A large area GEM detector

Serge Duarte Pinto*†‡, Matteo Alfonsi*, Ian Brock†, Gabriele Croci*, Eric David*,
Rui de Oliveira*, Bat-El Pinchasik*, Leszek Ropelewski*, Fabio Sauli*, Miranda van Stenis*

***Abstract*—A prototype triple GEM detector has been constructed with an area of ~2000 cm^2, based on foils of 66 cm × 66 cm. GEMs of such dimensions have not been made before, and innovations to the existing technology were made to build this detector.**

A *single-mask technique* overcomes the cumbersome practice of alignment of two masks, which limits the achievable lateral size. Refinement of this technique results in foils with performance similar to traditional GEMs, while lowering cost and complexity of production.

In a splicing procedure, foils are glued over a narrow seam, thus obtaining a larger foil. This procedure was shown not to affect the performance of the GEMs. The seam can be as narrow as 2 mm, mechanically strong enough to withstand the necessary stretching tension, and sufficiently flat to maintain homogeneous electric fields in the gas volumes above and below the foil.

These innovations should make the manufacture of GEM foils of 1 m^2 and beyond possible. With the planned high luminosity upgrade of LHC, a considerable demand for such large area MPGDs is expected for replacement of wire-based trackers. Other possible fields of applications are in large area photodetectors, and high granularity calorimeters using particle flow algorithms.

I. Introduction

The Gas Electron Multiplier (GEM), invented in 1998 [1], has proven to be a versatile electron amplification structure. Its independence of the readout structure, the fact that it can be cascaded to achieve higher gains at lower voltages, and the flexibility to construct it into complex shapes and geometries makes it an attractive device for tracking systems in high energy physics. Two of the current LHC experiments (TOTEM [2] and LHCb [3]) employ GEM-based trackers, both in the forward regions where high rate capability and fine granularity are required. With the plans for a high luminosity upgrade to SLHC, experiments need to prepare for a considerable increase in rate and, depending on the future bunch spacing, a twice as large increase in track multiplicity.

Many of the wire-based gas detectors currently used in the experiments will hardly be suitable for these harsh conditions. The slowly drifting ions cause space charge effects, which limit the rate capability to 10–100 kHz/cm^2. In micropattern gas detectors (MPGDs) rate capability is typically limited by discharge probability rather than space charge effects. In the case of (cascaded) GEMs, rate capability can be increased by about two orders of magnitude with respect to wire-chambers. However, MPGDs with dimensions exceeding ~0.5 m are not available thus far.

Manuscript received, 14 November 2008. This project was made possible by support from the RD51 collaboration for micropattern gas detectors.

*CERN, Geneva, Switzerland.
†Physikalisches Institut der Universität Bonn, Bonn, Germany.
‡Corresponding author: Serge.Duarte.Pinto@cern.ch

An effort has been started to make GEM technology available for such large size detectors. We made a prototype large area triple GEM chamber, aimed at an application in the TOTEM experiment, as an upgrade to its T1 tracker [4], currently a cathode-strip wire-chamber. The active area is ~2000 cm^2 and the GEM foils used were 66 cm × 66 cm. To produce foils of such dimensions, two limitations in the standard fabrication procedure had to be overcome. The standard technique for creating the hole pattern, involving accurate alignment of two masks, was replaced by a *single-mask technique*, see section II. To exceed the limited width of the base material (typically ~0.5 m) a splicing procedure was developed, as explained in section III.

II. Single-mask Technique

Production of GEM foils is based on the photolithographic processes commonly employed by the printed circuit industry. The left hand side of Fig. 1 shows schematically the steps involved in standard GEM fabrication. The GEM hole pattern is transferred by UV-exposure from flexible transparent masks to a copper-clad polyimide foil laminated with a photoresistive material. After development, the foil can be etched in an acid liquid, which removes copper from the holes, but not from where the photoresist still protects the copper. The next step is the etching of the polyimide substrate, for which the holes in the copper layers act as a mask.

To obtain a homogeneous symmetric hole geometry across the foil, it is imperative to keep the alignment error between top and bottom masks within 5–10 μm. As both the masks and the base material are flexible this alignment is far from trivial, and when foil dimensions exceed about half a meter this method is hardly feasible anymore. A way to overcome this hurdle is shown on the right hand side of Fig. 1. By using only one mask to pattern only the top copper layer, no alignment needs to be done. The bottom copper layer is etched after the polyimide, using the holes in the polyimide as a mask. The quality and homogeneity of the holes depends now critically on the control of the polyimide etching (which also defines the pattern of the bottom copper layer), where mask alignment used to be the limiting factor.

A. Polyimide etching

In the development of the single-mask technique, progress has been made in understanding the crucial parameters and conditions of the polyimide etching process. Polyimide etching is done in a basic solution containing ethylene diamine and potassium hydroxide (KOH). The potassium hydroxide has an isotropic etching characteristic, which means that material in contact with the etching liquid is removed at the same rate

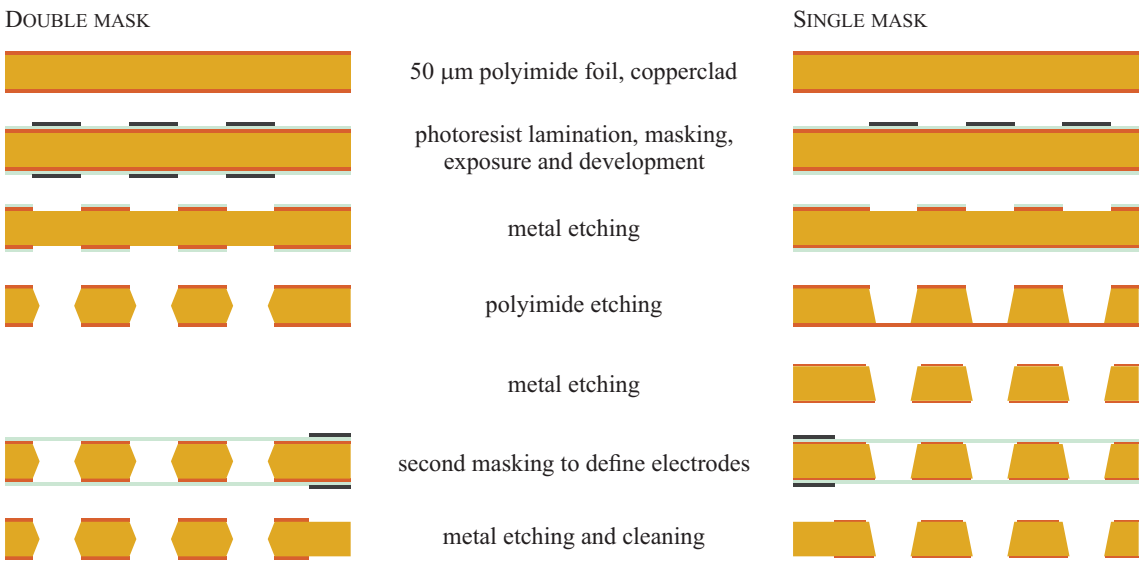

Figure 1. Schematic comparison of procedures for fabrication of a double-mask GEM (left) and a single-mask GEM (right).

in all directions. On the other hand, ethylene diamine etches strongly anisotropically, resulting in wide conical holes.

Pure isotropic etching results in holes that are always at least twice as wide as they are deep, and polyimide is removed until far under the electrode, as can be seen in Fig. 2 (foil made by Tech-Etch[1] using double-mask technique). The etching under

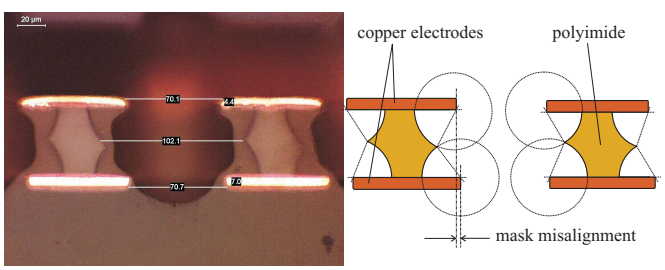

Figure 2. Left: cross-section view of isotropically etched polyimide holes (double-mask technique). The etching extends under the copper electrodes in an expanding circular profile, as shown in the reconstruction drawing on the right. GEM foil made by Tech-Etch.

the copper layer is generally unsatisfactory, but the low aspect ratio (defined as the ratio *depth*/*width* of a hole) really prohibits the use of isotropic etching for a single-mask technique. When etching with a solution of ethylene diamine only, although no material is removed under the copper, the conical edges are not steep enough to arrive at a high aspect ratio. In a solution based on both KOH and ethylene diamine, the steepness of the holes can be modified by controlling the composition of the liquid. The temperature must also be well controlled: raising the temperature increases the etching rate of KOH more than that of ethylene diamine. Furthermore, at temperatures exceeding ~55°C very local delaminations between copper and polyimide have been observed, that give rise to irregular etching patterns. Figure 3 shows that nearly cylindrical holes can be obtained using a single-mask technique, by tuning these parameters well.

[1]Tech-Etch Inc., 45 Aldrin Road, Plymouth, MA 02360 USA

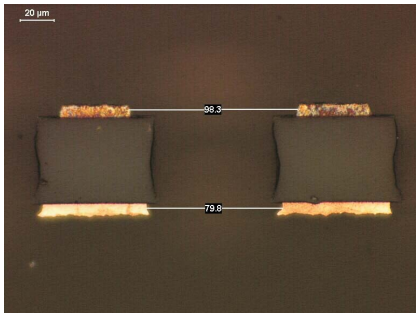

Figure 3. An almost cylindrical hole in polyimide, made with single-mask technique. The steep edges are a consequence of well controlled polyimide etching. The clearance of the copper around the edge of the hole is explained in section II-B

Also essential in the polyimide etching phase, is controlling the condition of the polyimide foil. As an example, Fig. 4 shows two samples from the same foil, that underwent exactly the same treatments at the same time, except for a bake-out before polyimide etching of the sample shown on the right. The

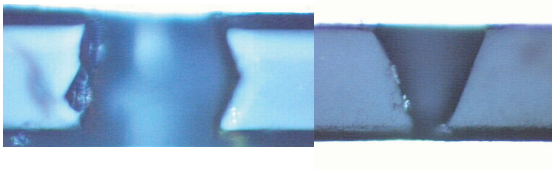

Figure 4. Polyimide hole profiles. The sample on the right was baked out before the polyimide etching phase.

sample on the left had only been exposed to ambient air, from which it apparently absorbed vapors that modified the speed and the level of control over the etching process tremendously. We assume that the dominant and possibly only vapor that causes this effect is simply water, as polyimides are known to be

hygroscopic[2]. A bake-out or similar treatment must be adopted in the production procedure to ensure a constant condition of the polyimide prior to etching.

B. Copper etching

As shown in Fig. 1, the etching of the top electrode using the single-mask technique is done in the same way as with the double-mask technique. The bottom electrode however, is etched both through the polyimide (which defines the pattern) and from the unprotected outer face of the copper. This is done by immersion of the foil in the acidic etchant, without applying direct current (electrolytic etching), and without physical protection in the form of a photoresist layer on any of the electrodes. Therefore both electrodes will be etched at the same time, and at the same rate. Hence the electrodes are slimmed to less than half their original thickness. Also, as the copper etching process is isotropic, a clearance arises around the edge of the hole in the polyimide. This is especially obvious in Fig. 3.

To minimize the width of this clearance (to reduce the effect of charging-up), the thickness of the electrodes must already be minimized before etching holes. Slimming down GEM electrodes was shown in [5] to leave the detector properties untouched, only reducing the material budget significantly. In [5] a microetch liquid based on ammonium persulfate was used. This type of liquid etches more efficiently at grain boundaries, giving the copper surface a matte look. Using this surface etchant at large areas, we found that the resulting copper thickness varies a few microns across the foil. With the single-mask technique, this causes some variation in hole diameter on the bottom electrodes, which gives rise to gain inhomogeneities. In addition, the increased surface roughness degrades the definition of the holes in the bottom. Such rough copper edges around the hole cause discharges in GEM operation.

Figure 5. High magnification cross section views of copper layers on GEMS, at the bottom edge of the hole. Both samples were etched on the surface, to modify the thickness of the layer. For the left sample, a microetch based on ammonium persulfate was used, the right sample was etched with chromic acid.

By using chromic acid instead of a microetch as a surface etchant, both issues of inhomogeneity and surface roughness are overcome, leaving a shiny surface. Figure 5 compares two bottom electrodes etched with one liquid and the other. In the sample shown on the right, the etching process was stopped so soon after the holes in the bottom were opened, that the edge of the metal is still very sharp. This is a natural consequence of the isotropic etching through the hole in the polyimide, and can typically be solved by moderate over-etching.

[2]The polyimide used at CERN for making GEMS (Apical AV from Kaneka Texas Corporation) has a documented typical water absorption of 2.9%

C. Performance

Measurements done with small samples (10 cm × 10 cm) of single-mask GEMS have shown a performance similar to standard GEMS in terms of gain stability and homogeneity, energy resolution, rate capability, discharge tolerance, and reproducibility. Figure 6 shows the gain characteristics of

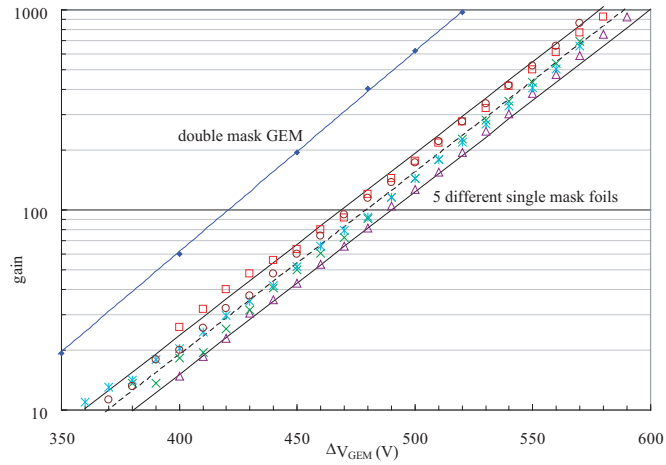

Figure 6. Gain vs. voltage curves for several 10 cm × 10 cm foils of single-mask GEMS and one double-mask GEM.

several single-mask GEMS, and for comparison a double-mask GEM. All curves were acquired in a single GEM configuration. Clearly, the single-mask foils need some 50 V more to obtain similar gain. However, their discharge limit is also higher, and typically the maximum working gain in equal conditions is similar (few thousand). The higher voltage needed for the single-mask samples is attributed to the wider holes in these productions, see Fig. 7.

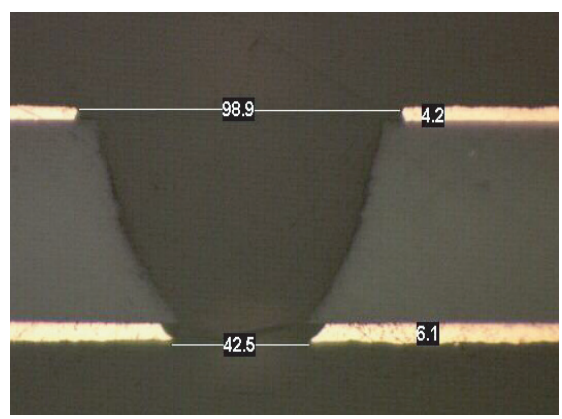

Figure 7. Cross section view of a hole, representative of the foils used for making the prototype. Indicated dimensions are in microns.

The rate capability of these foils in triple GEM configuration was tested with a copper x-ray gun. With this instrument, the rate can be tuned over a wide range. The result is shown in Fig. 8 as the effective gain as function of rate; the gain

was established by measuring the anode current. The gain is hardly affected by a charge flux that exceeds any practical application. During this test we also observed an initial gain loss (at the lowest rate) of about 30% due to charging up of the dielectric. However, no rate dependence of this effect was found throughout the range of the measurement, and the stabilization time constant was only 25 seconds.

Work is ongoing to engineer hole profiles such that single-mask GEMS have gain curves compatible with double-mask GEMS and minimal charging-up.

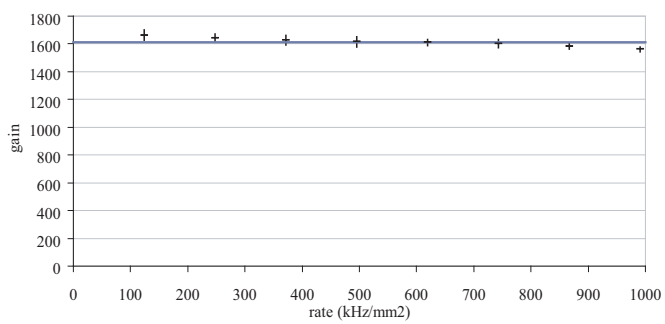

Figure 8. Effective gain vs. rate of copper x-ray conversions in a single-mask triple GEM arrangement. In a gas mixture of argon with 30% carbon dioxide, each conversion releases about 320 primary electrons. In this measurement, a ∅1.5 mm collimator was used, and anode current went up to 560 nA.

III. GEM SPLICING

Although the single-mask technique allows patterning foils of virtually any size, there are still limits to the dimensions of the base material. Double sided copper-clad polyimide is available from rolls of around half a meter wide. This width varies only minimally between suppliers.

A method was developed to splice foils together over a narrow seam, using a flexible polyimide coverlayer[3]. Coverlayers are commonly used in the PCB industry to protect flexible printed circuits without losing their flexibility. The coverlayer used here consists of a 25 μm thick Kapton HN substrate, covered on one side with an adhesive. The simple procedure is illustrated in Fig. 9. The glue of the coverlayer is a B-staged (semi-cured)

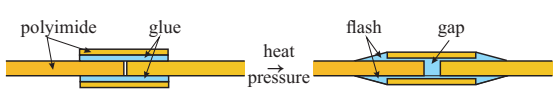

Figure 9. The principle of splicing GEM foils with slim strips of coverlayer.

acrylic adhesive, which polymerizes during a heat cure. The coverlayer has mechanical, thermal and dielectrical properties that are compatible with those of the GEM foils.

A. Splicing test

This method results in narrow, flat and strong seams that can be framed like normal foils. To test how GEMS perform after applying this method, we spliced two pairs of 3 cm × 3 cm GEMS together, see Fig. 10. A counting rate scan over the

[3]The material used throughout this work is Pyralux LF0110 Coverlay, from DuPont

Figure 10. Two 3 cm × 3 cm GEM foils glued together, to validate the splicing method.

seam of one of these glued pairs is shown in Figure 11. This can be regarded as a measure of the efficiency of the GEM for detecting 8.9 keV x-ray conversions in the drift region, which should be 100% in normal conditions. From Fig. 11 it is clear that the efficiency is normal until above the seam. Note that a collimator of 0.5 mm was used on the x-ray source which makes the inefficient area look wider than the seam. In the background it also shows a microscope image of a seam.

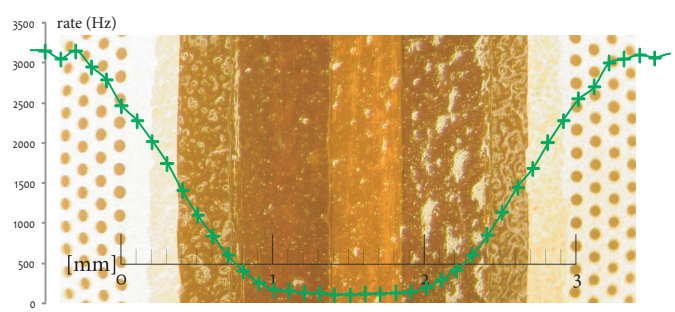

Figure 11. A counting rate scan over the seam of two spliced GEM foils. The measurement was taken with a copper x-ray source with a ∅0.5 mm collimator.

The high pressure exerted by a standard PCB laminator, typically ~ 20 bar, causes migration of the adhesive, resulting in a flash left and right of the seam. Furthermore, this pressure tends to expel the two foils, leaving a glue-filled gap in the middle. These effects are indicated in Fig. 9, and clearly visible in Fig. 11. Recent tests show that the effective widening of the seam by these effects can be eliminated by adjusting the pressure exerted while curing the adhesive. Optimizing this process one can reduce the width of the seam to ~2 mm.

IV. A full scale prototype

Based on the techniques described above, we built a large area prototype, see Fig. 12. It has an area of ~2000 cm^2, and is based on foils of 66 cm × 66 cm. This prototype is aimed for application in the TOTEM experiment, as a replacement of the T1 subdetector (currently a cathode-strip chamber). Figure 13 shows how a disc with adjustable radius can be made of ten such chambers. The overlap of chambers on both sides of a disc ensures complete coverage, and allows for alignment. With six such discs one can build a telescope similar to the current T1 subdetector of TOTEM.

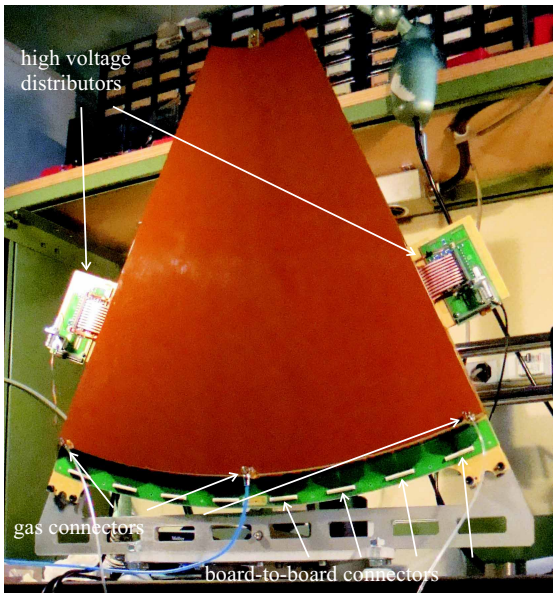

Figure 12. The prototype large area triple GEM detector, mounted on its support.

The prototype chamber uses a triple GEM configuration with a pad readout. Figure 14 shows the layout of the GEM foils. The two half single-mask foils were spliced in the middle, with the method described above. The edges of the foils and the alignment holes were etched in the same process as the GEM holes, to ensure perfect alignment and straightness. To reduce the energy deposited when a discharge occurs [6], the top electrodes are segmented and each segment is connected via a 10 MΩ resistor.

Figure 15 shows how the prototype is built up, and how the GEM foils connect to the high voltage distributor. The readout board is a two-layer printed circuit board, on a substrate of 200 μm FR4. On the top layer are 1024 readout pads, varying in area from 0.25 cm^2 to 6 cm^2. The traces connecting these pads to the readout electronics are on the bottom layer. This readout configuration is not optimized for the experimental application, but rather for simplicity, cost and ease of manufacturing. Readout chips are directly wire bonded to small hybrid PCBs, which connect to the detector via 130-pin board-to-board connectors[4]. The electronics foreseen for this detector were VFAT chips [4], developed for the TOTEM experiment. An attractive alternative may be the GP5, which in [7] was used on a pin-compatible hybrid board, using the same connectors.

[4]P5ks connectors from Panasonic. Part numbers for male: AXK6SA3677YG, and female: AXK5SA3277YG. These connectors are also used for this purpose by the GEM detectors of the TOTEM T2 telescope. [4]

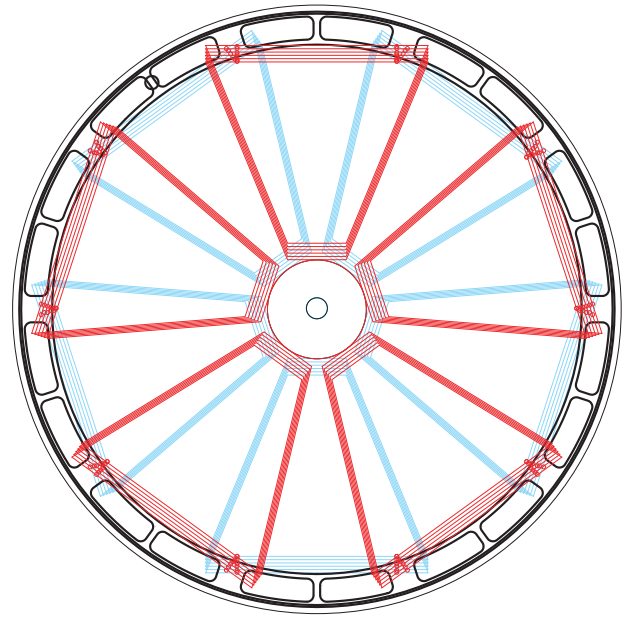

Figure 13. An idea for replacement of the current TOTEM T1 cathode strip chambers with large area GEM detectors. Discs of adjustable radius are built from 2 × 5 chambers in a back-to-back arrangement.

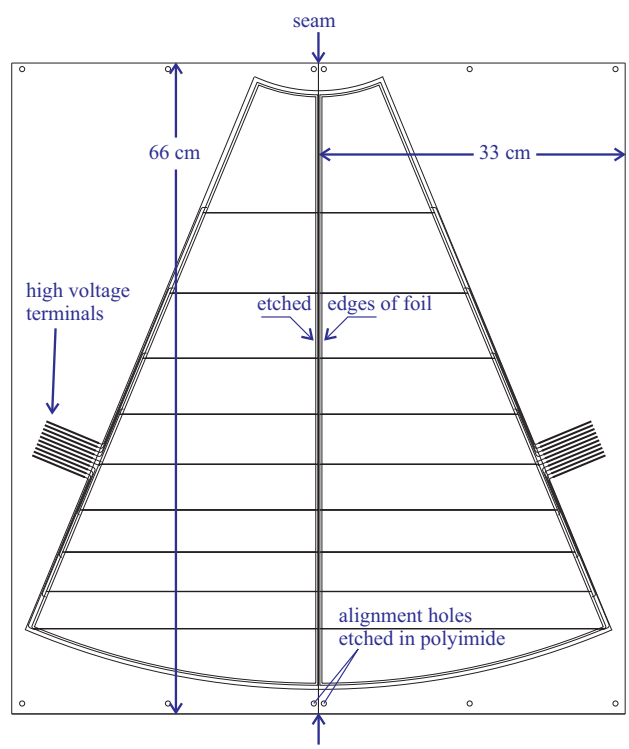

Figure 14. Layout of the GEM foils used for the prototype. The top electrodes are divided in sectors of ≤ 100 cm^2 to keep the capacitance per sector below 5 nF.

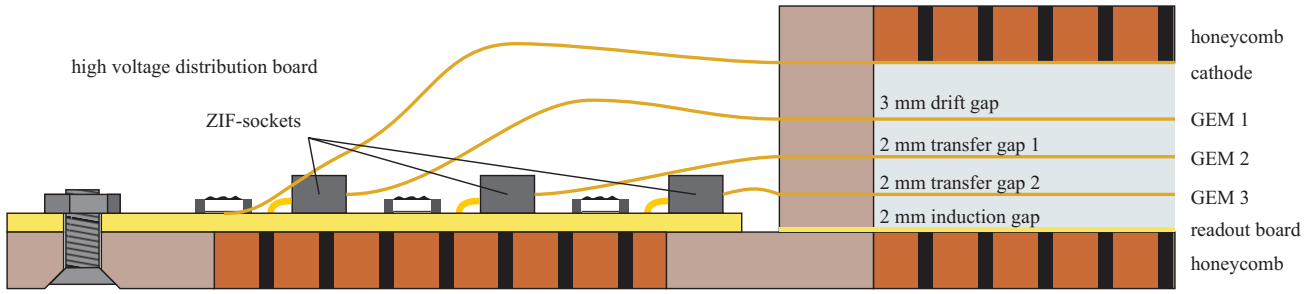

Figure 15. Schematic buildup of the chamber.

A. High voltage distribution

The segmented top electrodes of each GEM foil are connected to the high voltage distributor via traces that run along the edges of the foil. When the foils are framed (i.e. a spacer frame is glued on a stretched foil), these traces are embedded in the frames. In this way, the high voltage distribution board can be made compact, which makes it easier to screen, less vulnerable to pickup, and safer. To make the connections with the board, so called zero-insertion-force (ZIF) sockets[5] were used, rather than hand soldering the terminals to the board, see Fig. 16. These connectors have much finer pin spacings than one would normally use for high voltage purposes, but by connecting groups of pins together and leaving pins floating between these groups, isolation between channels is several kV and alignment of the strips in the socket is not critical. This can save a lot of hand work when the area (and therefore the number of sectors) is large. Moreover, using these sockets one can easily replace, debug or modify boards.

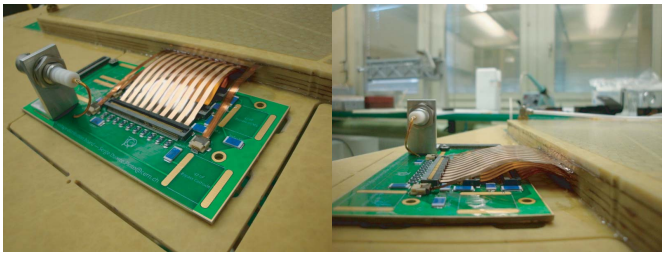

Figure 16. A compact high voltage divider board, using ZIF sockets to connect to the terminal strips of the GEM foils.

An even more compact solution for high voltage distribution, still under study, is to embed not only the routing but also the safety resistors in the frame. This would be possible by screen printing polymer thick film (PTF) resistors on the foil, in an area that will be covered by a frame. Figure 17 illustrates this method, and compares it to the method currently used. This method could simplify high voltage circuitry of large area GEM detectors considerably. As these resistors are not part of the voltage divider chain and are not supposed to carry any appreciable current (the leakage current of one sector is typically below 1 nA), the requirements for these resistors are extremely low. Nevertheless it proved difficult to find reliable PTF materials of such high resistivity (we aim for resistance values of 10 MΩ), especially if they have to be cured on a polyimide substrate.

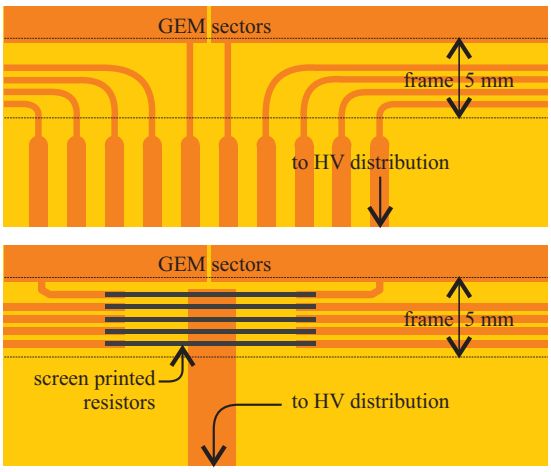

Figure 17. Two methods to connect GEM foils to the high voltage circuitry. On top the method applied in the prototype, with traces that connect to the sectors embedded in the frame. Below a method that is still under study, where the safety resistors are screen printed on the foil, and can therefore also be embedded in the frame.

B. Performance

Tests with the prototype showed performance consistent with the small area foils tested in the process of development. Its energy resolution was measured with copper x-rays (8.9 keV) to be 9.5% RMS (22.4% FWHM), see Fig. 18. A test beam is planned for spring 2009, in order to measure the efficiency of the detector. Further studies will include gain homogeneity, time stability, and rate capability, as well as discharge studies using an α-source.

V. Conclusions

The development of the single-mask technique and a splicing procedure for GEM foils opens the way for large area GEM applications. A prototype was made of a high rate particle tracker using both these techniques. Other possible applications include large area photodetection, and a digital HCAL for a future ILC.

[5]We used two types: FH28H-80S-0.5SH (80-pins) and FH12-06S-0.5SH (6-pins), both of Hirose. The former for the 10-terminal strips to the top sectors, and the latter for the single terminal strips to the bottom electrodes, including the cathode.

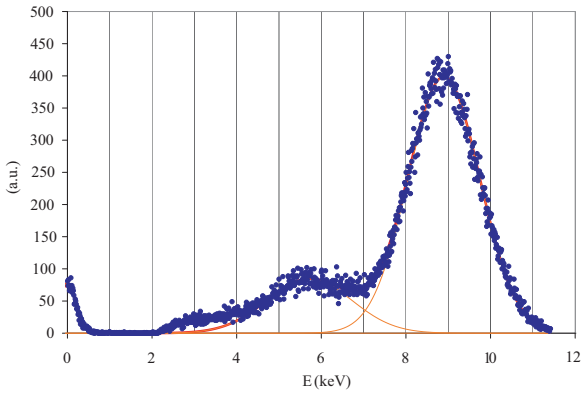

Figure 18. A pulse height spectrum of copper x-ray conversions in argon/CO_2 gas mixture, measured with the large prototype .

References

[1] F. Sauli, *GEM: A new concept for electron amplification in gas detectors.* Nucl. Inst. & Meth. A, vol. 386, issues 2–3, 21/2/1997, pp. 531–534.

[2] S. Lami, G. Latino, E. Oliveri, L. Ropelewski, N. Turini, *A triple-GEM telescope for the TOTEM experiment.* ArXiv:physics/0611178v1, 18/11/2006.

[3] G. Bencivenni et al., *High-rate particle triggering with triple-GEM detector.* Nucl. Inst. & Meth. A vol. 518, issues 1–2, 2004, pp. 106-112.

[4] The TOTEM collaboration, *The TOTEM experiment at the CERN Large Hadron Collider.* 2008 JINST 3 S08007.

[5] L. Shektman et al., *Light multi-GEM detector for high-resolution tracking systems.* Nucl. Inst. & Meth. A, vol. 556, issue 2, 15/1/2006, pp. 495–497.

[6] F. Sauli et al., *Discharge studies and prevention in the gas electron multiplier (GEM).* Nucl. Inst. & Meth. A, vol. 479, issues 2–3, 1/3/2002, pp. 294–308.

[7] D. Watts et al., *Performance of MPGDs with portable readout electronics.* IEEE-NSS 2008 conference record paper.