DEVELOPMENT OF THE GAS ELECTRON MULTIPLIER (GEM)

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ABSTRACT

We describe recent developments of the Gas Electron Multiplier (GEM), a thin composite mesh acting as proportional avalanche amplifier in gas counters. In beam tests we have verified the excellent efficiency, time resolution and localization accuracy for a GEM with micro-strip read-out. Efficiency, localization accuracy and operation in strong magnetic fields has been verified; operation at rates above 10^6 Hz/mm² and lifetimes corresponding to at least 10 mC/cm of collected charge have been demonstrated. Refinements in the manufacturing technology have permitted the realization of large size detectors (27 by 25 cm²), to be used in conjunction with micro-strip gas chambers. With an improved design, stable gains above two thousand have been reached (GEM2000); larger gains can be obtained increasing the thickness of the foils, cascading two GEMs at some distance or in electrical contact. Further developments of the technology and prospective applications are discussed.

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Abstract

We describe recent developments of the Gas Electron Multiplier (GEM), a thin composite mesh acting as proportional avalanche amplifier in gas counters*. In beam tests we have verified the excellent efficiency, time resolution and localization accuracy for a GEM with micro-strip read-out. Efficiency, localization accuracy and operation in strong magnetic fields has been verified; operation at rates above 10^6 Hz/mm² and lifetimes corresponding to at least 10 mC/cm of collected charge have been demonstrated. Refinements in the manufacturing technology have permitted the realization of large size detectors (27 by 25 cm²), to be used in conjunction with micro-strip gas chambers. With an improved design, stable gains above two thousand have been reached (GEM2000); larger gains can be obtained increasing the thickness of the foils, cascading two GEMs at some distance or in electrical contact. Further developments of the technology and prospective applications are discussed.

1. THE GAS ELECTRON MULTIPLIER

A GEM mesh consists of a thin insulating foil, metal-clad on both sides and perforated by a regular matrix of holes (30 to 50 mm², Fig. 1). Upon application of a difference of potential between the two metal sides, a dipole field develops in the holes and provides an effective amplification path for electrons released by ionization in the gas and drifting in the high field through the open channels [1]. Fig. 2 shows the electric field of the GEM structure in the thin cylindrical holes, at typical operating voltages.

More than a hundred GEM grids of various design and geometry, from a few cm² up to 700 cm² in size have been manufactured and tested in experimental set-ups, including as second element of amplification a Multi-Wire Proportional Chamber (MWPC), a Micro-Strip Gas Chamber (MSGC) or a printed circuit board (PCB) as read-out element. With an insulator thickness of 50 μ m and 5 to 15 μ m metal coatings, GEM meshes provide amplification factors well above 100, thus making detection of a small amount of charge in the second element amazingly easy in a wide range of gas fillings and operating conditions [2-4].

Fig. 1: Close view of the GEM mesh. Rows of holes at 140 μ m pitch have been created by chemical etching on copper-clad, 50 μ m thick kapton.

Fig. 2: Example of electric field lines and equipotentials in a GEM channel. Holes are 100 μ m wide, etched on 50 μ m insulator with 15 μ m thick conductors. The potential across GEM is 500 V, and the external fields 1 and 2kV/cm above and below the mesh, respectively.

* US Patent pending

Recently, a gain above two thousand has been reached with a mesh of improved design (ambitiously named GEM2000), offering the possibility to use a single GEM with PCB read-out as detector for X-rays and minimum ionizing particles.

Fig. 3 shows one of the large size GEMs manufactured at CERN and planned to be used, in conjunction with MSGC plates, for the construction of the central tracker in the HERA-B experiment [5].

Fig. 3: A large size GEM (27x25 cm²) mounted on its frame as prototype for the HERA-B tracker.

So far, the best quality GEM electrodes have been manufactured with an improved wet etching technology, developed at CERN's printed circuit workshop [6], and here only briefly described. The desired pattern, rows of holes 50 to 100 μm in diameter at 140 to 200 μm pitch, is inscribed on plastic films by a computer-controlled photo-composer. Two identical films are mounted on a holder and optically aligned, with an overall precision around 5 μm for the largest areas realized so far (30 cm on the side). A copper-clad kapton foil, coated on both sides with a thin layer of photosensitive resin, is inserted between the films and exposed to light. After curing, the foil is chemically treated and etched to remove the metal in regions corresponding to the holes. Immersion in a kapton-specific solvent (ethylene-diamine) then digs into the polymer from both sides, in a characteristic double-conical pattern with a profile controllable by fine tuning of the etching parameters. A second coarser masking and etching then removes the conductor around the borders of the pattern in order to prevent edge discharges, leaving offset electrical contact leads on both sides. A standard passivation with gold, nickel or chromium can be used to improve the surface smoothness and to protect from oxidation. Due to constraints in the etching procedures and to the availability of high quality metal-clad polymers, most GEMs manufactured so far have an insulator thickness of 50 μm and a metal layer 5 to 15 μm ;

various methods are being studied to increase the insulator (for higher gains) and reduce the metal thickness.

Before the installation in detectors, GEM meshes are tested for electrical insulation at low voltage in air, typically providing values above 2 G Ω , and at high voltage in dry nitrogen; most show a leakage current below 1 nA at 500 V, a value adopted as an acceptance criterion. The rejection rate, verified in several runs of several tens of pieces, is below 5%.

II. GEM AMPLIFICATION FACTOR

For systematic testing, GEM meshes are assembled within a small size MWPC, in place of one cathode plane, and with the addition of a drift electrode. Simply kept between two thin frames with rubber sealing O-rings, the meshes can be used again. Irradiating the detector with soft X-rays, both the direct and the GEM-amplified charges can be recorded, and the pre-amplification factor is simply defined as the ratio of the two as a function of applied voltages. High rate behavior and localization accuracy are studied mounting GEM electrodes with a MSGC plate as second element of amplification, or, for the higher gain models, Double and Super-GEMs, with a simple patterned printed circuit as read-out electrode. The detectors operate satisfactorily in a wide range of gases, and at high [7] and low pressures [8]; most measurements described here have been realized in a convenient, non-flammable mixture of argon and carbon dioxide in the volume proportion 70-30 and at atmospheric pressure.

Typical relative pulse height measurements realized with the GEM+MWPC structure are shown in Figs. 4 and 5 the corresponding GEM amplification deduced from ratios of values. For the particular model used, a maximum gain of a several hundred is routinely achieved. Captions in the figures describe the hole's geometry: 140/95/60 means a pitch of 140 μm between centers, 95 μm hole diameter at the metal opening and 60 μm at the kapton center.

Fig. 4: Example of relative gain curves measured with the GEM+MWPC assembly.

Fig. 5: Absolute gain (amplification factor) of the GEM mesh deduced from the previous plot.

As already discussed in previous works, a small increase in gain is often observed at startup, reaching a plateau after a time depending on the irradiation rate (few minutes at $\sim 10^4$ Hz/mm²). The amount of increase depends on the geometry: it is around 40% for the more conical holes (narrow in the center of kapton), but is absent for the more cylindrical ones as shown in Fig. 6. While obviously preferable for stable operation, cylindrical non-charging up GEMs are more difficult to manufacture, since the prolonged immersion in the kapton solvent can result in local under- and over-etching defects. Addition of a small quantity of water in the gas, increasing the kapton surface conductivity, completely eliminates charging up [3]. Alternative methods to obtain a reduced surface resistivity (around 10^{15} Ω/square seems appropriate) are being investigated in collaboration with other institutes [9, 10].

Fig. 6: Time dependence of relative gain for two GEMs. The one with narrow kapton holes exhibits a moderate increase due to charging up. Rate $\sim 10^4$ Hz/mm².

The systematic studies of amplification as a function of geometry show, as expected, that narrower holes yield a steeper exponential increase and a larger maximum gain, as can be seen in the compilation of Fig. 7. The maximum voltage that can be safely reached is determined by local defects more than by geometry, and of course depends on the gas mixture used. The pitch plays no role in the gain characteristics, but restricts the values of drift field for full collection (see later). We have found however that at narrow hole diameters a saturation effect appears, probably due to the loss of charges by diffusion, as apparent from Fig. 8 providing the correlation between the gain, measured in equal conditions, and the metal hole diameter.

Fig. 7: Compilation of amplification factors for several GEM geometries. The narrow hole models (type N) allow gains in excess of 2000.

Fig. 8: Summary of the GEM gains (at 500 V in Ar-CO₂ 70-30) as a function of the metal hole diameter. A saturation effect appears below 60-70 μm.

There is no advantage in reducing the diameter below 60-70 μm , an aspect ratio $\sim 1/1$ to the total foil thickness. An exponential extrapolation to zero diameter suggests a theoretical limiting gain around 10^4 , almost exactly what can be computed from the experimental value of the Townsend coefficient in this gas at the corresponding field (500 V over 50 μm) [11].

The hole diameter and pitch affect the collection efficiency of electrons released in the drift volume, as well as the distribution to the electrodes of ions produced in the avalanches. Drift and collection properties are being analyzed with the help of a commercial program that allows to compute electric fields in complex 3-D structures [12], followed by one describing drift and avalanche properties of charges in gases [13].

Experimentally, these properties are studied measuring pulse heights and currents in the structures for different field configurations. As an example, Fig. 9 shows the relative GEM gain, at fixed multiplication voltage, as a function of the collection drift field for a narrow hole GEM; in view of the negligible effect on amplification of the external field, unveiled by the field calculations, the measurement can be assumed to represent the GEM collection efficiency, or transparency.

Fig. 9: Relative pulse height (or transparency) as a function of the drift field for a 140 μm pitch GEM.

Full transparency at high values of drift field is required to obtain short collection times, and to minimize the distorting effect of external magnetic fields. In the example given, a field of 4 kV/cm can be reached with no losses; in the gas mixture used (Ar-CO₂ 70-30) the drift velocity at this field is almost saturated (to 7 cm/ μs) with minimum diffusion, and the Lorentz angle at 1 T is only 15° [14]. For higher values of magnetic field, a mixture richer in quencher and a design with more extended field tolerance (smaller pitch) would probably be preferable to keep the Lorentz angle small.

III. GEM AND THE MICRO-STRIP CHAMBER

An interesting use of the GEM mesh is as gain booster for the micro-strip chamber. Very powerful devices in terms of rate capability and localization accuracy, MSGCs are rather delicate to use and prone to failures caused by discharges at the operating voltage required for full efficiency [15-18]. We have assembled several detectors combining a GEM mesh with MSGC plates having an active area of 100x100 mm² and 200 μm pitch, and described in Ref. [17]; the gaps MSGC-GEM and GEM-drift electrode are 2 and 3 mm respectively. Realized with gold strips on thin diamond-coated thin glass, the MSGC is intrinsically capable of very high rates, above 10^6 Hz/mm² [19]. The detectors have been tested in set-ups including a high rate X-ray generator; Fig. 10 show typical combined amplification curves, as a function of cathode voltage in the MSGC and for increasing values of the GEM potential. As discussed in previous work, the GEM+MSGC detectors permits to reach high gains at voltages perfectly safe for both amplification elements; subjected to the combined action of a high intensity X-ray beam and of high specific ionization particles, they operate reliably and without discharges even in poorly quenched gas mixtures [3].

Fig. 10: Gain plots measured with 6 keV X-rays with a 10x10 cm² GEM+MSGC detector in Ar-CO₂.

We have verified the rate capability of the structure in various configurations and gain sharing. As an example, Fig. 11 shows the dependence of gain on detected X-ray flux in conditions of GEM amplification only (with the cathodes of the MSGC at low voltage); the gain remains constant well above 10^6 Hz/mm², demonstrating the absence of short term ion-induced charging up or space-charge effects in the GEM channels.

A peculiar and interesting mode of operation has been discovered: overly large signals are obtained with the MSGC maintained at unity gain (ionization mode). As seen in Fig. 10, an apparent gain of several thousand is recorded for low

voltage on the MSGC and a GEM pre-amplification factor of a few hundred. This apparent contradiction is explained by the different signal formation mechanism in the avalanche and ionization modes. While in the former the fast component of the detected signal, mostly due to ions, is only a fraction of the total charge, in the ionization mode all electrons leaving the GEM electrode induce a fast signal. Moreover, for the MSGC operated in the avalanche mode, a cancellation effect occurs due to the re-injection on the anodes of a fraction of the inverse polarity signal induced on cathodes. The two effects combine to make the ionization mode much more effective in inducing signals.

Fig. 11: Relative gain of GEM as a function of rate (6 keV X-rays). The detector was operated at a GEM gain of 90 and the MSGC in the ionization mode; the dashed line indicates the transition from a pulse height to a current measurement.

Several GEM+MSGC detectors, equipped with a fast analogue read-out electronics based on the PRESHAPE amplifier circuit with ~ 45 ns shaping constants [20] followed by gated ADCs, have been installed in minimum ionizing charged particles beams to ascertain their operating characteristics. All devices had an active area of 100×100 mm² with strips at 200 μ m pitch, although only a reduced number of adjacent channels could be read-out. In all detectors, the sensitive gap was 3 mm thick. In a test run realized in a magnet at DESY in July '97 [21] only the efficiency plateaux could be measured, and revealed no effect of a magnetic field up to one Tesla; in the CERN September-October run instead (without magnetic field) full tracking could be performed using as reference the COMPASS silicon micro-strip telescope [22].

Fig. 12 shows the pulse height spectrum recorded for minimum ionizing particles perpendicular to the detector in typical operating conditions, 380 V applied to the MSGC cathodes and 480 V on GEM (a pre-amplification factor around 100). The signal to noise ratio, defined as the peak of the Landau distribution over the rms of noise, is 160. The corresponding efficiency plateaux, measured for several values

of GEM voltage and reaching 99.2% are shown in Fig. 13; for precaution, the cathode voltage was not increased to reach full efficiency with the MSGC alone (about 600 V would be required).

Operation in the middle of the plateau, with both differences of potential around 400 V, is extremely stable and safe. The value of 20% efficiency measured at $V_{MSGC}=0$, at a pre-amplification of 150, is particularly amazing: it confirms the essential difference in signal formation between the avalanche and ionization modes. Indeed, for the MSGC alone, this value of efficiency is reached at a voltage corresponding to an avalanche gain of almost 1000.

Fig. 12: Cluster charge (total pulse height) recorded for minimum ionizing particles with the GEM+MSGC detector. The noise contributes to counting in the first channel only (suppressed in the plot).

Fig. 13: Efficiency plateaux for minimum ionizing particles in the GEM+MSGC detector as a function of the applied voltages.

The localization accuracy of the detector, $40\text{ }\mu\text{m}$ rms (see Fig. 14) equals the best achieved in MSGCs, demonstrating that the GEM electrode does not introduce detectable distortions or modulations.

Replacing the ADCs with a set of fast threshold-operated discriminators followed by TDCs for part of the runs, we have measured the time resolution of the detector: it has a Gaussian distribution with 5.4 ns rms and is fully contained within 20 ns , a time interval shorter than the LHC bunch crossing. This is better than what achieved with MSGCs [23], and is of course a direct effect of the very large signal/noise ratio.

Fig. 14: Position accuracy for tracks perpendicular to the detector plane, measured for a point in the middle of the efficiency plateau.

In a short test run at DESY we have verified that the efficiency plateau of the detector is not affected by the presence of a magnetic field perpendicular to the drift field (the worst case) up to one Tesla; Fig. 15 shows the comparison of efficiency measured without and with magnetic field, using a mixture of argon and dimethylether (DME). As tracking was not available, we could not check localization properties, but apart from the small distortion due to the Lorentz angle on drifting electrons ($\sim 10^\circ$ in our operating conditions) we do not expect any particular problem due to loss of transparency in GEM.

A very important issue in gas detectors is the one of ageing, permanent degradation of performances under conditions of intense irradiation due to the formation of polymers in the gas avalanches. We have installed a GEM+MSGC detector in our standard ageing set-up, described in Ref. [24], and started a systematic investigation on the possible effect of ageing on GEM. The detector itself is contained in a stainless steel vessel, and assembled using only materials certified clean by previous studies; irradiated continuously with a strong collimated X-ray beam, it is monitored continuously recording currents, pulse heights and counting rates.

Fig. 15: Comparison of efficiency plateaux measured with the GEM+MSGC detector without and with magnetic field (1 Tesla perpendicular to the electron drift).

The stability of performance is revealed by a constant overall gain as a function of collected charge, after correction procedures described in the reference; due to limitations in the maximum radiation flux that can be used, each measurement can take several weeks to months. Fig. 16 shows the present status of the measurement, realized with an argon-carbon dioxide gas filling at a pre-amplification factor around ten; after a small initial decrease, possibly due to polarization effects in the dielectric, the overall gain remains constant up to 10 mC/cm^2 . Our previous experience with MSGCs suggests that no ageing effects will be observed up to much higher collected charges. The measurement continues in other gain configurations, and will be repeated with the addition of water to the gas mixture (to eliminate charging up effects).

Fig. 16: Gain uniformity as a function of collected charge during an ageing measurement. The small initial decrease is probably due to residual polarization effects. The current density used for the irradiation is $\sim 5\text{ nA/mm}^2$.

IV. DOUBLE AND SUPER-GEM WITH PRINTED CIRCUIT READOUT

With the large gains reached in the most recent GEM models, direct detection of tracks is possible without other amplifying elements on a simple collection electrode. The advantages offered by this mode of operation are many: the readout circuit can be patterned in any desired geometry (strips, rings, pads...) depending on application; use of electrically semi-transparent resistive or narrow strips on a thin insulating support permits the pick-up of a controlled fraction of the signal on electrodes on the back side, in order to obtain two-dimensional read-out; absence of ions produced in the last gas volume eliminates problems of support charging-up and, possibly, of ageing.

In the earlier phase of the development, similar high gain conditions have been achieved with two meshes in cascade at some distance (Double-GEM), or in electrical contact (Super-GEM). The detector consists of an upper electrode, delimiting a conversion and drift region, of two consecutive, closely assembled GEMs, and of an induction gap terminating with a printed circuit board with parallel pick-up strips. With the application of suitable potentials, electrons released by ionization in the upper gas layer drift into the open channels of the first GEM, multiply in avalanche in the high field, transfer to the second GEM and multiply again. No alignment is necessary between the two meshes if they are at some distance; Super-GEMs, on the other hand, have to be carefully overlaid, within the limits of the general accuracy of manufacturing ($\sim 5 \mu\text{m}$). Signals are induced on pick-up strips on the PC board by the electron swarm leaving the second GEM, with an amplitude corresponding to the total drifting charge. Fig. 17 shows an example of combined charge gain for a double GEM detector, measured on the pick-up strips with an ^{55}Fe source, and a 90-10 gas filling of argon-dimethylether (DME). Even with a single GEM operating ($\Delta V_{\text{GEM1}} = 0$), signals are large enough for detection.

Fig. 17: Combined gain plots for the Double GEM+PCB detector. Gas filling Ar-DME.

The rise-time of the signal in the ionization mode, corresponding to the drift time of electrons across the last gap (about 30 ns) is a priori slower than in the avalanche mode; both are however faster than the rise-time of our amplifiers (45 ns) and are therefore indistinguishable. Moreover, as there is no slow ion component in the first case, signals are effectively shorter in duration implying a higher intrinsic rate capability. The lower GEM electrode facing the readout strips detects a signal equal in charge and opposite in sign; despite the large capacitance of the source, we have achieved an energy resolution at 6 keV of 25 % fwhm, sufficient for discrimination and triggering. This offers the possibility of using, for the localization of neutral radiation, cheap, high density analogue multiplexers such as those developed for particle physics, that require a gate to be operated. The GEM electrode could also be segmented in strips to offer coarse localization; the source capacitance will be correspondingly decreased.

Free from the constraints imposed by a MSGC as last element, a thin, double-sided printed circuit with perpendicular strips for the read-out can be used to achieve two-dimensional localization. In the Double-GEM detector, we have used a 50 μm thick, double-sided printed circuit with strips at a 200 μm pitch, 50 μm wide for the electrode facing the gas, and 150 μm for the outer coordinate, perpendicular to the first. The detector was exposed to the beam at CERN in the set-up already described; a preliminary analysis of the data show that full efficiency is reached with an extended plateau (Fig. 18) and very good pulse height correlation between the two coordinates.

Rather encouraging results have also been obtained by the so-called Super-GEM, obtained assembling two standard meshes in electrical contact. As this requires a precise alignment between the GEMs, the method is probably limited to small size devices.

Fig. 18: Efficiency for minimum ionizing particles measured in the beam with the Double GEM detector. The two GEMs were operated at equal potential differences; both can be increased up to 600 V.

V. ALTERNATIVE MANUFACTURING TECHNOLOGIES

Alternative manufacturing technologies are being explored in order to widen the range of possible geometries and sizes for the GEM electrodes. Attempts to use plasma etching have failed so far to provide satisfactory devices. Laser drilling has been instead successful, and has permitted to realize thicker prototypes with higher gains; moreover, the almost cylindrical shape of the channels guarantees the absence of charging-up. Fig. 19 shows a close view of a hole 110 μm in diameter, laser-drilled on 75 μm kapton foil; a 10x10 cm^2 prototype has been manufactured at CERN and tested. The original rather rough edges of the holes have been smoothed by a gentle conventional wet etching removing few microns of copper. The gain reached with the mesh exceeds 500 (see Fig. 20); the maximum operating voltage however (650 V) is lower than what would be expected from an extrapolation of the 50 μm data, possibly indicating a general lesser quality of the artwork. Convenient for the realization of prototypes in a wider range of foil materials and thickness, laser drilling tends however to be too expensive for the serial production of detectors.

Fig. 19: Close view of a laser-drilled, 75 μm thick GEM. Holes are about 110 μm in diameter at 200 μm pitch. The prototype tested has 10x10 cm^2 .

A new single-mask wet etching technology has been developed at CERN. After exposure to light through a patterned film on one side only, the kapton foil is etched exposing the holes (the other side being protected). Immersion in the kapton solvent then digs conical-shaped holes all the way down to the second metal layer. A controlled etching, designed to dissolve about half of the metal thickness, then removes completely the lower metal diaphragm, acting from both sides, while halving the upper metal thickness. Conical GEMs, as they have been named, operate very satisfactorily from all points of view except one: the charging-up under irradiation is larger (up to 100%), and seems to be affected

Fig. 20: GEM gain as a function of voltage for the 75 μm thick laser-drilled GEM.

only erratically by the addition of water. This is possibly a consequence of the presence of a narrow ring of pristine kapton surface around the entrance hole, due to the retreat of the metal during the etching process; we believe that the water adsorption properties of the original and of the etched surfaces are very different.

We have tested several conical GEMs as amplifiers in the two possible configurations: with the wider holes facing the conversion volume (160 and respectively 120 μm diameter holes at the metal and kapton levels), and in the reverse configuration (75 and 60 μm holes respectively). The gain curves as a function of voltage differ only slightly (Fig. 21), while obviously the transparency curves are very different (see Fig. 22).

Fig. 21: Summary of gain as a function of voltage for the conical GEM; the two curves refer to a drift of electrons into GEM into the narrow and the wide holes side.

Fig. 22: Transparency as a function of drift field for the conical GEM, measured at fixed gain for a drift of electrons into the narrow and the wide hole sides of the mesh.

The choice seems particularly interesting for applications where the ratio between optical and electrical transparency plays an important role (operation in magnetic fields, photon detectors in association with an internal photocathode). In view of the considerable advantages of a single-mask processing, particularly for larger size meshes, work is in progress to better understand the behavior of the conical GEM devices.

Various attempts have also been done to reduce the thickness of the metal of the GEM electrodes. The chemical etching procedure, that makes use of the engraved copper layer as mask, requires a metal thickness of at least 5 μm , 10 to 15 μm being preferable. A possible way to reduce the thickness is to remove part or all of the copper after engraving, relying on the thin residual adhesion layer (usually chromium) used for the manufacture of the sheet. We have found however that the uniformity of the under-layer (typically 10 to 100 nm thick) is not good enough to guarantee reproducibility, although several GEMs with the under-layer only performed satisfactorily. This requires further investigation, also in view of the better mechanical properties of the thin-layer GEMs (the increased elasticity makes them easier to stretch). Alternative metal coatings, like thin aluminum, have also been envisaged.

VI. CONCLUSIONS AND FURTHER WORK

The gas electron multiplier mesh was first described at this symposium exactly one year ago [2]; despite the modest gain achieved at the time (less than ten) it raised considerable interest. Further progress in the GEM manufacturing technology and in the understanding of its operating principles have led to the realization of devices with large sizes and gains well above a hundred. Coupled to a MSGC, the additional gain provided by the GEM mesh permits the operation of the

combined detector at substantially reduced voltages thus largely increasing its reliability, particularly in harsh conditions of use; safe operation has been demonstrated in non-flammable, poorly quenched gases and under the simultaneous exposure to a large flux of radiation and to heavily ionizing tracks, an essential requirement for trackers at LHC, HERA and other high-luminosity colliders.

Further developments by the CERN group and by others have demonstrated the soundness of the new technology, with the most advanced designs achieving a gain well above one thousand; at this point, the GEM device becomes a detector on its own, with a patterned printed circuit as read-out electrode. Bi-dimensional localization is simply achieved using a thin, double-sided circuit. A wide tolerance for correct performance to the value of the external fields makes the GEM grids insensitive to mechanical imperfections in the detector construction; virtually self-supporting, the mesh can be kept in position by simple gluing on thin frames, in good match with the light assembly schemes developed for low-mass detectors. Non-planar, cylindrical geometries are possible. The simplicity, ruggedness and low cost of the GEM detectors makes them very attractive for use in applied fields as X-ray position sensitive device. Operation in high pressure Xenon mixtures has been demonstrated recently [25].

The properties of controlled electrical transparency with a reduced optical transparency suggests the possibility of using one or more GEM meshes in cascade for the detection of electrons produced on solid photocathodes, for example the CsI used in Cherenkov Ring Imaging. By proper arrangement of the electrodes, photons and ions feedback from the last multiplying element to the photocathode can be strongly suppressed. A gas counter with a bi-alkali photocathode and a GEM-based amplifier is being developed at the Budker Institute in Novosibirsk in collaboration with our group [26]. The possibility of using a reverse photocathode geometry, with the photosensitive material deposited directly on one of the GEM electrodes, already proposed in previous work [2] is investigated at the Weizmann Institute of Science [27].

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VIII. REFERENCES

- [1] F. Sauli, GEM: A new concept for electron amplification in gas detectors. Nucl. Instrum. Methods in Physics Res. A386 (1997) 531.
- [2] R. Bouclier, M. Capeáns, W. Dominik, M. Hoch, J.-C. Labbé, G. Million, L. Ropelewski, F. Sauli and A. Sharma: The Gas electron Multiplier (GEM). IEEE Trans. Nucl. Science NS-44 (1997) 646.
- [3] R. Bouclier, W. Dominik, M. Hoch, J.-C. Labbé, G. Million, L. Ropelewski, F. Sauli, A. Sharma, G. Manzin: New observations with the gas electron multiplier (GEM). Nucl. Instrum. Methods in Physics Res. A396 (1997) 50.
- [4] C. Büttner, M. Capeáns, W. Dominik, M. Hoch, J.-C. Labbé, G. Manzin, G. Million, L. Ropelewski, F. Sauli and A. Sharma, Progress with the gas electron multiplier. CERN-PPE/97-73. Proc. 7th Pisa Meeting "Frontier Detectors for Frontier Physics" (Elba, Italy May 25-31, 1997).
- [5] HERA-B, An experiment to study CP violation in the B system using an internal target at the HERA proton ring. DESY-PRC 94/02 and PRC 95/01.
- [6] A. Gandi, R. De Oliveira and L. Mastrostefano, CERN-EST-SM, Geneva, Switzerland.
- [7] J. Seguinot and T. Ypsilantis, private communication at CERN.
- [8] A. Breskin, Weizmann Institute of Sciences, Rehovot (Israel). Private communication.
- [9] U. Wertenbach and G. Zech, Univ. Siegen (Germany).
- [10] G. Della Mea and V. Rigato, INFN Legnaro (Italy).
- [11] J. C. Armitage, S. Beingsner, R. K. Carnegie, E. F. Ritchie, J. Waterhouse: A study of the effect of methane and carbon dioxide concentration on gas amplification in argon based gas mixtures. Nucl. Instrum. Methods in Physics Res. A271 (1988) 588.
- [12] MAXWELL, Electric Field Simulator by Ansoft Co. USA.
- [13] GARFIELD, developed at CERN by R. Veenhof.
- [14] Extended transport tables can be found at: <http://www.cn.cern.ch/writeup/gas/examples/trans2000.html>
- [15] B. Boimska, R. Bouclier, M. Capeáns, S. Claes, W. Dominik, M. Hoch, G. Million, L. Ropelewski, F. Sauli, A. Sharma, L. Shekhtman, W. Dominik and L. Van Lancker: Study of ageing and gain limits on microstrip gas chambers at high rates. CERN-PPE/96-201. Proc. 5th Int. Conf. Advanced Technology and Particle Physics (Como October 7-11, 1996).
- [16] V. Peskov, B.D. Ramsey, P. Fonte: Surface streamer breakdown mechanisms in microstrip gas counters. Nucl. Instrum. Methods in Physics Res. A392 (1997) 89.
- [17] A. Barr, S. Bachmann, B. Boimska, R. Bouclier, A. Braem, C. Camps, M. Capeáns, V. Commichau, W. Dominik, G. Flügge, F. Gómez, R. Hammarstrom, K. Hangarter, M. Hoch, J. C. Labbé, D. Macke, G. Manzin, F. Meijers, G. Million, K. Muhlemann, V. Nagaslaev, A. Peisert, L. Ropelewski, O. Runolfsson, F. Sauli, R. Schulte, M. Schulz, A. Sharma, L. Shekhtman, C. Wolff: Construction, test and operation in a high intensity beam of a small system of micro-strip gas chambers. CERN-PPE/97-119 (1997).
- [18] B. Schmidt, paper presented at the Beauty 96 conference (unpublished).
- [19] R. Bouclier, M. Capeáns, G. Million, L. Ropelewski, F. Sauli, T. Temmel, R.A. Cooke, S. Donnel, S.A. Sastri, N. Sonderer: High rate operation of micro-strip gas chambers on diamond-coated glass. Nucl. Instrum. Methods in Physics Res. A 369 (1996) 328.
- [20] J. Hall, Front end electronics for the CMS tracker. Proc. Int. Workshop on microstrip gas chambers, Lyon (1995) 165.
- [21] In collaboration with M. Hildebrand, S. Hausman, Th. Hott, B. Schmidt, M. Ziegler, Physics Institute of the Heidelberg University, Germany.
- [22] In collaboration with M. Beck, S. Gerassimov, S. Masciocchi, S. Paul, L. Schmitt, Max-Planck-Institute Heidelberg, Germany.
- [23] J. F. Clergeau, D. Contardo, T. Ladzinsky: Study of the signal shape of a MSGC equipped with the RD20 preamplifier. Proc. Int. Workshop on microstrip gas chambers, Legnaro (1994) 64.
- [24] R. Bouclier, M. Capeáns, C. Garabatos, G. Manzin, G. Million, L. Ropelewski, F. Sauli, L. Shekhtman, K. Silander, T. Ropelewski-Temmel: Ageing of microstrip chambers: problems and solutions. Nucl. Instrum. Methods in Physics Res. A381 (1996) 289.
- [25] L. Shekhtman, BINP Novosibirsk, Russia. Private communication.
- [26] A. Buzulutskov, BINP Novosibirsk, Russia. Private communication.
- [27] A. Breskin, Weizmann Institute of Sciences, Rehovot, Israel. Private communication.