III *C*. Applications

1. Detectors for Tracking and Triggering

Due to their wide variety of geometry 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. This is then amplified by the amplification structure of choice. The amplified charge is collected on readout structures with a large variety of possible patterning and routed to the readout electronics.

MPGD based tracking detectors with triggering capability are being developed for the ATLAS and CMS muon systems to cope with the high particle rates of a few kHz/cm^2 expected at SHLC luminosities, replacing parts of the present muon trackers and trigger detectors. 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 and a time resolution of ~ 5 ns and have high radiation tolerance. The "bulk MicroMegas" technology is currently pursued to address these requirements, with involvement from INFN Naples, INP/NCSR Athens, NTU Athens, U Athens, U Thessaloniki, CERN and BNL. For LHCb, large area planar detectors based on triple GEM technology with a size of ~1000 x 250 mm^2 with a highly granular pad readout are being studied for muon tracking and triggering in the high rate environment of SLHC. Participating institutes are INFN Frascati and INFN Cagliari.

For the PANDA experiment at the future FAIR facility thin large-area planar triple GEM detectors are being developed at TU Munich, 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, as well as a large area tracker with 1000 x 2000 mm^2 acceptance and a spatial resolution of better than 300 µm, both with 2D strip readout, is being planned, with involvement from INFN Rome. 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. 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 projects are carried out with involvement from *MIT (still no questionaire?)* and Yale University as well as BNL, which is involved in 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 $\sigma_{r\text{-}\varphi}$ ~ 200 µm and σ_z ~500 µm, with very low material budget. This development is carried out at INFN Frascati.

In addition to their use in thin detectors, MPGDs are also widely studied for the use in time projection chambers (TPCs). They offer an improved spatial resolution, and a significant reduction of ion feed-back, relaxing the requirements on gating of the devices and, depending on the design, possibly allowing ungated operation of time projection chambers.

R&D for a high precision TPC is ongoing for the future ILC, organized in the ILC-TPC collaboration. In order to achieve the physics goals of the ILC, the main tracking TPC has to be able to reconstruct at least 200 space points on a track with a resolution of ~ 100 µm, over a maximal drift length of 250 cm in a 4 T magnetic field. Multi-track separation of 1 mm has to be reached.

These requirements are in part driven by the needs of particle flow algorithms, briefly discussed in the calorimeter section. 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. 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. U Freiburg, U Bonn and NIKHEF participate in the ILC-TPC development efforts.
NIKHEF also investigates small TPCs to be used in directionally sensitive dark matter searches. 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 developed by IN/NCSR Athens and NTU Athens.
A TPC based on GEM readout has been proposed by TU Munich 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.

2. Photon Detectors

The use of gaseous detectors coupled with CsI photo-cathodes 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 cathodes on the multiplier structures.

For the application in RICH detectors, a rather coarse spatial resolution is usually sufficient, thus ThickGEMs 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. These investigations are carried out at the Weizmann Institute, INFN Trieste and U Coimbra/Aveiro. At UNA Mexico, photosensitive ThickGEMs and RETGEMs are studied for an upgrade of the ALICE RICH, the VHMPID.
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, and is being further developed at BNL.

3. Calorimetry and Muon Detectors

Large area MPGD systems are being studied as potential solutions for digital hadron calorimeter and muon tracking/identification components of future Linear Colliders and SLHC upgrades respectively. 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).
The University of Texas at Arlington group has been developing large area GEM planes for a DHCAL with high density readout via the SLAC KPiX chip. UNAM, Mexico has similar interests in DHCAL development with GEMs.
A similar project directed at digital hadron calorimetry is being pursued at LAPP (Annecy) using micromegas. They are studying both analog and digital readout using the GASSIPLEX and HARDROC chips respectively. The University of South Carolina has also expressed interest in micromegas/readout electronics for calorimeter applications.
The use of THGEMs for large area calorimeter applications is being studied at the Weizmann Institute, MPI-Munich, and COIMBRA, Portugal. THGEMs offer the potential for low-cost large area devices that are mechanically robust and can operate at high gains.

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 _> 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. CERN, Brookhaven and INP, Athens are participating in these SLHC upgrade developments.

4. Cryogenic Detectors for Rare Events

GEM, THGEM, RETGEM and MHSP systems are being developed for application 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, the Budker Institute for Nuclear Physics is developing two-phase detectors, 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 GEMs 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.
Dark matter detectors are also being studied by a number of other groups: Weizmann Institute (THGEM), University of Zaragosa (Micromegas), UNAM (TGEMs and RETGEMs), University of Sheffield (THGEM), COIMBRA (MHSP, GEM, THGEM).

For applications in neutrino physics, the University of Sheffield is developing THGEM hybrid devices in combination with new generation silicon photosensors for operation in or above cryogenic liquids, notably liquid xenon. Their objective is to demonstrate robustness and reliability of MPGDs, particularly with liquids, and studies of gain issues. Neutrino physics applications are also being studied by the Weizmann Institute (THGEM for Super-Novae explosions), Budker Institute (Solar neutrinos), and the University of Zaragosa (Double-beta decay).

The University of Zaragosa is also the application of MPGDs to axion searches (CAST).

5. X-ray and Neutron Imaging

Gaseous detectors are used for neutron detection, usually by means of a hydrogenous converter. At PTB Braunschweig, detectors for thermal neutron as well as fast neutron (1 - 10 MeV) detection based on triple GEM readout with a neutron converter are being developed.

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.
At Budker Institute, X-ray detectors for diffraction experiments for the use at synchrotron radiation facilities based on triple GEMs are being developed. For the CAST solar axion experiment at CERN, X-ray detectors with 2D readout using Micromegas were designed and are opperated with contributions from INP/NCSR Athens and NTU Athens. The Weizmann Institute and U Coimbra/Aveiro are active in the study of ThickGEMs and other devices for X-ray detection and polarization measurements. At U Montreal, the combination of MPGDs with Medipix2 and Timepix silicon detectors is studied for the use in X-ray and neutron detection.

6. Astroparticle Physics

MPGDs also offer interesting possibilities for astroparticle physics applications. In many cases, this overlaps with the use of such devices in areas discussed above, since these astroparticle physics applications often demand tracking, photon or X-ray detection or cryogenic devices.
Common applications are X-ray detection, possibly with polarization measurement (INP/NCSR Athens, NTU Athens, U Zaragoza), cryogenic detectors for neutrino and dark matter detection (Budker, U Sheffield), and time projection chambers. At LPSC Grenoble, 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, while U Zaragoza studies a MicroMegas TPCs for rare event detection, such as dark matter studies and the search for neutrinoless double beta decay.

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, Nuclear Scattering Tomography for hadron therapy, X-ray imaging, and cancer diagnostics, and nanodosimetry.

The Weizmann Institute is studying the use of THGEMs for medical imaging, cancer diagnostics, and nanodosimetry. The imaging projects include the use of noble-liquid detectors. The Budker Institute are studying cryogenic two-phase detectors based on GEMs and THGEMs operating in xenon for PET applications. The TERA Foundation (Pavia) is developing very high rate GEM detectors for medical imaging.

The University of Sienna with INFN Pisa, and the TERA Foundation are developing GEM detectors for Nuclear Scattering Tomography/Radiography. The former group is also working 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.

The University of Athens, the Aristotle University of Thessaloniki, and CNSTN (Tunis) are pursuing medical applications of micromegas. CNSTN is developing a small gamma camera for nuclear medicine using micromegas to obtain information about the position of interaction of the gamma rays.

8. 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. Florida Institute of Technology is developing a GEM application 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.

The Ecole Nationale Superieure des Mines is developing RETGEMs with application to radon detection in the air as a early warning of earthquakes, and for UV visualization including remote forest fire detection.