Project Title:

RD 2012-3

Design and assembly of fast and lightweight barrel and forward tracking prototype systems for an EIC

Progress report (Q2 FY14 / Q3 FY14)

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Type of application:	Continuing funding request BNL EIC R&D contract RD 2012-3
Proposed Project Period:	October 01, 2014 - September 30, 2015
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Contents

1 Introduction

This report concentrates on a dedicated tracking system based on micropattern detectors, which focuses on the design and development of fast and lightweight detectors, ideally suited for a future EIC experiment. The science case and basic detector specifications have been documented in a White paper report [1]. The micropattern tracking detector system consists of:

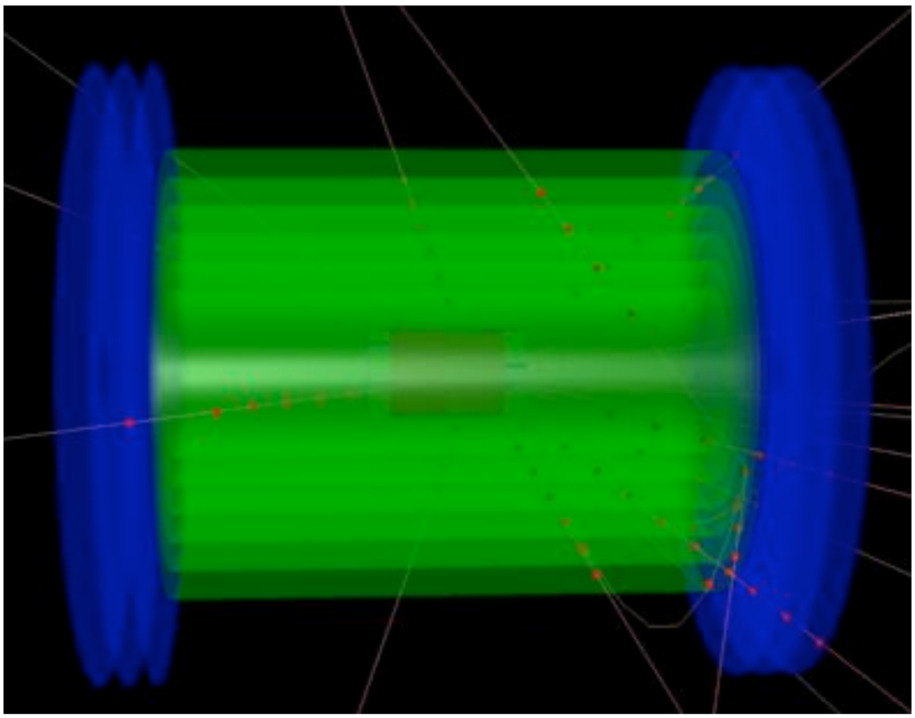


Figure 1: *GEANT simulation of a barrel (green) and rear / forward (blue) tracking system for an EIC detector.*

- Barrel tracking system based on MicroMegas detectors manufactured as six cylindrical shell elements
- Rear / Forward tracking system based on triple-GEM detectors manufactured as planar segments of three layers in the rear and forward directions

Figure 1 shows a 3D view of a GEANT simulation for a barrel and rear / forward tracking system which has been initiated by the R&D program documented in this report. The R&D effort focuses on the following areas:

- Design and assembly of large cylindrical MicroMegas detector elements and planar triple-GEM detectors

- Test and characterization of MicroMegas and triple-GEM prototype detectors
- Design and test of a new chip readout system employing the CLAS12 'DREAM' chip development, ideally suited for micropattern detectors
- Utilization of light-weight materials
- Development and commercial fabrication of various critical detector elements, in particular the commercial development of large single-mask GEM foil production
- European/US collaborative effort on EIC detector development (CEA Saclay and Temple University).

The report provides an overview of various R&D activities in the 2nd and 3rd quarters of FY14 (Q2 FY14 / Q3FY14) both in the barrel and rear / forward directions following the last meeting of the EIC R&D committee in January 2014. The separate proposal section discusses the needed resources to complete the R&D program for both the large cylindrical MicroMegas detector elements, planar triple-GEM detectors and in particular the urgent need for a dedicated common chip readout system. It should be emphasized that our R&D program is a dedicated development of various elements for a future EIC tracking detector system.

The chip readout system, mechanical support elements and simulations are common R&D efforts for both the MicroMegas and the triple-GEM detector systems. The R&D program profits enormously from funds provided by the BNL EIC R&D contract 'RD 2012-3' which addresses the following items in FY14:

- Forward GEM Tracking detector development:
  - Relocation of three labs at Temple University in September 2014 to the Science Education and Research Center providing outstanding dedicated lab resources by the College of Science and Technology consisting of a 2000 sq.ft. Class 1,000 clean room and a separate 800 sq.ft. GEM detector lab
  - Hire of a new mechanical engineer (James Wilhelmi) with the hire of Professor Jim Napolitano at Temple University which provides local engineering support in addition to the technical staff provided by the College of Science and Technology
  - Extensive characterization of single-mask GEM foils in terms of leakage current and optical uniformity of both small ($10 \times 10\,\mathrm{cm}^2$) and larger ($40 \times 40\,\mathrm{cm}^2$) foils in collaboration with Tech-Etch Inc.
  - Established reliable commercial source for single-mask produced GEM foils ($10 \times 10\,\mathrm{cm}^2$ - $40 \times 40\,\mathrm{cm}^2$) by Tech-Etch Inc. in collaboration with Temple University and Yale University
  - Assembly of small ($10 \times 10\,\mathrm{cm}^2$) triple-GEM test detectors
  - Commissioning of a new CAEN HV system for cluster studies using small $10 \times 10\,\mathrm{cm}^2$ triple-GEM test detectors
  - Completion of cosmic-ray test stand and ^{55}Fe source scanner

- Extensive utilization of DAQ / HV system for detector tests
- Procurement of Kapton ring spacers as a novel spacer grid layout
- Completion of all testing and tooling stations for the assembly of larger triple-GEM test detectors
- Completion of mechanical design of a large triple-GEM detector segment and support structure

- Barrel MicroMegas tracking detector development:
  - Design, assembly and test of three barrel MicroMegas small radius cylindrical shells
  - Assembly of MicroMegas detectors
  - Test of MicroMegas detectors in cosmic-ray test stand
  - Test of light-weight, low capacitance flex cables
  - Test of DREAM chip production versions
- GEANT simulations of barrel and forward tracking detector setup
- DVCS physics simulations

The College of Science and Technology at Temple University provides outstanding educational and research opportunities with a strong emphasis on minority students and undergraduate students. Professor Bernd Surrow managed to attract several outstanding students, both foreign and domestic. The funded BNL EIC R&D contract (RD 2012-3) has provided a huge attraction for students to join the Temple University group under the leadership of Professor Bernd Surrow.

Dr. Maxence Vandenbroucke is working since November 2013 at CEA Saclay focusing on the MicroMegas R&D program. The College of Science and Technology at Temple University generously provided support for a new postdoc Dr. Matt Posik focusing on all GEM R&D aspects, in particular the extensive characterization of single-mask produced GEM foils by Tech-Etch. While Dr. Maxence Vandenbroucke is continuing his engagement with this R&D program as a new staff member at Saclay starting October 01, 2014, we have identified with Dr. Matt Posik an outstanding candidate to continue as a new postdoc on the EIC R&D program presented here, which is in part the basis for our new continued funding request for FY15.

Two senior faculty members, Professors Zein-Eddine Meziani and Jim Napolitano, have joined the EIC R&D program presented here, which underlines the long-term emphasis the Temple University group places for the future EIC program. The Temple University group is hosting the 2014 Long Range Plan Town Meetings in QCD on September 13-15, 2014.

Dr. Franck Sabatié has been selected as spokesperson of an European Union initiative to engage several institutions in the EIC research program. This underlines one of the pillars of the collaborative work between CEA Saclay and Temple University to strengthen the scientific collaboration between European and US institutions. Dr. Franck Sabatié and Professor Bernd Surrow are working on establishing a Ph.D. program between Temple University and Université Pierre-et-Marie-Curie (Paris 6) or Université Paris Sud - Orsay (Paris 11) in partnership with CEA (Commissariat l'énergie atomique et aux énergies alternatives) Saclay which would allow Ph.D. students to complete their course programs in both France and the US and carry out a thesis research in micropattern detector development. Ph.D. students in this program would be supported by both Temple University and CEA Saclay. Temple University is strongly engaged in international programs with several campuses such as the Rome and Tokyo campuses.

2 Progress report - Q2 FY14 / Q3 FY14

2.1 Forward GEM tracking detector development

Overview The highlight of the recent work concerning the GEM detector development is the successful commercial production of single-mask produced GEM foils and the subsequent testing at Temple University. Almost two dozen samples of small GEM foils of $10 \times 10\,\mathrm{cm}^2$ have been measured both electrically in terms of their leakage current performance and their optical properties using the CCD camera setup at Temple University. Large GEM foils of $40 \times 40\,\mathrm{cm}^2$ have recently been received, which show equally superb electrical and optical performance. The production of single-mask produced GEM foils has therefore been firmly established. The next and final step concerns the production and testing of large samples up to $50 \times 120\,\mathrm{cm}^2$ in size. All measurements were carried out by Dr. Matt Posik who was hired in spring 2014 with generous support from the College of Science and Technology at Temple University. All GEM lab setups are now fully in place in the current Department of Physics. Preparations are underway to move to the new Science Education and Research Center with state-of-the-art laboratory facilities for the development of micropattern detectors.

Status: Most goals have been achieved in particular the very successful production of single-mask produced GEM foils by Tech-Etch. All testing of electrical and optical uniformity parameters were carried out at Temple University. The assembly of triple-GEM detectors using polyimide film ring based spacer grids is delayed until summer 2014 due to a change in the base material from Kapton to Apical. All GEM lab equipment items are in place and fully functional including assembly and testing setups along with a complete APV-chip and DAQ readout system.

Laboratory setup and infrastructure at Temple University The College of Science and Technology provided dedicated lab space for the development of micropattern detectors focusing in particular on triple-GEM detectors in the current Department of Physics:

- Clean Room (~ 500 sq.ft.), Class 1,000: Handling of bare GEM foils including leakage current measurements and triple-GEM detector assembly / Microscope inspection of GEM foils
- Detector lab (~ 1000 sq.ft.): Testing of triple-GEM detectors including cosmic-ray testing, ^{55}Fe-source testing and gas leak testing. A dedicated DAQ system based on the STAR FGT DAQ system is fully operational
- CCD camera lab (~ 500 sq.ft.) exclusively used for the optical scanning of GEM foils

The maintenance of the clean room is provided by the College of Science and Technology.

The current Department of Physics provides a well-equipped electronics and machine shop. The support from the technical staff was instrumental for the completion of various assembly and testing

Figure 2: *Complete GEM lab infrastructure at Temple University in the current Department of Physics showing a dedicated clean room for assembly and testing (b), the CCD-camera optical scanning table (a) and the actual GEM testing lab (c-e).*

setups. The electronics and machine shop along with the technical staff will be also available once the Department of Physics is located in a new building with the opening of the Science Education and Research Center starting in summer 2014.

Figure 2 provides an overview of the complete GEM lab infrastructure at Temple University in the current Department of Physics showing a dedicated clean room for assembly (b), the CCD-camera optical scanning table (a) and the actual GEM testing lab (c-e).

Figure 3 shows an overview of the new Science Education and Research Center. Professor Bernd Surrow played a leading role in the layout of a dedicated, large Class $1,000$ clean room facility ($1,800$ sq.ft.) shown in Figure 3 (a). The maintenance of the clean room is fully covered by the College of Science and Technology. The main focus of the research activities are large micropattern detector development and silicon sensor handling, testing and assembly. In addition to the Class $1,000$ clean room facility, Professor Bernd Surrow participated in the layout of a dedicated detector lab (800 sq.ft.) shown in Figure 3 (b).

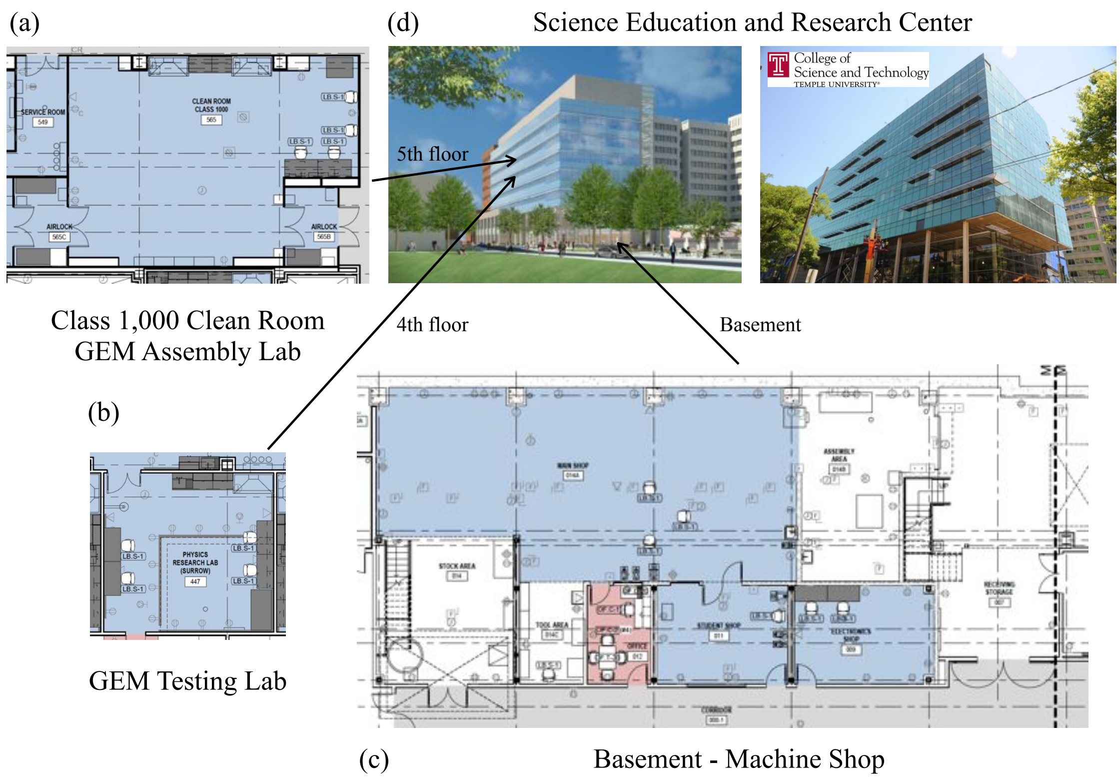


Figure 3: *Overview of the Science Education and Research Center (SERC) (d) with state-of-the-art laboratory infrastructure based on a large Class 1,000 clean room (a) and GEM testing lab (b) along with a large machine shop (c) providing support for the Temple University research programs within the Department of Physics. The photograph of the SERC building (d) was taken on June 16, 2014.*

Status: GEM lab infrastructure complete and fully functional. Preparations are underway to move to the new Science Education and Research Center in September 2014.

Commercialization of single-mask GEM foil production up to $40 \times 40\,\mathbf{cm}^2$ The Nuclear and Particle Physics community requires large quantities of large-size GEM foils such as for the upgraded CMS muon system and the ALICE TPC upgrade and eventually for an EIC detector. The CERN photolithographic workshop has therefore started a collaborative process with Tech-Etch to transfer the CERN technology [2] to Tech-Etch with the goal in mind to provide commercially produced large GEM foils based on single-mask techniques. The management at Tech-Etch signed all technology transfer agreements. The Temple University group agreed with the Tech-Etch management to start the process with the single-mask production of $10 \times 10\,\text{cm}^2$ GEM foils followed by FGT-type GEM foils (about $40 \times 40\,\text{cm}^2$) based on existing Gerber files. It was agreed that the Temple University group will test those foils and provide feedback to optimize the single-mask production at the Tech-Etch production plant. The Yale University group agreed to provide in addition 55Fe source measurements of single foils. The Temple University group has been hosting ongoing phone meetings between CERN, Tech-Etch, and other institutions including FSU, Temple University and Yale University. Samples of both $10 \times 10\,\text{cm}^2$ (18) and FGT sized $40 \times 40\,\text{cm}^2$ (3) single-mask foils have been shipped to Temple University. Figure 4 shows a photograph of two

Figure 4: *Photograph of two single-mask produced GEM foils showing B. Surrow holding a large* $40 \times 40\,cm^2$ *GEM foil and M. Posik holding a small* $10 \times 10\,cm^2$ *GEM foil inside the permanent Class 1,000 clean room in the current Department of Physics.*

single-mask produced GEM foils showing Professor Bernd Surrow holding a large $40 \times 40\,\mathrm{cm}^2$ GEM foil and Dr. Mat Posik holding a small $10 \times 10\,\mathrm{cm}^2$ GEM foil inside the permanent Class 1,000 clean room in the current Department of Physics at Temple University. The processing steps are illustrated in Figure 5. The bare Apical material and copper layers, followed by the coating of photoresist and laser direct imaging is shown in Figure 5 (a). The removal of unexposed photoresist and copper etching followed by the stripping of photoresist and removal of chrome adhesion layer is shown in Figure 5 (b). The first polyamide etching in EDA chemistry is shown in Figure 5 (c) followed by electrolytic etching to remove the backside copper shown in Figure 5 (d) and the subsequent second polyamide etching shown in Figure 5 (e). A cross-section is shown for comparison.

The production of larger foils is generally limited to a width of about 50 cm due to the size limitation of Apical base material distributed on standard-size rolls. Larger sizes such as those required for future EIC applications require an upgrade of the production line at Tech-Etch including the purchase of new imaging and larger chemical etching bath setups. This will be discussed below and in the proposal section.

The first type of characterizations performed on a GEM foil are electrical tests. As shown in Figure 6, a GEM foil is first placed in a gas tight plexiglass enclosure to provide a safe and dry nitrogen environment. The leakage current is then measured between the unsegmented side and segmented side, i.e. sector side for a GEM foil as a potential difference is applied up to 600 V. With increasing applied voltage, the current is monitored to avoid destructive discharge. The typical leakage current is generally below 1 nA. Figure 7 shows the results of such a measurement, in this case a single-mask FGT sized GEM foil from Tech-Etch.

This setup has been installed in the clean room at Temple University where this measurement is routinely performed in a clean environment by students as shown in Figure 6. All available

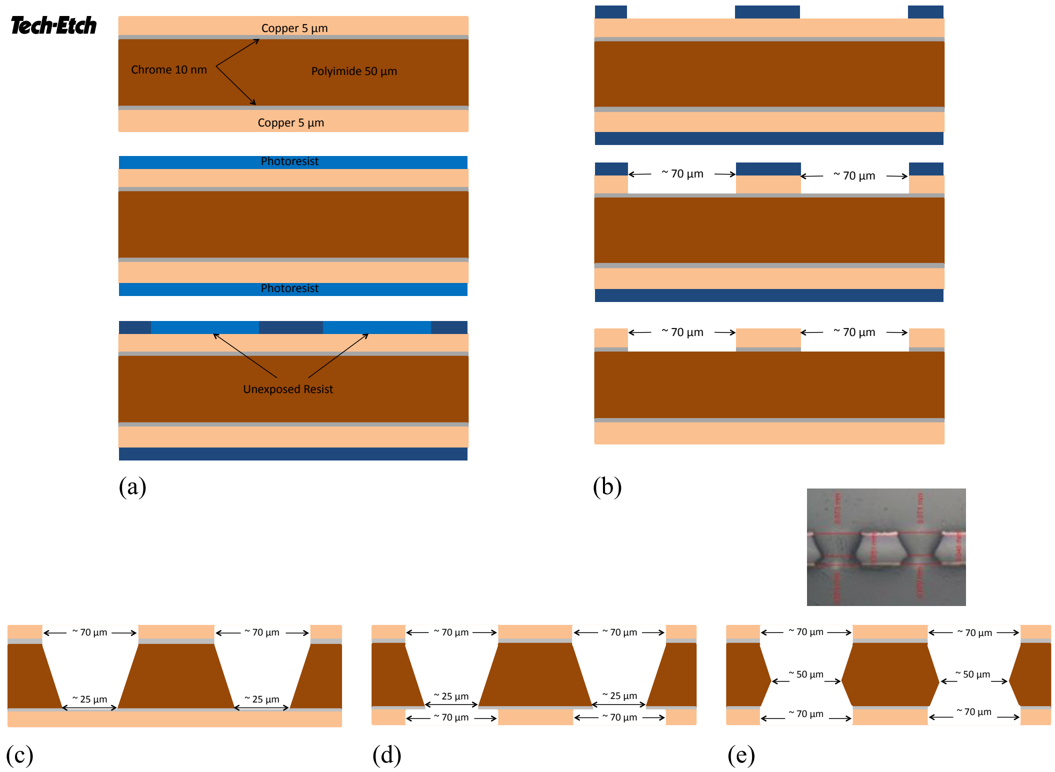


Figure 5: *Illustration of the main processing steps showing the bare Apical material and copper layers, followed by the coating of photoresist and laser direct imaging (a). The removal of unexposed photoresist and copper etching followed by the stripping of photoresist and removal of chrome adhesion layer is shown in (b). The first polyamide etching in EDA chemistry is shown in (c) followed by electrolytic etching to remove the backside copper shown in (d) and the subsequent second polyamide etching is shown in (e). A cross-section is shown for comparison.*

single-mask foils ($10 \times 10\,\mathrm{cm}^2$ and all sectors of the FGT sized foils) have been tested. The typical leakage current measured on all single-mask GEM foils was below 1 nA. The excellent electrical properties seen in these foils is primarily due to changing the insulating base material from Kapton to Apical. Kapton material has been previously used by Tech-Etch which showed clearly a larger leakage current performance typically below 10 nA, rather than below below 1 nA. Tech-Etch agreed with this finding since all GEM foils were independently tested using an identical electrical test setup. Apical is therefore clearly preferred over Kapton material and will from now on be used by Tech-Etch. The original COMPASS paper listed Kapton material based material for GEM foils, which was in fact Apical [3].

The development of large single-mask GEM foil production requires the setup of dedicated optical measurement tools. The CCD camera setup, as shown in Figure 8 (a), is a microscope coupled to a 2D motorized support to scan GEM foils with high precision. The apparatus is controlled by a MATLAB graphical interface shown in Figure 8 (b). This setup has been used to scan all available single-mask $10 \times 10\,\mathrm{cm}^2$ GEM foils, while a slightly modified version of this set up is currently scanning the single-mask FGT sized foils.

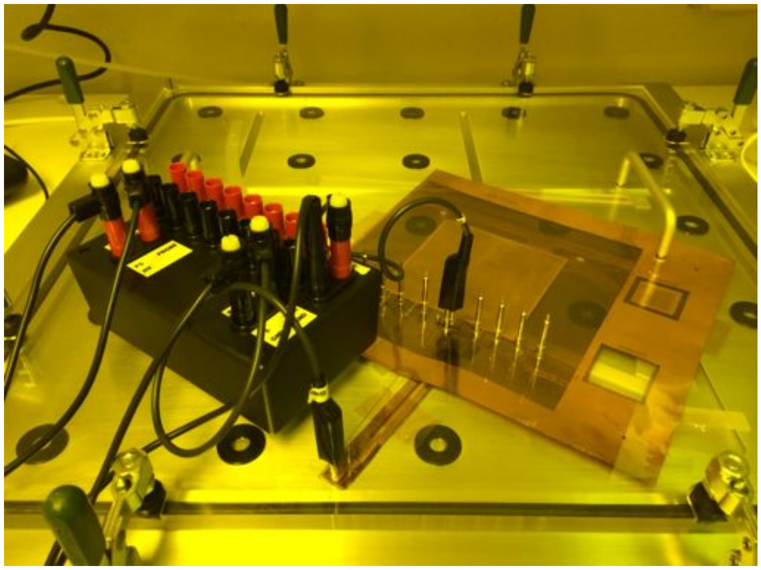


Figure 6: *Setup at Temple University to conduct electrical tests of GEM foils performed mainly by Temple University students.*

All $10 \times 10\,\text{cm}^2$ single-mask foils have been scanned and their geometrical properties, which determine the gain performance for a GEM foil, have been characterized. This includes measurements of the pitch, inner hole diameter, and outer hole diameter distributions of each foil. Figure 9 show typical distributions of the single-mask $10 \times 10\,\text{cm}^2$ GEM foils. As a consistency check with the measurements achieved by the Temple University group, Tech-Etch measurements of the foils geometrical quantities were also made. Figure 10 shows the cross-section of $10 \times 10\,\text{cm}^2$ GEM foil measured by Tech-Etch, which is consistent with that measured by the Temple University group. It should be noted that the procedure used by Tech-Etch to measure the geometrical parameters of the foils is very different from that of the Temple University group's. The Temple University group measures every hole on the foil, while Tech-Etch measures only nine holes at a much higher magnification. A comparison between the Temple University group's and Tech-Etch's measurements for the average inner and outer hole diameters for each of the $10 \times 10\,\text{cm}^2$ GEM foils can be seen in Figure 11. The error bars associated with the Temple University group's measurements represent the rms spread in the respective distribution. The average pitch measured by the Temple University group was found to be about $138\,\mu\text{m}$ and was very consistent from foil to foil. Additionally, the uniformity of the inner and outer hole diameters over the surface of the foil can influence its gain. The deviation of the inner (outer) diameter from the foil's mean diameter was studied for each $10 \times 10\,\text{cm}^2$ foil. The uniformity of the outer hole diameters showed a deviation of only about $\pm 5\,\mu$ m from the mean, while the deviations on the inner hole diameters, which vary more due to their dependence on the etching time, are well below $\pm 10\,\mu$ m, as shown for a typical uniformity measurement in Figure 12.

If the hole diameter size varies widely across the foils, then this will lead to different amounts of charge being produced as the initial electron passes through holes of different sizes in each of the foils. To help quantify the sensitivity of the track reconstruction capability of a GEM foil due to this effect, a simple track reconstruction exercise was carried out. In this exercise it was assumed that the charge produced from a GEM foil was read out by 20 readout strips that were $520\,\mu m$ in

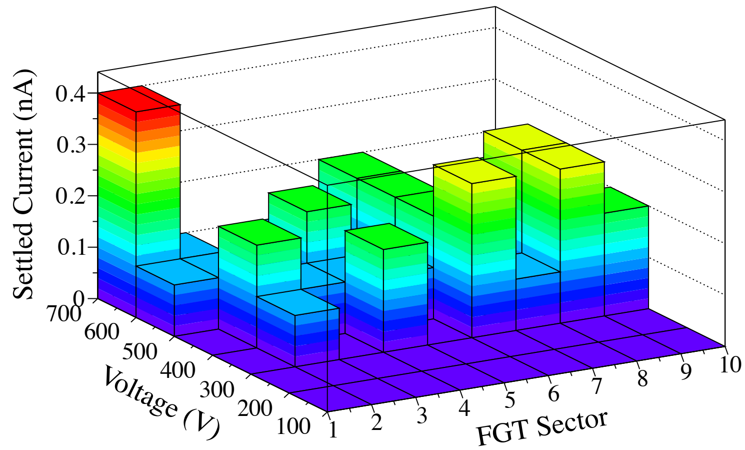


Figure 7: *Measured leakage settled current as a function of voltage and sector (1-9) for a single-mask FGT sized GEM foil (Tech-Etch). The settled current represents the value that our current measurement device (ISEG SHQ 222M) settled at with slight fluctuations around this number. The settled current is accurate to within approximately* $0.5\,nA$.

length and each strip had a pitch of $600\,\mu m$ and was separated by 80 μm. A random Gaussian shaped charge cloud was then generated at a position x within the range covered by the readout strips (about $-6000\,\mu m \leq x \leq 6000\,\mu m$). Figure 13 shows the amount of charge collected from the charge cloud in each readout strip. The reconstructed position of the particle, is a charge weighted sum given by

$$\langle x \rangle = \frac{\sum_i x_i Q_i}{\sum_i Q_i}, \tag{1}$$

where x_i is the position and Q_i is the charge of the i^{th} readout strip. The reconstructed position sensitivity to the charge was quantified by randomly varying the collected charge on each read out strip by $\pm 5\%$ and $\pm 50\%$. The reconstructed position was found not to rely too much on the charge fluctuations, as the change in $\langle x \rangle$ between the large charge variations of $\pm 5\%$ and $\pm 50\%$ was only a few μm. The most sensitive quantity to the charge variations was the resolution of the reconstructed position. Although even this was found not to be that significant overall, with the $\pm 5\%$ ($\pm 50\%$) charge variation producing about a 1% (4%) increase in the reconstructed width relative to a reconstructed position with no charge variation.

The optical setup, shown in Figure 8, that was used to scan the $10 \times 10\,\text{cm}^2$ GEM foils had to be slightly modified in order to accommodate the larger FGT sized GEM foils. This required installing a large ($86 \times 76\,\text{cm}^2$) steel plate over the 2D motorized support, which provided a large enough area for a FGT size GEM foil. The steel framing and glass that the FGT sized foil is encased in was also enlarged so that the entire foil is visible. Due to the limited range of motion of the 2D

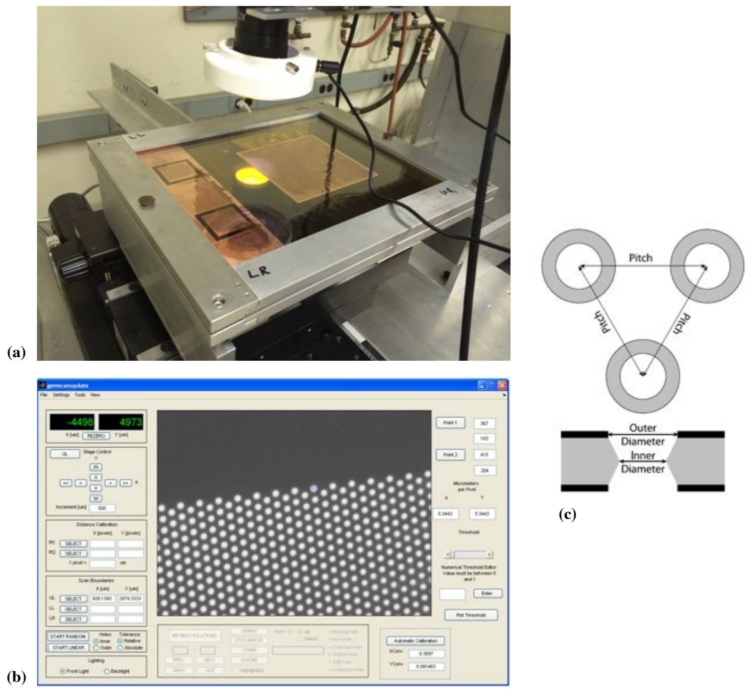


Figure 8: *(a) GEM foil scanner, (b) User interface and (c) Hole geometry of a GEM foil.*

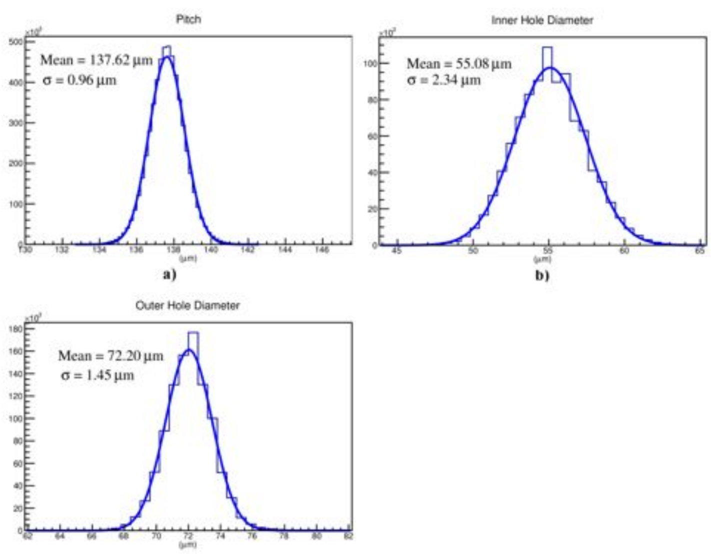


Figure 9: *(a) Pitch distribution, (b) Inner diameter distribution and (c) Outer diameter distribution of a single-mask* $10 \times 10\ cm^2$ *Tech-Etch GEM foil.*

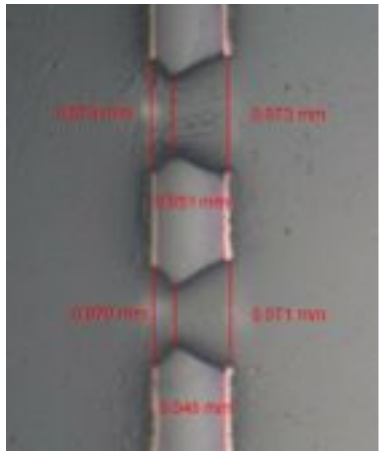


Figure 10: *Cross-section of a Tech-Etch single-mask* $10 \times 10\ cm^2$ *GEM foil.*

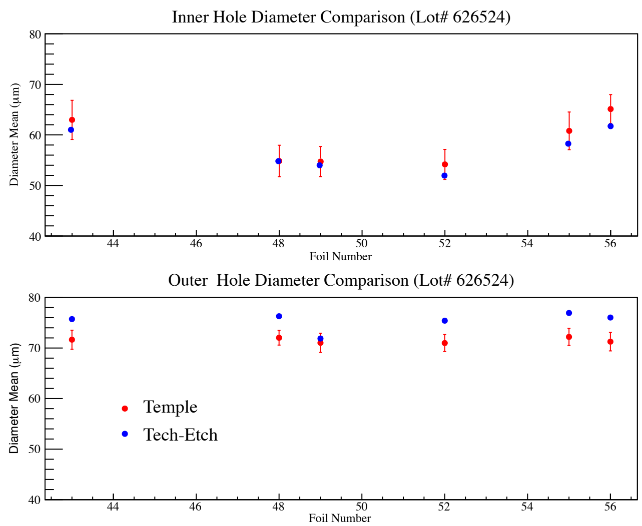


Figure 11: *Tech-Etch and Temple hole diameter measurement comparisons for single-mask* $10 \times 10\ cm^2$ *GEM foils.*

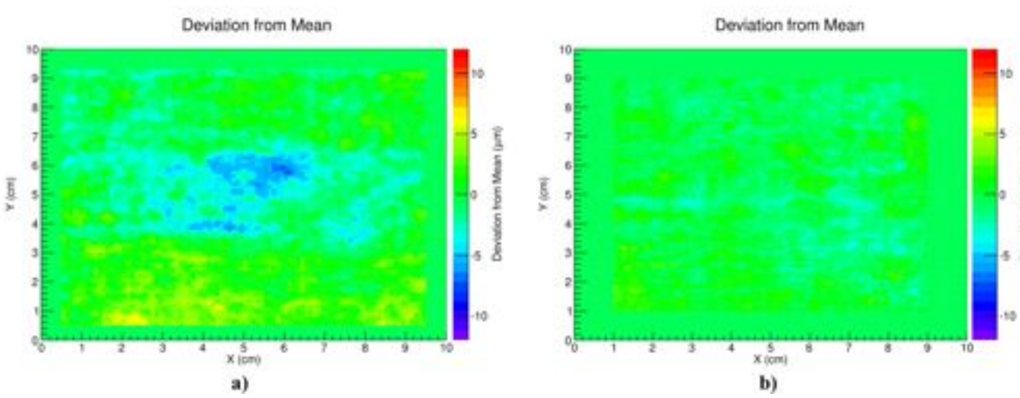


Figure 12: *Typical (a) inner hole diameter and (b) outer hole diameter deviations from the mean for single-mask* $10 \times 10\ cm^2$ *foils.*

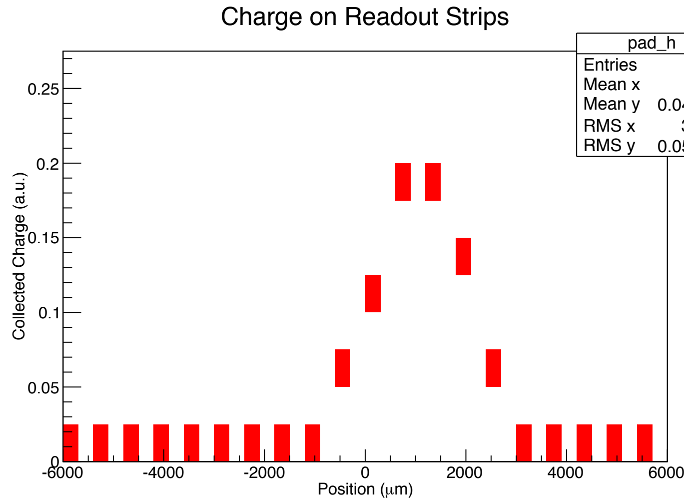


Figure 13: *The amount of charge collected on a simple readout strip geometry.*

support stage, one FGT sized foil needs to be divided into six optical scan regions in order to cover the entire active area of the GEM foil. By positioning the frame containing the foil at three specific locations relative to the CCD camera, three sections of the foil can be scanned. The other three sections of the GEM foil can then be scanned by rotating the frame containing the GEM foil by 180° and positioning it again at each of the three specific locations. The three locations used to complete half of the optical scans of a FGT sized GEM foil can be seen in Figure 14.

The modified optical setup has been completed and single-mask FGT sized GEM foil characterization is underway. Some of the initial scans from one of the six scan regions of a single-mask FGT sized foil have already been analyzed. These initial results appear to be similar with those measured for the single-mask $10 \times 10\,\mathrm{cm}^2$ GEM foils. The pitch and inner hole diameter distributions are shown in Figure 15 for one of the six CCD scan regions.

Status: All available single-mask foils ($10 \times 10\,cm^2$ and FGT sized foils) have been successfully electrically tested. Leakage currents are well below $1\,nA$. Geometrical characterization of all available $10 \times 10\,cm^2$ single-mask GEM foils have been completed. The optical measurement setup have been modified to characterize single-mask FGT sized GEM foils, and measurements are currently underway.

Test of DAQ system and APV-chip readout system A complete APV25-S1 chip based DAQ system has been set up at Temple University. Figure 16 (a) shows a photograph of the VME crate with two readout control modules and 12 readout modules allowing to read out a total of 240 APV25-S1 chips. Also shown is the actual DAQ computer located above the VME crate. A group of 5 packaged APV25-S1 chips as shown in Figure 16 (b) is mounted on a APV readout module which can be connected to a triple-GEM detector such as a small triple-GEM detector of size $10 \times 10\,\mathrm{cm}^2$ or a STAR FGT triple-GEM detector. Figure 16 (c) shows the typical mean pedestal distribution for a APV readout module with five 5 packaged APV25-S1 chips.

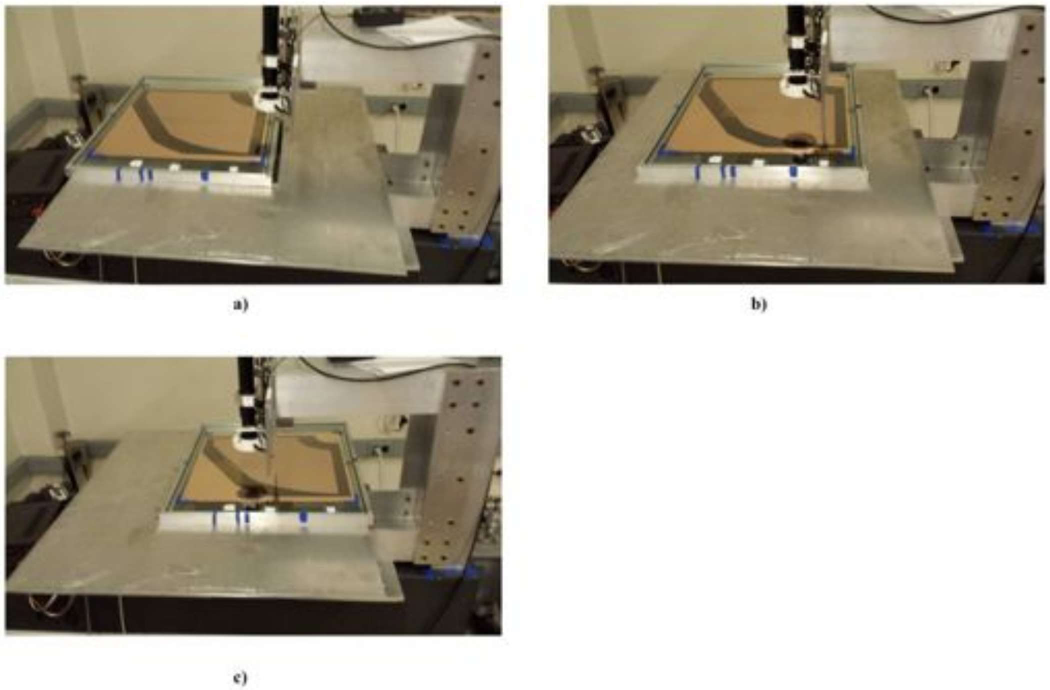


Figure 14: *(a), (b), and (c) show the three specific positions used to scan half of the FGT sized GEM foils. The remaining half of the GEM foil is scanned by rotating the frame with the GEM foil by 180° and repeating the scans at the same three locations.*

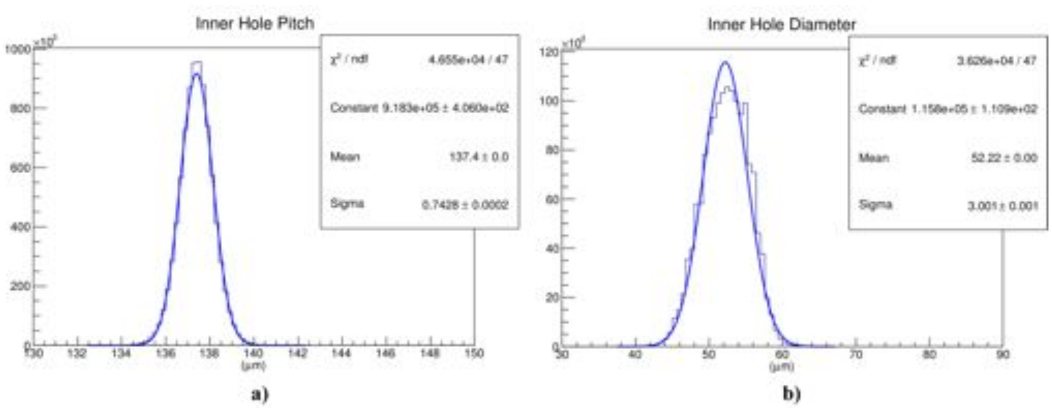
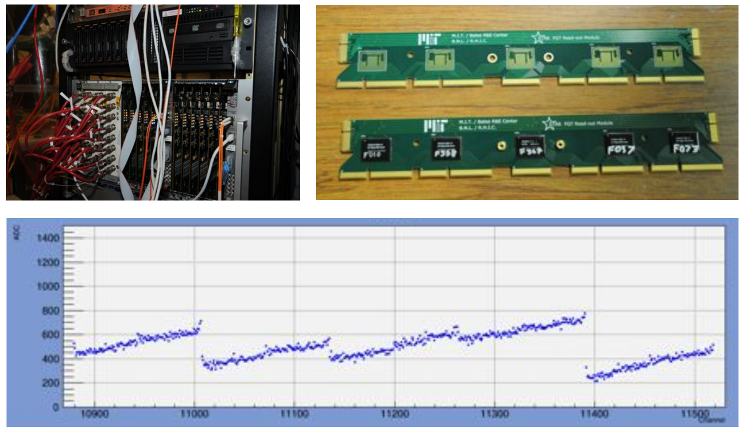


Figure 15: *(a) Pitch distribution (b) Inner hole diameter distribution for about 1/6 of a Tech-Etch produced single-mask FGT sized GEM foil.*

(a) (b)



(c)

Figure 16: *(a) Photograph of the complete VME crate with the actual DAQ computer located above the VME crate, two readout control modules and 12 readout modules allowing to read out a total of 240 APV25-S1 chips together with a APV readout module (b) and the mean pedestal distribution for one APV readout module (c).*

Status: Complete APV25-S1-based readout, control and DAQ system functional under routine operation by students.

Commercial fabrication of Kapton / Apical rings A novel design of a spacer grid based on arrays of thin-walled polyimide film rings between GEM foils has been designed. Figure 17 shows the full technical drawing of both 2 mm and 3 mm versions. Two companies are involved in the manufacturing process. Both have been chosen for cost optimization. American Durafilm in Holliston, MA provides the tubing material at a length of 36" and inner diameter of 2". Upon successful microscope inspection at Temple University, this material is then sent to Potomac in Lanham, MD for laser cutting according to our technical drawings shown in Figure 17. The initial discussion focussed on Kapton material. However, it has been decided to change the request to a different polyimide material using Apical material considering that Apical showed a superior electrical performance compared to Kapton based polyimide material for GEM foils.

Status: Delay in delivery of polyimide tubing material to summer 2014 followed by laser cutting of all polyimide rings. This is caused by the change of requesting a different polyimide material. Assembly process is expected to start by the end of August 2014.

Setup of assembly tools Assembly and stretching tools exist for FGT-type quarter sections. A new mechanical engineer started in January 2014 as part of the hire of a new senior faculty member at Temple University, Professor Jim Napolitano. The support for our new mechanical engineer is provided by the College of Science and Technology at Temple University. The stretching fixtures have been fully commissioned. Figure 18 shows the complete testing and assembly fixtures for FGT-type triple-GEM detectors. This setup will be used to built a set of two FGT-type triple-

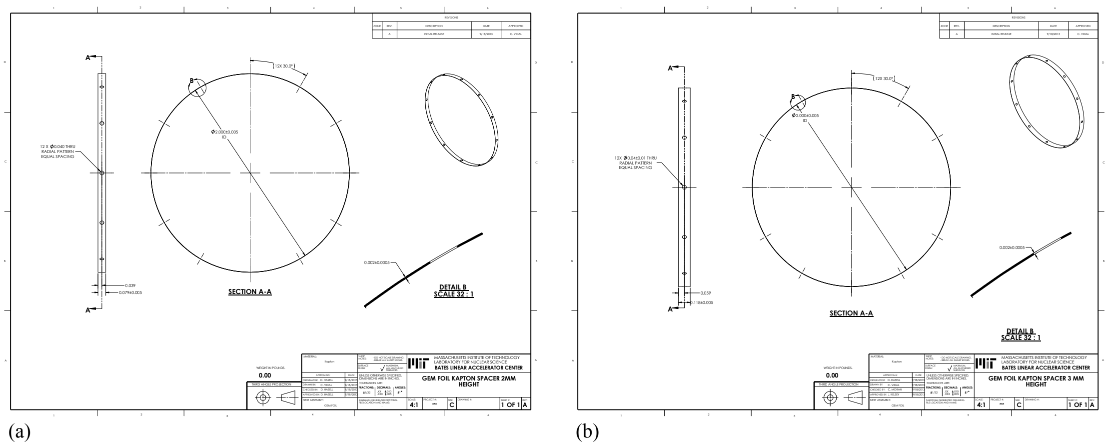


Figure 17: *(a) Polyimide ring with 2 mm thickness and (b) polyimide ring with 3 mm thickness.*

GEM detectors with Apical spacer grids and single-mask produced GEM foils. The testing and assembly fixtures include the leakage current setup (a-b), a microscope inspection station (c), a GEM foil stretching fixture (d), a soldering fixture with a new soldering exhaust fume setup (e) and two assembly fixtures (f) with special covers allowing gas flow after each assembly setup to verify that the leakage current performance has not been altered during a previous assembly step. The testing and assembly fixtures are setup on new stainless clean room tables inside the permanent Class 1,000 clean room in the current Department of Physics and will be moved to the new clean room facility in fall 2014.

Status: All assembly and stretching tools have been setup and are fully functional. The leakage current setup is under routine usage by students at Temple University.

^{55}Fe-source scan setup and large area cosmic-ray test stand Gain calibration is an essential tool in characterizing a triple-GEM detector. The automation of such a measurement has been enabled by the purchase of a Multi-Channel analyzer coupled to a precision pre-amplifier (ORTEC 142A) and a pulser for calibration. With the large active area foreseen for the next generation of triple-GEM detectors, it will be necessary to have multiple gain measurements to ensure gain uniformity. With the help of a XY scanning table, shown in Figure 20, we are developing an automated measurement to produce a 2D gain calibration map. In addition, we are preparing a cosmic-ray stand using two large-area scintillator tiles as shown in Figure 19.

Status: Operation of scanning table under LabView control. Synchronization of table movement and DAQ operation in progress. Large-area cosmic-ray test stand in preparation. Preparation of special readout card coupled to Multi-Channel analyser is in preparation.

Fabrication of large GEM foil storage units A SolidWorks design model, as shown in Figure 21, has been completed by a undergraduate student from the Department of Mechanical Engineering at Temple University. The large units will be manufactured and assembled by the machine

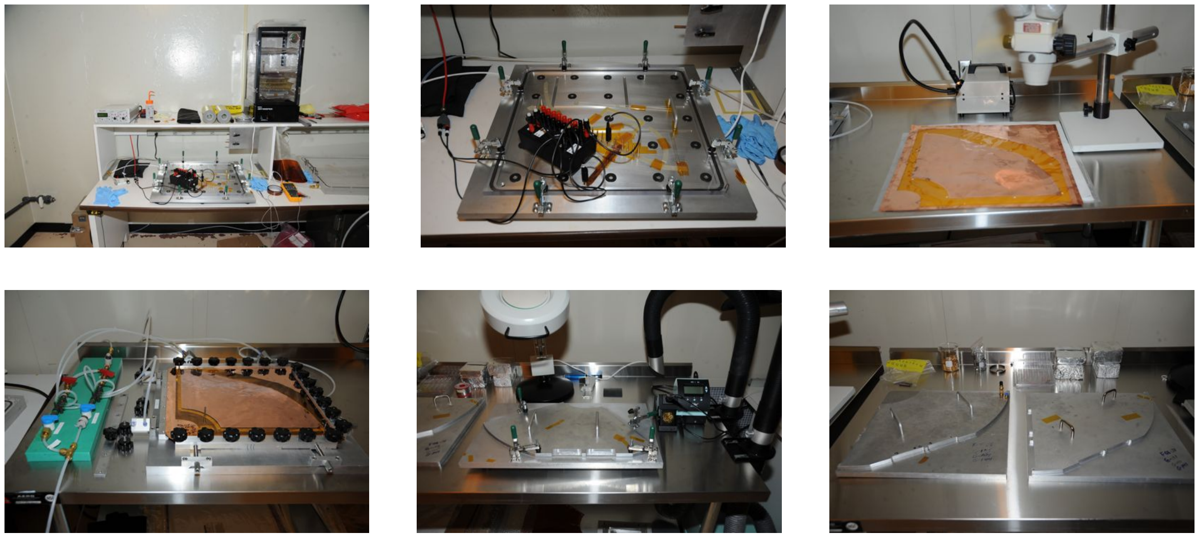


Figure 18: *The testing and assembly fixtures include the leakage current setup (a-b), a microscope inspection station (c), a GEM foil stretching fixture (d), a soldering fixture with a new soldering exhaust fume setup (e) and two assembly fixtures (f) with special covers allowing gas flow after each assembly setup to verify that the leakage current performance has not been altered during a previous assembly step.*

shop and will be available for the new SERC building in fall 2014.

Status: Fabrication, assembly and installation discussed with machine shop. Storage units will be available for the new SERC building in fall 2014.

Assembly of small triple-GEM prototype chambers In order to test GEM foils inside a detector, four triple-GEM prototype chambers of $10 \times 10\,\text{cm}^2$ have been prepared as shown in Figure 22. The tests will focus on the gain uniformity of small single-mask GEM foils and cluster size studies.

Status: Assembly of two test chambers have been completed. The assembly of two additional test chambers are preparation including the fabrication of frames.

Cluster size studies and HV system commissioning The spatial resolution required at the EIC for the triple-GEM detectors is about $100 - 200\,\mu$m, which is a standard performance for a GEM tracking detector. The spatial resolution results from a complex combination of the distance between electrode (the pitch), the size of the electron signal, and the signal to noise ratio of the detector. As a result, it is difficult to predict the spatial resolution of the detector at the design level and high granularity (small pitch) is often used to ensure the best performances. However this requires expensive readout boards, a large number of electronics channels, and therefore the

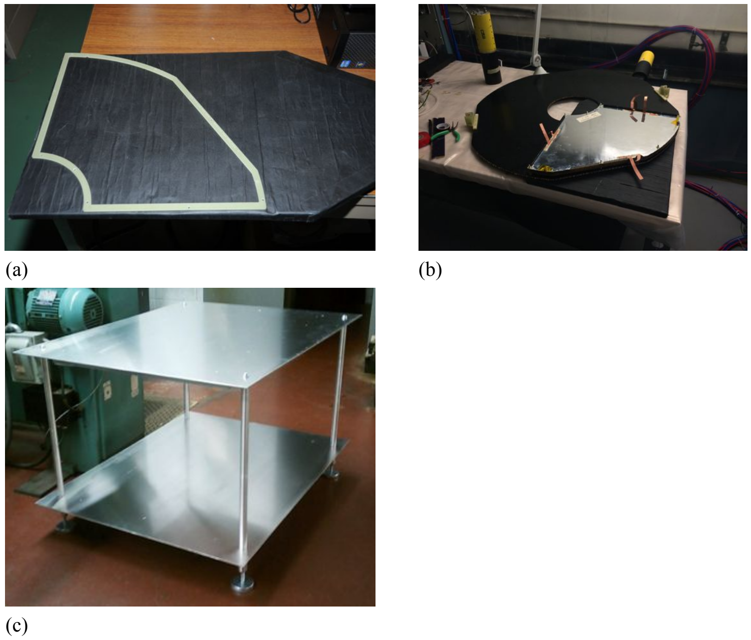

(a) (b) (c)

Figure 19: *Large-area scintillator counters (a) for a dedicated cosmic-ray test stand (c) for FGT-type triple-GEM detectors (b).*

need for power and cooling. The main idea is to adjust the individual potential difference around each triple-GEM detector layer. A multi-channel CAEN HV system has been acquired and fully commissioned as shown in Figure 23. The cluster studies will start once the small triple-GEM chambers are ready which is expected to be the case by fall 2014.

Status: Commissioning of multi-channel CAEN HV system completed. Cluster studies are expected to start in fall 2014.

Mechanical design of large triple-GEM detector segment and support structure The design of the next generation of triple-GEM detectors for an EIC detector requires minimal dead material and good uniform acceptance. We would like to stress that our mechanical design therefore focuses on lightweight materials and overlapping detector segments. A triple-GEM detector is inherently light. It consists of a stack of polyimide foils for electrodes and GEM amplification, and Mylar foils for gas-tight enclosure. Larger dead material is generally introduced by electronics and services. The idea here is to place all electronics and service components on the outer radial region of the detector (Figure 26 (b) and (d)) providing full mechanical support. This leaves the remaining part of the detector to be extremely light and allows to keep structural support at a minimum inside the active area. The layout of a GEM foil with 11 segments is shown in Figure 27. The preparation of Gerber files is in progress.

Each long segment will be supported on a wheel-like carbon-fiber structure as shown in Figure 24 (a) and (b). The chambers are stacked face-to-face to provide easier access and avoiding dead areas between detectors as shown in Figure 25 (a)-(e). A discussion with Eric Anderson, head

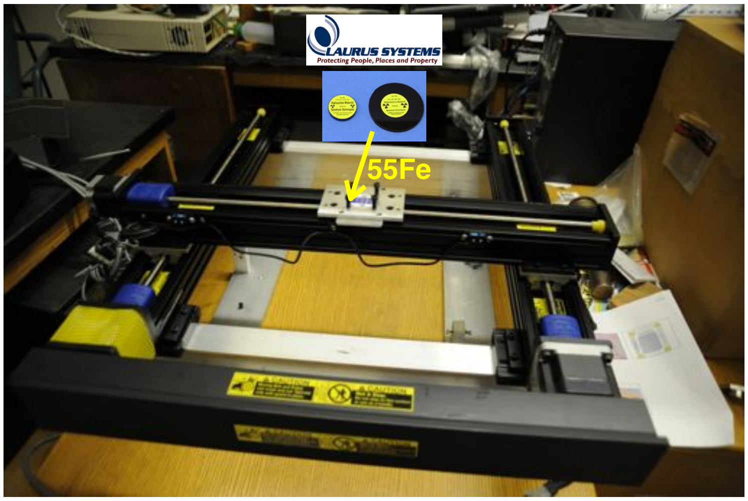
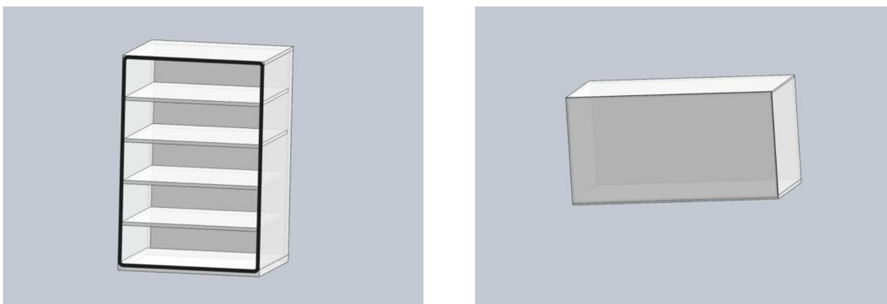


Figure 20: *Scanning table setup for a ^{55}Fe source scan of large GEM foils.*



(a) (b)

Figure 21: *SolidWorks layout of nitrogen storage cabinets for GEM foils.*

of the Carbon-Composite (CC) shop at LBNL, took place in November 2013 focusing on the feasibility to manufacture the proposed structure. The CC shop at LBL strongly encouraged us that such a structure could certainly be built upon final mechanical design review. The design will be discussed with two new collaborating institutions, Florida Institute of Technology under the leadership of Professor Markus Hohlmann and the University of Virginia under the leadership of Professor Nilanga Liyanage. The EIC R&D committee strongly encouraged such a collaborative effort. The fabrication will begin along with tooling preparation once agreement has been reached of the full design.

Status: SolidWorks design at Temple University completed. Preliminary design discussion with MIT Bates engineering team in April 2014. Collaboration with FIT and UVA building dedicated EIC triple-GEM forward segments. Prototyping of support material at Carbon-Composite shop at LBL planned for fall 2014 after agreement has been reached on the full design.

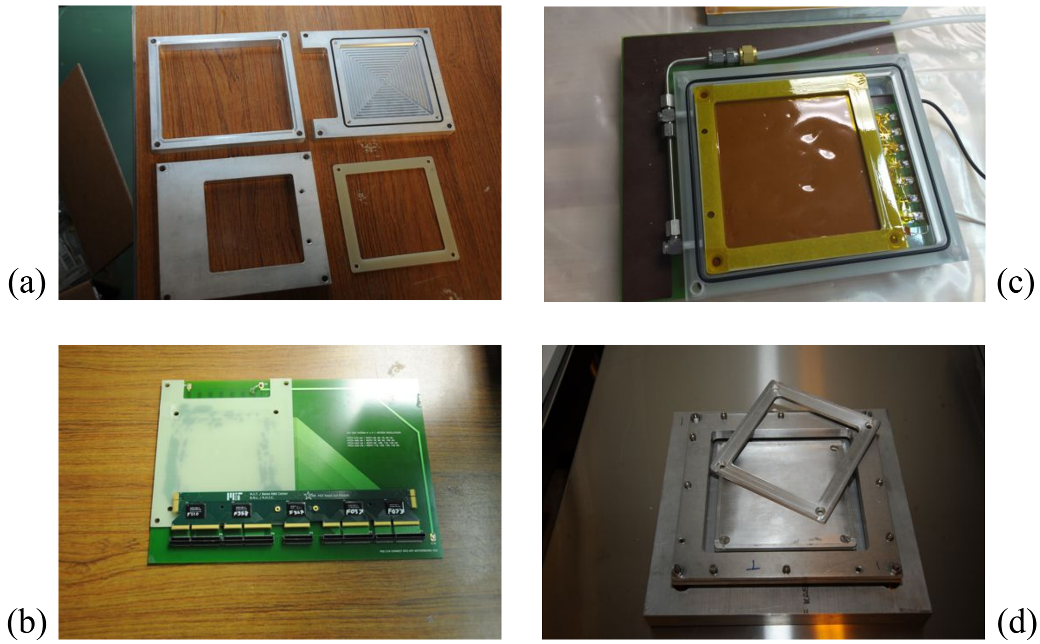


Figure 22: *Components of small triple-GEM prototype chambers of* $10 \times 10\,cm^2$ *(a), readout board with APV board interface (b), completed chamber (c) and stretching fixture (d).*

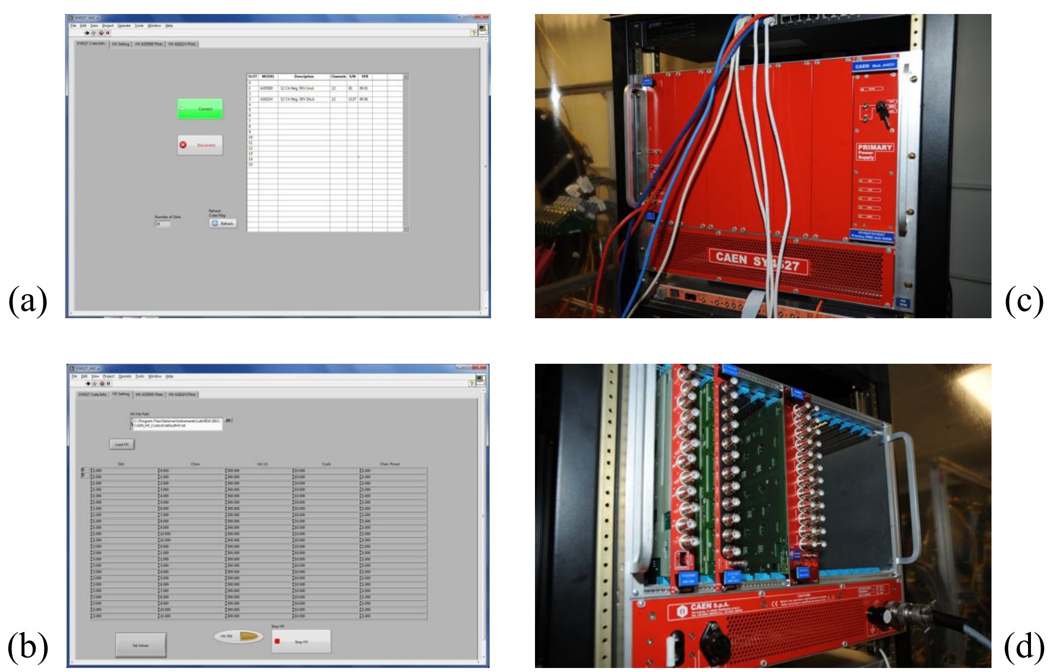


Figure 23: *CAEN HV system showing the front (c) and back-side (d) under lab view control (a-b).*

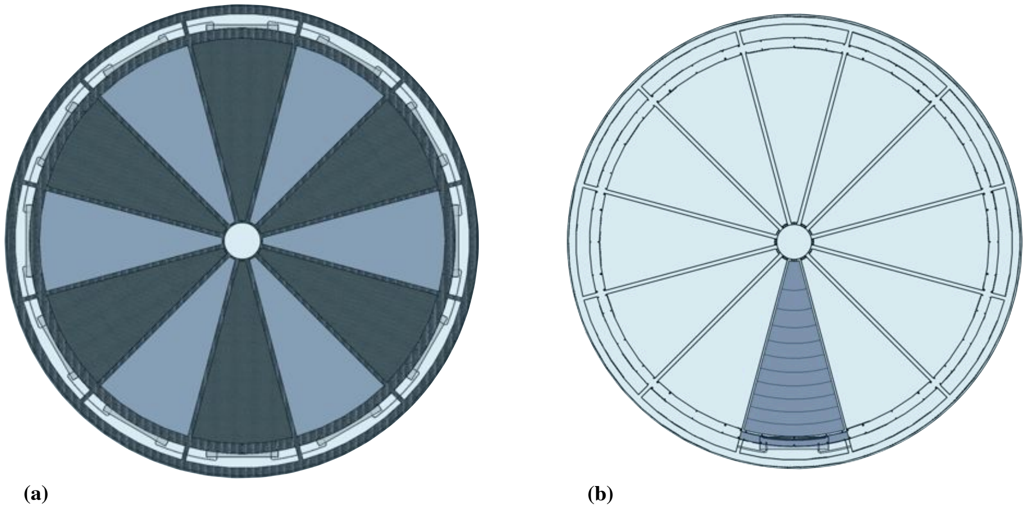


Figure 24: *Disk layout of 12 large triple-GEM detector segments.*

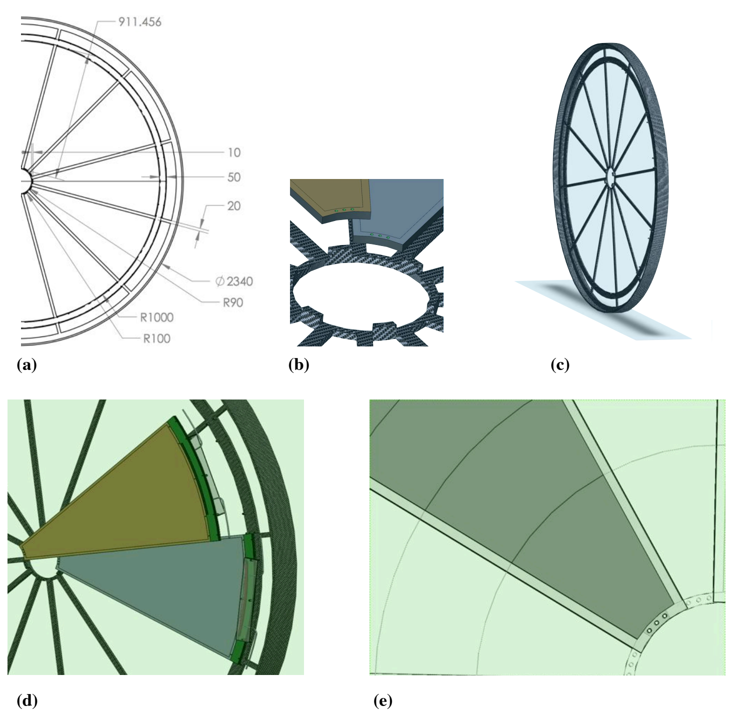


Figure 25: *Details of disk dimensions and support of individual triple-GEM detector segments.*

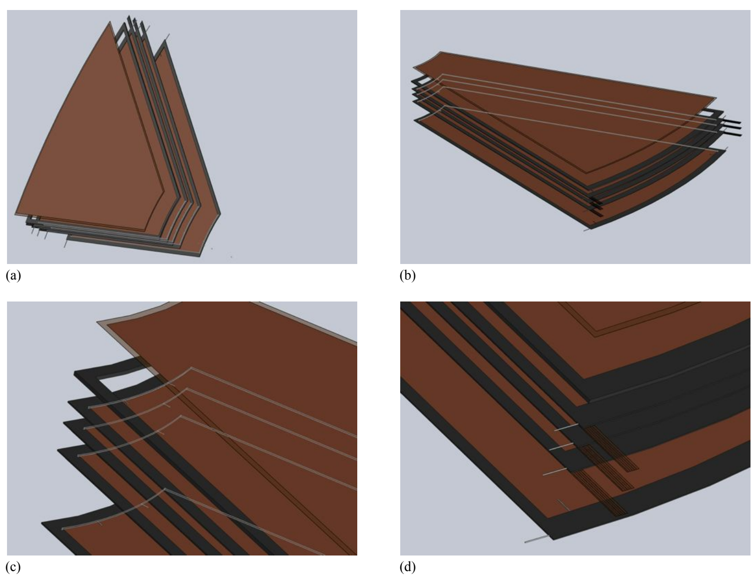


Figure 26: *Detailed view of segment design.*

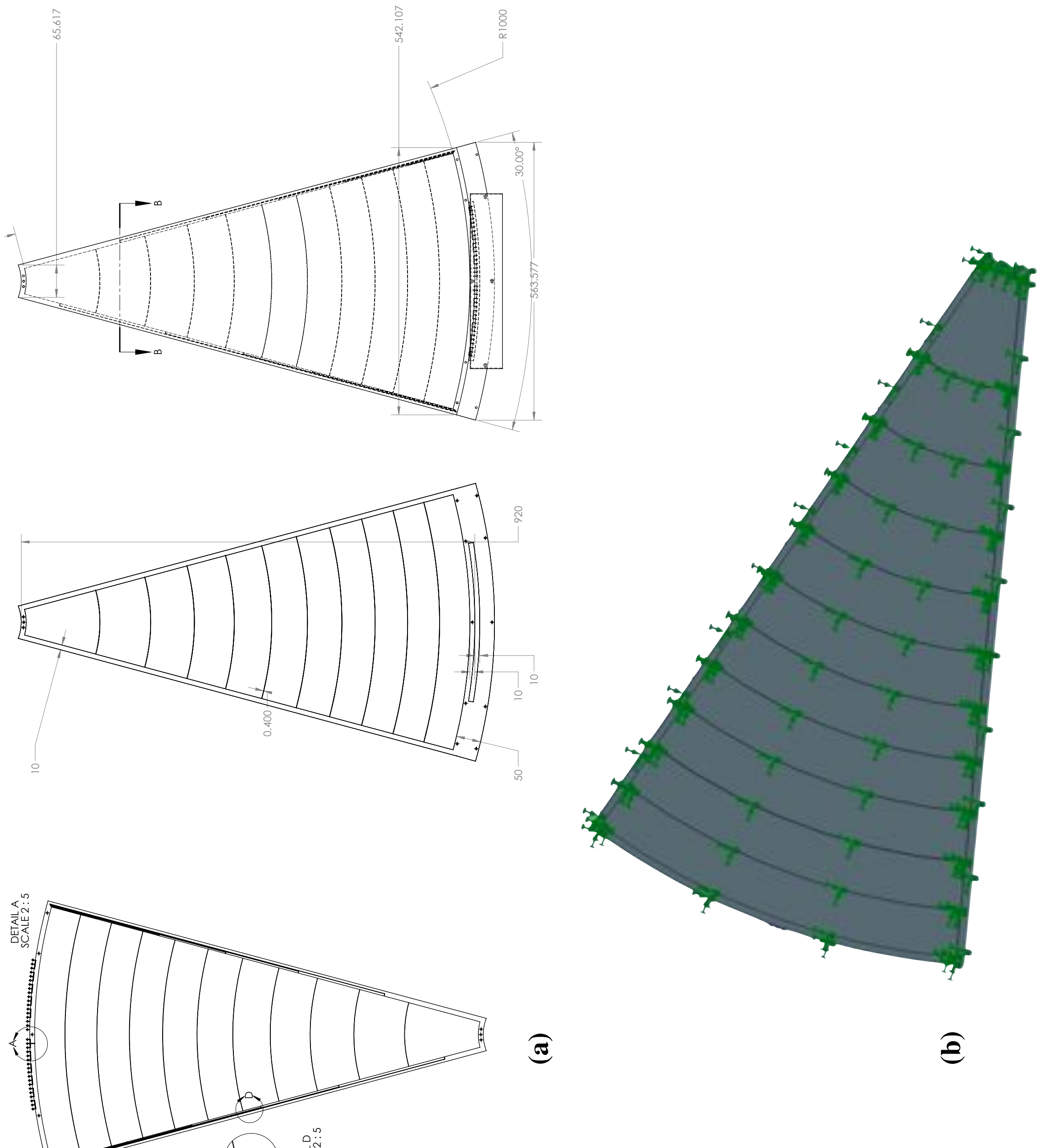


Figure 27: *Layout of large segment GEM foil with 11 sectors.*

2.2 Barrel MicroMegas tracking detector development

Characterization of a cylindrical 2D MicroMegas prototype The barrel MicroMegas R&D program proposes a MicroMegas barrel system as a central tracker for an EIC detector as shown in Figure 1. This barrel system is composed of several layers of cylindrical MicroMegas chambers, covering a radial region of approximately $10 - 60$ cm. Due to delays of the production of large radius prototype sectors at CERN covering an azimuthal angle of $60°$ with a radius of 50 cm, it was decided to start with the development of the smaller radial region sector consisting of a $180°$, 10 cm radius prototype shell in partnership with the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration. This shell would correspond to the inner-most layer of a MicroMegas barrel tracking system. The large bending of the structure is mechanically quite challenging due to large mechanical stress of the micromesh and readout electrode. This prototype offers the possibility to work with a full geometrical configuration of a barrel system.

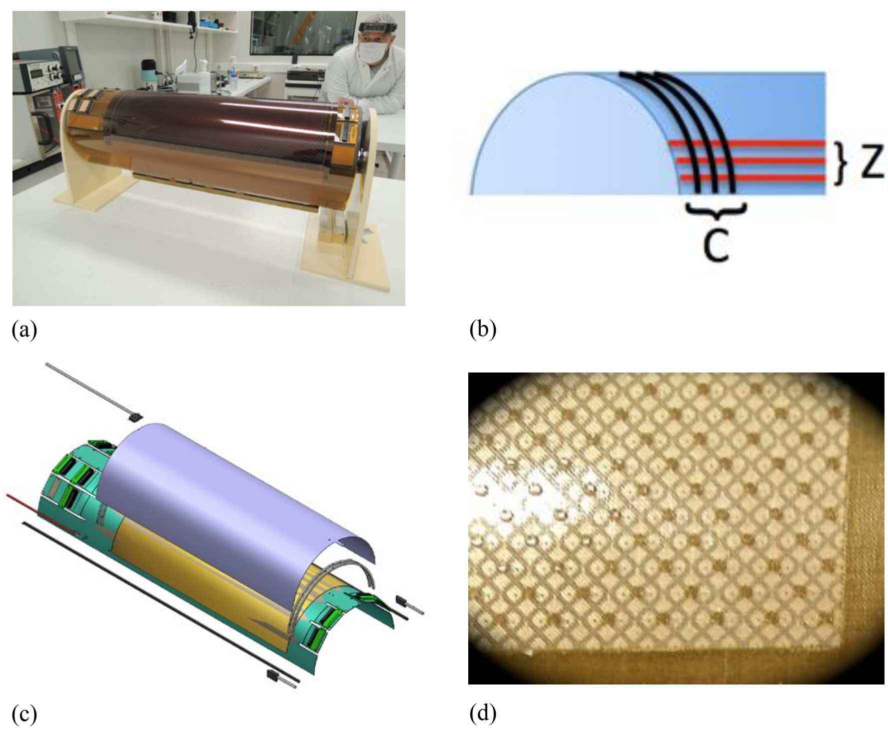


Figure 28: *Fully assembled prototype in Saclay's cleanroom (a), 2D readout scheme with C-Z strip orientation (b), Exploded view of the prototype (c) and detailed view of the active area with 2D readout diamond pads connected by strips along the C and Z projections seen under the woven micromesh (d).*

Prototype description The prototype chamber as shown in Figure 28 consists of cylindrical half with a radius of 9.5 cm and a length of 60 cm. This prototype tracking layer provides measurements of the longitudinal (Z) and transverse (C) coordinates as shown in Figure. 28. The chosen readout pitch of 0.87 mm results in $\sim$250 Z and $\sim$500 C strips per chamber. This detector follows closely the CLAS12 lightweight design and preserves the requirement for a future EIC barrel tracking system.

The characterization of this prototype has focused on the following key points:

- Basic characterization and efficiency measurement
- Rigidity of the self supporting structure
- Spatial resolution of a cylindrical MicroMegas and micro-TPC algorithm

Basic characterization and efficiency measurement The large bending of this prototype creates large mechanical stress of the different materials, in particular the metallic micromesh. Nevertheless, due to the high quality production at CERN and assembly at Saclay, this first prototype showed excellent performance. It has been tested in a cosmic ray test bench at Saclay for several days and operated in a very stable fashion. A run of 2.4 million cosmic ray events were taken during 113 hours. This data set has been used to map the efficiency of the detector as shown in Figure 29.

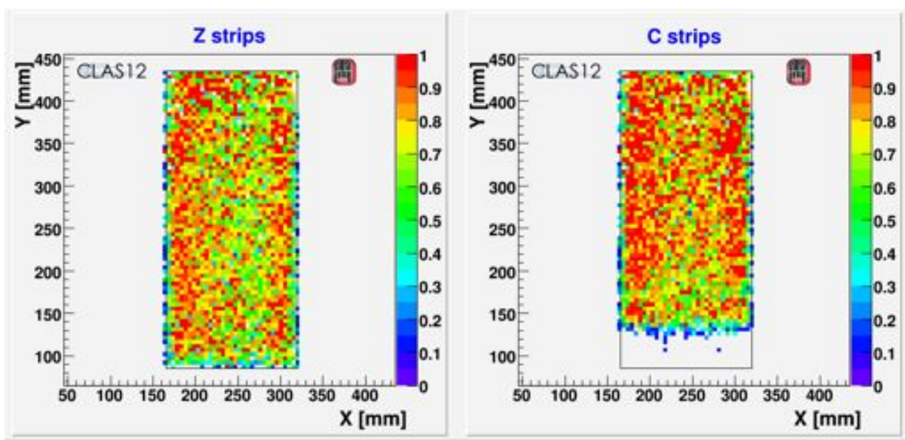


Figure 29: *Efficiency of cylindrical MicroMegas prototype for both projections in Z and C. The inactive area on the C projection corresponds to an area which was not read out.*

The overall efficiency has been measured to be 76% in Z and 81% in the C coordinate. These values are lower than the typical efficiency of a MicroMegas detector (> 98%). This is not unexpected taking into consideration the moderate gain and the 3 mm conversion volume. The data has been taken with an operating voltage of 410 V on the MicroMegas for safe operation, which is below the full efficiency operation mode. The use of resistive technology to increase the stability at high gain will be tested for the next generation of detectors for an EIC, in particular with the large 60° prototype, expected to arrive in a couple of weeks. The 3 mm conversion gap has been chosen to reduce the effect of the large magnetic field ($\sim 5\,$T) of the ASACUSA experiment. In the case of a perpendicular muon track, this gap is too low to provide enough primary electrons. Therefore it lowers the efficiency in the horizontal part of the half cylinder and it explains the lower efficiency in the middle of the 2D plots shown in Figure 33 along the Y axis.

Rigidity of the self supporting prototype Mechanically, the detector consists of a 100 μm FR4 readout printed circuit board with an embedded micromesh. The amplification electrode, or micromesh, is a 60 μm thick non-magnetic metallic woven mesh held at a distance of $\sim$128 μm from the readout PCB by pillars etched in photosensitive films. The drift electrode is a 250 μm copper coated Kapton structure held by carbon spacers on the side of the detector. The active area does not include any dead space. This lightweight design results in a very small material budget as required for an EIC tracking system. This prototype is a unique opportunity to test an EIC-like mechanical design as shown in Figure 30.

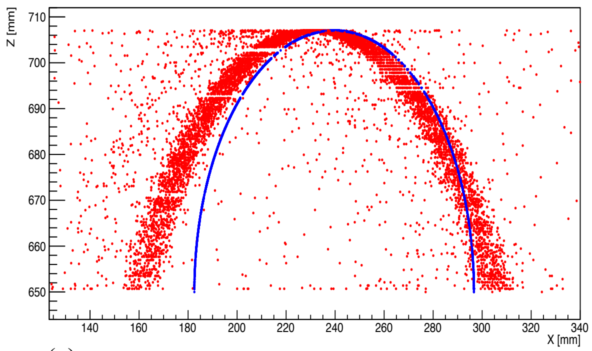
(a) (b)

Figure 30: *Cylindrical MicroMegas prototype in the cosmic-ray test bench (a) and detailed view of the detector edge (b).*

The orientation of the prototype detector in a cosmic-ray test stand (Figure 30) impacted the cylindrical shape due to gravity. As shown in Figure 31, the data have highlighted some minor deformations. The edges are further apart than excepted. Therefore it has been decided to add a mechanical structure on the side of the detectors, outside of the active area, for the next generation of prototype chambers as shown in Figure 31. This mechanical structure has been produced in one piece with 3D printing techniques at Saclay. This would have been very expensive with conventional techniques which would require to machine a large piece of raw material to the required cylindrical shape.

Spatial resolution of a cylindrical MicroMegas and micro-TPC algorithm Micropattern gas detectors detectors are usually used as planar detectors where the particle track angle with respect to the readout plane is around 90°. When the angle decreases, the charge is smeared over a wider area of the readout plane. The effect on the resulting signal amplitude is shown in Figure 32. This lowers the spatial resolution of tracks that are bent by the magnetic field in a collider-like detector configuration. These low momentum particles are reconstructed with less precision.

When the charge is more spread out, it becomes difficult to reconstruct the position of the incident particle because the signals have a lower amplitude and a weighted mean of the amplitude does not represent the exact position of the impinging particle anymore. That is the reason why a micro-TPC algorithm was studied which uses the time information in the drift volume similar to a TPC. The impact of the track angle on the resolution has been shown in a MC simulation of the MicroMegas chambers as shown in Figure 33.



(a)

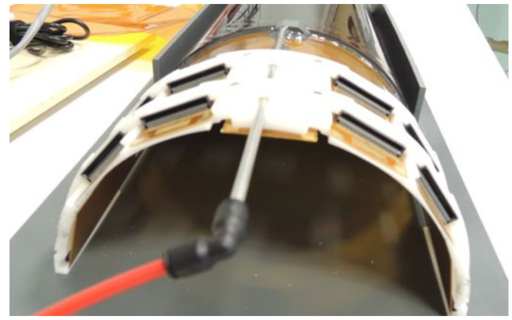

(b)

Figure 31: *Comparison between the expected position in the prototype plane (blue dots) and the reconstructed position of cosmic-ray tracks (red dots) (a) and 3D printed mechanical structure developed to correct for deformations (b).*

Figure 33 shows that the different versions of the micro-TPC algorithm perform better at large angles than the standard weighted mean algorithm [A]. The algorithm [B] uses the entry and exit points of the track in the gas volume to extrapolate to the original position. Algorithm [C] uses the full primary electron information to fit a straight line for the extrapolation. Algorithm [D] does the same as algorithm [C] with only using the time information of the first electron arriving at a given strip as in a real detector. All this shows that the method is correct and that the more information is included on the time of arrival of individual primary electron, the better the actual performance. Next generation of electronics will have to aim for the best time resolution possible to exploit these new reconstruction possibilities.

To test the conclusions of this simulation, a planar detector has been mounted on a special mechanical arm to precisely control the angle. The comic ray test bench capabilities in terms of spatial resolution are lower than the expected effect. New studies will be performed with more precise detectors.

Status: Full characterization of a half-cylindrical prototype has been performed at Saclay with cosmic rays. This prototype has proven the feasibility of using a MicroMegas detector with minimal material budget. Careful study of the data indicates the need to continue this R&D program with resistive technologies to increase the operational gain. Finally a MC simulation study has shown promising results for the reconstruction of particles at large angle.

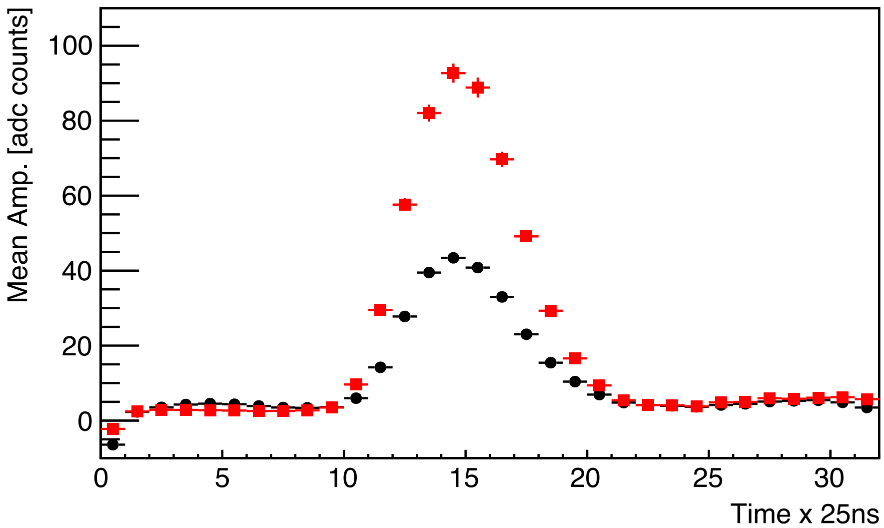


Figure 32: Average amplitude of MicroMegas signals with comic rays. Comparison between the sides of the cylindrical detector (black dots) and central region (red squares). Tracks perpendicular to the readout plane lead to a more concentrated charge that induces a larger signal.

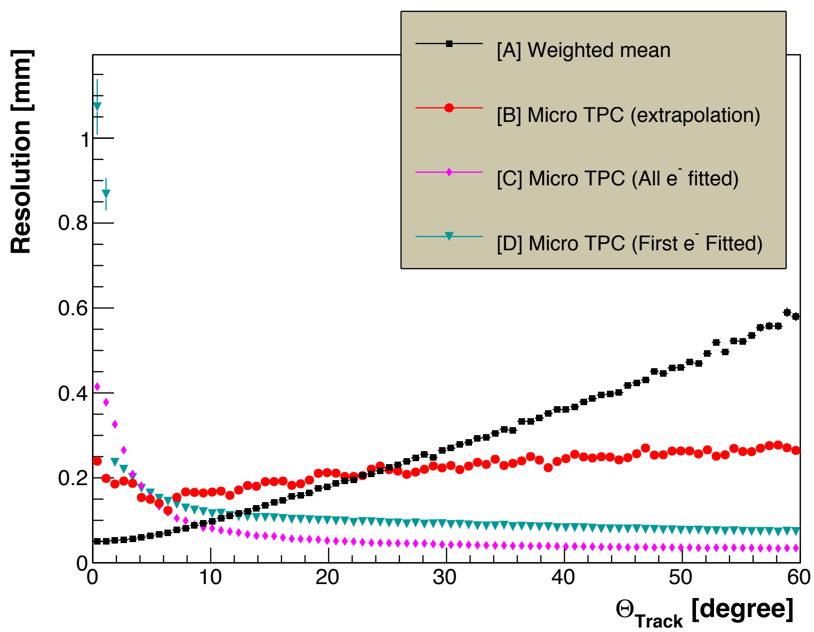


Figure 33: *MC simulation of the spatial resolution of a MicroMegas detector as a function of track angle for different reconstruction algorithms.*

2.3 Front-End Electronics development

The first batch of DREAM ASICs has been successfully produced this year. The production and test of the complete front-end electronics system has recently started. The main components are the Front-End Units (FEU) with 8 DREAM ASICs controlled by one FPGA. The FEU are mounted inside a standard electronics rack as shown in Figure 34 and directly connected to the detectors strips with special flat cables.

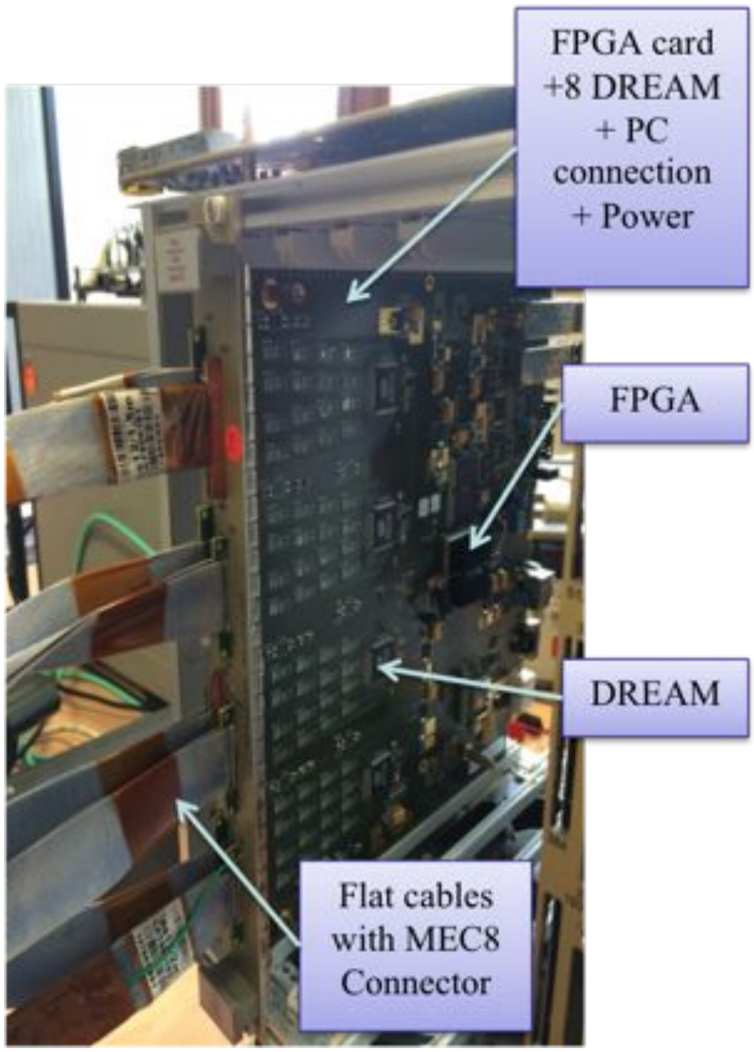


Figure 34: *DREAM front-end electronic card and front-end electronics system.*

The DREAM based system has been successfully tested with MicroMegas detectors. It is now replacing the AFTER/T2K based electronics to read-out 6 tracking chambers of the comics-ray test bench at Saclay. The comparison between the performances of the two systems is shown in Figure 35.

Figure 35 shows that the efficiency is much higher with the DREAM FEE due to better signal to noise performance. When the full efficiency is reached, both systems are significantly above

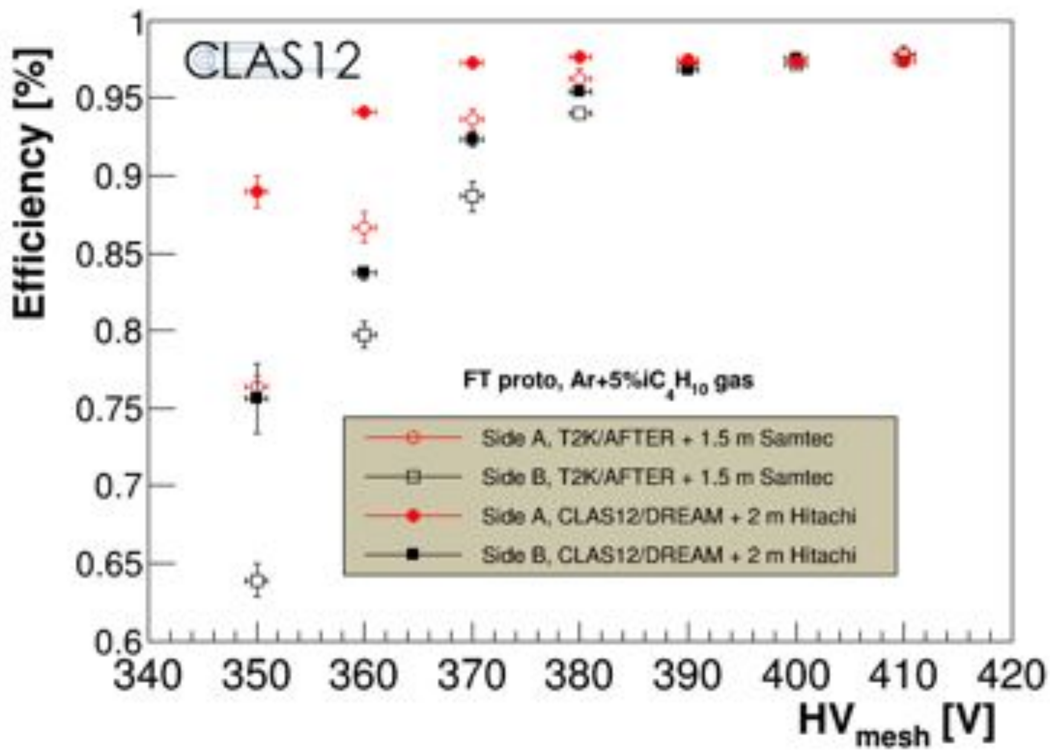
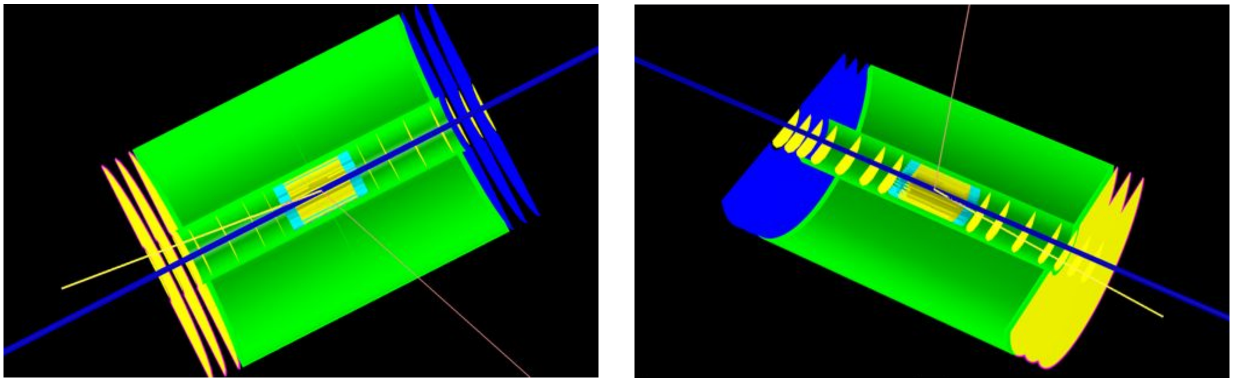


Figure 35: *Efficiency plateau of a CLAS12 prototype with the DREAM and AFTER front-end electronics.*

noise and there is no difference in detector performance. However the full efficiency is reached more than 20 V before with the DREAM chip version which is a significant improvement compared to the AFTER chip version. This was expected since the DREAM chip is optimized for large capacitance detectors unlike other ASICs such as AFTER or the APV-25. DREAM is based on the AFTER ASIC with several improvements in particular in the memory management to increase trigger capabilities. The DREAM system has been successfully tested up to a rate of 10 kHz. The setup of a DREAM chip based readout system for a triple-GEM detector will be discussed in the proposal section.

Status: Successful DREAM chip production and test of complete front-end system.

2.4 Simulations

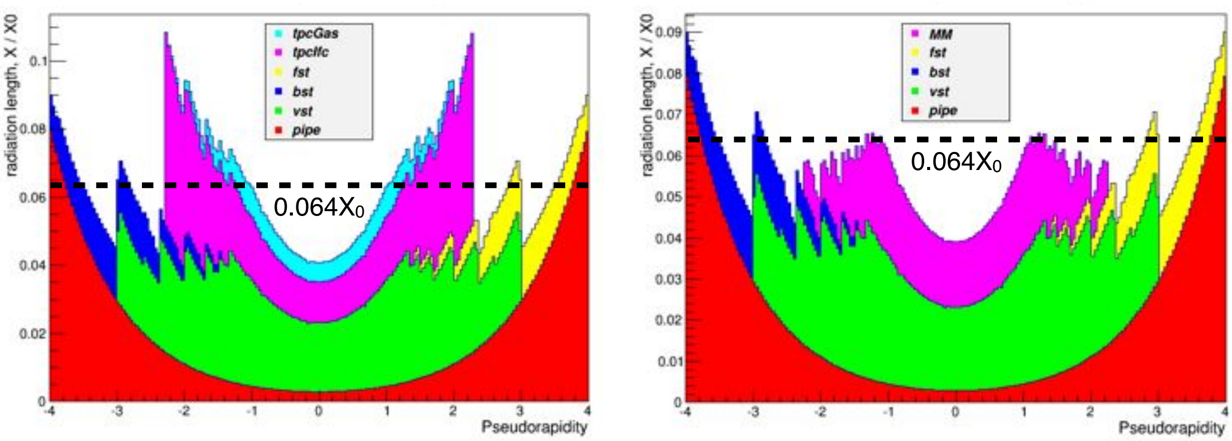


(a) (b)

Figure 36: *Screen captures of DVCS events generated by MILOU within the EICROOT framework.*

The simulation of EIC detector has moved forward focussing on the tracking detectors of the central region. The following milestone have been reached :

- Implementation of the barrel MicroMegas and Forward GEM tracker active volume description
- Material description of the MPGD detectors



(a) (b)

Figure 37: *Material scan for a TPC solution (a) and the MicroMegas barrel (b) solution [4].*

- Installation of the EICROOT software framework at CEA which is the first installation outside of the BNL computer facility
- Simulation of DVCS events using the FORTRAN based generator MILOU based on 15 GeV electrons on 50 GeV protons

- Test of the software interface between MILOU and EICROOT

The installation of the EICROOT framework, and, in particular all the necessary packages, turned out to be a rather difficult task outside the BNL computing environment. This has delayed systematic studies with physics events. A major simulation effort is beginning at Saclay to test the performances of the different tracking solutions as proposed here.

The material distribution in GEANT is shown in Figure 37. The MicroMegas detectors are still described with a relatively simple model using extrapolations from the CLAS12 experiment for the barrel and from the STAR experiment for the Forward GEM tracker. These distributions show that the barrel solution seems to compete favorably with a TPC solution in term of material budget.

Status: Realistic material description of the FGT and MicroMegas systems have been implemented in EICROOT and compared to the standard central detector model. EICROOT has been successfully installed on the Saclay's computer grid. DVCS physics events have been generated using the MILOU generator and systematics studies of the barrel performance are beginning.

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