EIC Detector R&D Progress Report:
from Jan 2015 to June 2015

Project Name: eRD6, Proposal for tracking and PID detector R&D towards an EIC detector

Project Leaders:

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Date: June 17, 2015

Past

What was planned for this period?

Brookhaven National Lab:

We planned to finish the analysis of the Fermilab test beam data taken with the minidrift detector. This included data with two readout planes, one a COMPASS style readout plane with XY strips and another with chevron pads. Measurements were made as a function of angle for each plane up to 45° and the position and angular resolution of the detector was measured using several different algorithms to analyze the data.
We also planned to finish the construction of the TPC-Cherenkov prototype detector during this period. This involved completing the study of the electrostatic simulation of the field cage using both a complete foil field cage as well as a three sided field cage with one transparent side made of wires to allow Cherenkov light to pass through to the photosensitive GEM detector. We also studied the effect of moving the photosensitive GEM into close proximity of the field cage. We also planned to complete all the mechanical assembly of the detector, including the field cage, TPC GEM assembly, photosensivive GEM assembly, gas enclosure, high voltage connections and optical components for the laser calibration system.

Florida Tech:

Finalize the analysis of GEM tracking data from the FNAL beam test in Oct 2013. Specifically, estimate how much multiple Coulomb scattering affects the resolution measurement for the large GEM detector read out with radial zigzag strips.

Submit a NIM paper on the beam test results.

Produce a common GEM foil design for forward tracking at the EIC, in collaboration with the groups from University of Virginia and Temple University.

Design components for mechanical stretching of the new FT GEM foils.

Stony Brook University:

The RICH prototype showed limited position resolution in the past test-beam campaigns and for overcoming the limitation we proposed to work on a resistive charge division scheme in

terms of simulating and testing with appropriate readout boards. It is hoped that this allows high precision single photon position resolution measurements.
After simulating and deciding for a reasonable readout scheme it is planned to prepare a suitable readout board with proper resistive anode layer and readout pads and the performance to be tested and verified with a radiation source that can be positioned relative to the readout board with high precision.

University of Virginia:

Finalize the common GEM foil design for EIC-FT-GEM[1] prototype.
The plan was to continue the collaboration with Florida Tech and Temple University to develop a common GEM foil design for the three different assembly techniques for triple-GEM detectors proposed by these 3 institutions.

Design a 2D stereo-angle readout board for EIC-FT-GEM prototype.
We have proposed an upgrade of 2D (u/v) flexible readout board design with some key improvements with respect to the previous iteration.

Develop new ideas for EIC-FT-GEM prototype.
We have planned to investigate new ideas in order to improve both the construction and performance of triple-GEM detectors.

Complete the analysis of test beam results and submit a manuscript on result to a peer-reviewed journal.
We have planned to complete the analysis of the FTBF test beam results with the large GEM including EIC-FT-GEM prototype and submit a paper for publication in peer-review journal line NIMA or TNS.

Yale University:

3-Coordinate GEM
During the past period it was planned to complete the analysis and prepare a paper on the results.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas (2-GEM+MMG)
During this period it was planned to make measurements on different operating conditions of the 2-GEM+MMG gain structure including for example further studies of different gas mixtures.
Studies were planned using the "Floating Strip" circuit[2] to provide spark protection for electronics as well as reducing the energy in a discharge, the region affected by the discharge and the recovery time.
It was also planned to begin studies using resistive coatings or planes to reduce discharge probability and possibly spread the signal spatially on the readout plane.

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[1] We use the generic term "EIC-FT-GEM" to refer to the design and prototyping of GEM detectors for EIC Forward Tracker R&D.
[2] https://indico.cern.ch/event/245535/session/4/contribution/5/material/slides/0.pdf

What was achieved?

Brookhaven National Lab:

Minidrift GEM

The analysis of the test beam data is now essentially complete. The final measured resolutions have now been obtained for both the COMPASS and chevron readout planes and are shown in Figure 1.

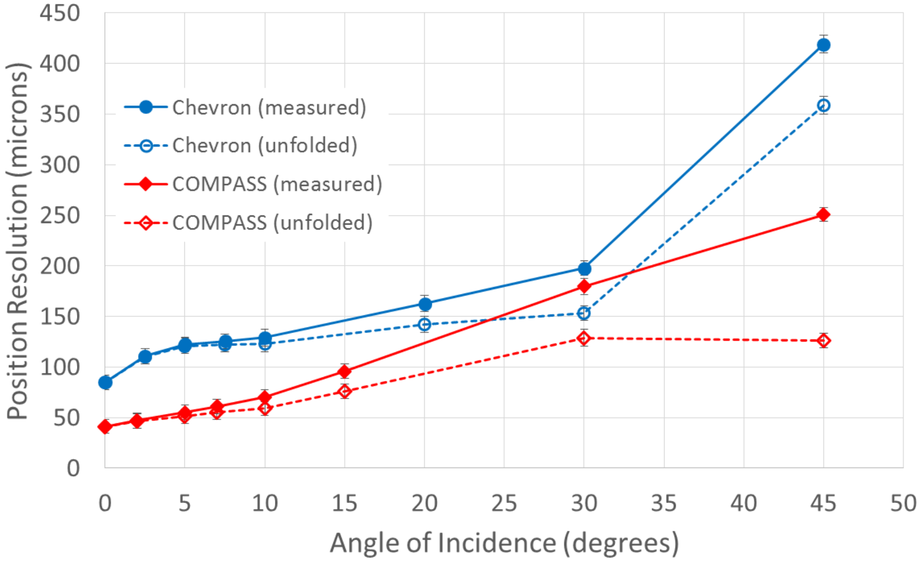

Figure 1 Position resolution for the COMPASS and chevron readout planes measured as a function of incident track angle. The dashed curves show the resolutions after unfolding the contribution from the timing uncertainty of the SRS readout system.

The measured resolution for the COMPASS readout plane, which has 400 μm readout strips, is ~ 50 μm at zero degrees and increases to ~ 250 μm at 45°. The measured resolution for the chevron readout plane, which has 2x10 mm^2 chevron pads, is ~ 90 μm at zero degrees and increases to ~ 420 μm at 45°. These resolutions were obtained with a so-called time sliced algorithm where a position centroid is calculated for each set of strips or pads above a certain threshold in each time 25 ns time bin of the SRS readout system. The resulting coordinates were used to fit a vector in the drift gap of the detector which was then used to determine both the position and angle of the track. During the analysis of the data we found that the uncertainty in phase of the clock in the SRS system relative to the trigger made a significant contribution (essentially 25 ns/√12 ~ 7 ns) to the position resolution obtained with the vector. If this contribution is unfolded from the measured resolutions, one obtains the dashed curves shown in Figure 1. After unfolding this, the resolution for the COMPASS plane drops to ~ 125 μm at 45° and the resolution for the chevron pads decreases to ~ 350 μm. However, this contribution can in principle be eliminated completely in future measurements by measuring the phase of the readout clock relative to the trigger on an event by event basis (or using a different readout system). We are also developing a new more sophisticated algorithm which deconvolutes the analog pulse shape from the total measured pulse for each pad or strip, and we believe we can ultimately achieve a resolution of substantially less than 100 μm at large track angles using this method.

Figure 2 shows the results for the measured angular resolution for both the COMPASS and chevron readout planes. The measurement of the angle is not affected by the uncertainty in the clock phase so there is no unfolding required. The angular resolution of the chevron pads is worse at small angles due to the fact that very few pads (~ 2-3) are hit at these angles. However, the angular resolution for both readout planes is less than 20 mrad for angles greater than 10°.

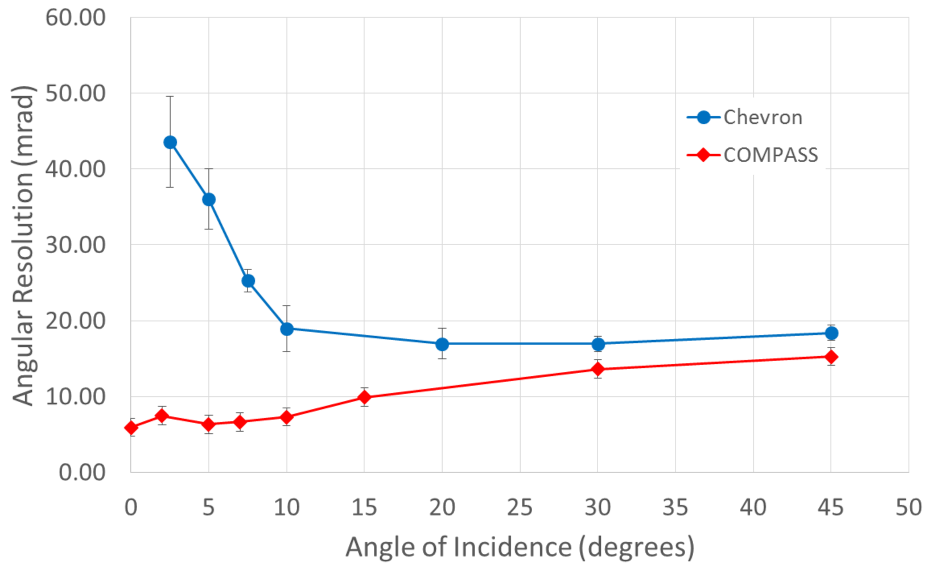

Figure 2 Angular resolution for the COMPASS and chevron readout planes measured as a function of incident track angle.

TPC-Cherenkov

The construction of the TPC-Cherenkov prototype is now complete and the assembled detector is shown in Figure 3. Figure 4 shows the three sided field cage inside mounted on the detector baseplate with the TPC GEM detector below. The fourth side of the field cage is removable such that another foil plane can be used or a wire frame can be installed that will allow Cherenkov light to pass through to the photosensitive GEM. Also shown is a GEM foil mounted on the movable stage that will hold the photosensitive GEM detector. The complete photosensitive GEM will be added at a later time after initial testing of the TPC portion of the detector, which is an operation that will have to be done inside a glove box due to the CsI photocathode.

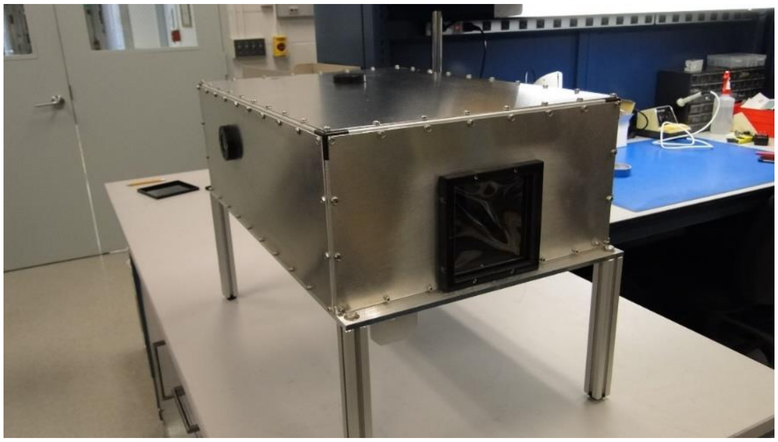

Figure 3 Assembled prototype TPC-Cherenkov detector.

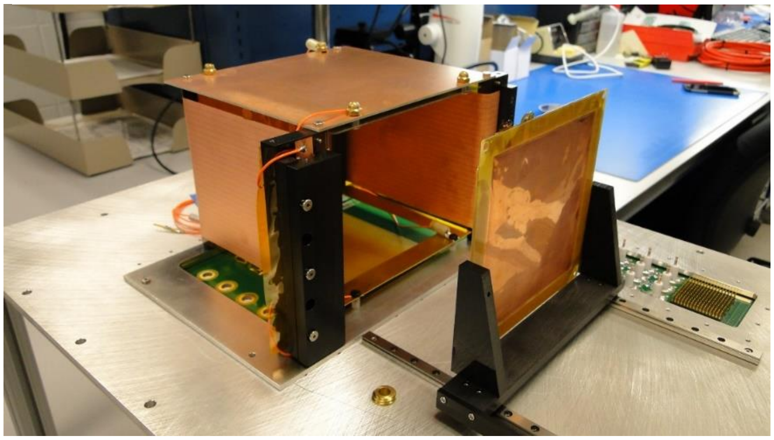

Figure 4 Three sided foil field cage and TPC GEM detector mounted to its baseplate. Also shown is a GEM foil mounted on the movable stage that will hold the photosensitive GEM detector.

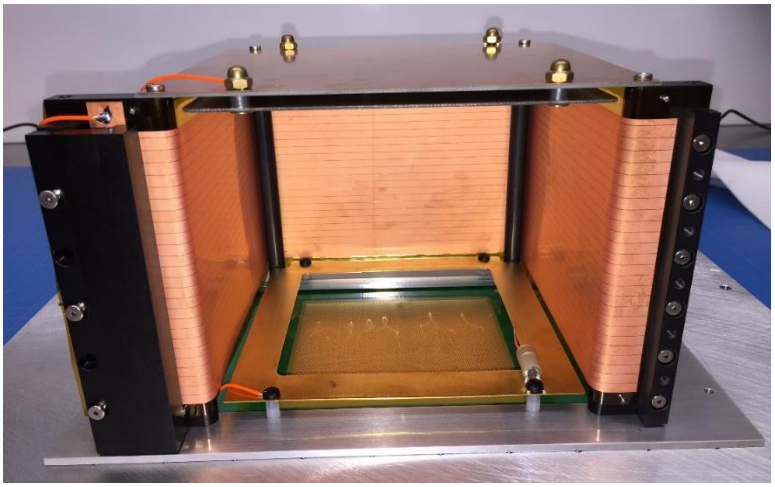

Figure 5 Inside of the three sided foil field cage with TPC GEM below.

Figure 5 shows the inside of the three sided field cage with the TPC GEM below. It contains 25 strips with a width of 3.9 mm and a 0.1 mm gap in between on both sides of the foil that are staggered by half a strip width to improve the field uniformity. The field uniformity was studied with a 3D electrostatic program (ANSYS) in order to determine the non-uniformities caused by the wire plane as well as the effect of having the photosensitive GEM in close proximity to the field cage. Figure 6 gives a comparison of the field uniformity, as measured by the deviation of the normal electric field vector in the drift direction, for a field cage with four foil sides versus three foil sides and a wire plane. The deviations in both cases are generally < 0.1%.

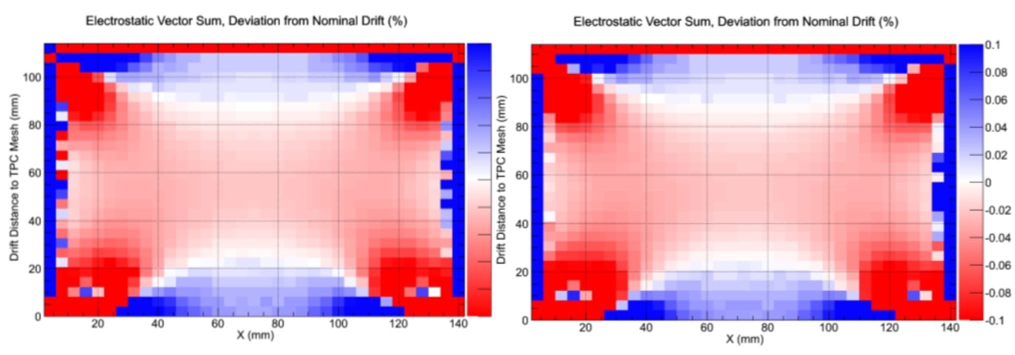

Figure 6 F Field non-uniformity, as measured by the deviation of the normal electric field drift vector from its nominal value, for a field cage with four foil sides (left) versus three foil sides and a wire plane (right). The drift direction is along the vertical axis and the wire plane sits at X=0.

We also studied the effect of having the photosensitive GEM in close proximity to the wire plane of the field cage. We studied this as a function of distance from the mesh of the photosensitive GEM to the wire plane over a range from 15 mm to 40 mm. Figure 7 shows the case of 15 mm separation compared with the case of having no mesh present. There is some small effect near the wire plane, but the deviations are generally less than 1%.

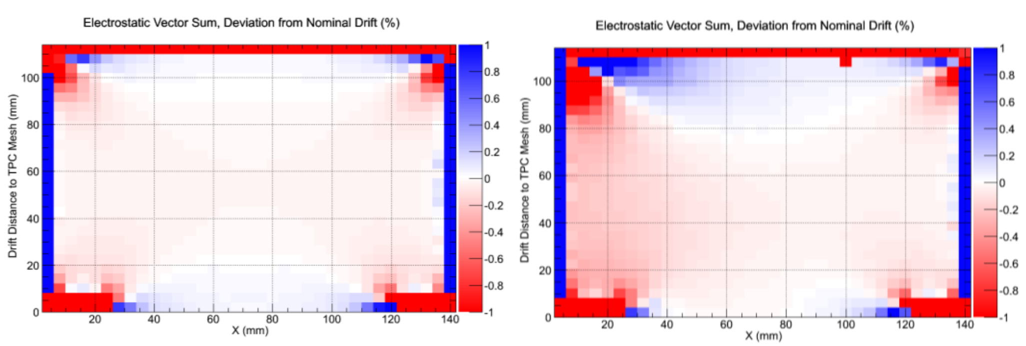

Figure 7 Field non-uniformity for the case of no mesh for the photosensitive GEM (left) versus having the mesh at 15 mm from the wire plane. The drift direction is along the vertical axis and the wire plane sits at X=0.

Most of the components of the detector have undergone preliminary testing and have performed well. The field cage has been tested to its full operating voltage of 1 kV/cm and exhibited no sparking or breakdown problems. The TPC GEM was configured as a minidrift detector and tested with sources and cosmic rays. Figure 8 on the left shows a cosmic ray track measured in the 16 mm drift gap with the minidrift configuration. The readout plane of the TPC GEM consists of 2x10 mm^2 chevron strips with a 0.5 mm zigzag pitch. Figure 8 on the right shows the position resolution measured for this plane with a highly collimated X-ray source. It gave an uncorrected resolution of 132 μm and a resolution of 98 μm after correcting for the differential non-linearity of the chevron pads.

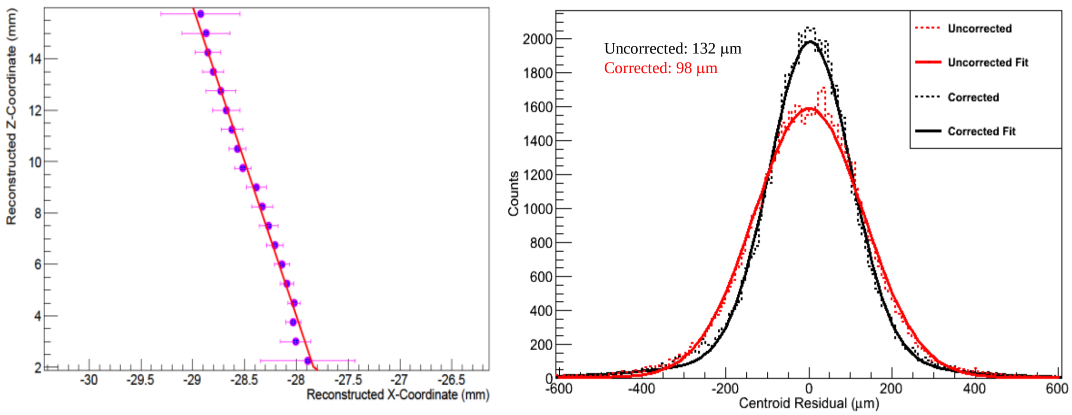

Figure 8 Initial tests of the TPC GEM detector. Left: Cosmic ray track found with the detector configured as a minidrift with a 16 mm drift gap. Right: Position resolution measured with the chevron readout plane using a highly collimated X-ray source. The red curve shows the resolution after correcting for the differential non-linearity of the chevron pads.

Florida Tech:

Resolution measurements of large GEM detector with radial zigzag strip readout taking multiple Coulomb scattering into account

As described in the previous report, the total radiation length of the detector materials in the 2013 FNAL beam test in the tracking system was about 14%, which affects the spatial resolution analysis due to multiple Coulomb scattering (MCS). Due to technical difficulties with the initial approach of adapting EicRoot to the beam test geometry, instead a stand-alone Geant4 simulation was created by Florida Tech to study the MCS effect and to extract the intrinsic detector resolution more precisely. The simulated detector configuration in the beam test is shown in Figure 9. Details such as GEM holes and readout strip geometry are not implemented in the simulation. FTFP_BERT is used as the physics list in Geant4, which includes the MCS model based on the Lewis theory. Perpendicular point-like beams start 20 mm away from the first tracker (REF1) and different beam momenta and particles are simulated.

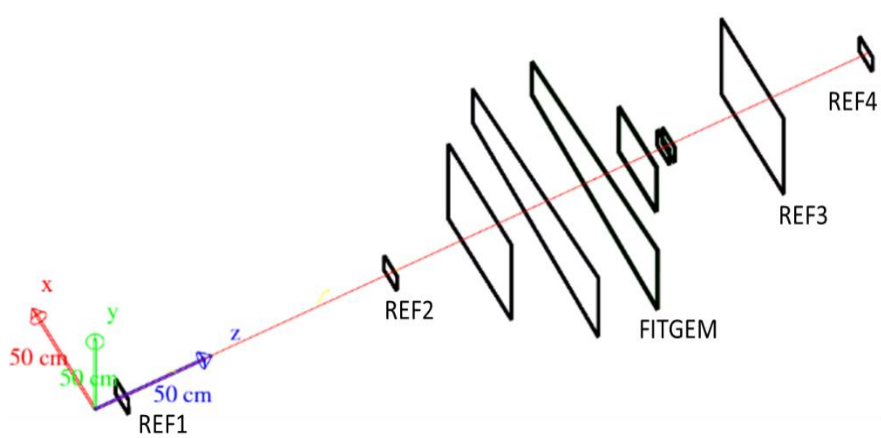

Figure 9 The stand-alone Geant4 geometry of all GEM detectors in the FNAL 2013 beam test. Florida Tech's large GEM with radial zigzag strips is labelled as "FITGEM".

The hit positions are histogrammed for each reference tracker detector and for the zigzag GEM. In the simulation, the zigzag GEM can be treated as a 2D detector in Cartesian system. In Figure 10, the left plot shows the hit position distributions for 25 GeV/c pions, while the right plot is for 120 GeV/c protons. Beams are widened significantly at lower momenta due to scattering and the hit distribution widens as the beam particles move downstream. The scattering angles between detectors can be calculated (Figure 11). The scatter is small at the beginning of the beam and it becomes large at the end of this 3-m long tracking system; the overall angle (between tracker 4 and tracker 1) is about 96 μrad with a 66 μrad rms.

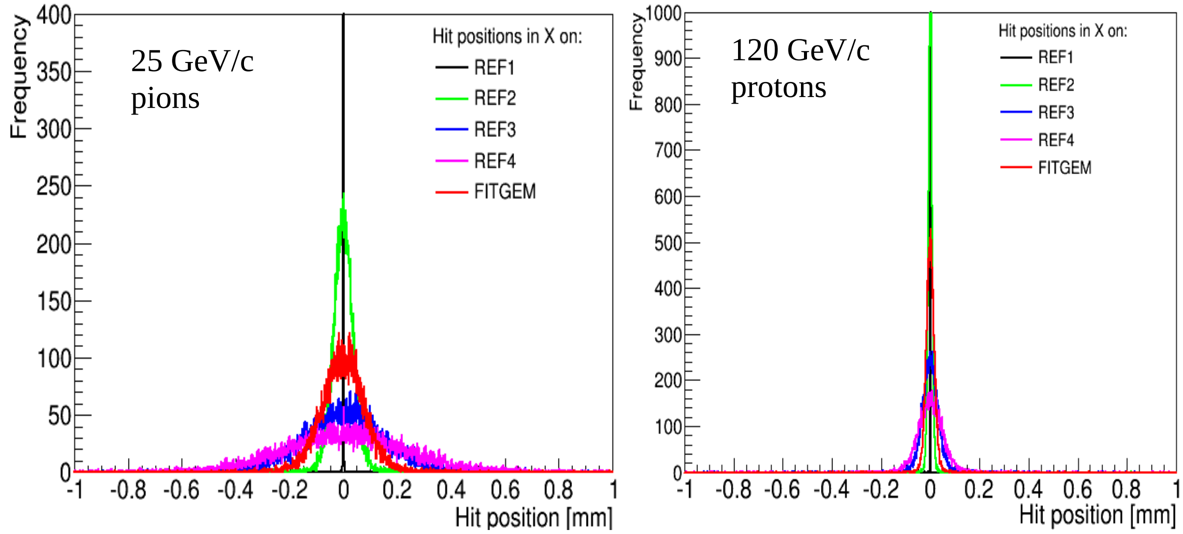

Figure 10 Simulated position distributions for the trackers and the FIT GEM detector with 25 GeV/c pions (*left*) and 120 GeV/c protons (*right*).

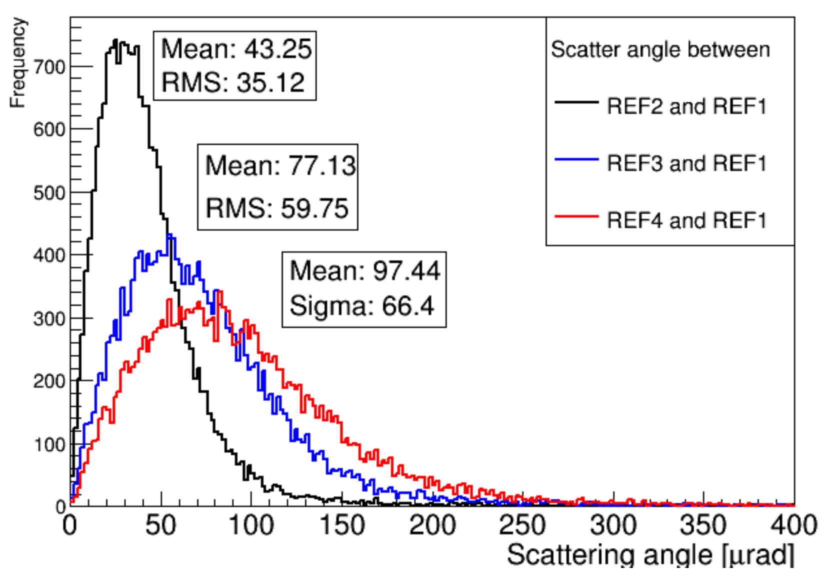

Figure 11 Distributions of scattering angles due to multiple scattering between different reference detectors. The mean and rms values of each distribution are shown on the plot.

The Geant4 simulation allows us to estimate track errors and intrinsic resolutions when MCS effects are included. In the initial simulation step, the intrinsic detector resolutions can be first set to zero (perfect resolution) but with MCS turned on, and then the hit positions are additionally smeared by a Gaussian as needed in the subsequent tracking step.
The tracker resolutions are studied first. We initially assume that the four tracker detectors have the same resolution and smear the simulated hit data with resolutions from 50-80 μm in 5 μm steps. For each smeared resolution, we calculate the exclusive track-hit residuals for each detector and get the residual widths, so we can compare exclusive residual widths from simulation with those observed in experimental data. When the residual widths match for a tracker detector, the corresponding smeared input resolution is taken as the intrinsic resolution of that detector. We do this in both X and Y coordinates and the average of the two is taken as the final resolution for a tracker detector. The resolutions of the four tracking detectors are found to be 73, 70, 59, and 68 μm, respectively (Figure 12).
Next, we transform from Cartesian to polar coordinates and smear the simulated data with these realistic intrinsic tracker resolutions and with MCS on, but we do not smear the simulated data for the zigzag GEM detector. The resulting width of the exclusive residual of the zigzag GEM is a measure of the interpolated-track error (IE) at the position of the zigzag GEM between tracker detector 2 and 3. For the experimental data, we have already measured the exclusive residual width (ER) for the zigzag GEM detector. The intrinsic resolution σ for the zigzag GEM is calculated by subtracting the two quantities in quadrature: $\sigma = \sqrt{ER^2 - IE^2}$.
Figure 13 shows the resulting intrinsic angular resolutions for the zigzag GEM in middle sector 5 at different HV points. The resolution is around 180 μrad on the efficiency plateau for just 2-strip and 3-strip clusters after the non-linear response of zigzag strips is corrected (see previous report). In the bottom right plot, we see that the overall angular resolution including single-strip clusters for the zigzag GEM is about 193 μrad at highest tested voltage. The measured resolutions for different positions on the zigzag GEM operated at 3200 V are also shown (Figure 14). These represent our final results on the resolution measurements for the large GEM with radial zigzag readout strips from the 2013 FNAL beam test data.

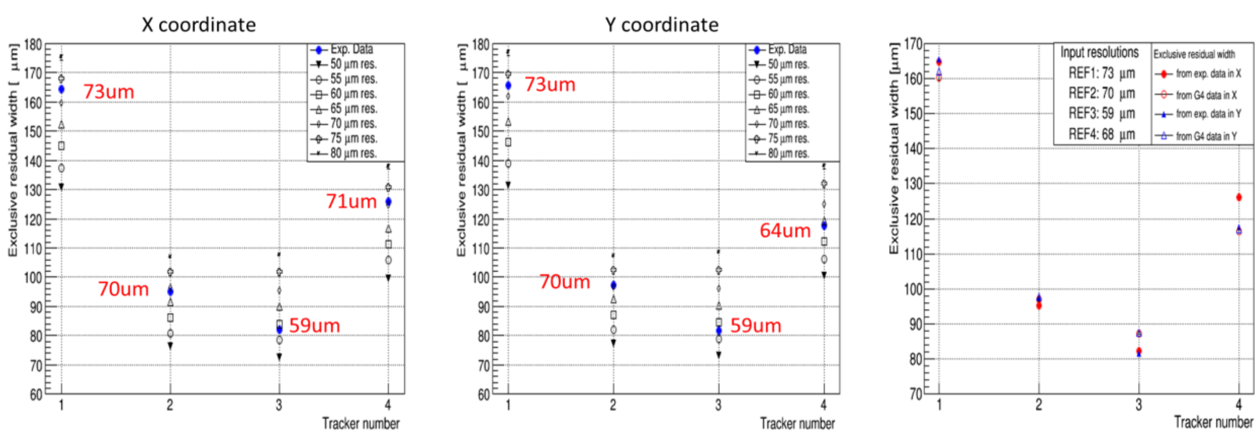

Figure 12 Exclusive tracker detector residuals simulated for different inputs for the intrinsic detector resolution (smearing) compared with experimental residuals (blue) in the beam test using the Geant4 simulation with MCS.

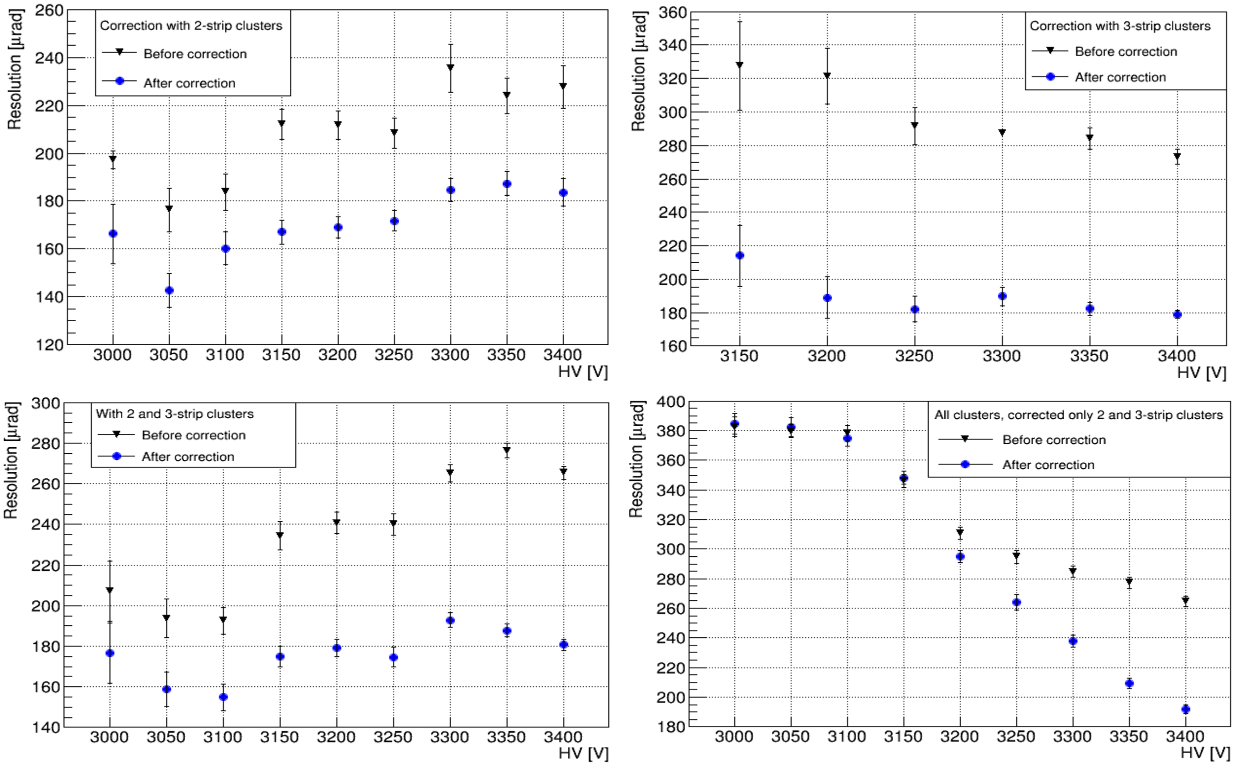

Figure 13 Measured intrinsic angular resolutions of the large GEM with zigzag readout at different drift voltages in middle sector 5 before and after non-linear response corrections and for different cuts on strip cluster size.

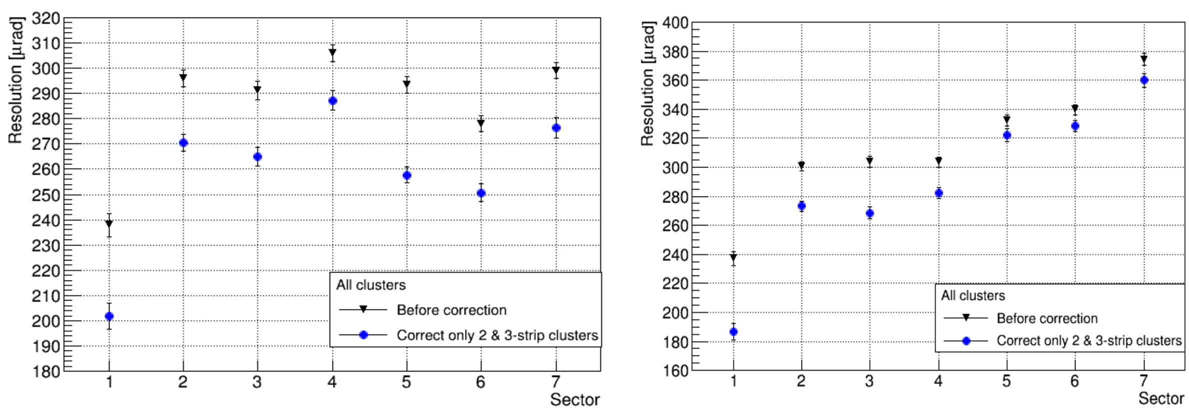

Figure 14 Measured angular resolutions at different positions before and after corrections when the drift HV is 3200V. *Left* (*right*) plot is for positions in the middle (upper) part of each sector.

Comparison of track-error and geometric-mean methods for resolution studies

We were previously using the basic geometric-mean method to calculate resolutions for the detectors. This method calculates exclusive residuals and inclusive residuals from track fits to the data only and then simply takes the geometric mean of the residual widths ($\sqrt{\sigma_{ex} * \sigma_{in}}$) as a measure of the intrinsic detector resolution. This method is simpler to use than the track-error method described above as it does not require simulation nor knowledge of the tracker resolutions. However, in the literature it is shown that the geometric mean method can mismeasure resolutions systematically and only works well when all intrinsic resolutions of trackers and probed detector are similar. These results in the literature were obtained without considering MCS. Since we made the effort to implement the track-error method using the Geant4 simulation to analyze our beam test data, we are in a position to compare the two methods also in the presence of MCS.

Figure 15 shows the results of this comparison for our FNAL beam test geometry with MCS taken into account. On the left plot of Figure 15, we use smeared resolutions of 50 μm for all four trackers and smear the resolution of the probed zigzag GEM detector from 40 to 290 μrad in 10 μrad steps. For each step, we calculate the resolutions with both methods. We observe that the track-error method gives almost perfect agreement between input resolution from Gaussian smearing and calculated intrinsic resolution over the full range, while the geometric-mean method mismeasures the intrinsic resolution of the probed detector systematically. We observe the same behavior when we smear the tracker resolutions with the actual resolutions measured from beam test data (Figure 15 right). The slope of a line fitted to the geometric-mean points indicates that the geometric-mean method mismeasures the intrinsic resolution for the beam test configuration by about 10%.

Figure 16 compares the two methods for HV scan data for the zigzag GEM from the beam test. The geometric-mean resolutions are consistently lower than track-error resolutions (Figure 16 left); the difference is 7-12% consistent with expectations from simulation.

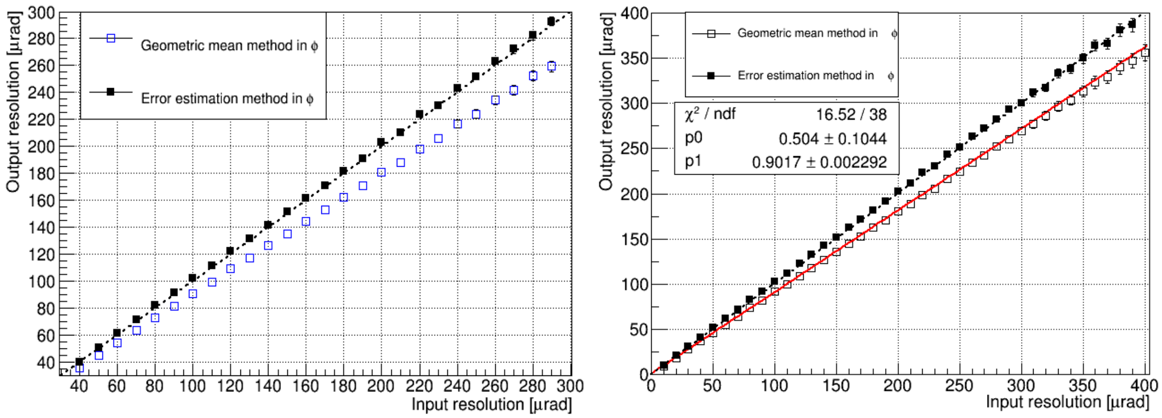

Figure 15 Calculated resolutions vs. input resolutions from smearing in the simulation (MCS included) for the probed zigzag GEM. The track-error method is compared with the geometric-mean method. Left: all tracker resolutions are set to 50 μm. Right: experimental resolutions for the tracker detectors are used.

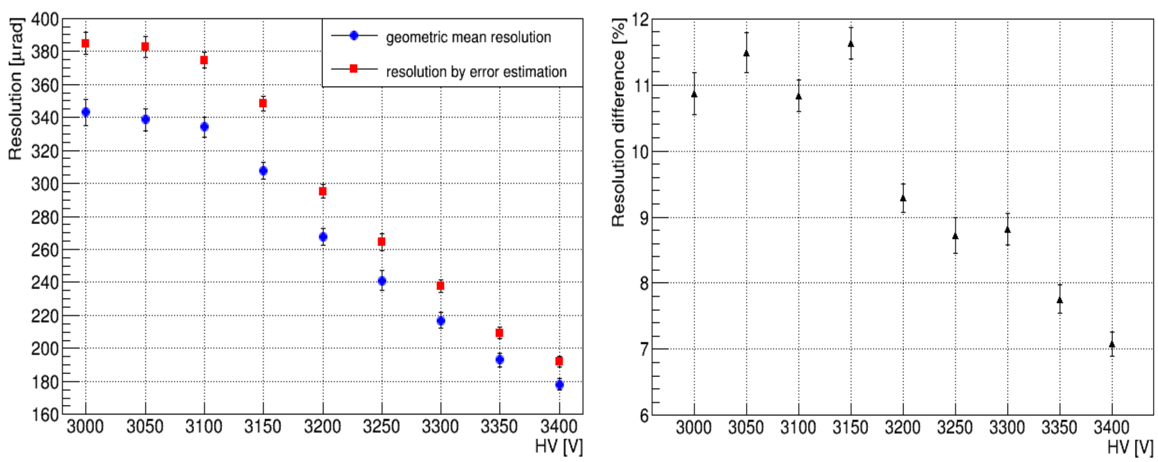

Figure 16 Resolutions for the zigzag GEM obtained with track-error method and geometric-mean method from beam test data. Left: Resolutions vs. drift voltage. Right: Difference between the two methods.

Joint eRD3/eRD6 Forward Tracker Group (Florida Tech, Temple U., U. of Virginia):

Design of large GEM foils for EIC forward tracking

Florida Tech's EIC post-doc Aiwu Zhang has developed the conceptual large GEM foil design for an EIC forward tracker into a full technical design; this design is implemented in Altium CAD software. This work was done with much input on various design details from the University of Virginia and Temple University groups, as well as from Tech-Etch Inc. The result is a common foil design, which will allow the three groups to test different detector assembly techniques using one common foil type. This approach will save future NRE cost on photolithographic masks for manufacturing these large GEM foils since only a single mask will be needed. The foils are expected to be manufactured by Tech-Etch in the US (see proposal below). Florida Tech will investigate purely mechanical foil stretching and chamber assembly with these new foils as pioneered by the CMS collaboration for large GEMs. Temple U. will assemble chambers by gluing components together and U. Va. will use a hybrid approach of the two methods.

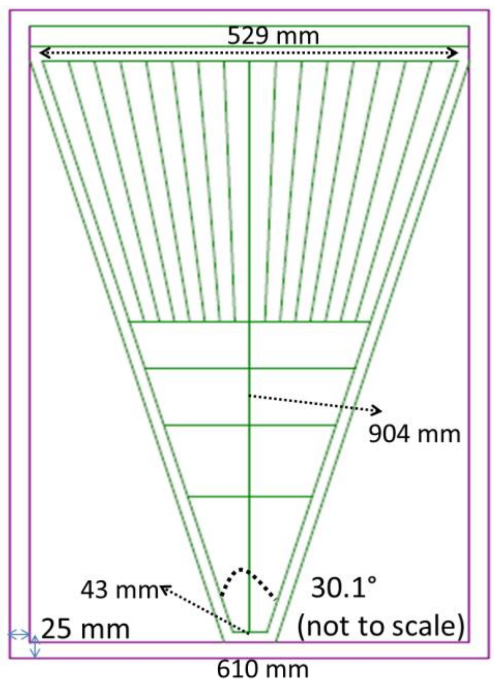

Figure 17 A sketch of the common EIC forward tracking GEM foil design. The inner green trapezoid represents the active area of the foil with GEM holes arranged in 8 inner radial and 16 outer azimuthal HV sectors.

The GEM foil design is finished, and a sketch indicating foil dimensions is shown in Figure 17. It is a trapezoid with a 30.1° opening angle that will allow for 0.1° overlaps between active areas of adjacent detectors when a full forward tracker disk is constructed from 12 of these GEM detectors. Several considerations inform the choice of dimensions for this common GEM foil. Since currently the actual size of a forward tracker for the EIC is by no means specified, we aim at maximizing the GEM foil area in this R&D design for now. The idea is that it will be easier to scale the detector down later if so desired rather than having to scale it up. For the same reason, the design has the GEM going as close to the beam as possible for now; the distance from the beam line to the short end of the foil is 8 cm. The raw foil material (apical) comes in roles with a fixed 610 mm width and the company (Tech-Etch) needs 25 mm on all four sides around the design to mount a foil when etching holes (see purple rectangles in

Figure 17). In addition, we need to leave 15 mm margins for frames that are needed for chamber assembly. Consequently, the active area of the GEM foil has 43 mm width at the short end of the trapezoid, 529 mm at the wide end, and a length of 904 mm, which gives a total active area of ~2,585 cm^2. One side of the foil is divided into 24 sectors of similar area (~107 cm^2 each) to reduce the energy of any potential discharges. Among these sectors, eight at small radius are segmented in radial direction and 16 at larger radius are segmented in azimuthal direction. All segments will be supplied with HV from the wide side of the trapezoid.

To explain the common foil design, we first compare the different requirements from the TU, U. Va, and FIT groups (Figure 18). For the TU and U. Va groups, HV to each sector is required to be accessible outside the GEM detector when it is closed, so there are 25 square HV pads for outside access at the wide edge of the foil (24 pads in red on the top surface of the foil for the HV sectors and one pad on the bottom of the foil for HV connection to the bottom surface).

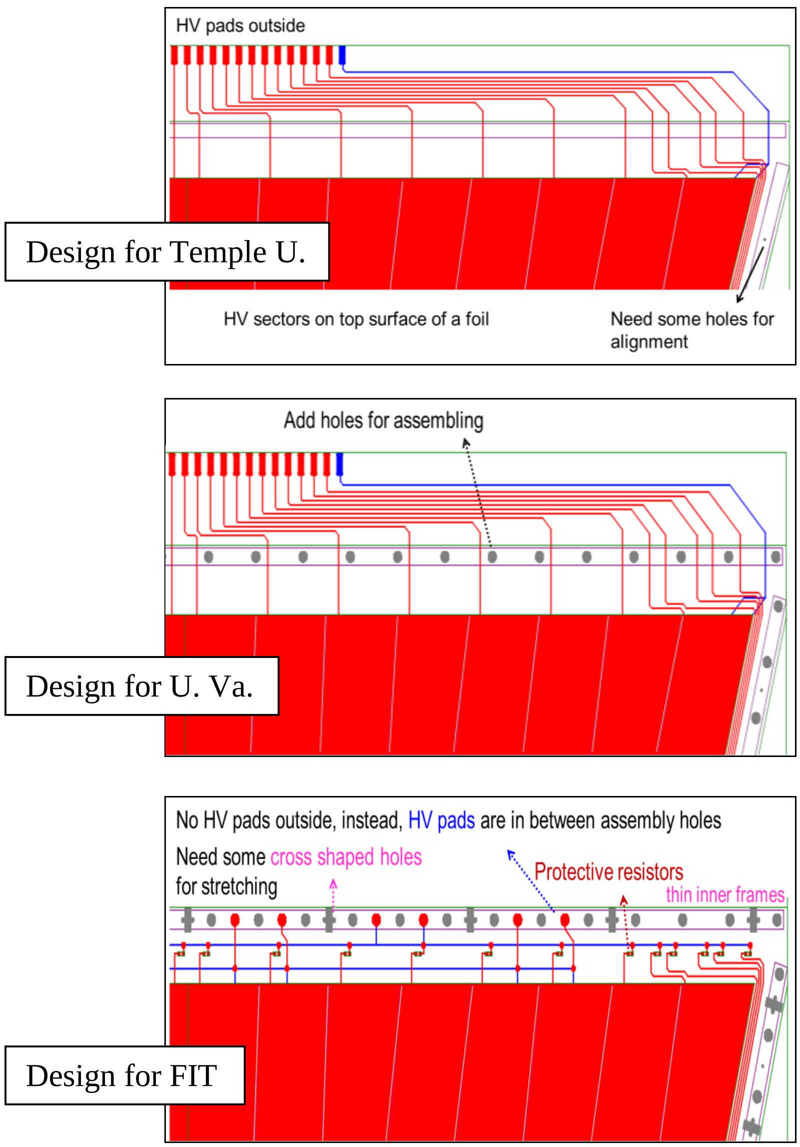

Figure 18 GEM foil designs that accommodate various assembly methods pursued by each of the groups. Red lines and areas are on the top surface of the foil and blue lines are on the bottom of the foil.

The only difference between the TU and U. Va requirements is that U. Va needs some assembly holes while TU does not need those. The reason is that TU will glue all foils and frames together while U.Va will glue foils to frames, but then will mechanically assemble framed foils into a GEM stack. The FIT group, which will use a purely mechanical stretching method to assemble the triple-GEM detector, needs the assembly holes as well as additional cross-shaped holes for inserting square nuts into the frames for foil stretching. In addition, FIT will mount protective resistors onto the foils close to each HV sector so that an entire foil can be powered with just two HV lines. These lines will connect to HV pads which are in between the assembly holes. Due to the nature of the mechanical stretching method, all HV pads must be on the top surface of a foil. Given the location of HV traces for the TU and U. Va designs, we cannot avoid additional HV lines on the bottom surface, which in turn requires making HV connections from bottom to top surfaces of a foil.
The resulting common foil design that accommodates all requirements is shown in Figure 19. The HV connections between top and bottom surfaces are achieved by putting pads at the same position on both sides with an array of small GEM-like holes (0.1 mm size) and by gluing these holes with conductive glue (e.g. H20E from EpoTek) after foils are produced. This gets around the need for vias on the foils, which according to Tech-Etch are difficult and expensive to produce.

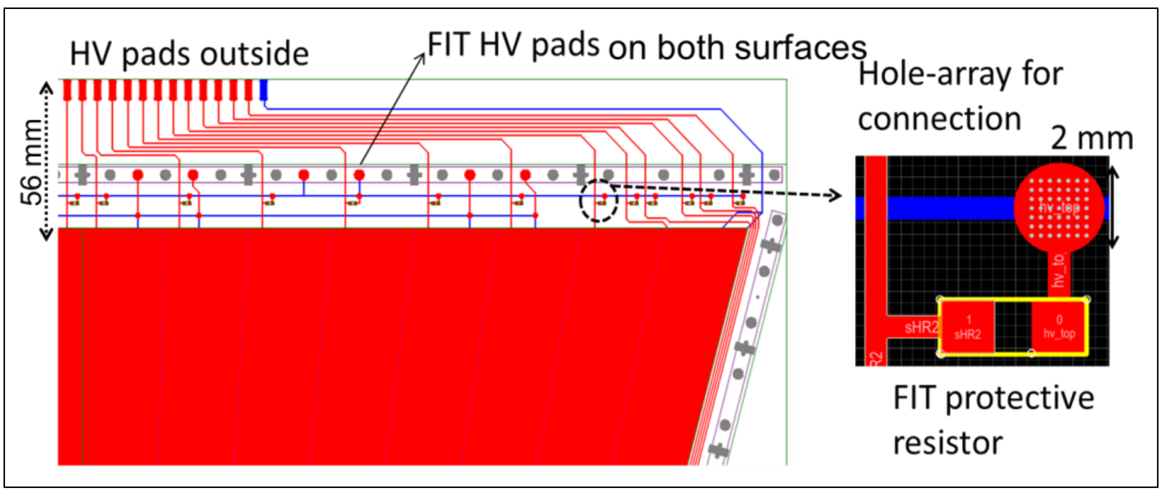

Figure 19 The common GEM foil design. On the right, a solution for making HV connections from the top surface to the bottom surface of the foil is shown.

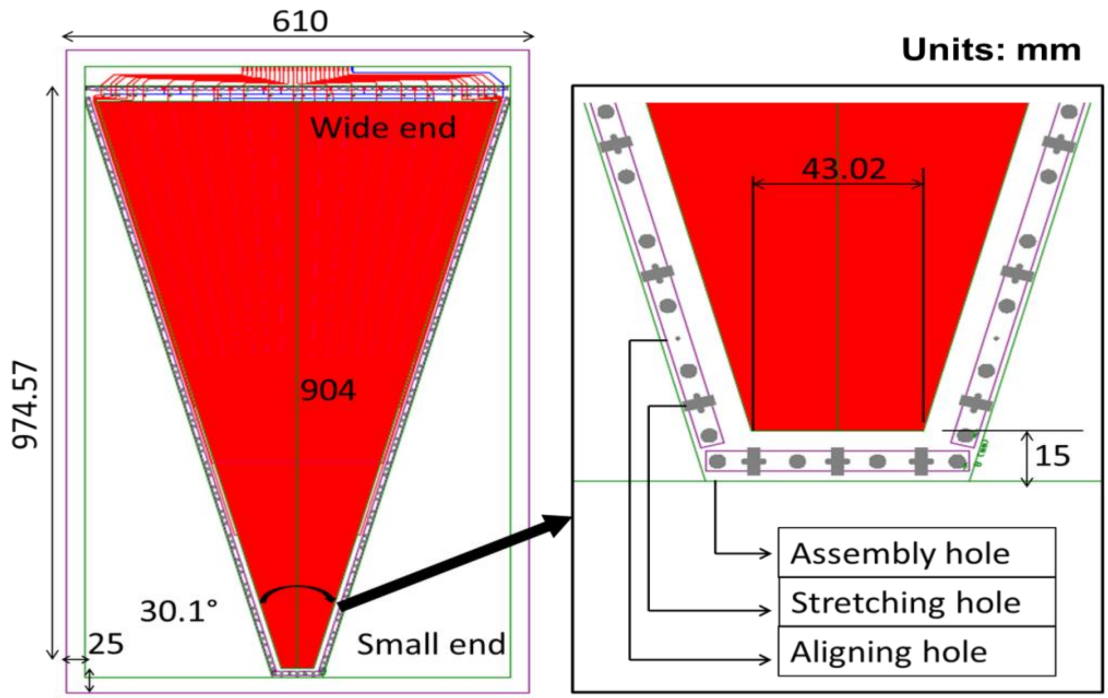

Figure 20 Overview of the technical design of the common GEM foil (left) and details of the small radius region (right). The purple rectangles indicate inner frames for mechanically stretching the GEM stack.

A full view of the common foil design is shown in Figure 20 (left); on the right side of this figure the details at the narrow end of the trapezoid are shown. There are 126 assembly holes of 4 mm size for making the GEM stack and 60 cross-shaped holes for stretching.

Stony Brook University:

The description and results from the test-beam campaigns, SLAC and Fermilab FTBF were written in an IEEE journal (TNS) style and submitted to the journal. The reviewed manuscript was returned for revision in April to us and we returned the revised manuscript in the mid of June.

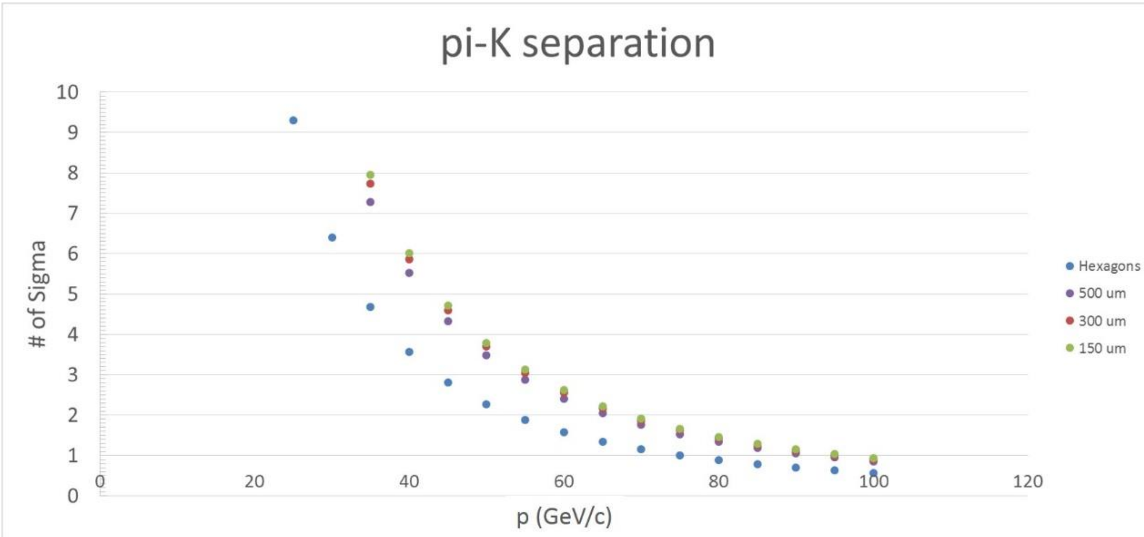

Figure 21 Pion and Kaon separation power.

One of the results of our measurements at FTBF showed for the expected ring radius and width that the segmentation of the readout, we have used for our prototype is not sufficient. This can be seen in Figure 21 where several worst case scenarios were assumed: dispersion in the gas, segmentation of the RICH readout, momentum spread $\delta p/p$ = 5% of the FNAL beam line, and a constant term of 240 μm (from the fit) to account for all other factors. The radiator gas, CF_4 provides only little diffusion so that charge sharing over more than one pad on the readout plane is essentially excluded. To overcome this limitation one has to either reduce the pad size which will result in a significantly higher channel count or to introduce effects to increase the size of the charge cloud. Since the diffusion limits the geometrical enhancement of the cloud we are investigating the possibility to let the charge disperse on a resistive surface over more than one pad while keeping the pad size the same.
The simulation model is based on the "Telegraph-equation" which describes in one dimension the space-time evolution of a charge density on a wire. The model is extended to a plane by means of a two-dimensional RC network. Approximations are taken into account for obtaining a closed form of the solution to the Telegraph-equation by assuming a point charge (delta-function) deposited on the resistive surface with its edges at infinity. The delta-function is convoluted with a Gaussian for describing a finite charge distribution. This procedure describes the space-time evolution, i.e., dispersion of a charge cloud on a resistive anode, *Q(t)* and subsequently *capacitively or direct* coupling to a separate conductive pad readout. The geometry of the pads, in terms of size and shape is a major part of this investigation.
The simulation is also taking into account that the charge is not deposited instantaneously but rather has a space-time evolution itself while created: *R(t)* depicts the development of a charge cluster arriving on an anode and *L(t)* longitudinal distribution of that cluster. Also electronics shaping time effects, *A(t)* are taken into account, i.e., the rise time of a signal and the decay in the electronic processing. All these effects need to be included as convolutions into the model and are depicted in Figure 22.

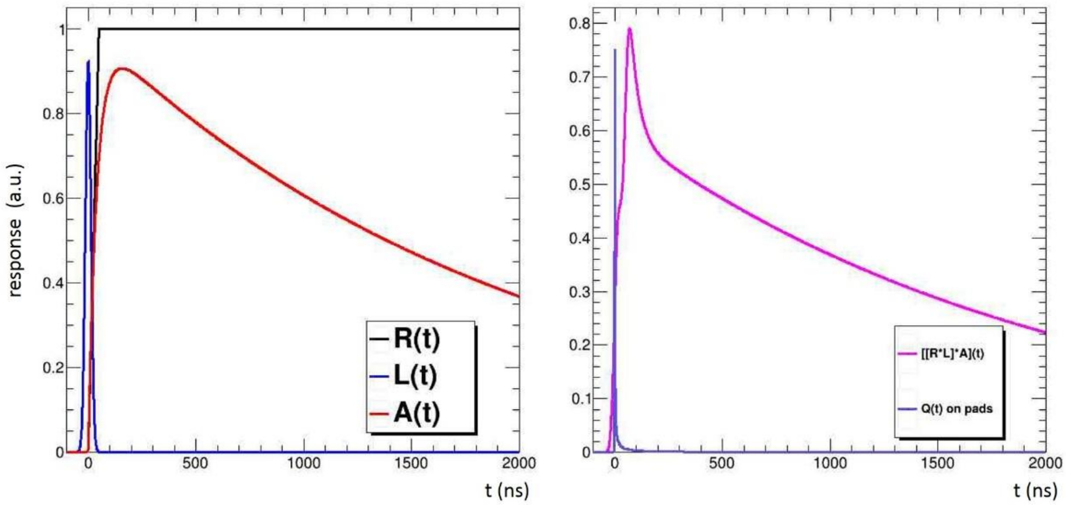

Figure 22 Contributions of various detector effects to the charge diffusion on a resistive anode (see text).

As a further step the simulation will be used to investigate the proper response of the pads to the signal with a pad response function (PRF), which describes the measure of a pad signal amplitude as a function of space point position relative to the pad. Single clusters with different widths will be created and varied in position across the pad. From this a theoretical pad response function is generated as a function of cluster position with respect to the pad center.
We have set up a framework to simulate the dispersion of a charge cloud resulting from an electron avalanche in a multiple GEM stack according to Figure 23. The origin of the charge cloud is of no concern and the procedure can generally be applied to any charge avalanche production with properly described parameters.

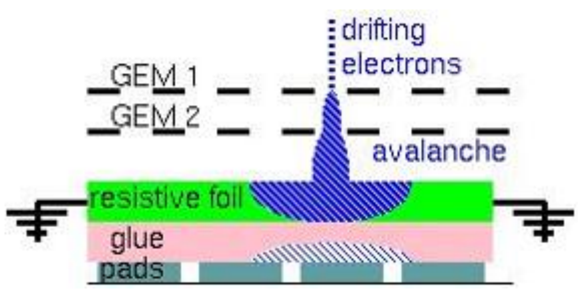

Figure 23 Concept of charge dispersion through resistive layer onto readout pads.

We verified our framework with existing measurements of other groups (Carleton University) based on 2 x 6 mm^2 pads and Ar-CO_2 counting gas. Figure 24 shows the calculation of the response of a typical charge signal from a triple-GEM on a 5 x 3 matrix of readout pads. The central pad shows the main deposition of the charge cloud and the immediate neighboring pads show clearly the sharing of the signal after dispersion of the signal over time.

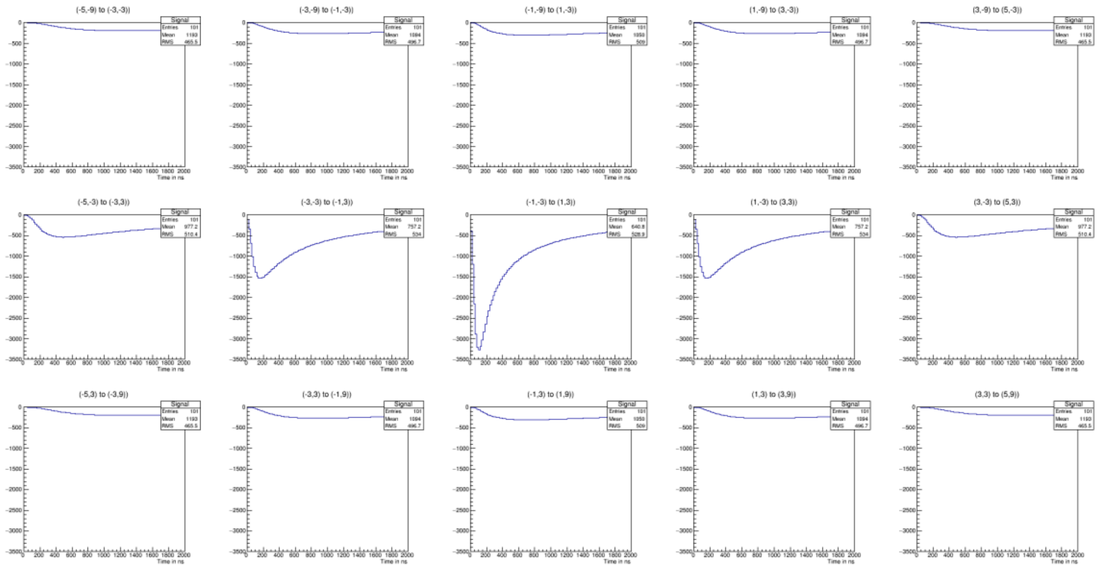

Figure 24 Time evolution of charge through dispersion on a resistive layer.

Figure 25 shows the calculation of a PRF based on the charge distribution of Figure 24 but extended to a total of four times the pads, i.e., sixty pads.

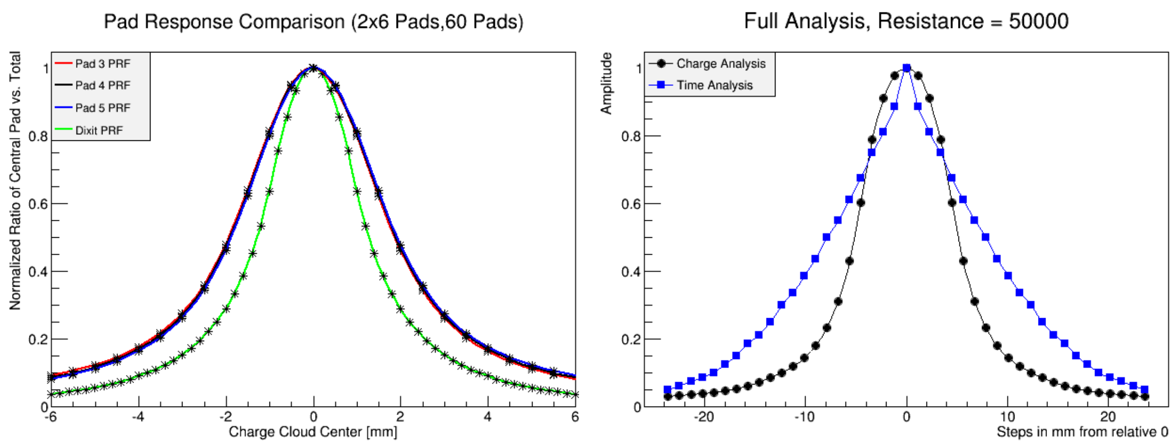

Figure 25 Left: PRF calculation for 2x6 mm^2 pads, compared to results from previous investigations. The difference in the result is from different parameters for the electronics used in the parametrization. Right: same calculation for 9x9 mm^2 pads. Note the different x-scale. In addition a PRF as a function of the time of the amplitude was attempted.

We started simulating a rather large pad size (9 x 9 mm^2) which is available as a readout board from our collaborator at Florida Tech. Unfortunately, this size turns out to be impractically large so that we will not achieve the required spread for sharing charge over more than one pad.

We are now simulating the existing readout board design with hexagonal pads at hand that was used for the test-beam campaigns. We are adjusting the resistive layer for optimizing the charge sharing.

The simulation is being evaluated and by varying the readout pads as well as parameters of the resistive anode a set of optimized readout schemes will be developed and produced to be tested within laboratory conditions.

University of Virginia:

Common GEM foil design for EIC-FT-GEM prototype.

The core of the EIC-R&D activities at UVa for this cycle was to the design of the common GEM foil in collaboration Florida Tech (Prof. Marcus Hohlmann and Dr. Aiwu Zhang) and Temple University (Bernd Surrow and Dr. Matt Posik). We held regular bi-weekly working group meetings which also involved Dr. Dick Majka from Yale Univ. and people from Tech Etch Company to discuss the requirements from each group and finalize the drawing of the foil. The work has been was led by Aiwu Zhang from Florida Tech and the details and descriptions of the common GEM foil design are presented in the Florida Tech section.

2D stereo-angle flexible readout board for EIC-FT-GEM.

We have started the design of a new 2D stereo-angle (u/v) flexible readout board for EIC-FT-GEM. Preliminary discussions of the feasibility of the readout, with all front end electronics located at the outer radius of the chamber were held with experts at CERN. Preliminary drawings of the flexible board are done. However the actual drawings of the readout board will be completed only after the validation of the common GEM foil design as discussed in the previous paragraph.

Develop new ideas for EIC-FT-GEM prototype.

We have been exploring new ideas to facilitate the construction of large area Triple-GEM detectors and minimize the risk of failure associated to the assembly of large GEM detectors. We are also looking at a way to make a GEM detector with lower material budget in order to minimize the multiple Coulomb scattering and the detector-induced background in a high rate low energy photon environment. These generic studies, while not specific to the EIC Forward Tracker detector R&D, are of high importance to EIC-FT-GEM prototype development.

- *New construction technique for triple-GEM detectors*

We proposed a new construction technique for triple-GEM detectors in which the frames supporting the stretched GEM foils are no longer glued together in the final assembled chamber. Using this technique, the framed GEMs are stacked together and closed using plastic bolts and nuts. O-rings are placed between the frames to seal the detector from the gas leak. Figure 26 show the cross sectional view (top) and an exploded view (bottom) of the triple-GEM detector based on the novel construction technique. The key motivations for this study is to allow the possibility to re-open GEM chamber during and after construction to replace or re-test individual damaged or faulty GEM foils at any given step. This is critically important for large GEM chamber where a spark caused by the presence of impurity during the assembly process or a heavily ionizing particle during operation of the chamber could lead to a short in one of the large number of HV sectors of the GEM foil. Having the possibility to replace the foil with the damaged HV sector is a very important aspect of the R&D for EIC forward trackers.

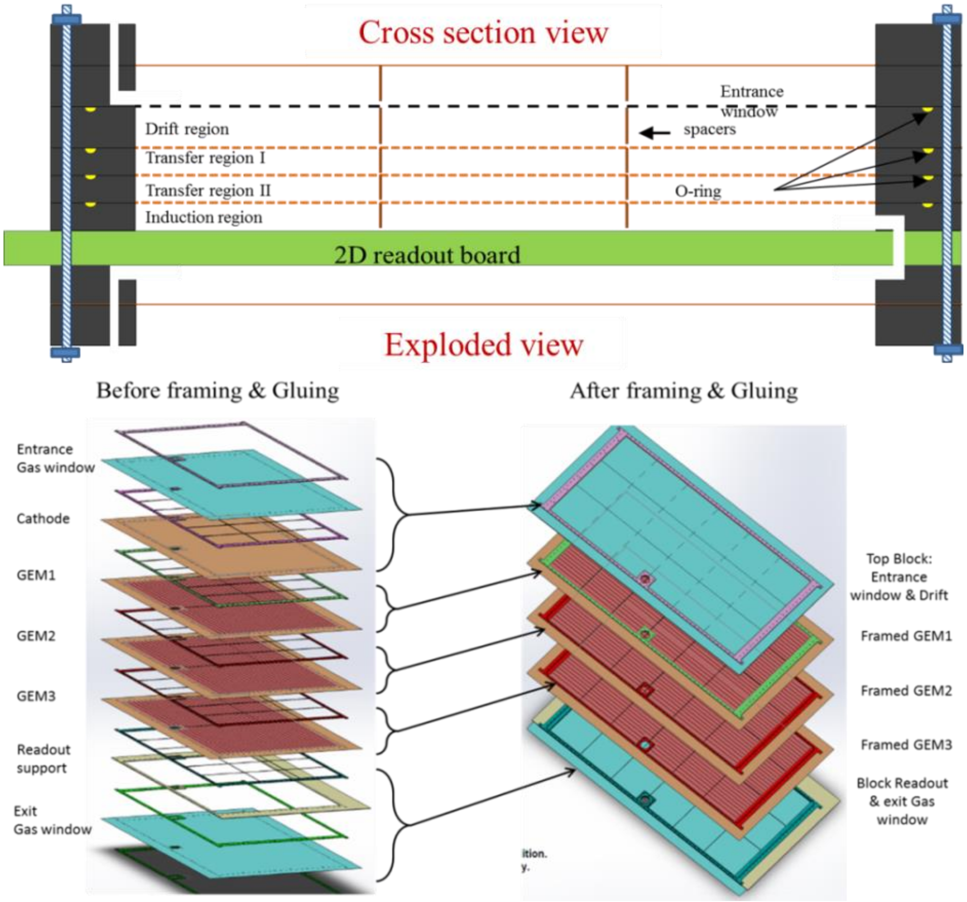

Figure 26 New construction technique applied to the large pRad GEM

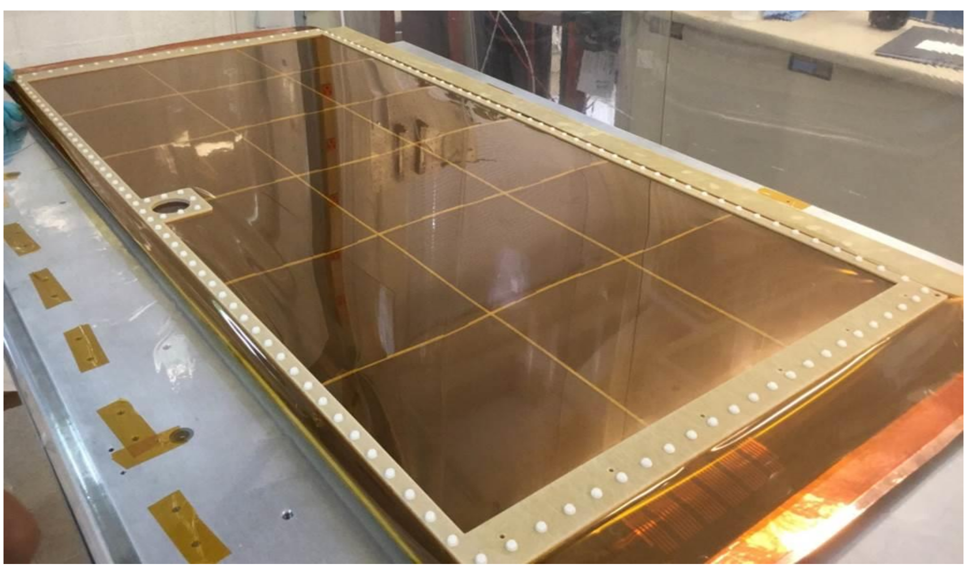

Figure 27 Large pRad GEM built using the new construction technique

A large size (100 x 56 cm^2) triple-GEM was recently built for the future pRad Experiment in Hall B at JLab using the new construction technique**.** Figure 27 shows a picture of the pRad chamber with the plastic bolts and nuts clearly visible all along the edge of chamber. The construction of the chamber has been completed and the preliminary tests with cosmic shows that the chamber performing as expected. Further tests and characterization are ongoing.

- *Low-mass GEM detector with Cr-GEM foils*

The material budget of triple-GEM detectors used in current and future high energy and nuclear physics experiments is dominated by the GEM foils. However the material of the GEMs need to be kept as low as possible to limit the background induced by the trackers in high rate low energy photons environment as well as to reduce the multiple scattering of the particles of interest for good tracking and energy resolution measurement. As shown on Figure 28, the base material of a standard GEM foil, has very thin (100 nm) layer of Chromium (Cr) layer sandwiched between the copper (Cu) electrodes (5 µm) on each side of the Kapton (50 µm). The idea of the Cr-GEM foil is to remove the Cu layer on each side of the GEM foil and to use the Cr layer as electrode on which the potential drop is applied to create the electric field in the GEM holes

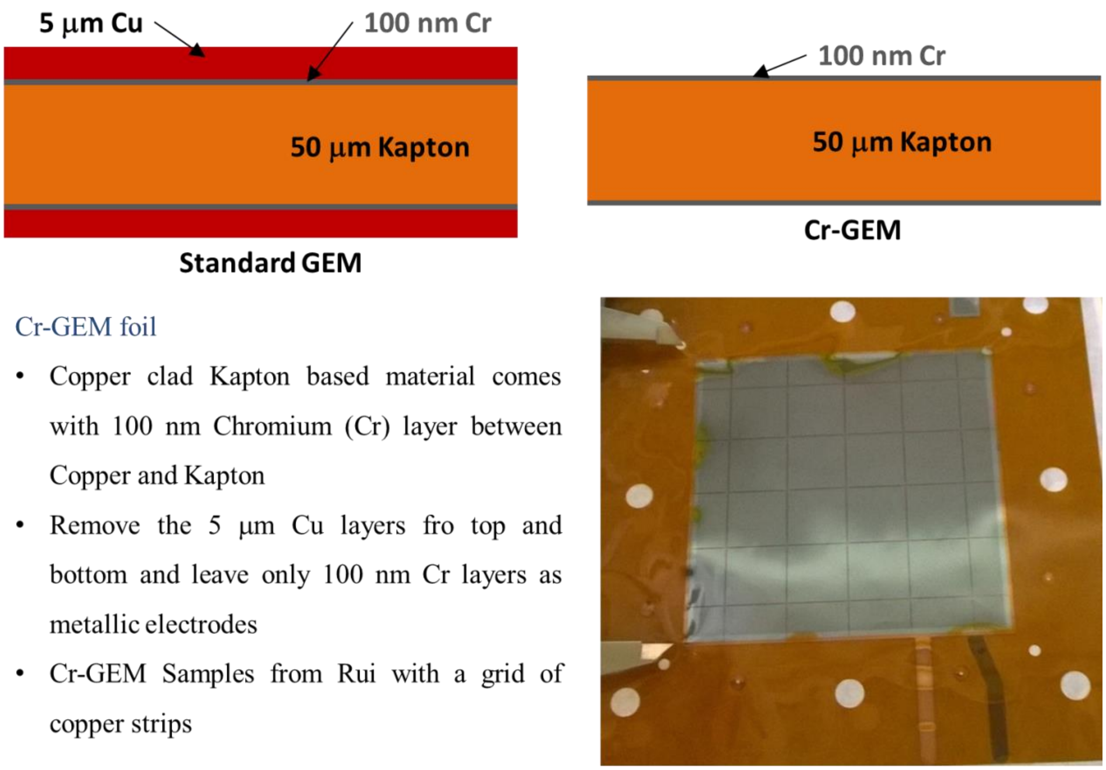

Figure 28 Concept of the Cr-GEM detector

The tables of Figure 29 shows a 50% improvement in term of radiation length for a triple-GEM detector based on Cr-GEM foil compared to conventional GEM foil. The contribution of the 100 nm Chromium layers has been neglected.

Triple-GEM detector with standard GEM foil

	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	5	8.96	14.3	1	0.0350	0.0045
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	5	8.96	14.3	0.2	0.0070	0.0009
Copper-350	1	5	8.96	14.3	0.75	0.0262	0.0034
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	**0.471**	**0.090**

Triple-GEM detector with Cr-GEM foil

	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	0	8.96	14.3	1	0.0000	0.0000
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	0	8.96	14.3	0.8	0.0000	0.0000
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	0	8.96	14.3	0.2	0.0000	0.0000
Copper-350	1	0	8.96	14.3	0.75	0.0000	0.0000
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	**0.235**	**0.060**

About 50% reduction in the amount of material in a EIC-FT-GEM with Cr-GEM

Figure 29 Material budget comparison of triple-GEM detectors with Cr-GEM foil and standard GEM foil

We recently built a small (10×10 cm^2) triple-GEM prototype with Cr-GEM foils purchased from CERN workshop. A picture of the Cr-GEM foil is shown on Figure 28 (bottom right) with the silver-colored Cr layer of active area. Preliminary results on Figure 30 show that the performances are the prototype are very similar to what we would expect from a detector with standard GEM foils. We are currently testing the prototype in our x-ray box to study the long term stability under very high rate and discharge probability with heavily ionizing particle.

2D cluster Map with of Cr-GEM cosmics

Characterization of Cr-GEM with Sr90

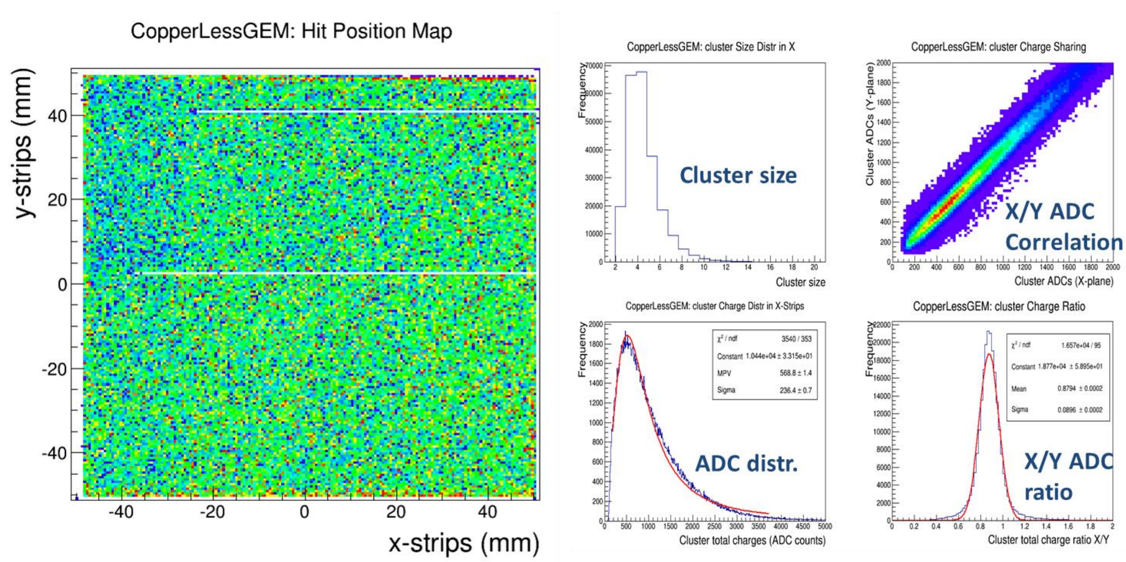

Figure 30 Characterization of Cr-GEM prototype

Further studies are needed for a direct gain comparison with a standard GEM foil and we plan to investigate the large size production with Tech Etch and CERN workshop.

Analysis of FTBF test beam results and draft of the manuscript to be submitted to a peer-reviewed journal.

The analysis of the FTBF test beam data is now completed and concentrates on the performances of the first EIC-FT-GEM prototype and the study of the spatial resolution with its 2D stereo-angle strips readout board. We are in the process of writing a paper on the test beam results be submitted for publication in a peer-review journal such as NIM A or TNS.

<u>Yale University</u>:

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas

A large range of measurements have been made on several 10 cm x 10 cm chambers with different readout plane geometries and different gas mixtures.

Key parameters for TPC gain structures are energy resolution and ion back flow (IBF) – the ions escaping the gain structure and flowing back into the main TPC drift volume. Because of the very low drift velocity of positive ions in the TPC drift field these ions can build up and significantly distort the drift field hence distorting the ionization trails of charged particles as the ionization electrons drift through the distorted field.

This investigation aims at using the intrinsic ability of micropattern gas detectors (MPGD) to limit IBF to produce a gain structure with low IBF that will not require use of a gating grid with inherent dead time.

In our last report we presented initial results that look quite promising, showing IBF (anode or readout plane current divided by cathode current) of less than 0.5% while maintaining good energy resolution needed for good PID.

In the last period we have expanded these measurements to a variety of working gases including both Neon and Argon mixes. We have conducted further studies on the discharge behavior of the gain structure including fabrication and testing "floating strip"[i] spark protection interconnect card. (We note that the fabrication of this card was funded from ALICE TPC upgrade R&D funds) We have also designed and ordered pieces for a MMG chamber with resistive coating on the readout plane. This technology is reasonably developed and should provide a way to both limit discharges and help spread the signal on the readout plane.

Calculations have also been done on performance of a stacked gating grid structure described by Howard Weiman[3]. Based on the encouraging results of these calculations we have ordered wire planes to test this structure.

Details of all these results are presented below.

IBF and Energy Resolution Measurements for 2-GEM + MMG Structures.

<u>Figure 31</u> and <u>Figure 32</u> show the setup for measuring energy resolution (anode connected to pre-amp, shaper amp, ADC and PC) and IBF (anode and cathode connected through current meters). The energy resolution is the width (std. dev.) over peak position for the ^{55}Fe x-ray. IBF is the measured cathode current divided by the anode current. The "screen" electrode is set at the same voltage as the cathode but isolated from the cathode and collects ions produced outside the chamber that would otherwise give spurious cathode current.

[3] http://www-rnc.lbl.gov/~wieman/alice%20upgrade%20gating%20grid.pdf

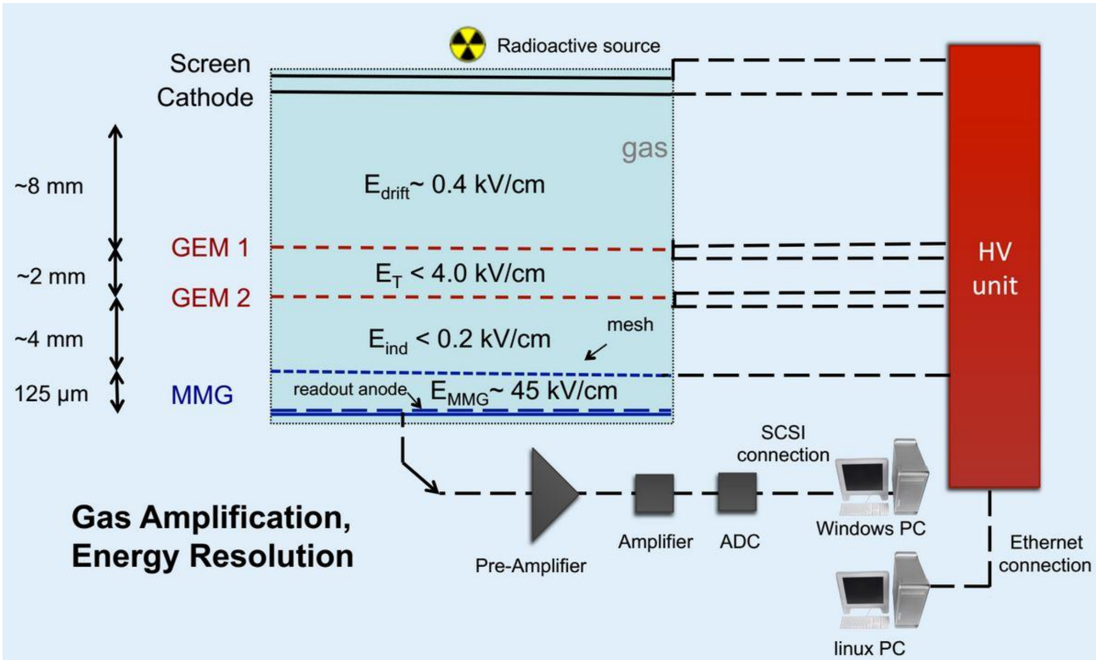

Figure 31 Typical setup for measuring gain and energy resolution for a 2-GEM+MMG hybrid gain structure.

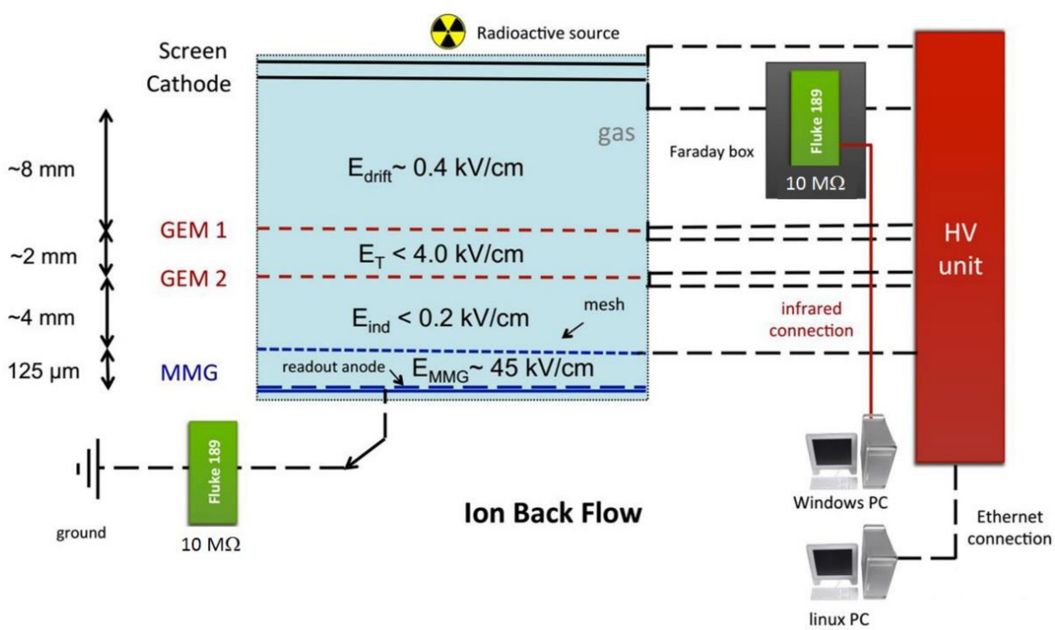

Figure 32 Setup for measuring ion backflow. The meters are used with mV setting (least count = 1 mV) to measure the voltage drop across the 10 MW internal resistance. The battery powered meters can be floated to high voltage and read out via an IR to USB connection to a computer.

Figure 33 shows a plot of energy resolution *vs.* IBF for 90%Ne + 10%CO_2 gas mix. The different curves are for different voltage settings on GEM2 (middle GEM). The points along a given curve are for different MMG voltage settings with the voltage on GEM1 (top) changed to keep the overall gain at 2000. As presented in the last report there is a tradeoff between energy resolution and IBF.

Simulations done by the ALICE group for the ALICE TPC have shown that resolution for the ^{55}Fe peak should be better than 14% to not degrade the TPC PID resolution. We have also tested neon mixes with CF_4 added but we have found that at higher transfer fields (above ~1.5 kV/cm) there is significant electron capture by CF_4 so one must take care to work with appropriate transfer fields. At 4kV/cm the signal is reduced by more than an order of magnitude.

Figure 34 shows a plot of energy resolution *vs.* IBF for various Neon gas mixes. Each curve is for a given gas mix and the points along a curve are for different MMG voltages, varying the GEM voltages to keep the total chamber gain at 2000. The differences between different mixes are not large, but adding a little methane does give slightly better performance.

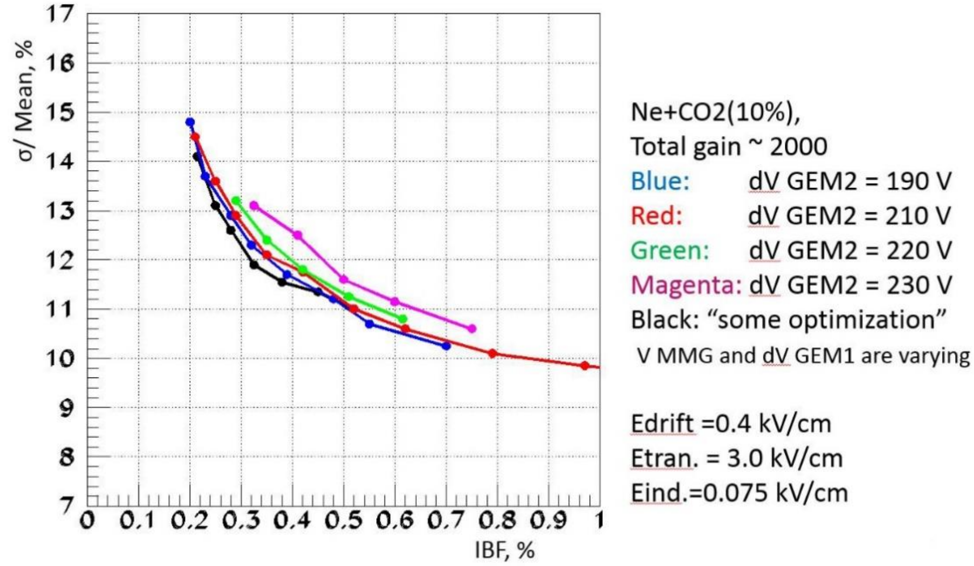

Figure 33 Energy resolution *vs.* IBF for various voltage settings on the gain elements.

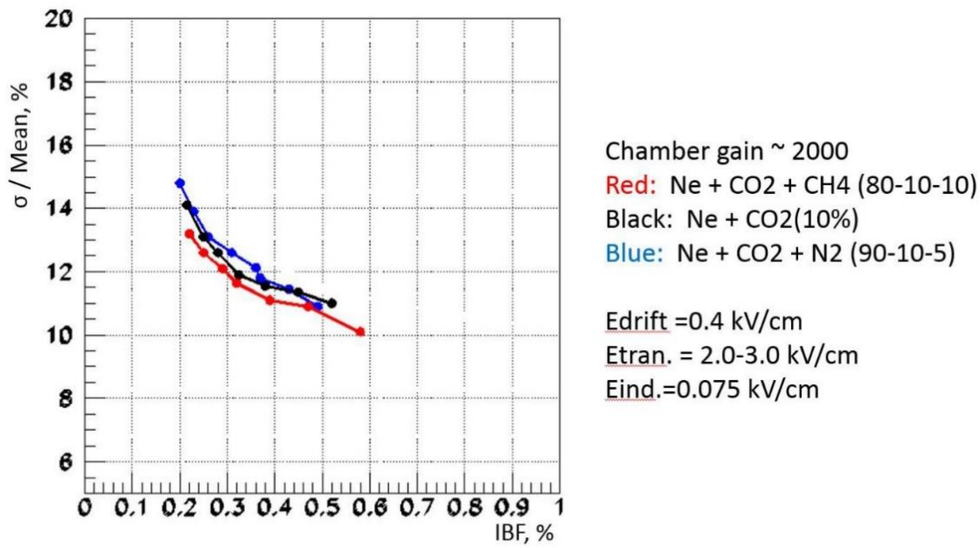

Figure 34 Energy resolution *vs.* IBF for various neon gas mixes.

Figure 35 shows a plot of energy resolution *vs.* IBF for two Argon gas mixes. Each curve is for a given gas mix and the points along a curve are for different MMG voltages, varying the GEM voltages to keep the total chamber gain at 2000.
These data show it is possible to achieve IBF less than 0.5% with good energy resolution for a variety of gases.

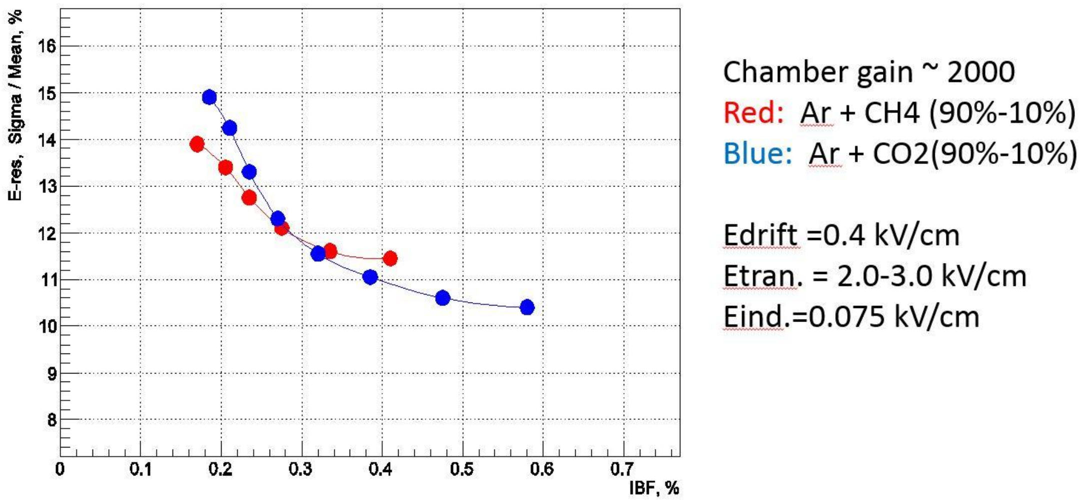

Figure 35 Energy resolution *vs.* IBF for various argon gas mixes.

Discharge behavior of 2-GEM + MMG Structures.
In our last report we presented data on discharge behavior of 2-GEM + MMG chambers using an α source to provide high ionization density. These showed rates of less than 10^{-8} per α. Using funds provided for ALICE TPC upgrade R&D we constructed two 21 cm x 26 cm and tested them in beams at CERN. At very high rates in a hadron beam we find that the discharge rate is approximately 1,000 times higher than a 4-GEM chamber tested at the same time. The measured spark rate is 3.5 x 10^{-10} per MIP traversing the chamber perpendicular to the readout plane using the standard ALICE TPC gas ($Ne/CO_2/N_2$: 90 parts/10 parts/5 parts). We note that all discharges were in the MMG, not in the GEM foils, and that the MMG is very robust against discharges. Since the discharge is to the readout plane however, care must be taken to protect the readout electronics. We implemented the "floating strip" protection mentioned in our last report[4]. This circuit performed well and no electronics were damaged. We plan to carry out lab tests on this circuitry to measure the dead time resulting from a discharge.
We have ordered pieces for a MMG chamber with a resistive layer and plan to study the discharge and charge sharing characteristics and durability of this chamber.

Stacked Grid Gating Structures.
In collaboration with Howard Weiman[5] we have done calculations and simulations of the performance of a novel stacked grid structure to suppress IBF. The basic idea is to arrange an array of grids between the gain structure in a TPC and the main drift volume. The grids are normally biased to be transparent for electrons drifting in from the main volume and ions drifting back from the gain structure. For a structure with a depth of a few cm biased to be transparent to drifting charges (electrons or ions), it takes hundreds of microseconds for an

[4] https://indico.cern.ch/event/245535/session/4/contribution/5/material/slides/0.pdf
[5] http://www-rnc.lbl.gov/~wieman/alice%20upgrade%20gating%20grid.pdf

ion to drift through the structure but when the structure is biased appropriately to collect ions it takes tens of microseconds to collect the ions. Thus one could have a gating structure that is totally open with ~80% live time. Calculations performed by one of our graduate students using ANSYS and Garfield++ have shown the idea basically works however if one needs very high ion rejection the ion clearing time gets long due to stragglers that are initially in low field regions, Figure 36 illustrates this for configurations with wire planes and mesh planes with the clearing field parallel/anti-parallel to the TPC drift field. The full report on this study is available at:
http://rhig.physics.yale.edu/~rmajka/GatingGrid/MEGG_Summary.pdf
We have ordered wire planes and instrumentation to test this idea experimentally and vet the calculations. It is also possible that by changing the field configuration during the ion clearing cycle one can reduce or eliminate the tail of stragglers (move the low field region during the clearing). This is not easy to simulate with the tools available so we will also test this.

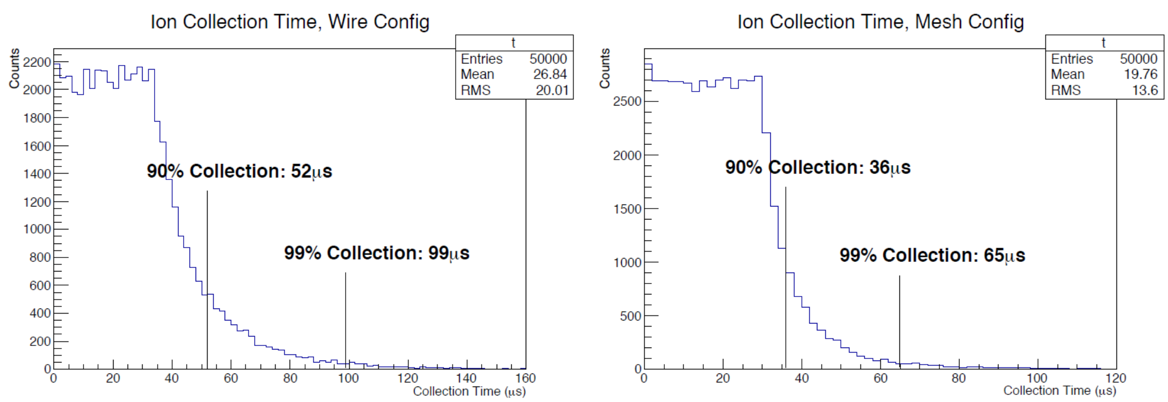

Figure 36 Ion clearing times from a stacked grid array for wire planes (left) and mesh planes (right). For this calculation 50,000 positive ions are placed randomly in the array and each is traced until it lands on a grid. The histogram is of the time it takes an ion to reach the grid.

What was not achieved, why not, and what will be done to correct?

Brookhaven National Lab:

We did not completely finish the analysis of the test beam data for the minidrift detector due to the additional studies we did to understand the effect of the uncertainty in the timing of the phase of the readout clock relative to the trigger and how that contributed to the position resolution we obtain with the time slice vector reconstruction method. However, that study is now essentially complete, and in the process, we studied an algorithm that could even further improve the resolution that can be obtained with this type of detector. We believe that it is possible to obtain a resolution well below 100 μm at large angles by eliminating the time uncertainty in future measurements and using this more sophisticated algorithm. We plan to finalize these studies within the next few weeks and submit the final results for publication.
The final assembly of the TPC-Cherenkov prototype detector is now complete except for the installation of the wire plane of the field cage and the photosensitive CsI GEM. We will fully test the TPC portion of the detector before installing the photosensitive GEM, since that operation will have to be done inside a glove box, and it will be much more difficult to work with the detector after it is installed. We will also study the position of the photosensitive GEM relative to the wire plane before installing the CsI photocathode which will allow easier investigation of any high voltage problems.

Florida Tech:

Most of the work that we had planned to do in the past 6 months is done. The change in the simulation environment led to some delay in finalizing two papers for publication. We plan on submitting these to NIM A and JINST soon, hopefully at least one before the review committee meeting in July. The design of forward tracker chamber components other than GEM foils has not started because the design work for the common foil took somewhat longer than expected.

Stony Brook University:

The setup of the simulation framework and initial calculations have been finished. We were hoping for obtaining results that allow us to experimentally verify the simulations. However, the charge dispersion is not feasible for the geometries used. We are investigating other geometries of pad structures and we are improving the calculation effort for the simulation.

University of Virginia:

The manuscript on the test beam results of the first EIC-FT-GEM prototype was delayed by the analysis and other high priority activities in our group. We plan to send the paper for submission by the end of the summer (2015).
The design of the support GEM frames for the second EIC-FT-GEM prototype has not started yet and only preliminary work on the design of the 2D u/v readout board was performed. This part of the R&D strongly depends on the final design of the common GEM foil and therefore needs to be completed after the completion of the foil design.

Yale University:

3-Coordinate GEM

A major failure of our computer cluster delayed completion of the analysis of these data. The analysis code has now been largely recovered and recreated on other facilities.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas

Parts are in hand or ordered to test using a resistive plane to limit discharge energy and also improve charge sharing, but the idea has not yet been tested. We expect this will occur in the next period.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

Brookhaven National Lab:

Our main activity during the next funding cycle will be to test and study the TPC-Cherenkov prototype detector. Initially these will be mainly lab tests with radioactive sources and cosmic rays in order to test the TPC portion of the detector. We will also test different gases with the TPC detector in order to study various properties such as drift velocities, ion backflow, etc. We will then install the Cherenkov portion of the detector and begin study its operation and how it relates to the operation of the TPC. This will require fabricating the CsI photocathode, which we plan to do at Stony Brook using their evaporation facility that was used for the PHENIX HBD detector. We will require their help and support for this procedure. In addition, we need to measure the quantum efficiency of the photocathodes produced there, which will utilize our existing VUV spectrometer at BNL. However, some of the optics of this spectrometer must be replaced in order to make it fully functional, which will require some additional funding.

After the initial tests of both the TPC and Cherenkov detector in the lab, we plan to test the combined detector in a test beam at Fermilab. We expect that this test will occur sometime during the spring of next year.

We expect that the analysis of the minidrift GEM detector data will be fully completed by the time of the next funding cycle and no further support will be requested for this activity.
All of the above activities are within the scope of the original R&D plan.

Florida Tech:

We plan to submit a paper to NIM on the results of the beam test of the large-area GEM with zigzag readout strips soon, followed by a second paper on examining the geometric mean method for resolution studies, e.g. to JINST.
The EIC forward-tracking GEM foil design is finished. Next, we'll design the frames, drift board, and readout board with improved zigzag strips for a complete design of the full chamber prototype.
Together with Temple U. and U. Va, we plan to invest in an infrastructure upgrade at Tech-Etch that will enable them to produce large GEM foils for our research program (see section on joint Forward Tracker proposal below). Florida Tech and the forward tracker group will continue to meet regularly with Tech-Etch to monitor this process.
In our lab, we need to set up the large zigzag GEM detector and measure its gain and uniformity with an X-ray gun since the gain was actually not measured in the beam test.
Finally, we want to study the performance of small GEM detectors with zigzag strip readout also in a magnetic field using our small table-top 1T magnet.

Stony Brook University:

We are optimizing the pad structures for charge dispersion. Once the right set of parameters has been found we will be producing a readout board and testing it with the existing irradiation facility at the BNL instrumentation department.

We will be working on refurbishing an in-house evaporator and upgrading it to a high-vacuum device with appropriate instrumentation. Funding was missing for purchasing equipment and mirror blanks in order to perform mirror-coating with MgF_3 in-house which is crucial to obtain reflectivity un the wavelength range for the RICH detector.

University of Virginia:

For the next cycle from June 2015 to December 2015, we plan to:

Submit the paper on the FTBF test beam results for publication in NIM A or TNS peer-review journal.

Continue the collaboration on the common GEM foil design with Florida Tech, Temple University and Tech Etch Company.

Investigate the feasibility of large Cr-GEM foil with Tech-Etch and CERN.

Complete the design of the support frames and u/v readout board for EIC-FT-GEM prototype II.

Yale University:

3-Coordinate GEM
In the coming year we will complete the analysis and publish the results.

Hybrid Gain Structure for TPC readout
A paper is in preparation on the present studies. In the coming year we plan to measure the properties of 2-GEM + MMG chambers with resistive planes with respect to discharge behavior, charge spreading on the readout plane and durability of the resistive layer. Something not included in the original plan is to measure the properties of an extended grid. Since this may well offer the ability to operate a TPC with almost continuous readout at relatively low added cost we believe this is an important study that will be undertaken. Critical issues remain the same: develop methods for operating a TPC at high data rates while maintaining low ion feedback, good energy resolution and robust operation (low discharge rate).

Joint eRD3/eRD6 Proposal for Commercial Production of Large GEM foils and GEM Prototype Chamber Development by Forward Tracker Group (Florida Tech, Temple U., U. of Virginia):

The goal of the R&D pursued by the Forward Tracker group is to construct and study realistic prototypes of large GEM chambers that will eventually evolve into a technical design for the actual forward tracker to be installed in an EIC detector. Now that a GEM foil design suitable for EIC Forward Tracker prototype chambers has been completed, the three groups involved in this effort propose to implement this design via commercial production at Tech-Etch. This will pave the way for domestic production of GEM foils for the actual forward tracker of an EIC detector. Obviously, such a development will also strongly benefit the entire NP and HEP communities. For example, large GEM detectors are being developed or considered for the SBS, SoLID, CMS, and ALICE experiments.

As anticipated in our previous report (Dec 2014), the three groups jointly request funding for this purpose in FY16 and FY17. In FY17 and continuing in FY18, the group plans to request additional funds for the other required chamber components, such as drift foils, strip readout boards/foils, frames, and possibly readout electronics. As with the foils, we would prefer to source all these components domestically. We put a priority on the foil development since this critical aspect is the most R&D intensive and involves a commercial partner, so it should be addressed first.

Tech-Etch Inc. has been collaborating with various academic institutions on the commercial fabrication of GEM foils for almost ten years. This development has now culminated in the successful fabrication of 10×10 cm^2 and 40×40 cm^2 single-mask produced GEM foils [1]. Single-mask techniques are critical to extend the size of GEM foils to large sizes. Going to sizes beyond 40×40 cm^2 is a critical R&D step which needs to be carefully worked out in terms of processing at the company side and the actual application on the academic institution side. Feedback from the academic institutions to the manufacturer during this development stage will be indispensable concerning electrical performance measures and in particular GEM parameter qualification with optical techniques. Each institution will focus on different aspects of the assembly of full-size triple-GEM detectors such as foil stretching and spacer grid layouts. Those aspects are described in detail in our progress report above.

A two-year development program to produce large-size GEM foils has now been worked out with Tech-Etch as outlined in the letter shown in Figure 37. The management at Tech-Etch is fully committed to pursuing this next step. Following the successful production and validation of single-mask GEM foils of 10×10 cm^2 and 40×40 cm^2 sizes, we propose for each of the three institutions to order 18 large GEM foils of the new common design, i.e. a total of 54 large-area GEM foils. This will allow each of the three institutions to build three large-size GEM chamber prototypes using their specific chamber designs and makes a provision for 50% spare foils.

Funding for this order is being requested from the EIC Detector R&D program. The total NRE cost for this project has been estimated to be $200,000 (see Tech-Etch letter). This is not the full cost required to prepare a new GEM production line and tooling, but Tech-Etch Inc. will be providing additional internal funds to pursue this important development.

Due to the anticipated availability of funding for the EIC R&D program, the Forward Tracker group proposes the following staged schedule, which Tech-Etch Inc. has agreed to:

- FY2016: First payment of $100k NRE cost around January 2016
- FY2017: Second payment of up to $100k NRE cost around January 2017 plus production cost for 54 large GEM foils

The cost per foil is currently estimated at $1,750 (see Tech-Etch letter). Tech-Etch is committed to starting a new production line as soon as the initial payment of FY16 funds has been made and to provide prototype foils for test setups and quality assurance purposes during the calendar year 2016. Production quality foils would follow in spring 2017.

TU and U. Va will separately request R&D funding of approximately $50k for the SoLID experiment at JLab which if granted would then lower the EIC R&D request for NRE cost in FY17. While the SoLID experiment is mainly focusing on a future Chinese supplier of GEM foils, a recent JLab Director's Review of the SoLID experiment concluded that developing a domestic option for large-size GEM foils is critical to the success of the project.

The two-year funding request for commercial development of large GEM foils is broken down by institution (Florida Tech, TU and U. Va) in the following way:

- $33k in FY16 per institution (NRE cost)
- Up to $33k (NRE cost) and $31.5k (foil cost) per institution, i.e. max. $64.5k per institution in FY17

Additional funding requests in the out-years for chamber components are estimated as follows:

- FY2017: Components for 3 chambers to be constructed in 2018 (one by each group)
  - Drift foils - $1,500
  - Large readout boards/foils incl. NRE – $12,000
  - Carbon-fiber frames incl. NRE - $12,500
  - Total: $26,000

- FY2018: Components for 6 chambers to be constructed in 2019 (two by each group)
  - Drift foils - $3000
  - Large readout boards/foils – $12,000
  - Carbon-fiber frames - $15,000
  - Beam test - $10,000
  - Electronics – TBD (depending on actual needs at that time)
  - Total: ≥ $40,000

If funding becomes available earlier, we will be able to move up these efforts and corresponding procurements by following an accelerated schedule.

Tech-Etch

TECH-ETCH, INC.
45 ALDRIN RD., PLYMOUTH, MA 02360 USA
TEL 508 747-0300 • FAX 508 746-9639

11 July, 2015

Dr. Bernd Surrow
Temple University
1801 North Broad Street
Philadelphia, PA 19122

Re: Production of Large Area GEM Foils

Dear Dr. Surrow,

Tech-Etch has been involved in the fabrication of GEM foils for over ten years, and with this letter I would like to communicate Tech-Etch's commitment to expand our capabilities to include Large Area GEM foils. As you know, we have worked closely with CERN and have acquired a license to fabricate GEM foils using CERN's patented single mask method. We've fabricated hundreds of GEM foils for dozens of institutions, and we are prepared to upgrade our facility and equipment to accommodate your need for 54 large area prototypes in 2016, and production foils starting at some later date.

Tech-Etch is requesting NRE charges of $200,000 for the engineering, tooling, fixturing and equipment modifications necessary to accommodate foils of this size. Additionally, we are estimating a cost of $1750 per foil. It is understood that funds would likely be issued over a two year period. Tech-Etch is willing to begin facility modifications and tooling fabrication as soon as it is confirmed that funding for the first year has been secured.

Sincerely,

TECH-ETCH, Inc.

George Keeler
President

Figure 37 Tech-Etch letter outlining commitment to produce large-size GEM foils.

What are critical issues?

Brookhaven National Lab:

The main critical issues are to demonstrate that the TPC and Cherenkov detectors can be operated first individually and then as a combined detector. In order to do that, we need appropriate readout electronics for the TPC and to make good photocathodes for the photosensitive GEM. We will initially use the SRS readout system for the TPC, but based on our studies with the minidrift detector, there are certain limitations as to how well this will work. We have several smaller readout systems, including a 128 channel DRS4 system with very good timing resolution, a 24 channel Struck FADC system with a long (10 μsec) digitization buffer, and we will also investigate a system using the VMM2 readout chip which should soon be available. However, we will eventually need to acquire a more suitable readout system for the full TPC. We are hopeful that the SAMPA readout chip being developed for the ALICE TPC will eventually become available for this purpose.

In order to measure the quality of the CsI photocathodes produced at Stony Brook, we need to measure their quantum efficiency with our VUV spectrometer. In order to do this, we must replace some of the optics of the spectrometer, which we have postponed doing for some time. However, it is now time to do this in order to be able to use it for these studies.

Florida Tech:

The most critical issue specifically for Florida Tech is the continued availability of our post-doc Aiwu Zhang for another year. The significant progress at Florida Tech described in the "What was achieved?" section above including the preparation of two publications is to a very large extent due to Aiwu's very hard work on the project. Without him, the EIC R&D effort at Florida Tech would very likely collapse. His design work on the common GEM foil is also directly benefitting two other groups in the consortium. Due to the low overhead rates at Fl. Tech, his employment is a very cost-effective investment for the consortium. Consequently, we request that funding be provided to renew his position for a third year in FY16.
The second most critical issue for Florida Tech is turning the large GEM foil design into actual foils. See the joint proposal by the forward tracker group for more details.
Finally, low mass materials should be used as much as possible for EIC tracking detectors. In our continued chamber design work we will try to reduce the material budget as much as possible.

Stony Brook University:

It is critical to show the charge sharing via dispersion with existing pad structure to overcome the position resolution of ring imaging and not increasing the channel count.

University of Virginia:

As we already stated in the previous report, domestic production of large area GEM foil remain the critical issue for the R&D effort toward GEM-based EIC Forward tracker. The US-based Tech Etch Company remains to our knowledge, the only alternative CERN workshop, capable to produce high quality large GEM foil. However, the current capability of Tech Etch is limited to GEM foil of size of roughly (50×50 cm2), smaller than the sizes required for EIC-FT-GEM.

It is crucial for the EIC that the community supports Tech Etch Company in their effort to upgrade their infrastructure and production capability for large GEM foils.

Yale University:

Hybrid Gain Structure for TPC readout
Critical issues remain the same: develop methods for operating a TPC at high data rates while maintaining low ion feedback, good energy resolution and robust operation (low discharge rate).

References

[1] M. Posik and B. Surrow, "Research and Development of Commercially Manufactured Large GEM Foils, arXiv:1506.03652 [physics.ins-det], submitted to Nucl. Instr. and Meth.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located and who supervised their work.

Brookhaven National Lab:
This work is being carried out by members of the BNL Physics Department. The workforce is listed below (in % FTE)

C. Woody	Senior Scientist	20%
B. Azmoun	Physics Associate	100%
	Post undergraduate student	100%
	Postdoc	5%
	Technician	30%

The student was funded for ~ 50% FTE out of EIC R&D funds and supervised by the Senior Scientist. All other personnel are paid by the BNL Physics Department.

Florida Tech:
The workforce is listed below (in % FTE)

Marcus Hohlmann	Professor	25% (not directly funded under this R&D program)
Aiwu Zhang	post-doc	100% (fully funded under this R&D program, located at Florida Tech and supervised by M. Hohlmann)

Stony Brook University:
None of the labor at SBU is funded by EIC R&D. The workforce is listed below (in % FTE):

K. Dehmelt	Research Scientist	50%
T. K. Hemmick	Professor	10%
E. Michael	Undergraduate student	25%
N. Nguyen	Undergraduate student	25%

University of Virginia:
None of the labor at UVa is funded by EIC R&D. The workforce is listed below (in % FTE):

N. Liyanage	Associate Professor	25%
K. Gnanvo	Research Scientist	40%
V. Nelyubin	Senior Research Scientist	5%
H. Nguyen	Post-doctoral	5%
X. Bai	Graduate Student	10%

Yale University:
None of the labor at Yale is funded by EIC R&D. The workforce is listed below (in % FTE).

R. Majka	Senior Research Scientist and Scholar	10%
N. Smirnov	Research Scientist and Scholar	50%
	Graduate Student	25%
	Graduate Student	25%
	Graduate Student	25%
	Graduate Student	25%

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

Brookhaven National Lab:

There is no other external funding for this R&D effort.

Florida Tech:

Florida Tech has no external grants in nuclear physics. There is a base grant in HEP for CMS that has some synergy with R&D work on large-area GEMs.

All work described above was accomplished with the EIC R&D funds.

Stony Brook University:

There is no other external funding for this R&D effort.

University of Virginia:

UVa has DOE basic research grant from Medium Energy Physics. The work on Cr-GEM is funded with the research grant.

The group also has DOE grants through JLab for the construction of the SBS GEM trackers.

Yale University:

In the past year, ALICE R&D funding from DOE has supported the construction of two 21 cm x 21 cm 2-GEM + MMG chambers and a test beam run at CERN. Data from these efforts will be published separately from the work described above.

Publications

Brookhaven National Lab:

A paper giving the final results of our study of the minidrift detector is in the final stages of preparation and will be submitted to the IEEE Transactions on Nuclear Science within the next few weeks.
Preliminary results from the minidrift detector have been published in the IEEE Conference Proceedings:

"Study of a Short Drift GEM detector for future tracking applications at PHENIX", M. Purschke et al., Conference Record Proceedings of the 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference, Seoul, Korea, October 2013.

Florida Tech:

A. Zhang, et al., "Performance of a Large-area GEM Detector Read Out with Wide Radial Zigzag Strips," (under preparation for submission to NIM A)
A. Zhang, et al., "Study of the Geometric-Mean Method for Determining Spatial Resolution of Tracking Detectors in the Presence of Multiple Scattering," (under preparation for JINST)
Presentation at 2015 IEEE/NSS conference requested.

Stony Brook University:

Performance of a Quintuple-GEM Based RICH Detector Prototype, submitted to IEEE-TNS, peer-reviewed manuscript revised and re-submitted.
Presentation at 2015 IEEE/NSS conference requested.

University of Virginia:

K. Gnanvo, et al. "Large Size GEM for Super Bigbite Spectrometer (SBS) Polarimeter for Hall A 12 GeV program at JLab", Nucl. Inst. and Meth. A782, 77-86 (2015).

K. Gnanvo, et al. "Test Beam Performances of Large area GEM prototypes for the Electron Ion Collider (EIC) Tracking R&D and Experiments at Jefferson Lab." (under preparation for submission to NIM A or IEEE-TNS).

We are also planning to present at the MPGD 2015, the Fall DNP meeting, and IEEE/NSS conferences.

Yale University:

A publication is in preparation on the results described above and presentations are planned for CPAD, the Fall DNP meeting and IEEE/NSS.

Budget for FY16

Brookhaven National Lab:

The following is our request for additional EIC funds to carry out the R&D described above during the next funding cycle. This was also listed in our previous report from Dec 2014.

1. Parts and supplies for TPC/Cherenkov prototype - $15K
2. New optics for VUV spectrometer - $10K
3. Support for beam test - $15K

Total without overhead - $40K
Total with overhead - **$60K**

Florida Tech:

We request funding for personnel (EIC post-doc Aiwu Zhang, 3rd year**,** $92k fully loaded) for all of FY16.

The Florida Tech share of the joint NRE cost for foil production at Tech-Etch is one third or $33k. Please see more details in the joint forward tracker proposal section.

In total, we request $92k + $33k = **$125k**.

Stony Brook University:

We are requesting funding for the large evaporator refurbishment: e-gun with 4 pockets, 5kW, XY sweep, Indexer for a total of **$43k**.

Temple University:

The Temple share of the joint NRE cost for foil production at Tech-Etch is one third or $33k. Please see more details in the joint forward tracker proposal section.

In addition to the requests made in the eRD3 report and proposal, Temple requests **$33k**.

University of Virginia:

The U. Va. share of the joint NRE cost for foil production at Tech-Etch is one third or $33k. Please see more details in the joint forward tracker proposal section.

In total, U. Va. requests **$33k**.

Yale University:

Yale is not requesting funds for this funding cycle.

Institute	Costs (k$)	Overhead (k$)	Total (k$)
BNL	40	20	60
Florida Tech	125	included	125
Stony Brook	43	included	43
Temple (joint effort)	33	included	33
UVa	33	included	33
Yale	-	-	-
Sum			**294**

Table 1 Funds requested by institutes.

Institute	Costs (k$)	Overhead (k$)	Total (k$)
BNL	40	20	60
Florida Tech	125	included	125
Stony Brook	-		-
Temple (joint effort)	33	included	33
UVa	33	included	33
Yale	-	-	-
Sum			**251**

Table 2 Minimum funds needed.