Project Title:

eRD3

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

Progress report (Q4 FY14 / Q1 FY15)

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Type of application:	Continuing funding request BNL EIC R&D contract eRD3
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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:

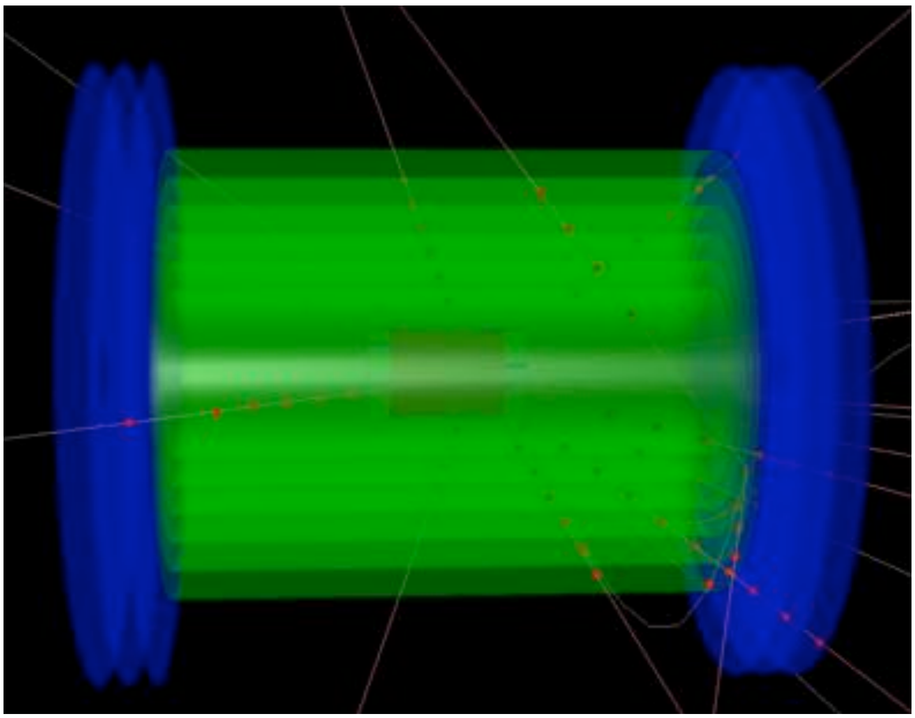


Figure 1: *GEANT simulation of a barrel (green) and rear / forward (blue) tracking system for an EIC detector.*

- 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 4th quarter of FY14 (Q4 FY14) and the 1st quarter of FY15 (Q1FY15) both in the barrel and rear / forward directions following the last meeting of the EIC R&D committee in July 2014. The allocation of funds of \$240k for FY15 as stated in the award letter from August 01, 2014 have not been obtained yet. These resources are needed 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. As stated in the closeout report following the last EIC R&D committee in July 2014, preference should be made to the GEM R&D effort due to budget limitations. We acknowledge this, but would like to point out that the MicroMegas R&D program is the only one of its kind within the whole EIC R&D program. 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 has profited enormously from funds provided by the BNL EIC R&D contract so far:

- Forward GEM Tracking detector development:
  - Relocation of three labs at Temple University delayed to January/February 2015 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. and comparison to the single-mask produced foils at CERN ($10 \times 10\,\mathrm{cm}^2$).
  - First characterization of large single-mask GEM foils ($50 \times 50\,\mathrm{cm}^2$) in terms of optical uniformity in collaboration with Yale University and Tech-Etch Inc.
  - Common design of large GEM foil layout ($50 \times 100\,\mathrm{cm}^2$) for dedicated EIC forward sector in collaboration with Florida Institute of Technology and University of Virginia

  - Assembly of small ($10 \times 10\,\text{cm}^2$) triple-GEM test detectors
  - Commissioning of a new CAEN HV system for cluster studies using small $10 \times 10\,\text{cm}^2$ 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

A key highlight was the presentation and publication of the successful commercial test and fabrication of single-mask produced GEM foils at the 2014 IEEE conference [2].

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 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 which was submitted in fall 2014, but which we have not received yet.

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 hosted 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. A proposal to foster such collaborative efforts will be submitted to the Provost Office in March 2015 following the solicitation to enhance international programs at Temple University.

2 Progress report - Q4 FY14 / Q1 FY15

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 $10 \times 10\,\text{cm}^2$ 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 $40 \times 40\,\text{cm}^2$ 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 $50 \times 120\,\text{cm}^2$ in size which has recently been started. In addition, comparative measurements of $10 \times 10\,\text{cm}^2$ produced at CERN have been made. 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. His further support critically depends on the release of allocated funds for FY15 from the EIC R&D program. All GEM lab setups are 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. The actual move is scheduled for January / February 2015 after various logistics and technical delays.

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 postponed until the arrival of approved funding for FY15. 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 ($\sim 500\,$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 ($\sim 1000\,$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 ($\sim 500\,$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.

(a) (b) (c) (d) (e)

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).*

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 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). The actual new SERC Clean room detector laboratory (a-b) and SERC detector assembly and test laboratory (c-e) is shown in Figure 4.

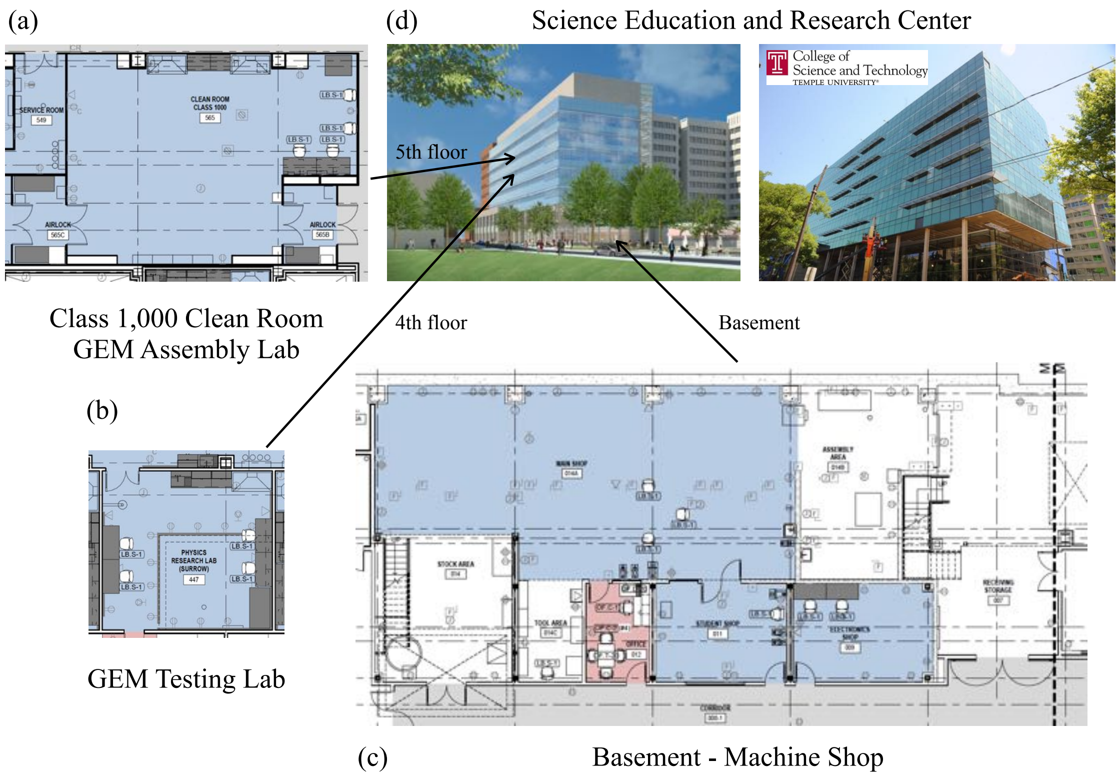


Figure 3: *Overview of the Science Education and Research Center (SERC) (d) with state-of-the-art laboratory infrastructure based on a large Class 1,000 clean room (a) and GEM testing lab (b) along with a large machine shop (c) providing support for the Temple University research programs within the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

Status: GEM lab infrastructure complete and fully functional. The scheduled move to the new Science Education and Research Center is set for January / February 2015.

Commercialization of single-mask GEM foil production 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 [3] 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 $10 \times 10\,\mathrm{cm}^2$ GEM foils followed by FGT-type GEM foils (about $40 \times 40\,\mathrm{cm}^2$) 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 $10 \times 10\,\mathrm{cm}^2$ (18) and FGT sized $40 \times 40\,\mathrm{cm}^2$ (3) single-mask foils and by now also $50 \times 50\,\mathrm{cm}^2$ single-mask foils have been shipped to Temple University.

Figure 4: *New SERC Clean room detector laboratory (a-b) and SERC detector assembly and test laboratory (c-e).*

A key highlight was the presentation and publication of the successful commercial test and fabrication of single-mask produced GEM at the 2014 IEEE conference [2]. Figure 5 shows from left to right Dr. Matt Posik, Dave Crary (Tech-Etch) and Matt Campbell (Tech-Etch) at the Tech-Etch Industry stand during the 2014 IEEE conference.

(a) 40×40 cm^2 Optical Results The optical analysis (the electrical anlysis was presented in last years proposal) of all three 40×40 cm^2 foils manufactured by Tech-Etch and sent to Temple University for testing followed the same procedure that was described in last years proposal. The 40×40 cm^2 foils were divided into six CCD scan regions in order to not exceed the translational limitation of our 2D stage. Figure 6 shows how the 40×40 cm^2 foils were divided in order to scan the entire active area of the foil.

Distributions of the pitch, inner, and outer hole diameters were measured. Many of the same geometrical behaviors found in the 10×10 cm^2 (presented in last years proposal) were also seen in the larger foils. In particular the pitch displayed the narrowest distribution and the inner hole diameters showed a larger deviation from the mean than the outer hole diameters. Also like the 10×10 cm^2 foils, the hole diameters were found to have excellent uniformity across the 40×40 cm^2 foils, where deviations were found to be smaller $\pm 10 \mu m$, as shown in fig. 7. The inner (outer) hole diameter deviation distribution widths generally ranged from $\sigma = 1.7 \rightarrow 3.0\ \mu m$ ($\sigma = 1.1 \rightarrow 1.8$

Figure 5: *Tech-Etch GEM foil industry stand at the 2014 IEEE conference showing from left to right Dr. Matt Posik, Dave Crary (Tech-Etch) and Matt Campbell (Tech-Etch) .*

μm), where σ is determined from the Gaussian fit to the respected distribution.

Considering all three of the 40×40 cm^2 foils, we measured a near constant pitch of about 138 μm in each CCD scan region across all foils. The average inner (outer) hole diameters were found to be consistent over all CCD scan regions across all three foils, as shown in fig. 8 (fig. 9). The mean inner (outer) hole diameter across all three foils was measured to be 53.13 μm (78.64 μm), which are similar to the double-mask GEM foil values found in ref. [4].

(b) 50×50 cm^2 With the successful production of the 40×40 cm^2 GEM foils, Tech-Etch has begun the process of manufacturing 50×50 cm^2 single-mask GEM foils. Foils of this size represent the largest foils that Tech-Etch can produce without upgrading their manufacturing equipment. An initial production test batch has revealed promising results, displaying average inner and outer hole diameters which display similar geometrical properties as the previously produced smaller area GEM foils. Tech-Etch is currently collaborating with CERN to better fine tune the hole diameter uniformity over the area of the 50×50 cm^2 GEM foils and expect to have optimized results within the next couple of months.

(c) CERN Single-Mask 10×10 cm^2 Comparison In order to provide a direct comparison to the foils produced at Tech-Etch, 3 10×10 cm^2 single-mask GEM foils were purchased from CERN. The CERN foils, like the Tech-Etch foils, use apical as the polyimide layer. In fact Tech-Etch orders their raw material from the same distributor as CERN.

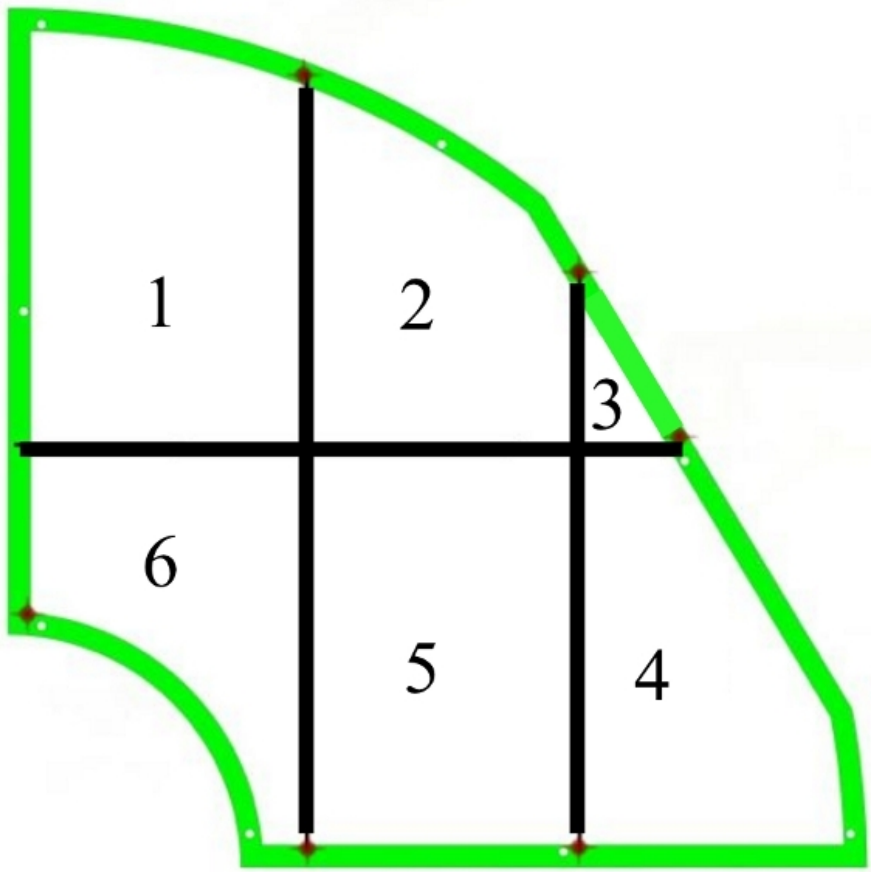


Figure 6: *The division of a 40×40 cm^2 GEM foil into six CCD scan regions (1-6).*

The electrical performance of the CERN foils were tested by measuring the leakage current of each foil. This measurement used the same setup and procedure that was used to measure the electrical performance of the Tech-Etch foils. All of the CERN foils showed similar results compared to the Tech-Etch foils, with leakage currents typically measured to be below about 1 nA.

The same optical setup that was used to measure the geometric properties of the Tech-Etch GEM foils, was used to measure the geometrical properties of the CERN foils. The optical scans of the CERN foils have begun. Unfortunately only about 80% of the inner hole diameter was completed for just one of the CERN foils due to a hardware failure that prevents us from scanning anymore foils. We are awaiting funding to repair the issue.

A comparison of the inner diameter, deviation, and pitch between the CERN (partial inner hole diameter data) and Tech-Etch foils has been made. Figure 10 shows the inner hole distribution for a CERN and a representative Tech-Etch foil. The mean inner diameter size between the two foils are similar to one another. The Inner hole diameter deviation from the mean is shown in fig. 11. From this figure it can be seen that the CERN foil shows a more uniform inner hole diameter than the Tech-Etch foil. Finally, a comparison of the pitch was made in fig. 12 between the CERN and Tech-Etch foils. While the mean of the CERN pitch distribution agrees with what was found in

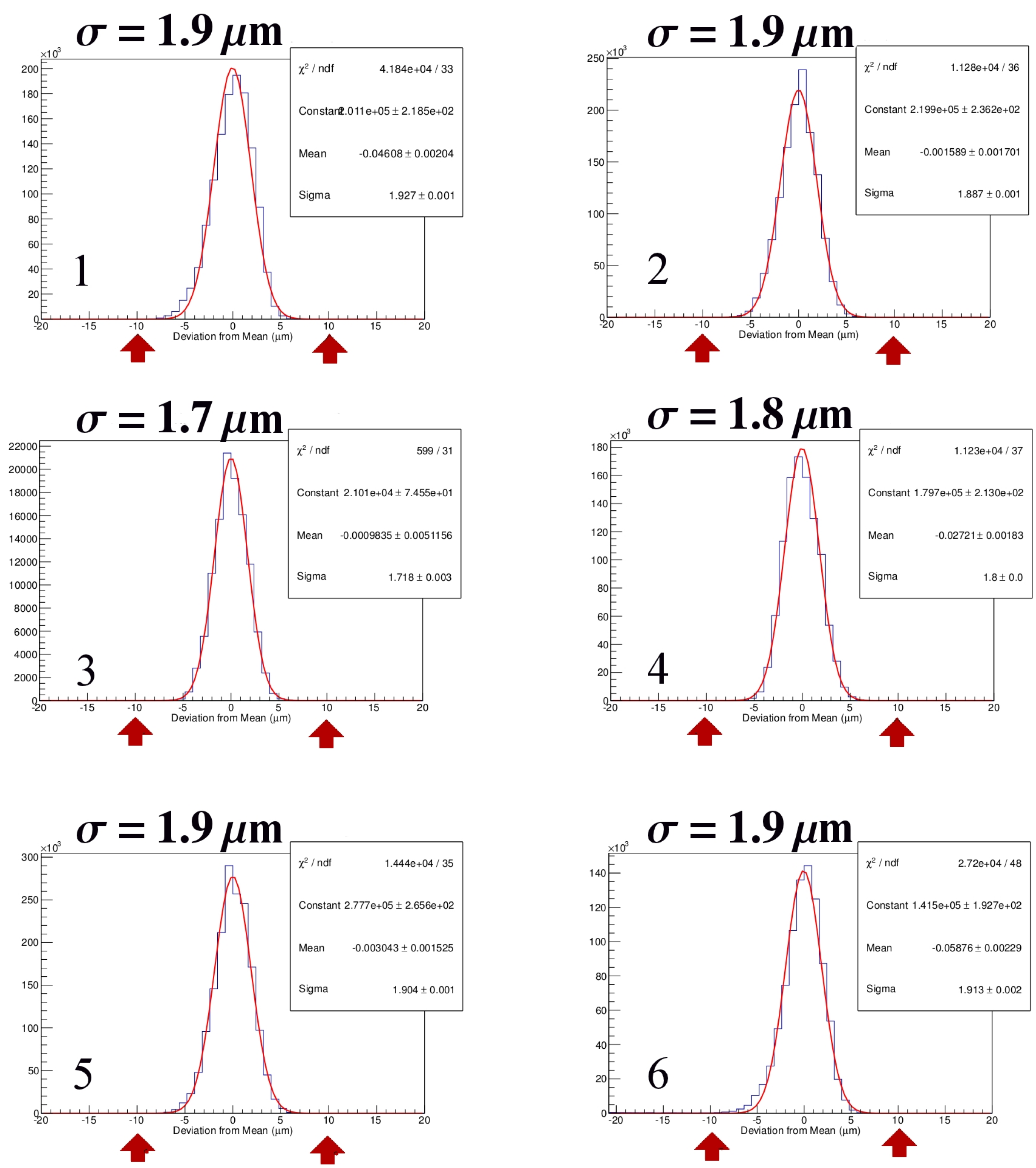


Figure 7: *Inner hole diameter deviation from mean for CCD scan regions 1-6. The red arrows mark the ±10 μm position.*

the Tech-Etch foil, the CERN pitch displays a double peak structure with each peak separated by about $3\mu m$. There were several etching defects noticed while looking through the CCD images of the CERN foil which was partially scanned, a few can be seen in fig 13. These etching defects could possibly explain the double peak seen in the pitch, but more scans will need to be done to know for sure.

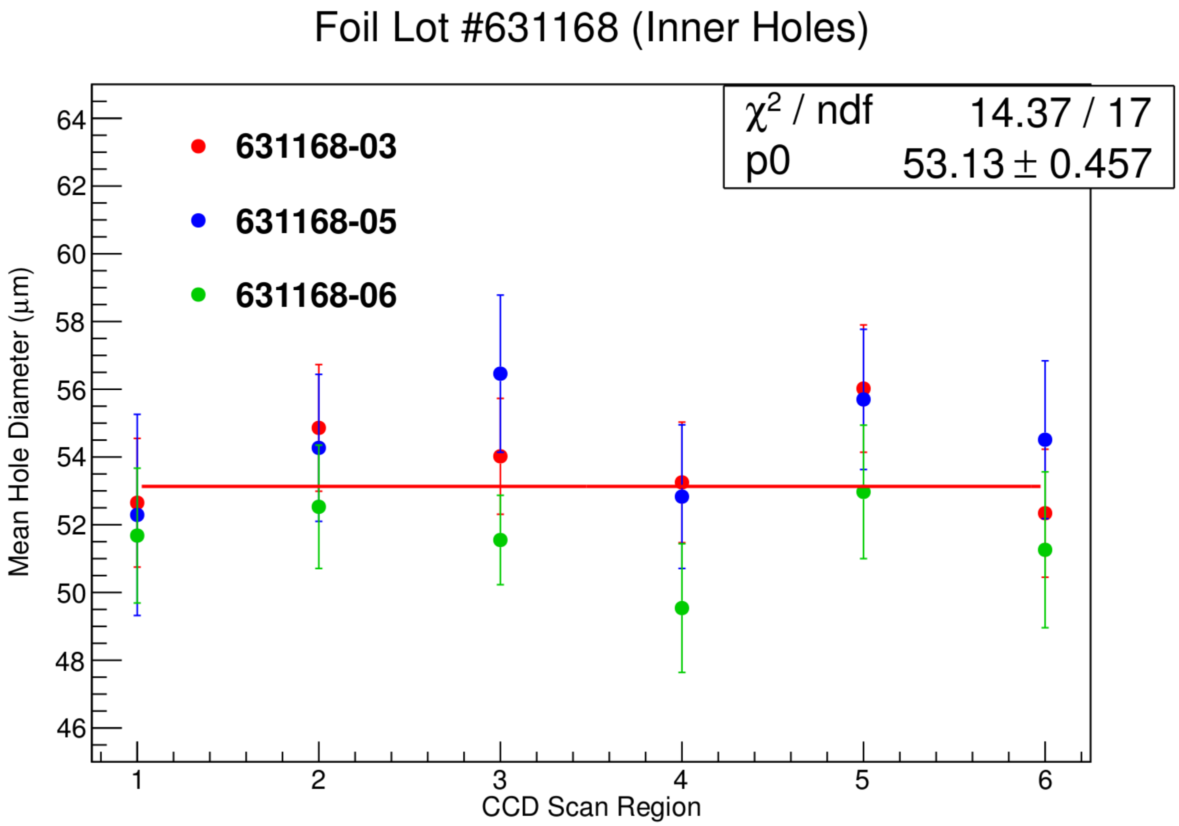


Figure 8: *Average inner hole diameters for each CCD scan region for all three 40×40 cm^2 foils. The error bars represent the sigma of a Gaussian fit to that particular distribution. A constant line is fit to get the mean inner hole diameter across all of the foils.*

Status: Successful completion of 10×10 GEM foil and 40×40 GEM foil measurements along with the start of the first 50×50 GEM foil samples.

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 14 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 14. 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 and delay in beginning of assembly due to lack of allocated funds for FY15.

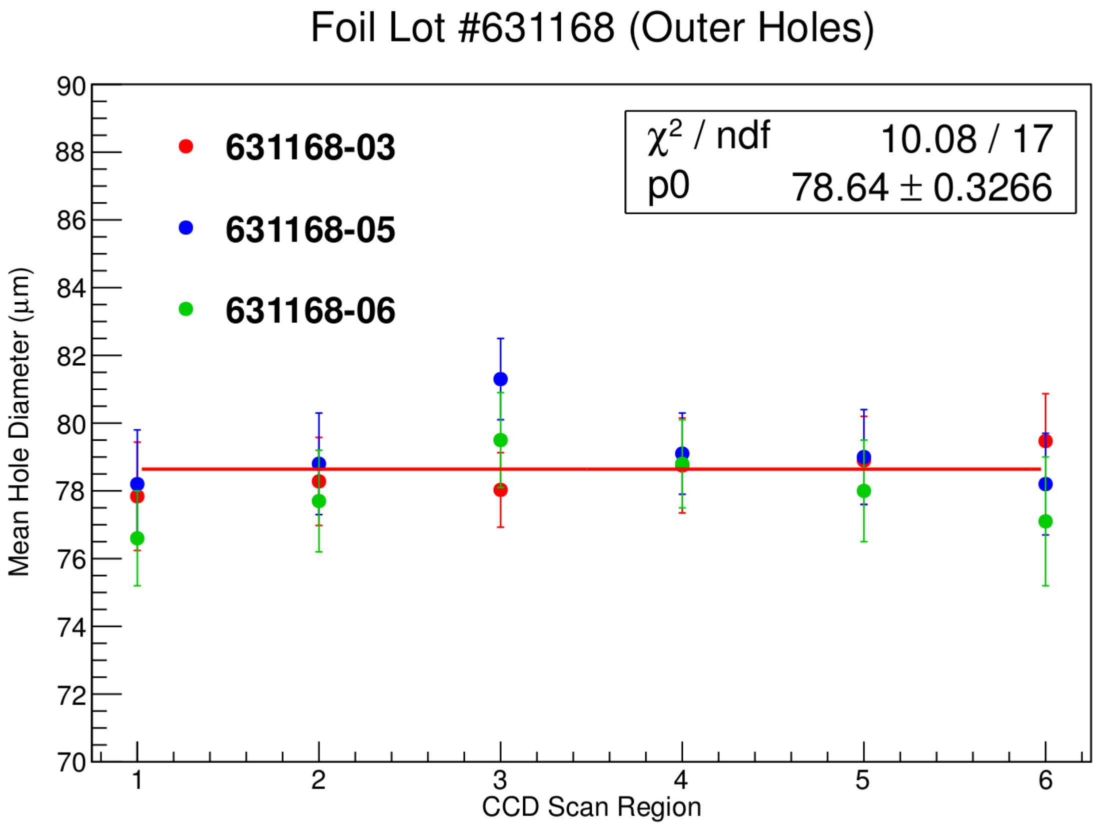


Figure 9: *Average outer hole diameters for each CCD scan region for all three 40×40 cm² foils. The error bars represent the sigma of a Gaussian fit to that particular distribution. A constant line is fit to get the mean outer hole diameter across all of the foils.*

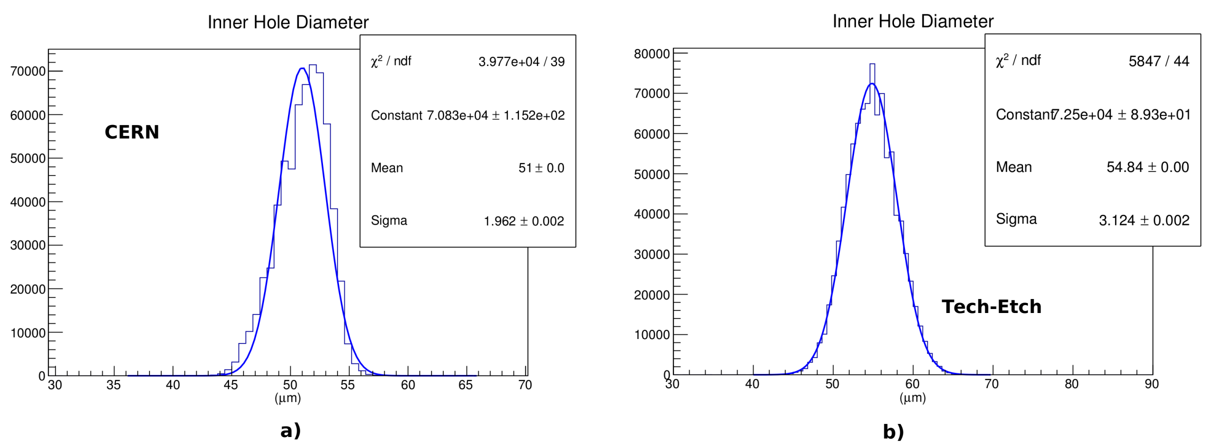


Figure 10: *Inner diameter distribution. a) A CERN foil. b) A Tech-Etch foil.*

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

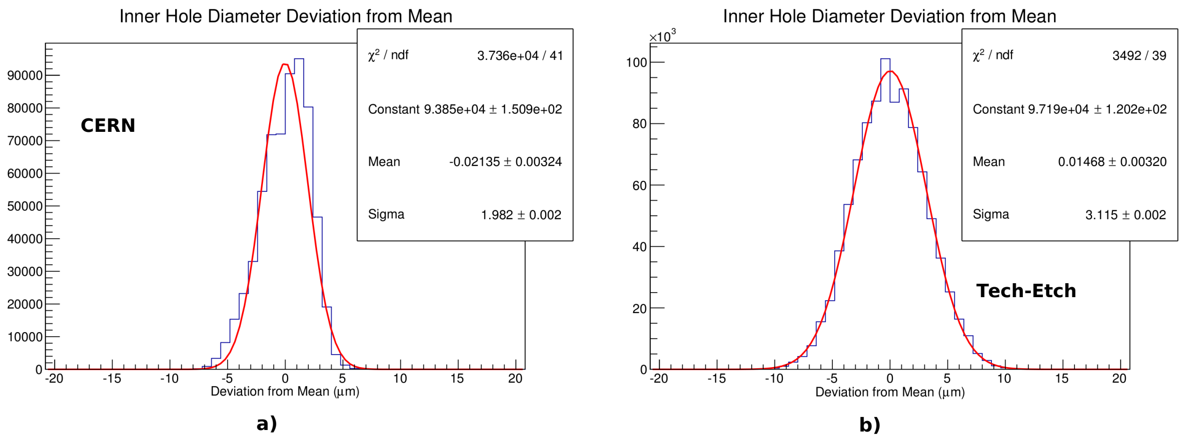


Figure 11: *Inner diameter deviation from the mean distribution. a) A CERN foil. b) A Tech-Etch foil.*

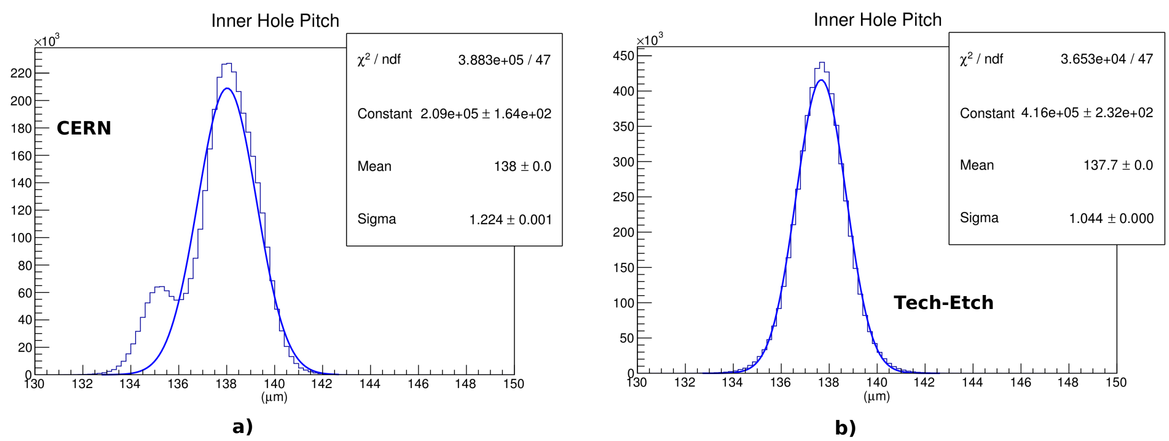


Figure 12: *Pitch distribution. (a) A CERN foil. (b) A Tech-Etch foil.*

provided by the College of Science and Technology at Temple University. The stretching fixtures have been fully commissioned. Figure 15 shows the complete testing and assembly fixtures for FGT-type triple-GEM detectors. 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 January / February 2015.

Status: All assembly and stretching tools have been setup and are fully functional and ready to be used once the assembly can start after the arrival of FY15 funds. The leakage current setup is under routine usage by students at Temple University.

Fabrication of large GEM foil storage units A SolidWorks design model, as shown in Figure 16, 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 shop and will be available for the new SERC building in January / February 2015.

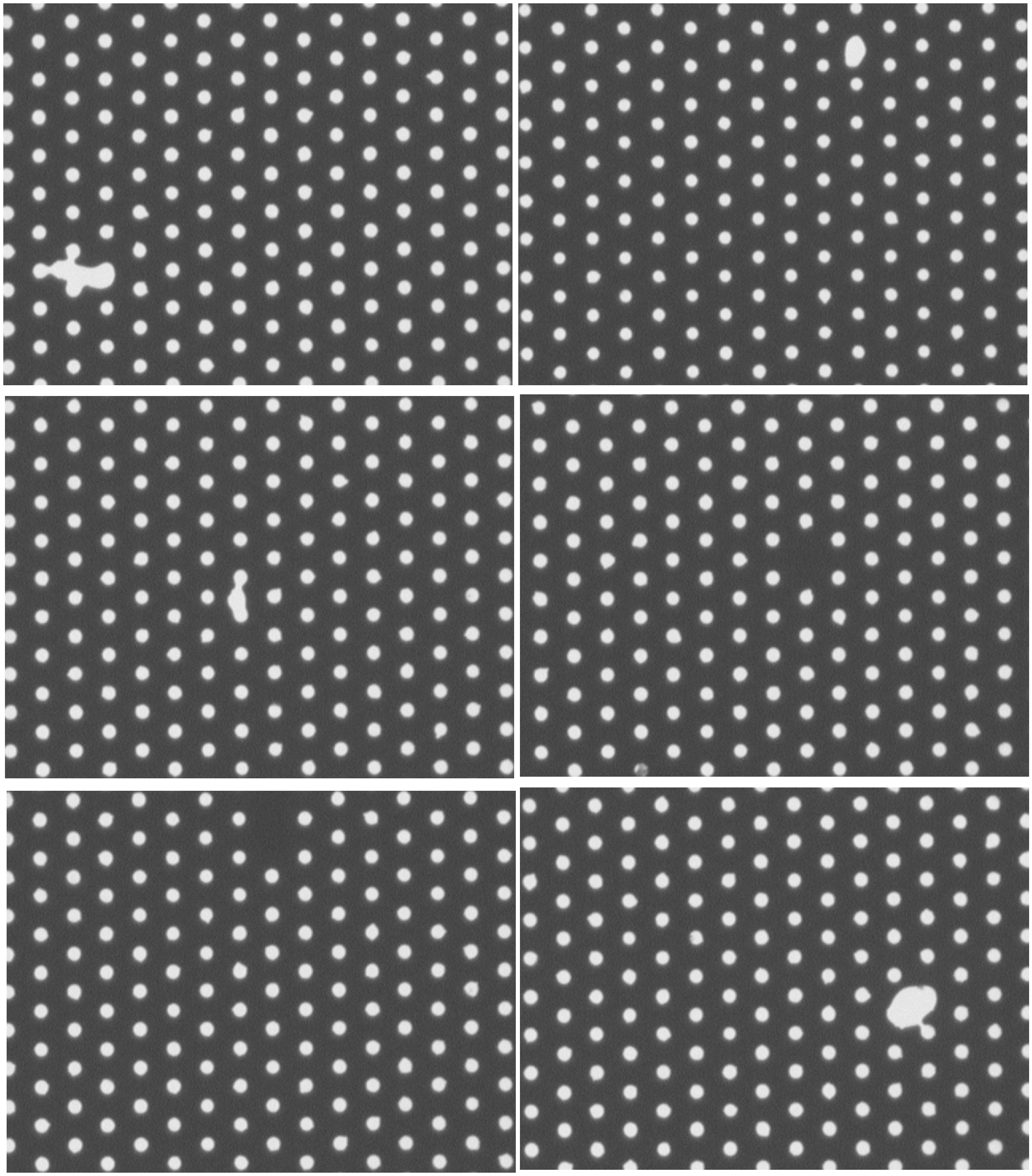
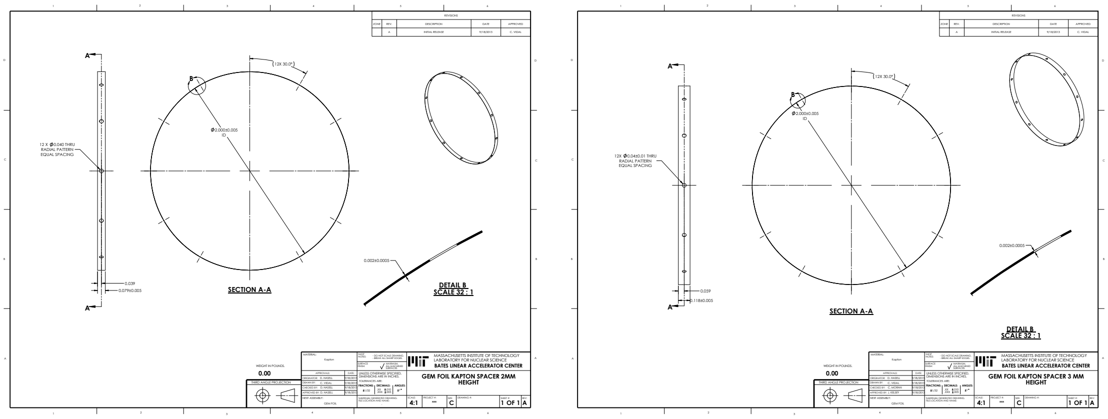


Figure 13: *Selected CCD images from a CERN single-mask 10×10 GEM foil showing foil etching defects.*

Status: Fabrication, assembly and installation discussed with machine shop. Storage units will be available for the new SERC building in January / February 2015.



(a) (b)

Figure 14: *(a) Polyimide ring with* 2 mm *thickness and (b) polyimide ring with* 3 mm *thickness.*

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 19 (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 20. 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 17 (a) and (b). The chambers are stacked face-to-face to provide easier access and avoiding dead areas between detectors as shown in Figure 18 (a)-(e). A discussion with Eric Anderson, head 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.

The R&D plans concerning the Forward GEM tracking detector efforts will address and complete several items:

- Characterization of large single-mask GEM-foils up to $50 \times 50\,\mathrm{cm}^2$
- Assembly and test of $40 \times 40\,\mathrm{cm}^2$ sectors with Apical ring spacer grids and single-mask GEM

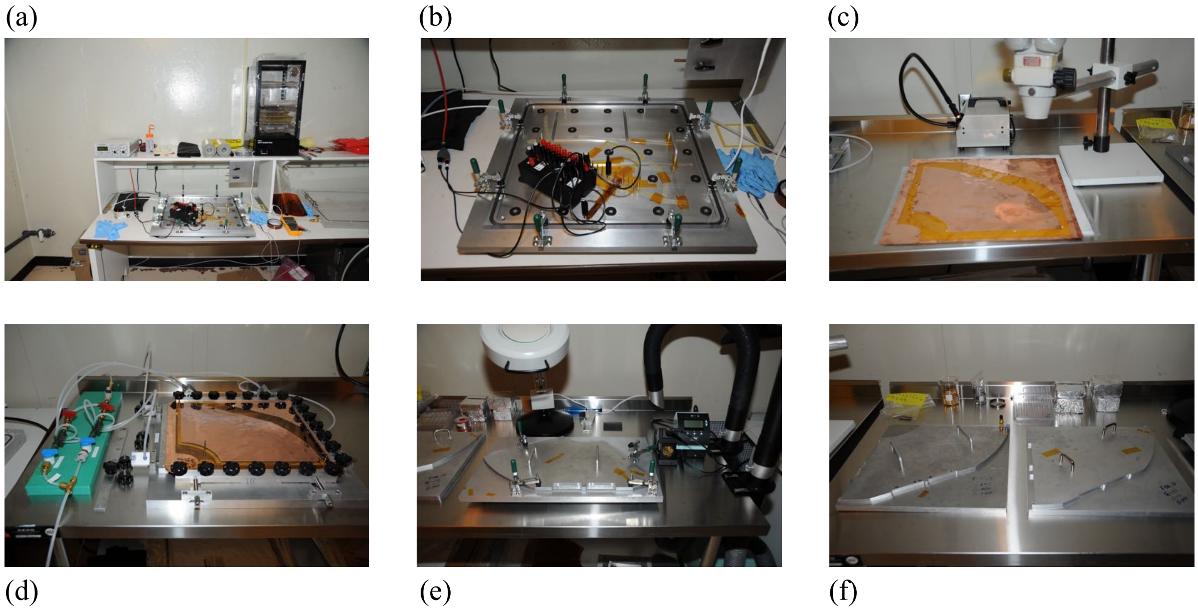


Figure 15: *The testing and assembly fixtures include the leakage current setup (a-b), a microscope inspection station (c), a GEM foil stretching fixture (d), a soldering fixture with a new soldering exhaust fume setup (e) and two assembly fixtures (f) with special covers allowing gas flow after each assembly setup to verify that the leakage current performance has not been altered during a previous assembly step.*

foils

- Cluster size studies and gain 55Fe studies with small triple-GEM detectors of $10 \times 10\,\mathrm{cm}^2$
- Finalizing design of large dedicated EIC triple-GEM segment $50 \times 120\,\mathrm{cm}^2$
- Systematic 2D readout foils tests and commercial production of very large 2D readout foils of 50×120 cm^2
- Commercialize production of very large single-mask GEM-foils of 50×120 cm^2

The last three items are the main focus of a dedicated effort at Temple University in beginning a new collaboration with the Florida Institute of Technology (FIT) group headed by Professor Marcus Hohlmann and the University of Virginia (UVa) group headed by Professor Nilanga Liyanage. Both groups have been so far part of the RD2011-6 EIC R&D program. The EIC R&D committee encouraged several GEM detector R&D groups to work more closely together. Such efforts already started with the single-mask production of GEM foils with FIT, Temple University and Yale University. Each group has a diverse set of expertise which will be very beneficial for the design, assembly and test of a dedicated EIC triple-GEM forward detector segment. More details for all of the above R&D programs will be provided below.

Status: SolidWorks design at Temple University completed. Preliminary design discussion with MIT Bates engineering team completed. Collaboration with FIT and UVA building dedicated EIC

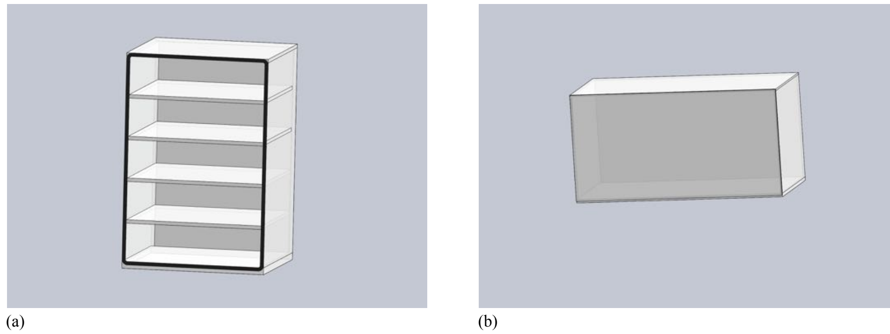


Figure 16: *SolidWorks layout of nitrogen storage cabinets for GEM foils.*

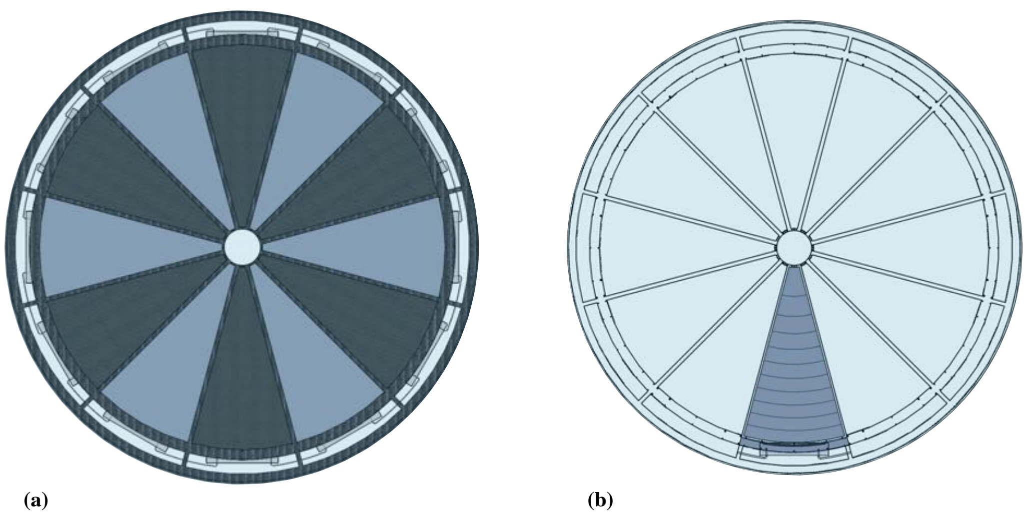


Figure 17: *Disk layout of 12 large triple-GEM detector segments.*

triple-GEM forward segments has started. Prototyping of support material at Carbon-Composite shop at LBL discussed in September 2014.

Final design and commercialize production of very large single-mask GEM-foils of 50×120 cm^2 Over the past year, bi-monthly phone conversations between Temple University, FIT, and UVa have been taking place to discuss creating a large area GEM tracker for an EIC. These discussions have now accumulated into a working common large area GEM foil design between the respective institutions.

The current GEM tracker design is a disk which consists of 12 trapezoidal GEM foil wedges, shown in fig. 21. Each wedge has an opening angle of 30 degrees, an outer base 55 cm, and length of about 96 cm. The outer base limited to under 55 cm due to the width constraint of the raw materials used to make the GEM foils. The foil area is divided into 4 azimuthal segments, which are then divided in half to give a total of 8 azimuthal segments, at the lower base of the foil. Above the azimuthal segments are 18 radial segments. All segments were defined such that no one segment has an area larger than 112 cm ^{2}.

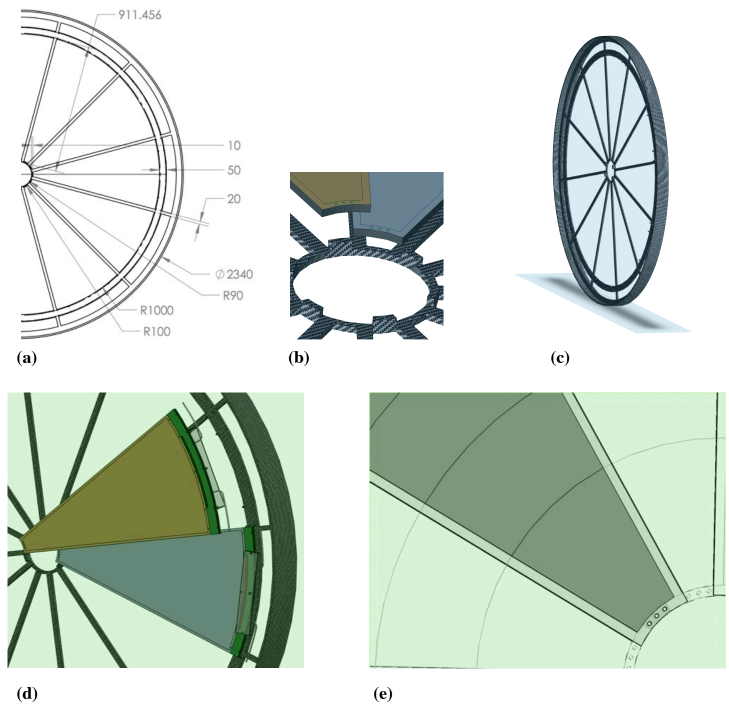


Figure 18: *Details of disk dimensions and support of individual triple-GEM detector segments.*

Status: A Gerber file layout is in preparation followed by a discussion with CERN and Tech-Etch. Tech-Etch agreed to produce in general such large foils. This would complete the proposed GEM R&D program requiring substantial NRE costs which will be requested in July 2015 in collaboration Florida Institute of Technology and the University of Virginia.

Upgrade of optical CCD scanning setup for large GEM foils up to 50×120 cm^2 The optical analysis setup at Temple University is currently restricted to a CCD scan region of $\sim 10 \times 12\,\mathrm{cm}^2$, due to the limited range of motion in the X-Y stage. Scanning large area GEM foils with Temple University's current optical analysis setup requires dividing the GEM foil into smaller CCD scan regions and repositioning the GEM foil relative to the CCD camera; this is a very time consuming process. A complete scan of an EIC type foil using Temple University's current optical setup would take on the order of two weeks per foil side. Therefore in order to efficiently scan large area GEM foils, there is a plan to upgrade the optical analysis setup. This would allow for the complete characterization of an EIC type GEM foil in one CCD scan. Dr. Carl Haber (LBNL) suggested to consider a rotational stage setup. A visit to LBNL was made in September 2014. Temple University is providing in the SERC building large optical tables for this new setup.

Status: A preliminary design has been made, but the completion of the design and in particular the procurements of the optical CCD scanning setup requires the availability of allocated EIC R&D funds for FY15 at Temple University.

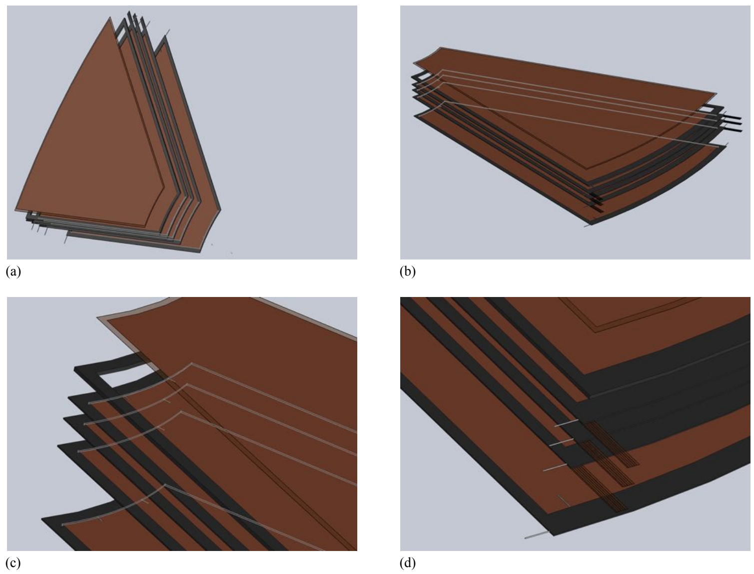


Figure 19: *Detailed view of segment design.*

Assembly and test of $40 \times 40\,\mathbf{cm}^2$ sectors with Apical ring spacer grids and single-mask GEM foils It is planned to build two FGT-type triple-GEM detectors using Apical spacer grids. The design has already been discussed in the previous report. We expect to have all Apical rings available shortly with the change of the base material. Furthermore, we plan to use only single-mask produced GEM foils which have already been received and all electrical and optical measurements have been successfully completed. It will be necessary to fabricate a mold to initially hold all Apical rings in place. It has not been decided if gluing Apical rings together might be necessary.

Status: The procurement of frames and thus the completion of the actual triple-GEM detectors requires the availability of allocated EIC R&D funds for FY15 at Temple University.

Cluster size studies and gain 55Fe studies with small triple-GEM detectors of $10\times10\,\mathbf{cm}^2$ A new CAEN HV system has been fully commissioned. This system will be used to individually under LabView control to adjust each potential difference around each GEM foil. The assembly of small, $10 \times 10\,\mathrm{cm}^2$, triple-GEM detectors is underway.

Status: All components have been acquired, apart from the frames, which are needed for gluing frames to existing single-mask $10 \times 10\,cm^2$ GEM foils. The procurement of frames and other basic mechanical items requires the availability of allocated EIC R&D funds for FY15 at Temple University.

Systematics 2D readout foils tests and commercialize production of very large 2D readout foils of 50×120 $\mathbf{cm}^2$ The layout of the large triple-GEM detector segment follows in spirit the STAR Forward GEM Tracker design [5]. The FGT does not use a solid 2D readout plane, but a 2D readout foil which has been manufactured by Tech-Etch Inc. based on a separate SBIR grant. Initial discussions with Tech-Etch Inc. indicated that extending the FGT 2D readout foil in size is not an issue. However, an upgrade of the production facility might be needed. The layout of the 2D readout plane will be driven by the hit resolution requirement for an EIC detector.

Status: It is planned to measure the capacitance and cross-talk for FGT-type 2D readout foils which is a critical parameter for the expected noise performance. The design of new 2D readout structures is also carried out as part of the collaborative effort with Florida Institute of Technology and the University of Virginia. The procurement of a Keithley electro-meter requires availability of allocated EIC R&D funds for FY15 at Temple University.

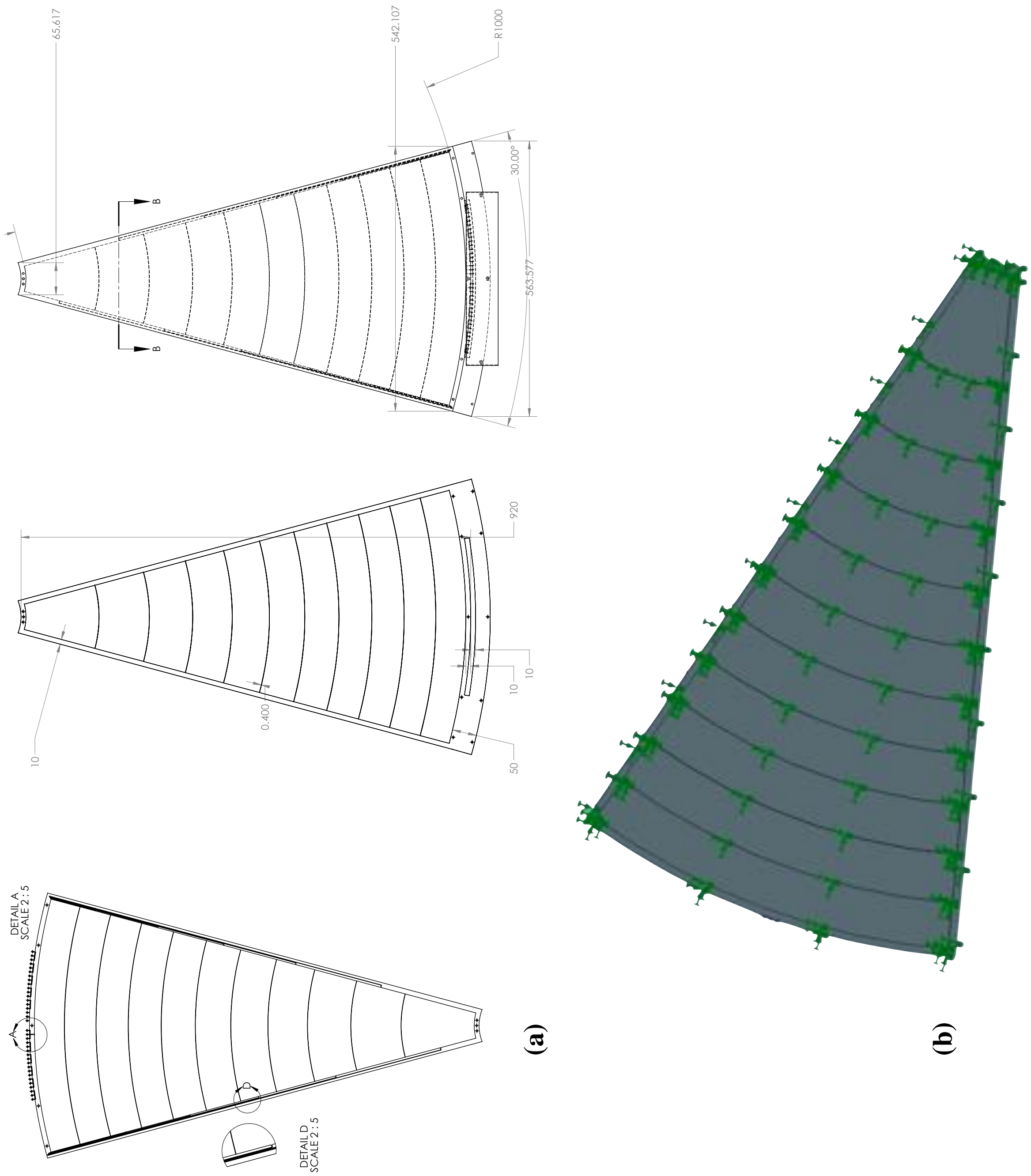


Figure 20: *Layout of large segment GEM foil with 11 sectors.*

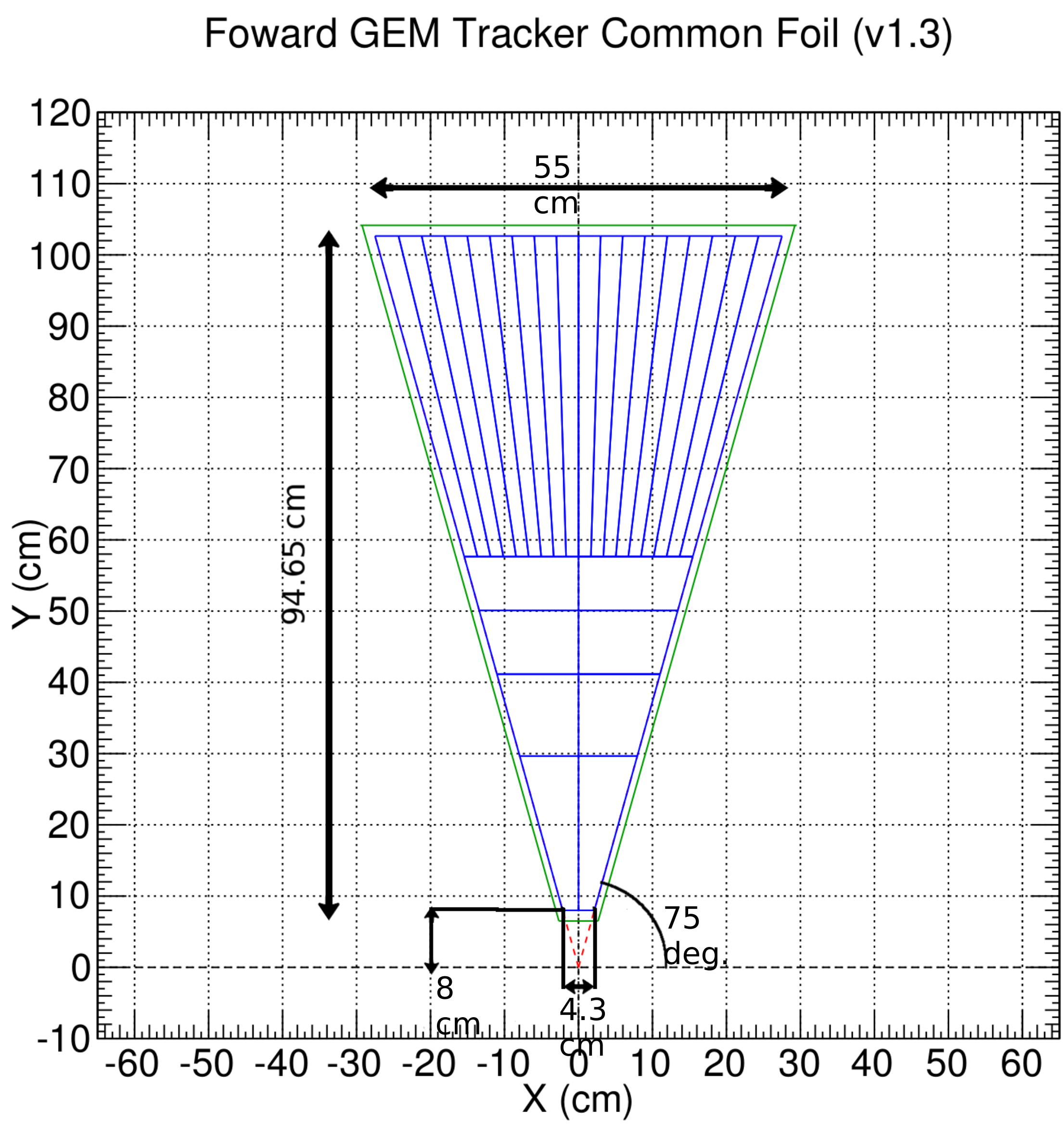


Figure 21: *Initial large area GEM foil design for use in an EIC tracking detector. The blue lines represent the GEM foil, while the green lines correspond to a frame around the GEM foil. The frame thickness is currently at 1.5 cm.*

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.

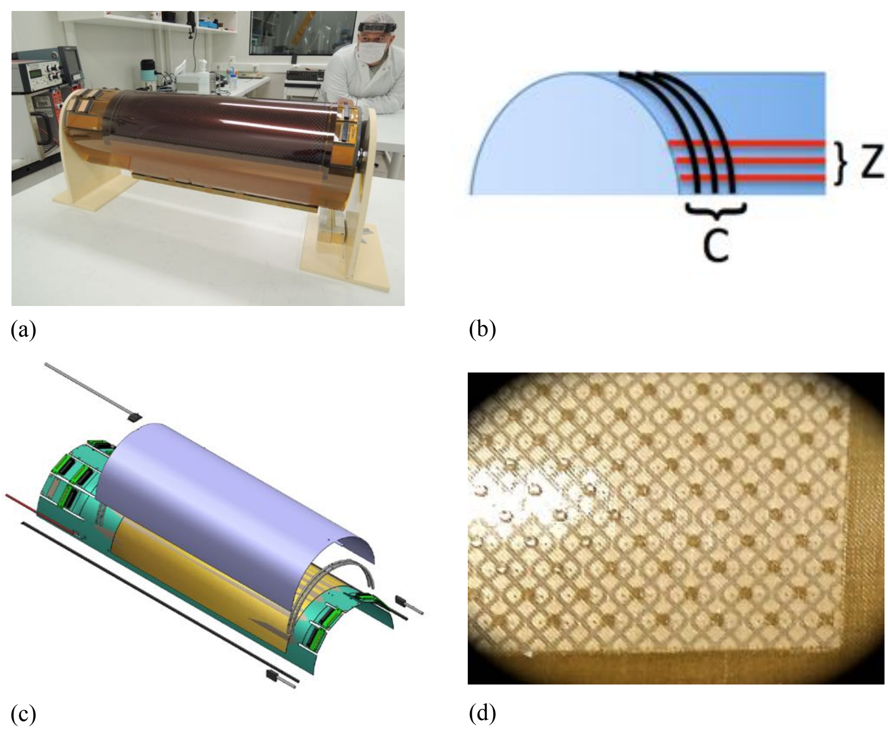


Figure 22: *Fully assembled prototype in Saclay's cleanroom (a), 2D readout scheme with C-Z strip orientation (b), Exploded view of the prototype (c) and detailed view of the active area with 2D readout diamond pads connected by strips along the C and Z projections seen under the woven micromesh (d).*

Prototype description The prototype chamber as shown in Figure 22 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. 22. The chosen readout pitch of 0.87 mm results in ∼250 Z and ∼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 23.

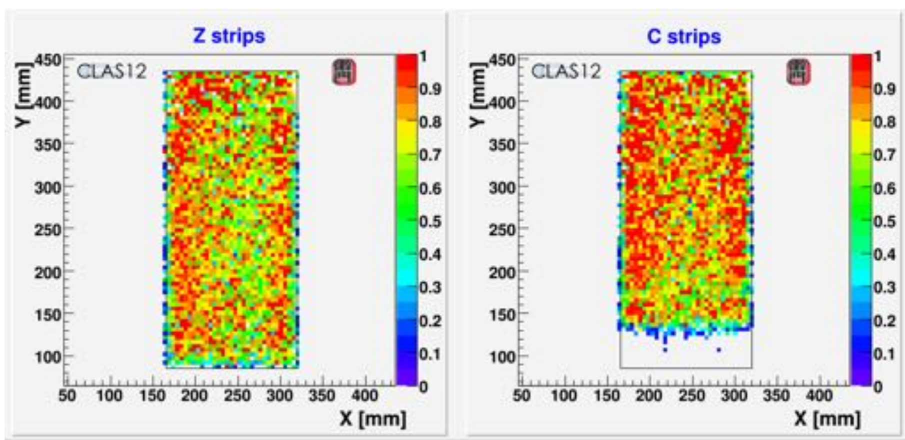


Figure 23: *Efficiency of cylindrical MicroMegas prototype for both projections in Z and C. The inactive area on the C projection corresponds to an area which was not read out.*

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 (~ 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 27 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 24.

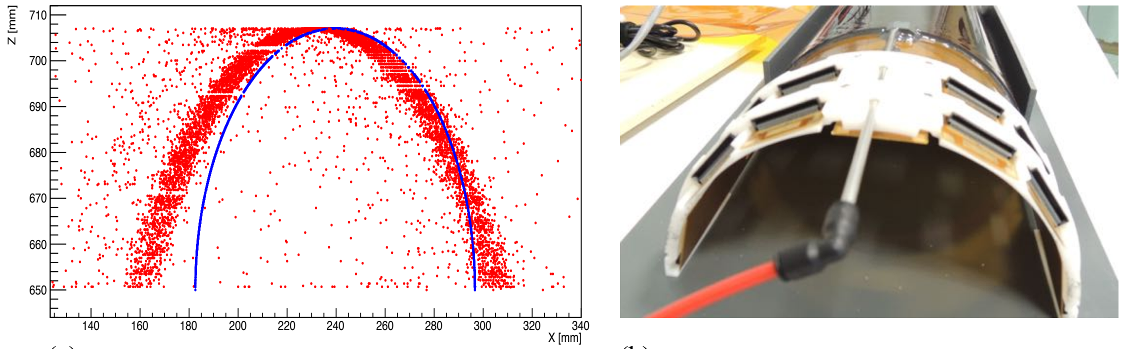
(a) (b)

Figure 24: *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 24) impacted the cylindrical shape due to gravity. As shown in Figure 25, 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 25. 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 26. 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 27.



(a) (b)

Figure 25: *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 27 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. Generally, further progress relies on additional dedicated support for this R&D program as presented in the last proposal submitted in June 2014 and presented in July 2014.

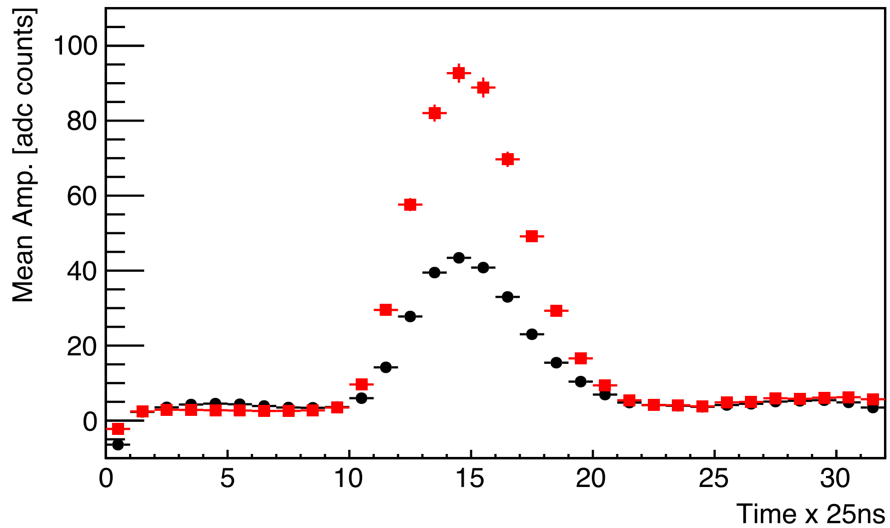


Figure 26: Average amplitude of MicroMegas signals with comic rays. Comparison between the sides of the cylindrical detector (black dots) and central region (red squares). Tracks perpendicular to the readout plane lead to a more concentrated charge that induces a larger signal.

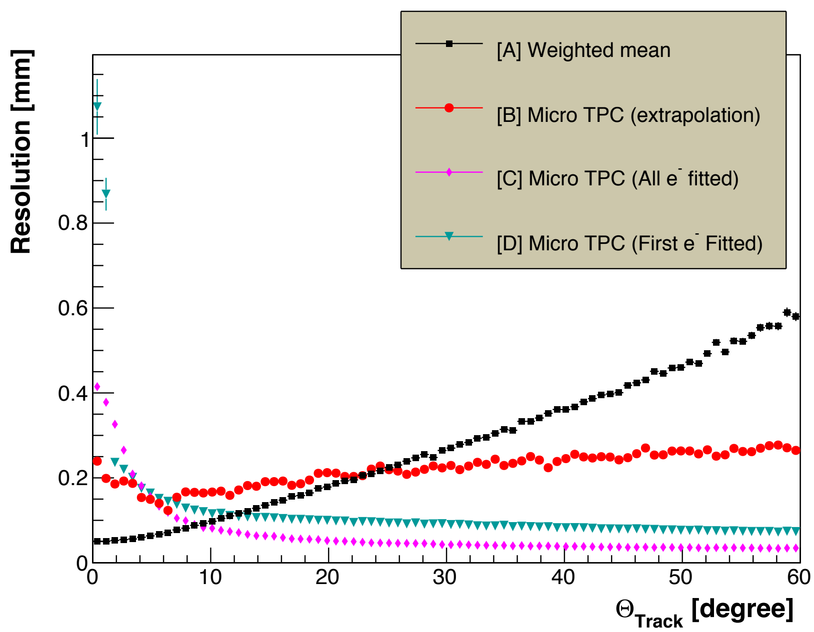


Figure 27: *MC simulation of the spatial resolution of a MicroMegas detector as a function of track angle for different reconstruction algorithms.*

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 28 and directly connected to the detectors strips with special flat cables.

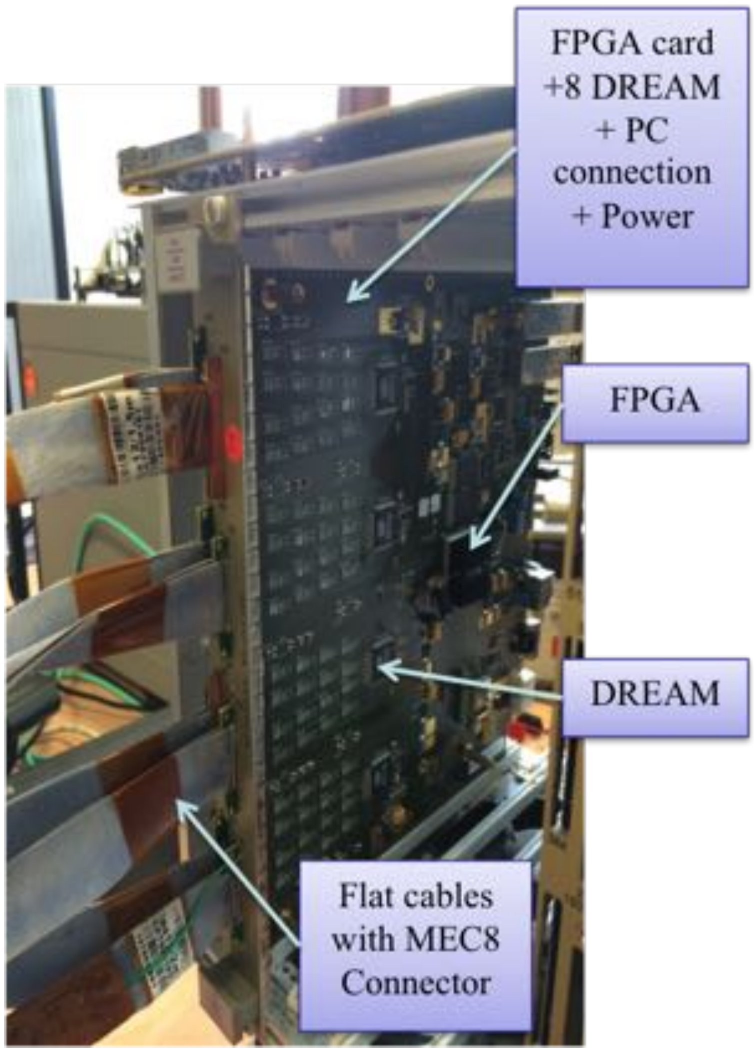


Figure 28: *DREAM front-end electronic card and front-end electronics system.*

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 29.

Figure 29 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

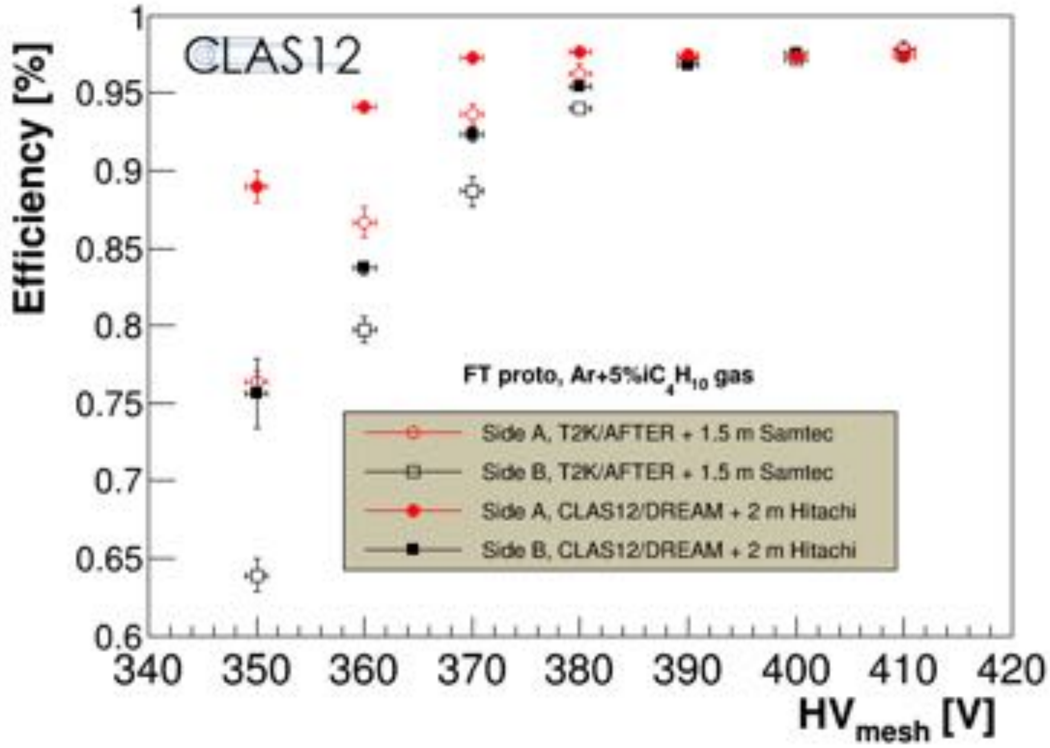


Figure 29: *Efficiency plateau of a CLAS12 prototype with the DREAM and AFTER front-end electronics.*

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 briefly discussed below.

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

The R&D plans concerning the Front-End electronics development will address several items:

- Setup of a DREAM chip based readout system applied to a large triple-GEM detector
- Design/Fabrication of a Very-Front-End-Board (VFEB)
- Studies of packaged/bonded DREAM ASIC
- DREAM ASIC irradiation studies
- Evaluation of a multi-VFEB system

DREAM has been created specifically for high capacitance detectors (mostly MPGDs) in high rate environment, where limited or no deadtime was an absolute requirement. It was not initially designed for use in a collider environment but some developments are possible for such uses.

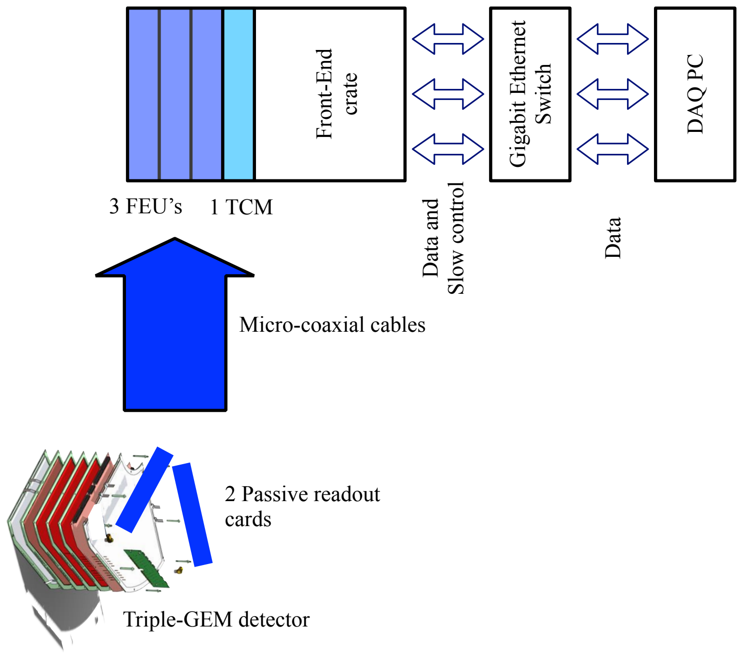
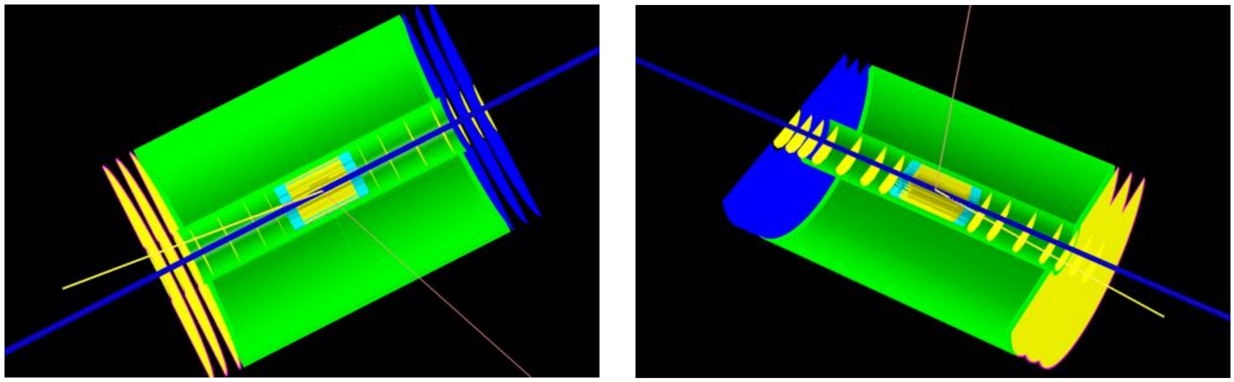


Figure 30: *Schematic of complete DREAM chip based readout system for the STAR FGT triple-GEM detector.*

We propose to setup a DREAM chip based readout system applied to a large triple-GEM detector using the existing STAR FGT triple-GEM detector. Figure 30 provides an overview of such a setup. The major design required is the design of a passive readout module which provides a link between multi-pin connectors on the triple-GEM detectors and the already tested low-mass flex-cables similar to the MicroMegas system. The remaining Front-End and DAQ part is essentially identical to the MicroMegas application. We plan to perform a systematic comparison between an APV25-S1 readout system and a DREAM chip system. This R&D will be critical to demonstrate the applicability of a common chip system for an integrated barrel / forward EIC tracking system.

Further progress has been delayed until the arrival of allocated funds for FY15.

2.4 Simulations

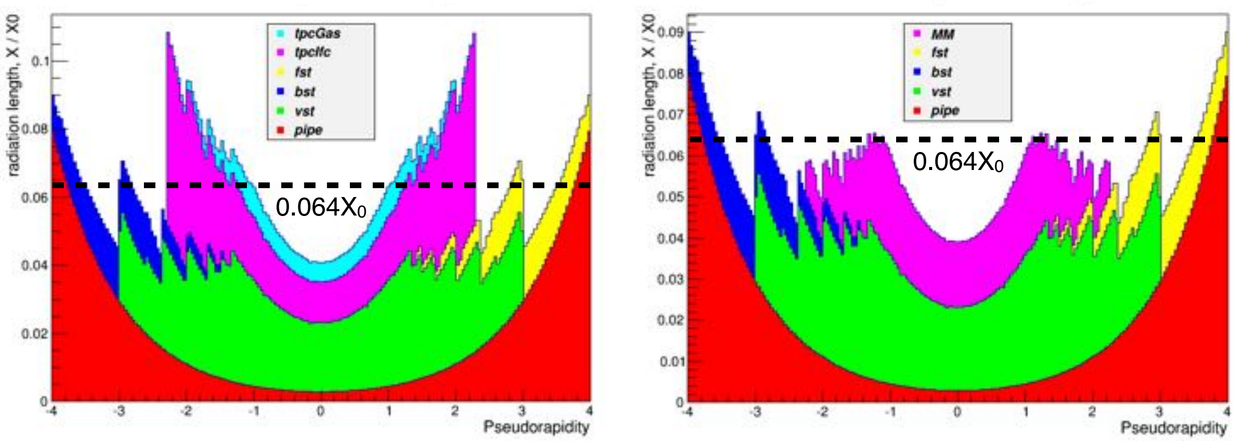


(a) (b)

Figure 31: *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 32: *Material scan for a TPC solution (a) and the MicroMegas barrel (b) solution [6].*

- 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 32. 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.

A new dedicated computer farm has been identified at Temple University within the new Science Education and Research Center. The installation of the EICROOT software framework will be carried out on this farm similar to the successful installation at CEA which is the first installation outside of the BNL computer facility. The main focus will be devoted to kinematic variable resolution studies of a combined barrel MicroMegas and forward triple-GEM system.

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