cell providing simultaneously both energy and hit time information and a readout architecture which would allow the chip to be triggered externally. Given the resources needed for such a development it is likely that the Timepix2 chip will be designed so satisfy as many users as possible.

TASK 3
Development of large-area detectors with pixel readout

The original motivation of combining a MPGD and Medipix2 and Timepix chips as active anode was the development of a new readout system for a large Time Projection Chamber at a future linear collider. A key point that has to be solved to enable CMOS pixel readout of MPGD in high energy physics is the production of large area detectors. Recent progress in the development of edgeless silicon detectors and the possibility to bring power and I/O connections through the back of the CMOS chip using “through-wafer vias" technology may ultimately lead to the development of chips which are 4-side buttable [114]. Properly integrated into large systems, multi-pixel anode readout of micro-pattern gas detectors may represent an invaluable tool for the next generation of particle physics experiments. However, a major R&D effort will be required in the future to fully exploit this potential.

TASK 4
Development of portable multichannel systems for detector studies

Existing readout systems like e.g. the VFAT chip for TOTEM or the PASA+ALTRO chain for ALICE could be implemented in a portable readout system in a straight forward way. This could facilitate the access to electronics by all the participating groups and it would avoid parallel developments of very similar systems by the individual groups.

TASK 5
Discharge Protection Strategies

Discharge protection is a mandatory part of frontend electronics for gaseous detectors. Successful implementations applied to the LHC experiment wire chambers consist of protection diodes integrated on the chip for each frontend channel in addition to a discrete set of resistors and diodes on the PCB in front of the frontend inputs. This solution can be applied to MPGDs with relatively large granularity.

A second solution consists in covering the MPGD anode by a highly resistive layer. This solution is particularly attractive for composite devices in which the inputs of a front-end chip are directly used as the MPGD anode. Actually, it is impossible to add external protections to this type of devices. Preliminary tests have already shown the protection efficiency of a few micrometer highly resistive amorphous silicon layer deposited on the top of a Timepix chip. The optimization and the full characterizations of this protection method are still in progress.

This technique can be extended to higher surface “standard” PCB or Kapton anodes planes. In this case, several materials could be used for the highly resistive layer as amorphous silicon deposition or screen printed resistive inks. This resistive layer can possibly be segmented as the anode of the MPGD. These methods will also require extensive characterizations including material ageing and study of the signal spread due to the resistive layer.

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start/Delivery Date
WG5-1/ Definition of front end electronics requirements for MPGD	CERN ALL	Description of MPGD signal characteristics and review of existing state-of-the-art gas detector	Document	m6/m12

		electronics applicable to MPGDs		
WG5-1/Definition of front end electronics requirements for MPGD	Nikhef INFN Bari INFN Frascati CERN Grenoble Melbourne Mumbai Pavia CEA Saclay INFN Siena BNL, Ottawa/Carleton	Draft specifications for common readout chip 'SUPER ALTRO'	Report, budget request	m6/m12
WG5-1/Definition of front end electronics requirements for MPGD	Nikhef INFN Bari INFN Frascati Grenoble Melbourne Mumbai Pavia CEA Saclay INFN Siena BNL	SUPER ALTRO design and production phase		m12/m36
WG5-2/Development of general purpose pixel chip for active anode readout	Nikhef Bonn Freiburg CERN Grenoble Novosibirsk CEA Saclay	Draft specifications for novel pixel chip (e.g. Timepix2)	Report, budget request	m6/m12
WG5-2/Development of general purpose pixel chip for active anode readout	Nikhef Bonn Freiburg CERN Grenoble Novosibirsk CEA Saclay	Pixel chip design and production phase	New pixel chip (e.g. Timepix2)	m12/m36
WG5-3/Development of large areas detectors with pixel readout	Nikhef Texas Univ. Bonn Grenoble Melbourne Montreal TU Munich CEA Saclay	Design and construction of multi-pixel anode readout	MPGD detector readout by CMOS pixel chips	m1/m60
WG5-4/Development of portable multichannel systems for detector studies	TU Munich Napels, Tucson, Valencia/U. Politecnica	Design and construction of portable multichannel systems	Prototype system	m1/m12
WG5-5/Discharge Protection Strategies	Nikhef CEA Saclay	Test of partially integrated spark protections using CMOS 0.35µm technology with large Micromégas	Report, prototype	m1/m12

		Design and test of fully integrated spark protections for large Micromégas	Report, prototype	m6/m24

III-F. Production (WG6)

OBJECTIVE
Development of cost-effective technologies and industrialization (technology transfer)

TASK 1
Development and maintenance of a common "Production Facility"

To reduce costs, it is in the interest of the collaboration to share the resources that are used to produce MPGDs. By de-facto CERN's TS-DEM-PMT workshop has played this role by providing detectors to experiments and institutes, many of which are members of the collaboration. It is at CERN where the technology to produce GEMs was created and many innovative ideas to fabricate MPGDs and read-out boards have been generated and put in practice. The PMT workshop has experienced personnel available whose full time job is to produce circuits and detectors and provide them to the collaboration members at cost. PMT is capable of producing detectors in prototype quantities and in series for small experiments (TOTEM GEM, T2K Micromegas). This mix of creating production processes, prototyping of various MPGDs and producing small series, combined with the experience of transferring production technology to industry (e.g. GEM, ATLAS TRT) suggests that CERN's workshop should be the common production facility for the collaboration.

With the current equipment in PMT it is possible to produce large detectors in small quantities but possibly not with the level of quality needed for repeatable productions of large MPGDs. Some equipment is limiting the maximum possible size of the MPGDs (e.g. laminator, exposure equipment, ovens, chemical bathes) and certain production steps can therefore not be made in the most optimal way. Current resources of CERN do not allow the level of investment needed to improve this situation without any external help.

To develop and maintain the common production facility at the required level, the following tasks have to be performed:

Task/Milestone Reference	Participating Institutes	Description	Deliverables	Start/Delivery Date
WG6-1/a) Estimate of production needs	All	Type, size, number of MPGD	List for each type, report	m1/m3
WG6-1/b) Inventory of production capability	CERN	Type, size, quantity, quality	List for each type, report	m1/m2
WG6-1/c) Estimate resources to adapt capability	CERN	Costs for new machines and manpower to operate them	Cost estimate for equipment and manpower, report	m1/m4
WG6-1/d) Request resources for adapting facility	All		Budget request	m4/m5
WG6-1/e)) Offer to external users "ready-	All	Define design electronics	Report and budget request for chamber	m6/m12

to-use" small-size GEM, Micromegas, THGEM and other detectors from CERN pool		specifications and testing procedures.	Production	
WG6-1/f) Operate production facility	CERN		MPGD	As of now

TASK 2

MPGD production industrialization (quality control, cost-effective production, large-volume production)

Quality *assurance* is needed once a development of a detector type is out of the prototyping phase. Quality *control* in the sense of all tests and controls needed during production to guarantee that the technical parameters of the circuits are within the specification, is an important factor of quality assurance. For the final products currently measurements such as leakage current, sparking voltage and certain visual controls are used.

To have production better under control and to be able to compare different methods of fabrication or production sites certain objective standards are needed. E.g. a standard method and tools to measure hole-sizes of GEMs, with well-defined acceptance criteria may even help to improve the cost. The creation of these standards may be part of WG 2, Task 1 (Development of common test standards).

A strict quality assurance plan with highly detailed manufacturing procedures and quality control should be put in place for any large-volume production. It is expected that the quality control used in the common production facility can be adapted for large-scale productions. Final quality-assurance procedures can only be made for the larger-scale projects.

The aim of the common production facility is to develop production processes and to produce MPGDs in small to medium quantities. To be able to produce larger quantities (several hundreds per year of a single large type) the equipment and the organization of operating the facility may need to be different. Depending on many parameters this may require investments by the common production facility or it may need the involvement of industry. Only when the different parameters of a specific project are known (e.g. type, size, material, volume, delivery times, available budget) it can be decided which path to take.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverables**	**Start/Delivery Date**
WG6-2/a) Define QA standards	CERN, NTU Athens, Bonn, Yale, Trieste, UA Tucson, BNL, CEA Saclay	List of control parameters and control method	Manual for each MPGD type	m1/m12
WG6-2/b) Establish QA procedure for bulk order	CERN, NTU Athens, Bonn, Yale, Trieste, UA Tucson, BNL, CEA Saclay	Detailed QA steps for manufacturer	Manual	Tender date

WG6-2/c) Establish production method for bulk order	CERN, NTU Athens, Bonn, Yale, Trieste, UA Tucson, BNL, CEA Saclay	Detailed fabrication steps for manufacturer	Manual	Tender date

TASK 3
Collaboration with Industrial Partners

There are several reasons why industrial involvement may be needed:

- The demand for MPGDs is larger than the common production facility can provide
- Allow price reductions due to large scale or industrial manufacturing methods
- Assure the availability for commercial applications

As the technology to produce most types of MPGDs is highly specific and difficult (THGEM is an exception), a transfer of technology is needed. This transfer is not easy: the technology to produce MPGDs is completely different from normal industrial production methods. If there is no commitment for larger orders, companies are generally not interested or the transfer may take long; companies may be reluctant to set up technology transfer contracts as they may have difficulties identifying the market for this type of product or fear licensing issues.

CERN has experience in transferring production technology to industry and has set up several contracts with commercial companies to produce GEMs for example. The results for MPGDs are unfortunately not yet very successful as despite the fact that the transfer has taken place several years ago, even for GEMs of the small 10x10 cm size the quality is not yet up to the required level. One of the companies producing GEMs seems to be reluctant to collaborate with CERN to solve some remaining quality issues, while another company decided suddenly to stop producing GEMs.

There is therefore a high risk that the production of large MPGDs in industry may not immediately give the required results.

CERN's Technology Transfer unit is active in this field and has helped TS-DEM to collaborate with several companies. It is expected that the experience that is built up with the transfer of GEM technology will be invaluable for other MPGD projects. Qualification of companies before transferring technology, contractual obligations, IP licensing and other issues are a few of the subjects that may improve the chances of a successful transfer.

Industry involvement can also be useful for carrying out selected production steps (e.g. the stretching of mesh for Micromegas, exposure step for GEMs).

Task/Milestone Reference	Participating Institutes	Description	Deliverables	Start/Delivery Date
WG6-3/a) Define IP and TT policy	NIKHEF, CERN Coimbra/Aveiro, NTU Athens, Yale, Trieste, UA Tucson, BNL, Rehovot, CEA Saclay	Rules for handling IP in RD51, framework for TT	MoU annex, policy paper	IP m1/m2 TT m2/m8

WG6-3/b) poll industry on their interest in MPGD	NIKHEF, CERN, Coimbra/Aveiro, CERN, NTU Athens, Yale, Trieste, UA Tucson, BNL, Rehovot, CEA Saclay		Report	m1/m12
WG6-3/c) Define conditions requiring industrial production	NIKHEF, CERN, Coimbra/Aveiro, NTU Athens, Yale, Trieste, UA Tucson, BNL, Rehovot, Saclay		Report	m1/m12
WG6-3/d) Transfer production procedure to industry	NIKHEF, CERN, Coimbra/Aveiro, NTU Athens, Yale, Trieste, UA Tucson, BNL, Rehovot, CEA Saclay		Manual, milestone list, contract	Tender date
WG6-3/e) Define conditions for subcontracting	NIKHEF, CERN, Coimbra/Aveiro, NTU Athens, Yale, Trieste, UA Tucson, BNL, Rehovot, CEA Saclay		Policy paper	m1/m12

III-G. Common Test Facilities at CERN (WG7)

OBJECTIVE
Design and maintenance of common infrastructure for detector characterization

The development of robust and efficient MPGDs entails the understanding of their fundamental properties and performance at several stages of their development phase. This implies a significant investment for detector test beam activities to test prototypes and to qualify final detector-system designs, including integrated system tests. The measurements in test-beam facilities cover efficiencies, noise, time, position and energy resolutions - basically all the critical performance parameters for new detector systems. Additionally, characterization of specific detectors designed for operation in large particle background requires targeted aging tests in irradiation facilities.

A common effort in this direction is justified by the large number of groups involved in MPGD development and by the efficiency that can be gained by making common investments in infrastructures, thereby avoiding the duplication of efforts. In addition, as members of the RD-51 collaboration, research groups will get easier access to the test beams and irradiation facilities by making common requests and grouping the test campaigns.

TASK 1
Development and maintenance of a common Test-Beam Facility

- Construction and installation of the basic setup, including trigger and tracking devices, high precision mechanics, gas systems, laminar-flow cabinet and services;
- Definition of a flexible DAQ system, as well as a flexible control system to set up and monitor detector parameters;
- Definition of a common approach in data analysis and development of a common software framework for this task;
- Evaluation of possible integration of a magnet in the test beam set-up.

CERN's PS and SPS can provide a variety of particle species with a wide momentum range. A test set-up will be permanently installed in one of the CERN beam lines, allowing quick and easy access for the different user communities developing MPGDs. The collaboration will develop common general infrastructures (including gas systems), DAQ/controls, as well as test beam analysis software that can easily integrate additional detector systems. It will serve as a vehicle for community building and will address individual component performance, as well as combined performance and integration issues whenever appropriate. A high precision, fast beam telescope will be provided, possibly complemented at a later stage with a magnet. Timing/trigger modules will provide timing measurements between asynchronous beam-particles and a synchronous readout clock.

The test beam setup will be built up over a time span of a few years:
<u>Year 1</u>: Setting-up of gas systems, services, mechanical supports, trigger, telescope and DAQ/control systems, followed by the first MPGD test campaigns. These will also allow for the development of a first version of the common monitoring and analysis software for this basic setup.

Year 2: Consolidation of basic infrastructures, and inclusion of a larger set of Devices Under Test (DUTs). The readout, control and the DUTs can then be treated as extensions of the basic infrastructure and be carried out and analyzed as part of a standard hardware and software framework.

Several research groups will work together on setting up the basic facilities and maintaining them. These infrastructures shall be semi-permanent, with most equipment (like counting room infrastructures, gas systems, services etc) kept in place permanently. The collaboration foresees typically 2 annual test beam campaigns each of a few weeks duration.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start / Delivery Date**
WG7-1/a.1) basic setup: services and infrastructure	Geneve Univ.	Definition and installation of the services and infrastructure (cables, racks, computers..)	Infrastructures and services ready	m1/m12
WG7-1/a.2) basic setup: gas system	CERN, Naples-INFN	Definition and installation of a common gas system	Gas system commissioned	m1/m12
WG7-1/a.3) basic setup: trigger	CERN, Geneve Univ.	Design and commissioning of the trigger device and logic	Beam trigger ready	m1/m12
WG7-1/a.4) basic setup: tracking and mechanics	CERN, Athens Univ., Athens NTU, CEA Saclay, Demokritos, Thessaloniki, Arlington UT, Geneve Univ.	Installation of a tracking telescope as well as high precision support mechanics	Tracker and mechanics ready	m4/m12
WG7-1/b.1) basic DAQ framework	Athens Univ., Athens NTU, Saclay, Bonn, Demokritos, Thessaloniki, Naples-INFN, Univ. Geneve	Development of the common DAQ framework, supporting the basic setup of the facility	Basic DAQ ready for users	m1/m12
WG7-1/b.2) upgrade of DAQ framework	Athens NTU, Bonn, Univ. Geneve	Upgrade and extension of the DAQ framework to its full functionality, taking into account all the demands for this facility	DAQ fulfilling all demands	m12/m24
WG7-1/b.3) control system framework	Athens NTU, Univ. Geneve	Development of a common control system framework	Control system ready for users	m1/m12

Task/Milestone Reference	Participating Institutes	Description	Deliverable Nature	Start / Delivery Date
WG7-1/c.1) basic analysis framework	Athens Univ., Athens NTU, Bonn, Thessaloniki, Univ. Geneve	Development of a common analysis framework, supporting the basic setup of the facility	Basic analysis tools ready for users	m1/m12
WG7-1/c.2) upgrade of the analysis framework	Athens Univ., Bonn, Athens NTU, Thessaloniki, Univ. Geneve	Upgrade and extension of the analysis framework to its full functionality, taking into account all the demands for this facility	Analysis tools supporting all demands	m12/m24

TASK 2
Development of common irradiation infrastructures and irradiation test programme

- Contribution to the design specifications of the new GIF++ Gamma-irradiation facility at CERN, in order to install a dedicated, permanent setup for the RD-51 collaboration;
- Develop a plan to use and contribute to the upgrade of the CERN PS-T7 proton and neutron facilities, for radiation-hardness characterization of detector components (assembly materials, electronics, etc).

The RD-51 irradiation program will focus on using CERN facilities to optimize the development and selection of the most suitable radiation hard technologies for the various MPGD detector components and, at a later stage, assess and monitor the radiation hardness of the qualified components during production.

Standard beam tests using secondary beams of various particle types can normally provide particle fluxes of the required intensity to test the performance and radiation hardness of particle detectors. However typical irradiated areas cover 10×10 cm^2 at most. The CERN gamma irradiation facility (GIF), which started operation in 1997 [126], allows for the testing large area detectors by exposing them to an uniform high gamma flux from an intense ^{137}Cs source. The large flux of 660 keV γ-rays emerging from the source creates typical LHC background conditions. Therefore GIF has been heavily used to test whether the detection efficiency and the resolution of the LHC detectors are affected by the background radiation. Until 2004, detectors placed in the GIF facility could simultaneously be tested in the SPS X5 fixed target beam. Following the dismounting of the SPS West Area beams, simultaneous beam tests are no longer possible and the present facility is scheduled to be shut down towards the end 2009. An upgrade of the facility, called GIF++ , is under study taking into account the needs to develop detectors, especially for SLHC, with an improved layout of the test zone, higher source intensity and the simultaneous presence of a high-energy particle beam. The MPGD community will contribute to the design specifications of the new facility, such that specific needs for the development of MPGDs (e.g large detector sizes) are taken into account. In addition, the RD51 community plans to install some dedicated infrastructures in the facility, like gas systems, services, DAQ and controls for the MPGD detectors.

Also at CERN, the PS-T7 24 GeV/c proton and neutron irradiation facilities [127] are widely used by detector communities for characterization of materials, detectors and electronics. The proton facility allows irradiation of samples with an active area up to 2×2 cm^2 to fluences up to 5×10^{13} protons/cm^2/hour; in the mixed field of the neutron irradiation facility samples of up to 30×30×30 cm^3 and 5 kg weight can be exposed to fluences up to 10^{12} neq/cm^2/hour (1 MeV neutron equivalent). The CERN PS-T7 irradiation facilities provide a number of advantages, such as exposure to high particle flux in reasonable time, fast turnaround, the possibility to move samples into the beam without entrance into irradiation area, and a well organized infrastructure that minimizes administrative and setting up procedures.

Within the RD51 collaboration strategic choices will be made on priority items and common test campaigns, in particular in the domain for materials qualification.

Task/Milestone Reference	**Participating Institutes**	**Description**	**Deliverable Nature**	**Start / Delivery Date**
WG7-2/a.1) GIF++ specifications	CERN	Gather information on the specifications for the GIF++ required by the collaboration: source, beam, gas system, space required in the irradiation area as well as for the DAQ infrastructure.	Report to the GIF++	m1/m6
WG7-2/a.2) GIF++ schedule	CERN	Plan of the use of the GIF++ by the collaboration	Slots request to GIF++	year by year
RT7-2/a.3) control system	Athens NTU	Develop a control system for the device to be used. Current measurements can be used as a first monitor of the DUTs behavior under irradiation	Facility ready for ageing measurements (in current mode)	m6/m18
WG7-2/a.4) trigger devices and logic		Definition of the devices and the logic for triggering the beam during the irradiation in GIF++	Beam trigger ready	m9/m21
WG7-2/a.5) DAQ for beam measurements		Development of the DAQ for measurements with beam under irradiation	DAQ ready	m12/m24
WG7-2/a.6) integration in the analysis framework		WG7-1/c develops a common analysis framework for test on beams. Measurements on GIF++ beam must be integrated in this framework	GIF++ measurements supported in analysis tools	m15/m24
WG7-2/b.1) component list to be validated	CERN	Preparation of the list of common components, glues, etc requiring radiation hardness validation	Report	m1/m6

IV. Scientific Organization

Collaboration Organization

In the following we present organization, which was agreed upon during the workshop held in Amsterdam, April 16-18, 2008. Currently the collaboration comprises members from 54 institutes. The management structure of the collaboration is shown in Fig. 17.

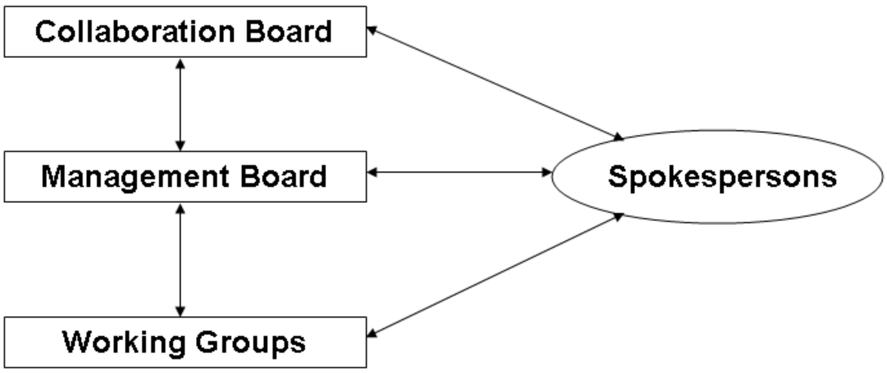


Fig. 17. Role of the Collaboration Board and Spokespersons within the Collaboration Structure.

Details of the collaboration structure are outlined below:

- Concerning all scientific matters the Collaboration is governed by the RD-51 Collaboration Board (CB). It is also responsible for coordinating the financial planning and other resource issues of the Collaboration and, in particular, for managing the Common Fund as well as any other source of common funds. The CB is composed of one representative from each collaborating Institute, with voting rights; the Spokespersons and the Finance Coordinator as ex-officio members, without voting rights. The CB elects the Chairperson of the CB and its Deputy from among the Members of the Collaboration for a period of two years.

- The CB decides on detailed procedures for the management of the Collaboration, setting up specific bodies and functional positions for such tasks.

- The Spokespersons as defined in the General Conditions Applicable to Experiments Performed at CERN, represent the Collaboration to the outside. The Spokespersons are elected following the procedure agreed upon by the CB for a period of two years.

- The Management Board (MB) supervises the progress of the work program along the lines defined by the CB and prepares decisions for and makes recommendations to the CB. Five elected members of the MB are nominated by the CB Chairperson, after consultation with the Collaboration, for election by the CB. Ex officio members of the MB are the Spokespersons, the CB Chairperson and its Deputy, and the Finance Coordinator ("Secretary").

- The Finance Coordinator is responsible for managing administrative issues and the Common Fund as well as any other source of common funds Following the deliberations of the Collaboration Board the CB appoints the Finance Coordinator from among the Members of the Collaboration for a period of two years.

- The Spokesperson nominates the Working Group Conveners which are appointed by the CB. They coordinate the execution of and monitor the progress of the project as defined by the CB. They report regularly to the MB.

V. Resources and Infrastructure

Resources requested from CERN:

RD51 does not request a direct financial contribution from CERN.

The collaboration would like to ask for the following resources and infrastructure at CERN:

1. Access to irradiation and test beam facilities (including the possibility to keep "semi-permanent" setup). The collaboration foresees typically 2 annual test beam campaigns each of a few weeks duration.

2. Privileged access to CERN TS-DEM Printed Circuit Workshop (similar to present availability level). Participation in investments for production infrastructure to stay in line with technology advances.

3. Access to Silicon Bonding Laboratory

4. Access to central computing resources and Grid access for MPGD simulations.

5. Limited amount of office space.

Test-Beam Facilities:

Below, is the short description of test-beam facilities available at the collaborating institutes. No investments from the RD51 common fund are currently planned for these facilities.

1) Electron/Postron Beams at DESY (Hamburg)

DESY II can provide electron or positron beams with an energy variable between 1 GeV and 6 GeV, a small energy spread of about 5% and intensities of up to 5000 particles cm^{-2} s^{-1}, depending on beam line and secondary target (DESY II delivers in parallel test beams to up to three areas using a fixed target). Next to CERN, which has beam facilities for even higher energies and different particles (hadrons, muons and neutrinos), DESY is currently the only laboratory in Europe which can deliver high energetic particles in the multi-GeV range.

The test beam areas provide sufficient space for the installation of large scale detector prototypes. They are equipped with huts to house data acquisition system and control electronics and data connections to the DESY computer centre exist. The beam areas are shielded providing working space for operators. Safety equipment is in place such that gaseous detectors can be used even with flammable gases. Translation stages are available for remote controlled positioning of test equipment in the beam lines.

Within the EU programme EUDET, the DESY test beam was equipped with a high field (1T) superconducting magnet (PCMAG), and a high precision silicon pixel telescope (σ<3μm). This infrastructure will be available to the members of the RD51 collaboration. An additional strip telescope (σ<15μm) will also be provided for the community.

2) Neutron Beams at PTB **(**Braunschweig**)**

PTB can provide calibrated and well specified neutron beams in a broad energy and dose range. They are available either as monoenergetic (or quasi-monoenergetic) neutron fields, as intense, broad-energy (1 10

MeV) neutron beams for irradiation applications, or, for detectors with Time-of-Flight (TOF) capability, as pulsed, broad energy neutron beams, where energy selection is provided by TOF measurement.

Quasi-monoenergetic reference fields are available from thermal neutrons up to energies of 200 MeV for calibration purposes, partly in collaboration with partners from other institutions. With the exception of thermal beams installed at nuclear reactors, monoenergetic or quasi-monoenergetic reference fields are produced by bombarding low-Z targets (D, T, ^{7}Li) with light ions (p, d) accelerated with Van-der-Graaf accelerators or cyclotrons.

Monoenergetic neutrons can only be obtained under ideal conditions. In reality, however, the effects of finite target thickness, neutron scattering in the target surroundings and the finite detector size as well as breakup reactions at higher projectile energies cause deviations from the ideal situation, i.e. the fields are only quasi-monoenergetic with a high-energy peak of finite width and a low-energy continuum. More details of the available quasi-monoenergetic beams and their properties can be found in [128].

Intense broad energy collimated neutron beams are available at the PTB accelerator facility [129], using deuteron or proton beams on a thick Be-target. The energy spectrum ranges from several 100 keV to ca 10 MeV. For details on neutron yields and spectra see [130]. The collimated neutron flux available is up to ca 10^8 $s^{-1}cm^{-2}$ at 0.5 m distance form the target. Using pulsed beam and TOF technique neutron fluxes of ca $3x10^5$ $s^{-1}cm^{-2}$ in 3 m distance from the target are obtained. The pulses have a width of ca 1.5 ns with a pulse spacing of 500 ns. For research applications where PTB is part of the collaboration, beam time is free of charge and will be made available by application via the local partner. Commercial irradiations will be subjected to full-cost coverage by the customer.

<u>Institutes resources:</u>

Below, is the summary of the available resources and infrastructure which could be made available for the members of the collaboration by participating institutes:

infrastructure	Micro-structure production facility	gas detector development lab	clean room, assembly facility	gas and gas purification systems	facilities for gas and materials studies	facilities for thin film deposition	deveopment, production, testing	irradiation facilitiy
institute								
Alessandria								
Amsterdam / NIKHEF			*				*	*
Annecy								
Argonne / Nat'l Lab								
Arlington, TX			*					
Athens NCSR Demokritos				*				*
Athens NTU								
Athens Univ.								
Aveiro + Coimbra				*		*		
Barcelona								
Bari			*	*			*	

Bonn				*				
Braunschweig								*
Budapest / RMKI			*					
Budapest Univ.								
Bursa								
Cagliari		*		*			*	
Coimbra								
Columbia, SC								
Frascati								
Freiburg			*				*	
Geneva / CERN	*	*	*	*	*	*	*	*
Geneva Univ.								
Grenoble								*
Hamburg, DESY								
Hefei								
Helsinki		*	*		*			*
Kobe								
Kolkata								
Lanzhou				*				*
Melbourne, FL								
Mexico City								
Montreal							*	*
Mumbai								
Munich / MPI								
Munich TU			*				*	*
Napels								
New Haven, CT / Yale								
Novara								
Novosibirsk			*	*			*	*
Ottawa / Carleton		*	*					*
Rehovot / Weizmann		*	*	*		*	*	
Rome / INFN Sanita Group			*			*		
Saclay	*	*	*	*			*	*
Sheffield		*		*				*
Siena		*	*				*	
St Etienne			*	*				
St Petersburg								
Thessaloniki								
Trieste			*				*	
Tucson, AZ								
Tunis								
Upton / BNL		*	*	*			*	
Valencia / IFIC								
Valencia / Iniv. Politec.								
Zaragoza				*				

VI. Partners and Their Fields of Contributions

town	institute	WG1				WG2					WG3								WG4				WG5					WG6			WG7		sum
		T1	T2	T3	T4	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T6	T7	T8	T1	T2	T3	T4	T1	T2	T3	T4	T5	T1	T2	T3	T1	T2	
Alessandria	University																																0
Amsterdam	NIKHEF	1	1	1		1	1	1	1	1	1		1				1		1		1	1	1	1	1					1	1	1	20
Annecy	LAPP	1					1						1																				3
Argonne	Argonne Nat'l Lab	1									1												1										3
Arlington	University of Texas	1					1						1												1						1		5
Athens	NCSR "Demokritos"	1		1				1			1	1	1		1	1	1														1	1	11
Athens	Nat.Tech.Univ. Athens	1	1	1		1	1	1	1		1				1	1	1			1	1								1	1	1	1	17
Athens	University					1			1		1						1			1	1										1		7
Aveiro, Coimbra	University	1	1					1	1			1		1	1	1	1			1	1									1			12
Barcelona	Universitat Autònoma	1	1																1	1													4
Bari	University		1	1				1			1				1				1	1			1										8
Bonn	University		1								1													1	1				1		1		6
Braunschweig	PTB														1																	1	2
Budapest	RMKI		1				1		1		1						1																5
Budapest	University		1				1		1																								3
Bursa	Uludag University									1									1	1	1												4
Cagliari	University							1			1																						2
Coimbra	LIP							1			1						1																3
Columbia, SC	Univ. South Carolina	1					1						1																				3
Frascati	LNF, INFN										1												1										2
Freiburg	University					1					1													1									3
Geneva	University	1				1																									1		3
Geneva	CERN	1	1	1	1	1	1	1	1		1									1	1		1	1				1	1	1	1	1	18
Grenoble	LPSC					1										1			1		1		1	1	1								7
Hamburg	DESY					1					1																						
Hefei	USTC	1	1			1	1	1	1	1																							7
Helsinki	HIP	1		1				1																									3
Kobe	University		1				1																										2
Kolkata	Saha Institute																		1	1	1	1											4
Lanzhou	University	1	1												1		1																4

Melbourne	Florida Inst of Tech	1																1					1		1								4
Mexico City	Univ. Nacional Aut	1	1				1		1		1	1	1	1																			8
Montreal	University			1									1		1	1	1								1								6
Mumbai	Tata Institute														1								1										2
Műnchen	MPI		1										1																				2
Műnchen	Technische Universität	1		1			1		1		1														1	1							7
Napels	University	1				1					1															1					1		5
New Haven, CT	Yale		1					1	1		1																		1	1			6
Novara	TERA Foundation	1		1					1								1						1										5
Novosibirsk	Budker Institute													1	1	1	1							1									5
Ottawa	Carleton University	1	1			1										1			1		1	1									1	1	9
Rehovot	Weizmann Institute	1	1				1		1	1	1	1	1	1	1	1	1													1			13
Rome	Sanita Group, INFN	1									1																						2
Saclay	IRFU, CEA	1	1	1	1	1	1	1	1	1	1				1	1							1	1	1	1	1	1	1	1		1	21
Sheffield	University	1	1									1		1		1																	5
Siena	University	1															1						1										3
St Etienne	Ecole Nat. Sup. des Mines	1		1	1		1		1									1															6
St Petersburg	NPI	1	1			1	1																										4
Thessaloniki	Aristotle University	1		1		1		1			1						1			1											1		8
Trieste	University		1						1			1																	1				4
Tucson	University of Arizona	1	1														1									1			1	1			6
Tunis	CNSTN																1			1	1												3
Upton	BNL	1		1							1	1					1						1						1	1			8
Valencia	IFIC							1												1													2
Valencia	Universidad Politecnica																									1							1
Zaragoza	University		1											1		1			1	1													5
	sum of participants/task	30	23	13	3	14	17	15	17	6	23	7	9	6	11	11	17	2	8	12	10	3	12	7	8	5	1	2	8	9	11	7	

Tab. 2. Summary of the expression of interest of participating institutes in different RD-51 Working Groups Tasks (WG1 – WG7).

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