FURTHER DEVELOPMENTS OF THE GAS ELECTRON MULTIPLIER (GEM)


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ABSTRACT

We describe the development and operation of the Gas Electron Multiplier, a thin insulating foil metal-clad on both sides and perforated by a regular pattern of small holes. The mesh can be incorporated in the gas volume of an active detector to provide a first amplification channel for electrons, or used as stand alone. We report on the basic properties of GEMs manufactured with different geometries and operated in several gas mixtures as well as on their long-term stability after accumulation of charge equivalent to several years of operation in high luminosity experiments. Optimized GEMs reach gains close to 10000 at safe operating voltages, permitting the detection of ionizing tracks, without other amplifying elements, on a simple printed circuit board (PCB), opening new possibilities for detector design.
1. INTRODUCTION

The Gas Electron Multiplier (GEM) [1] is a thin insulating foil (~50 μm Kapton) copper-clad (typically 5-15 μm thick) on both sides and perforated by a high density, regular matrix of holes. Typically, the distance between holes (pitch) is 140-200 μm and the diameter of the holes opening varies between 40 and 120 μm. The mesh is realized by conventional photolithographic methods as used for the fabrication of multi-layer printed boards [2]. Upon application of a potential difference between the GEM electrodes, a high dipole field develops in the holes focusing the field lines between the drift electrode and the readout element. Electrons drift along the channels and the charge is amplified by a factor that depends on the field density and the length of the channel.

In 1996 the first GEM was successfully assembled in a MWPC to demonstrate its operating principle [3]. Fig. 1 shows a typical example of amplification curves for a more interesting device, a high rate MSGC coupled to a GEM electrode; the assembly is shown in the inset. With the GEM mesh under voltage, higher overall gains are achieved, improving the reliability of the gaseous device that can be operated at lower voltages, a fundamental feature in the case of MSGCs. The GEM effective amplification factor, defined as the ratio between the doubly amplified and the direct signal for the 5.9 keV line, is extrapolated once the direct signal is not detected anymore. In Fig. 1, with 500 V in the mesh the amplification is ~200. Note the use of a non-flammable gas mixture, Ar-CO2 at atmospheric pressure. Amplifications well above hundred have been demonstrated in a wide range of gases [4].

2. OPTIMIZATION OF GEM

The maximum safe operational voltage is determined by local defects more than by geometry, and it depends on the gas mixture. The amplification of the GEM mesh depends on geometry and operating conditions. Simulation studies and experimental results have been carried out in order to optimize these parameters. Hole diameter, pitch and geometry of the hole are determined by the manufacturing process; the thickness of the mesh is at present limited by the availability of high quality polymers metal-coated apt to be chemically processed.

2.1 Influence of hole diameter

In order to achieve higher gains, the field density in the amplifying channel can be increased by raising the potential difference between the upper and lower GEM electrodes, or by reducing the diameter of the channel. Fig. 2 shows the correlation between the effective GEM gain and the hole diameter, measured at equal gas and field conditions. As discussed later, a field-dependent fraction of the electron avalanche is collected by the lower GEM electrode, and does not contribute to the transmitted signal. We define the ratio of detected to input charge “effective gain” of the system, smaller than the real GEM gain by an amount that depends on the field values (see below). In Fig. 2, an exponential fit to the points extrapolates to the expected gain for a 50 μm thick parallel plate geometry deduced from the known value of the Townsend coefficient [5]. A saturation effect is apparent at diameters below 60±70 μm; as it
will be discussed later, this is due to increasing losses of electrons in the avalanche (due to diffusion) to the lower GEM electrode (see section 3). One should note that the fractional loss depends almost linearly from the value of the transfer field; the measurements in Fig. 2 have been obtained at a rather low values of field permitted by the GEM+MSGC configuration. The saturation effect, whilst limiting the possible gain enhancement, has the very positive effect of reducing substantially the dependence of gain from the precision of the GEM manufacturing process: we have indeed found that the gain uniformity over the active area of the device is largely improved for hole diameters below the saturation value.

### 2.2 Influence of pitch

The pitch plays no role in the gain characteristics, but combined with the hole diameter affect the collection efficiency, or electrical transparency, for electrons released in the drift volume, as well as the distribution of ions produced in the avalanches. The GEM electron collection efficiency is evaluated measuring the gain for a fixed GEM voltage as a function of the upper drift field, as shown in Fig. 3 for a GEM of 140 $\mu$m pitch and 90 $\mu$m holes, and for a GEM of 200 $\mu$m pitch and 100 $\mu$m holes. At high drift voltages some field lines reach the upper electrode, reducing the transfer of electrons into the channels; at low fields, diffusion plays a role in losses. Full electrical transparency at high drift values is needed to ensure short collection times and to minimize distortions in magnetic fields. We have exposed a MSGC+GEM to a high energy positron beam in Desy in a magnetic field of 1 Tesla perpendicular to the electric field and the measured efficiency (~99%) was not affected [2], as expected.

### 2.3 Influence of hole shape

The geometry of the holes affects the charging-up, a short-term, rate-dependent instability of the electrode manifested usually as a small increase of gain due to the presence of insulating material close to the multiplication channels. Experimentally we have found that the amount of increase depends on the geometry, reaching about 60% for the more conical holes but totally absent for a cylindrical geometry, as shown in Fig. 4. In principle this gain shift can be corrected making the insulating surface slightly conductive; methods like diamond coating [6] or the addition of a small, controlled quantity of water vapour have been successfully tested [4].

### 3. GEM WITH PRINTED CIRCUIT BOARD

A new mode of operation was discovered while using MSGCs at zero cathode voltage, the so-called ionization mode. As seen in the leftmost side of Fig. 1, the effective gain is high enough to ensure detection of radiation. The amplitude of the signals in the ionization mode corresponds to the total charge and the rise time is the drift time of electrons across the last gap (30 ns), a priori slower than in the avalanche mode; however both are faster than the rise time of our amplifiers -45 ns- and are therefore indistinguishable.

The high gains achieved by the most recent GEM models permit to use a cheap, single printed circuit board (PCB) as readout element. The assembly consists of an upper electrode delimiting a 3 mm thick conversion and drift
region, followed by a GEM and of a thin induction gap (0.5-3 mm) realized with a passive PCB with parallel pick-up strips at 200 μm. An important advantage of this new design is that the currents from potential discharges in the high voltage element will not flow into the amplifiers, reducing the possibility of damaging the electronics.

Fig. 5 shows the effective GEM gain as a function of the lower field in the GEM+PCB structure. An optimized field in the low, transfer volume allows at high GEM voltages to increase the gain by one order of magnitude before entering in the parallel plate avalanche mode. From the measured currents in all the detector elements (Fig. 6), it is apparent that a fraction of the electron current in the avalanche flows into the lower GEM electrode; for a transfer field around 8 kV/cm, this fraction is about 20%. An outcome of the lateral spread of the avalanche during its development along the multiplying channel, the fractional loss is gas dependent, and presumably smaller for heavily quenched mixtures. One should note that, aside from resulting in a loss of signal, the lost current is small enough, even for high rate operation, not to disturb the operation of the detector as far as power supplies and protection resistors are suitably designed. In extreme cases, a coarse stripping of the lower GEM electrode, with individual resistors, could be used to reduce potential drops and improve protection in case of discharges.

Fig. 7 and Fig. 8 show respectively the effective GEM gain, defined as the charge detected on the PCB board, as a function of voltage for different concentrations of Ar-CO₂ and Ar-DME, measured with a GEM and PC board at 0.5 mm distance. In DME, for optimized fields, a gain of 2·10⁴ is measured at the upper end of the GEM operating voltage. A gain above 2000 is attained in pure DME at higher voltages, proving that the intrinsic dielectric rigidity of the mesh is determined mainly by the gas properties and not by surface breakdown.

Several GEM+PCB detectors with an active area of 100x100 cm² have been exposed to a ⁹⁰Sr source to evaluate their efficiency for fast electrons selected by triggering on external scintillation counters. Only a reduced number of channels could be readout with an analogue electronics based on the fast PRESHAPE amplifier circuit having 45 ns shaping constants [7] followed by gated ADCs. The relative efficiency plateau for different concentrations of Ar-DME and in Ar-CO₂ 70-30 are shown in Fig. 9 for a drift field of 2 kV/cm and a transfer field of 6 kV/cm.

As demonstrated in earlier papers [8] the lower GEM electrode detects a positive signal; in the ionization chamber mode (GEM+PCB) signals are identical and opposite. This can be used for triggering purposes, both for timing and for energy selection. We have also experimented with a finely stripped lower GEM electrode to explore the possibility of two-dimensional readout, with rather encouraging results. One should not forget however that in this configuration one major advantage of the GEM structure (the decoupling of the readout strips from high voltage sources) is lost; moreover, for a 2-D readout, one of the pickup electrodes has to be kept at high voltage with the consequent problems of HV capacitors. A safer and more flexible geometry consists however in realizing the PCB readout electrode as a matrix of pads, interconnected on the back side to form readout strips; this solution has the
advantage of being totally symmetric in the two projections from the signal induction point of view. An even more flexible assembly making use of a resistive foil as final electrode is being investigated; the pickup circuit (strips, pads or any other geometry) can then be simply approached to the semi-transparent electrode for signal pick-up. In this case, and using a thin foil insulator coated with a resistive layer as electrode, the operating voltages can be offset in order to keep the lower GEM electrode at ground potential easing the readout of induced signals there.

4. LONG-TERM BEHAVIOUR

Gaseous detectors often show a degradation of their performance (ageing) at high radiation doses, attributed to the formation in the avalanches of polymers due to gas pollution, materials used in the construction, organic gas mixtures, etc. [9]. To study the long-term behaviour of the GEM mesh, a diamond-coated MSGC assembled with a moderate gain GEM was installed in a dedicated set-up. The elements used in the construction are non-outgassing materials according to foregoing studies. Previous long-term tests with coated MSGCs under the same cleanliness conditions in Ar-DME certified the absence of ageing in the MSGC plate [8] (no analysis had been carried out for Ar-CO2).

Working at moderate voltage in the MSGC cathodes, for Ar-CO2 the gain is initially enhanced due to the charging-up of the GEM foil followed by a gain decrease that affects permanently the exposed area; after this effect the gain reaches a stable value (Fig. 10). Under the same conditions, for DME the gain remains stable after the initial charging-up. Working in ionization mode (\(V_c=0\) V), some tests have been also done adding 3000 ppm of water vapour to the previous gas mixtures to prevent the initial charging-up. However, the test in CO2 failed due to the appearance of increasing currents in the GEM, possibly due to a chemical reaction between CO2 and water, favoured by the action of ionizing radiation, and affecting the electrical properties of the materials in the assembly. In DME the gain stays stable from the very beginning of the irradiation.

5. CONCLUSIONS

One and a half year after the operation of the first GEM, simulation and experimental results have been carried out to achieve larger amplification factors. Presently, gains up to and above \(10^4\) are reached, making the operation of gaseous detectors assembled with GEMS much more reliable. Correct operation of MSGCs with GEM has been demonstrated in non-flammable gas mixtures, in particle beams with and without magnetic field, in presence of heavily ionizing radiation and its long-term stability at high rates. A new, cheap and simple technology for gaseous detection is put into operation: GEMs assembled with a printed circuit board. In this new device, the decoupling between the avalanche and the readout electrode eliminates possible damages to the electronics due to discharges; the absence of ions in last gas volume eliminates support charging-up and possibly ageing.
REFERENCES


FIGURE CAPTIONS

Fig. 1 Gain as a function of voltage applied to the MSGC cathodes for different GEM voltages. The geometry of the mesh is quoted in μm: 140 is the pitch or distance between centres, 90 the hole diameter at the metal opening and 60 at the Kapton centre.

Fig. 2 Measured effective gain of GEMS in Ar-CO₂ [70-30] with different metal hole diameters.

Fig. 3 Collection efficiency or electrical transparency as a function of the drift field in a GEM of 140 μm pitch and 90 μm holes and a GEM of 200 μm pitch and 100 μm holes.

Fig. 4 Time dependence of gain for several hole shapes under a particle rate of 10⁴ Hz/mm².

Fig. 5 Effective GEM amplification as a function of the field in the transfer volume.

Fig. 6 Currents measured in all the GEM+PCB electrodes as a function of the transfer field.

Fig. 7 Effective GEM gain as a function of voltage for different concentrations of Ar-CO₂.

Fig. 8 Effective GEM gain as a function of voltage for different concentrations of Ar-DME and for pure DME.

Fig. 9 Relative efficiency plateaux for fast electrons measured with the GEM+PCB in several gas mixtures.

Fig. 10 Long-term behaviour of MSGC+GEM in Ar-CO₂ at high irradiation rate.
Gain

GEM # A17A (140/90/60)

$E_{\text{drift}} = 3.5 \text{ kV/cm}$

Fig. 1

Effective GEM Gain

$\Delta V_{\text{GEM}} = 500 \text{ V on 50 } \mu\text{m}$

Fig. 2
**Fig. 3**

Relative Pulse Height

- MSGC + GEM A17A (140/90/60)
  - $\Delta V_{GEM} = -467$ V

- MWPC + GEM 2 (200/100/70)
  - $\Delta V_{GEM} = -360$ V

**Fig. 4**

Relative GEM Amplification Factor

- GEM#72 140/90/60
- GEM#A17A 140/90/60
- GEM#88 200/130/110

X-ray flux: $10^4$ Hz/mm²
Effective GEM Amplification

![Graph](image.png)

**Fig. 5**

GEM H2 + PCB

$E_{\text{drift}} = 1.4 \text{ kV/cm}$

$\Delta V_{\text{GEM}} = 550 \text{ V}$

Ar-CO$_2$ 70-30

![Graph](image.png)

**Fig. 6**

GEM H2 + PC Board, Ar-CO$_2$ [70-30]

$\Delta V_{\text{GEM}} = 500 \text{ V, } E_{\text{drift}} = 1.6 \text{ kV/cm}$

$E_{\text{drift}} \uparrow$ 3.5 mm

$\Delta V_{\text{GEM}} \uparrow$ 0.5 mm

$E_{\text{transfer}}$ (estimated)

![Graph](image.png)
Fig. 7

Effective GEM Gain vs. $\Delta V_{\text{GEM}}$ (V) for GEM H2 + PCB and ARGON-CO$_2$ mixtures.

Fig. 8

Effective GEM Gain vs. $\Delta V_{\text{GEM}}$ (V) for GEM H2 + PCB and ARGON-DME mixtures.
Fig. 9

- Relative Efficiency vs. \( \Delta V_{\text{GEM}} \) (V)
- Ar-DME 90-10
- Ar-DME 80-20
- Ar-DME 50-50
- Ar-CO\(_2\) 70-30

Fig. 10

- GEM A17A (140/90/60) + MSGC
- Charge (mC cm\(^{-1}\))
- Relative gain
- \( \Delta V_{\text{GEM}} = 468 \) V
- \( E_{\text{drift}} = 3.7 \) kV/cm
- \( E_{\text{transfer}} = 2 \) kV/cm
- \( V_c = -320 \) V
- Total Gain ~ 3000
- Charge density: 4.5 nA/mm\(^2\)

X Rays off for 29 hours

X Rays off for 29 hours