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MPGD: new developments and applications

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1. Introduction

The choice of MicroPattern Gaseous Detectors (MPGD) for relevant experiment upgrades tests the degree of maturity, the level of dissemination within the High Energy Physics (HEP) community and the reliability of these counters. At LHC, ATLAS and CMS are equipping the forward regions with novel MPGD trackers with triggering capabilities: at ATLAS large size, about 1 x 2.5 m^2, resistive MICROMEGAS will cover a total surface of 1200 m^2 [1], at CMS triple GEM detectors with size up to 1.2 x 2.5 m^2 are being produced for a total GEM-foil surface of 1000 m^2[2]; ALICE has approved the upgrade of the TPC read-out sensors by 4-layer GEM counters covering in total 130 m^2[3]. The gaseous photon detectors of COMPASS RICH-1 are being replaced by hybrid MPGDs including two layers of staggered THGEMs and a MICROMEGAS multiplication stage that will equip a total surface of 4.5 m^2 having the delicate mission of single photon detection[4]. The present MPGD achievements have been largely favoured and supported by the CERN-based technological collaboration RD51[5, 6], formed among approximately 500 physicists from 86 institutions in 25 countries; the RD51 activity has determined a fundamental boost in the MPGD field thanks to a wide networking activity for the dissemination of know-how and technologies and by providing common infrastructures and tools for the R&D. The MPGD status and perspectives are illustrated by discussing the path towards the MPGD ultimate performance (Sec. 2), the approaches to MPGD realization by novel technologies (Sec. 3) and the wide-range application portfolio (Sec. 4). The authors largely refer to the scientific contributions at the very recent 4^{th} International Conference on MiroPattern Gaseous Detectors[7], where a clear picture of present and on-going efforts in the sector has emerged.

2. The path toward the ultimate MPGD performance

At present, the performance in running experiments of the better established technologies, namely MICROMEGAS and GEM, are similar: space resolution slightly better than 100 μm, time resolution around 10 ns that, thanks to a dedicated effort, has been reduced to 4.5 ns for the LHCb GEM detectors [8], operative gain of a few time 10^3, always below 10^4, material budget of a few X_0 ‰ and rate capabilities up to 100kHz/cm^2 that can be raised by about two orders of magnitude in pixelised detectors, both GEMs[9, 10] and MICROMEGAS [11] used at the COMPASS experiment. Extremely fine space resolution is the goal of the GridPix detector[12], obtained building a miniaturized micromesh over the Timepix chip[13] by a post processing process. Recently, a set of 160 GridPixes have being used to read-out the EUDET TPC prototype[14]: the preliminary results indicate a space resolution of about 100 μm, namely fully driven by the electron diffusion in the TPC, thus suggesting a negligible intrinsic contribution by the GridPix itself. Time resolution well below 100 ps is pursued by two different approaches.
The Fast Timing Micropattern (FTM) detector[15] makes use of a stack of multiple amplification gaps by fully resistive components in order to make the single gap transparent to fast signals, which are read out by external planes: fine time resolution is obtained by multiple measurements as in multilayer RPCs and a first two-layer prototype has been tested providing 1.5 ns resolution. Cherenkov light is produced in a thin solid state radiator with fully negligible time Jitter; $O(100)$ photoelectrons can be detected when a minimum ionizing particle crosses a 1 cm-thick crystal; minimizing the

photoelectron drift path a time resolution $O(10\text{ps})$ can be reached; so far the principle feasibility has been verified by extracting photoelectrons from an Al cathode illuminated by 100 fs long laser pulses and detecting them in a MICROMEGAS prototype[16].
Rate capabilities up to 1 MHz/cm^2 are the goal of the micro-resistive-well detector, μ-RWELL[17], a single layer resistive device characterized by fine space resolution, of about 60 μm, and a simple assembly procedure. A similar goal, namely rate capabilities up to a few times 1 MHz/cm^2 is pursued by resistive MM with pad read-out, as studied both within the SCREAM project[18] and by developing the High Performance MICROMEGAS[19].
Low rates of Ion Back Flow (IBF) from the multiplication region are required both to operate TPCs at high rates by removing the gate electrodes and in gaseous photon detectors, where the photocathode is damaged by the IBF bombardment. For the upgrade of the ALICE TPC, four-layer GEMs will be used, with different geometries, standard GEMs and double pitch ones, and staggered alignment: IBF below 1% is obtained without compromising the energy resolution[20]. Similar figures can be obtained with a hybrid detectors formed by two-GEM layers and a MICROMEGAS one[21]. In the field of large size gaseous photon detectors the status of the art is represented by the hybrid MPGD counter under construction for the upgrade of COMPASS RICH-1, formed by two THGEM layers with staggered alignment followed by a MM stage, where the first THGEM is coated with a CsI film and acts as photocathode: IBF rates below 5% are obtained as well as stable operation up to gains as large as 10^5[22]. In the field of gaseous PMTs for the visible domain making use of fragile bi-alkali photocathodes the requests of reduced IBF rate are even more stringent. In spite of the reduced quantum efficiency, approximately 60 % of the vacuum device one, the need of sealed detectors and of selected materials to deal with the chemical reactivity of the bi-alkali photocathodes, these devices offer a relevant advantage: their insensitivity to the presence of magnetic fields. Presently, the most advanced development is the one pursued in Japan in collaboration with Hamamatsu: using staggered grids with different geometry, gaseous PMTs with surfaces of a few time 10 cm^2, gains up to 10^4 and IBF rate below 10^{-3} are obtained[23].
Large gains are required to detect intrinsically feeble signals, as those generated by single photoelectrons and to favour the MPGD dissemination beyond HEP. The already mentioned μ-RWELL aims at gains as large as 10^5 by a single multiplication stage, while the development of the hybrid single photon detectors already able to operate at gains as high as 10^5 will be further continued to increase the present gain limit by one order of magnitude [22].

3. MPGDs by novel technologies

The introduction of the MPGDs has been made possible by the industrial development of the modern photo-lithographic technology. Nowadays, MPGD realization by novel technologies can further support the progress in the field as tested by the following selected examples.
The process of wafer post-processing for the GridPix detector has already been mentioned; the post-processing is realized at the Fraunhofer Institut in Berlin, Germany.
As already recalled, the most advanced gaseous PMTs for the detection of visible light are built using PMT approaches from the PMT technology at Hamamatsu, Japan.
The MicroPixel chamber, μ-PIC[24], is a 2-D tracker characterized by a completely industrial production process by PCB technologies. More recently, μ-PIC production by Micro-Electro-

Mechanical Systems technologies, MEMS, has been attempted in collaboration with DAI Nippon Printing Co., Ltd., Japan: the use of different material, namely Si and SiO_2, of more challenging geometrical parameters, not easily obtained by the standard PCB technology, and the process accuracy make it possible to obtain larger gain, better response uniformity and increased space resolution[25].
A graphene layer is ideally a membrane transparent to electrons and opaque to ions, namely an ideal tool for IBF control and it can also be considered as a gas separator within a gaseous detector: for instance, if applied to a MICROMEGAS the use of different gas mixtures in the drift and multiplication gaps can be envisaged. Preliminary exercises are being performed in order to apply one or more graphene layers onto a GEM foil [26] or using Polydimethylsiloxane, PDMS, as graphene substrate on a MICROMEGAS mesh[27].
The concept of the MicroStrip Gas Detector, MSGD[28], the first MPGD ever proposed, is being revisited introducing one more electrode between the anode and cathode strip in order to mitigate the strong electric filed at the strip edges and a novel read-out is proposed: the strip substrate is replaced with Indium Zinc Oxide, IZO, coated glass used in Liquid Crystal Display technology, LCD, and the signal read-out is by photodiode elements detecting the electroluminescent light produced in the amplification process[29]. The development is performed in collaboration with Sharp Corporation, Japan. An exciting device is obtained making use of GEMs by photo-etchable glass (PEG3 by HOYA Corporation, Japan) and reading out by a conventional CCD device the electroluminescent light produced during the multiplication process: using a CF_4 atmosphere in the detector, 500 thousand photons are produced by the amplification of a 5.9 KeV X-ray. Images with 0.5 mm resolution are obtained[30]. The R&D is supported by AIST, National Institute of Advanced Science and Technology, Japan.
These examples indicate that the collaboration with high technology industries and the support of public institutions dedicated to technology transfer largely favour the access to up-to-date technologies in order to improve both the fabrication process and the performance of the MPGDs.

4. MPGD applications

The large number of applications and the diversified fields where MPGDs are in use or proposed for test furthermore the success of these technologies and, even more relevant, of the wide potentialities, that are not yet fully exploit and will require more development and dedication. This rich panorama is illustrated in the following by examples chosen to underline the main directions of applications: they are not intended to present an exhaustive catalogue.
It has already been recalled that MPGDs have been introduced and are being developed towards ultimate performance to answer the challenging requirements of experiments in fundamental research, in particular in the HEP sector. The obvious consequence is that the applications in fundamental experiments are several. Both MM and GEM trackers have been used for the first time on a large-scale base to detect particles scattered at small angles at COMPASS [31]. In this same experiment important steps towards the use of MPGD in very high intensity environments have been implemented with the installation of pixelized GEMs[32] and pixelized MM[33]. The forward region of the LHCb experiment is equipped with a large system of triple GEM trackers[34]. The TOTEM LHC experiment is equipped with an extended tracker system formed by circular GEM

trackers. GEMs are being implemented at the HallA experiment at JLab[35]. MSGD trackers have been operated at the DIRAC[36] and at HeraB[37] experiments. The read-out of the TPC in the near detector at the T2K neutrino experiment is MM-based. A MICROMEGAS detector has also been operated at the axion experiment CAST[39]. A triple GEM cylindrical detectors instruments the vertex region of the KLOE2 experiment[40] and a second cylindrical detector inspired by this one is under construction for BESS-III in Beijing[41] . The same approach has been considered for CMD-3[42] at the Budker INP VEPP-2000 Collider. Cylindrical MM have been developed for the experiment CLAS12[43] at JLab and are now one of the options for tracking at the future Electron Ion Collider (EIC)[44]. A variety of MPGD approaches are being tested for the read-out of the TPC at ILC: GEMs [45], MicroMegas[46] and GridPIXes[12, 14]. The future use of MPGDs in the major LHC experiments to match the LHC luminosity upgrade phase 1 and to upgrade the COMPASS RICH-1 photon detection system are mentioned in Sec.1.
Nowadays, MPGD-based detectors are developed to be used in low energy nuclear physics. A TPC operated at low pressure using light gases (H, D, He), that also represent the active target of the experiment, will be operate at the National Superconducting Cyclotron Facility (NSCL) in Michigan[47]. The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) makes use of a double-sided TPC with MICROMEGAS readout designed to measure the energy-dependent cross-section in neutron-induced fission of actinides at Los Alamos Neutron Science CEnter (LANSCE)[48]. Neutron detection by MPGDs has been a reality since several years thanks to the MSGD-based D0 refractometer in operation at the Institut Laue Langevin (ILL)[49]. More recently, neutrons have been detected using GEM detectors and polyethylene converter[50] at Frascati ENEA Tokamak. High-efficiency n-detectors based on GEMs where the neutrons are converted in a set of $^{10}B^4C$-coated lamellas orthogonal to the GEM planes[51] is under development for applications at the European Spallation Source (ESS).
THGEMs are at the base of different developments aiming at novel read-out detectors of large volume noble liquid TPCs for rare event experiments. In two-phase liquid Ar TPCs, THGEMs operated in gaseous Ar atmosphere are proposed for the DUNE experiment[52]; alternatively, the read-out by GAPD of the electroluminescence produced during the amplification process in THGEMs is considered [53] in the CRyogenic Avalanche Detector (CRAD). Recently, THGEMs have been successfully operated in liquid Xe detecting by PMTs the light produced by electroluminescence in the liquid[54]; moreover, coating the THGEM with a CsI film, it is possible to detect both the ionization and the scintillation signal produced in the liquid Xe. Micro-bulk MM, built making use of radio-pure materials, are studied for the neutrinoless double beta decay experiment PANDAX-III[55] at the Jinping Underground Laboratory, China. The NEWAGE0-3b′ Detector at the Kamioka mine, Japan, is developing a negative-ion TPC[56] using a μ-PIC detector coupled to a GEM foil: the use of negative ions allows the measurement of both ions and electron drift time, thus providing absolute event coordinates also operating in trigger-less mode. MICROMEGAS are foreseen for axion search in the experiment IAXO[57], for WIMPs search at TREX-DM [57] and for dark photon search at P348[58], the experiment PADME also dedicated to dark photon search will use GEMs[59].
The use of MPGDs for applications of general interest for society includes the fields of medical imaging, non-destructive and large-size object inspection, nuclear plant and radioactive waste monitoring, micro-dosimetry, medical beam monitoring, tokamak diagnostic and geological studies by

muon radiography. Dedicated MPGD technologies are developed for these purposes as the Resistive Plate WELL (RPWELL)[60] and the Scintillating GLASS-GEM detectors already mentioned in Sec. 3. The GEMpix[61], a multi-purpose detector obtained coupling a GEM multiplier and a Timepix chip, has been successfully used for monitoring radioactive waste at CERN, to perform 3D measurements of the energy released in a water phantom in the hadrotherapy treatment facility CNAO, as Gamma ray monitor to measure radiotherapy doses at Policlinico Tor Vergata in Rome, as X-ray monitor at the Inertial Fusion test facility Petal, France, and at the KSTAR Tokamak reactor in Korea, as monitor in proton tomography prototypes at NIKEF. It is considered for directional dark matter searches either with carbon nanotubes or as read-out detectors of the Negative Ion Time Expansion Chamber NITEC.

5. Conclusions

As shown, presently MPGDs represent a world in fast and dynamic evolution thanks to an intense development activity aiming to reach the ultimate detector performance, the introduction of novel technologies and the continuous widening of the application portfolio. The analysis of the present status of the art and of the ongoing activity suggests that this positive trend will continue in the next decade and further relevant advancement is expected.

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