

RD6 TRACKING/PID CONSORTIUM PROGRESS REPORT & FUNDING REQUEST

FY 2014

We report on the progress to date, specifically our highly successful sector test of forward arm tracking plus ring imaging Cherenkov detector. We also specify the desired funding throughout FY14.

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Introduction and Collaboration Status

OVERVIEW

The RD6 Collaboration dates to the first round of EIC R&D funding and is among the first of the so-called “Consortia” combining efforts and resources across multiple institutions with similar interests and talents. We are currently nearing the end of the two-year program proposed in May 2012. The principle goal of that program was to work toward a sector test of forward tracking prototypes during a single beam period. We are pleased and proud to report that the sector test has already taken place in October 2013.



Figure 1 Participants in the EIC Sector Test at FNAL.

BNL tested a minidrift detector to demonstrate that this device can overcome the resolution degradation experienced by most MPGD detectors for tracks impinging at large angles. Yale tested the so-called 3-coordinate readout scheme which allows for reduced channel count from tracking chambers by adding geometrical pattern recognition to the standard charge-matching technique. UVA and Florida Tech tested multiple detector including prototypes at “full-size” EIC as well as channel-count reduction via the zig-zag charge division. Stony Brook tested their compact RICH (1 meter radiator CF_4 as compared to 3 meters used by LHCb) to demonstrate clean hadron ID up to 32 GeV/c (highest available secondary beam energy at FTBF).

Groups from Brookhaven National Lab, Yale University, University of Virginia, Florida Institute of Technology, and Stony Brook University set up apparatus as shown on the title page of this report using four of the six available stations at the Fermilab Test Beam Facility. This effort is the largest to date at FTBF and was comprised of 19 detector stations all of which worked flawlessly and collected data over a three week period.

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COLLABORATION STATUS

Recently, interest has peaked in the development of a fast TPC for the EIC. As a result new groups have already joined our consortium and others are discussing membership. Presently one group from Lawrence Livermore National Laboratory (headed by Ron Soltz) and one from the Weizmann Institute of Science (headed by Alexander Milov) have joined the consortium with specific interests in the development of a large TPC. Two other groups are currently in negotiation to join, also with interests in the development of the TPC for central tracking at EIC.

Progress Report

WHAT WAS PLANNED FOR THIS REPORTING PERIOD?

The BNL group:

The main goal for the second half of 2013 was to carry out a beam test of the minidrift GEM detector at Fermilab. The purpose of this test was to try and improve on the measurement of the position resolution of the detector as a function of angle that was done at CERN last year. We also planned to complete the analysis of the CERN data during this time, but the precision of that measurement was limited by the fact that the detector was placed a large distance (~ 2 m) from the telescope that was used to project beam tracks into the minidrift detector. The test at Fermilab used a much more precise silicon telescope that was located less than 30 cm from our detector. The Fermilab test was also carried out in conjunction with tests of detectors from four other groups from the EIC Tracking Consortium, which helped to coordinate the R&D efforts of all of these groups.

We also planned to continue the development of a fast, compact TPC with a GEM readout combined with particle id capabilities using a separate photosensitive GEM detector to detect Cherenkov light.

The Florida Tech group:

Design and fabrication of pcb's with zigzag strip readout. Integration of zigzag pcb's into GEM detectors and testing of performance

The Stony Brook group:

The main goal for the Stony Brook group during this reporting period was the analysis of the test beam data from the SLAC electron run and taking data during the sector test. We specifically chose a funding profile that put development of in-house mirror evaporation into the FY14 funding period.

The UVa group:

Construction of the large trapezoidal GEM prototype. Characterization and testing the performance of the prototype at the beam test at Fermilab.

The Yale group:

The major activity during this period was the preparation for and execution of the test beam run at Fermilab.

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WHAT WAS ACHIEVED?

BNL group:

The analysis of the data from beam test of the minidrift GEM detector at CERN in October 2012 was completed. The detector was tested in the H6 beam line as part of a test of a set of micromegas detectors by the ATLAS Collaboration. We used their micromegas to measure the beam tracks and extrapolate to the position in our detector. Unfortunately, the micromegas were located ~ 2 m from our detector, which resulted in a fairly significant error ($\sim 100 \mu\text{m}$) in the extrapolation. Nevertheless, we were able to unfold this contribution from our measured position resolution, and we obtained results on both the position and angular resolution of the minidrift detector as a function of angle.

Figure 2 shows the main results of the CERN measurement. At small angles, it is not possible to measure a vector in the minidrift detector, so a simple centroid of the charge distribution on the strips gives the best measurement of the position. At larger angles, the uncertainty on the centroid measurement increases dramatically, and the vector measurement provides much better precision on the position. Figure 3 shows the resolution of the angle measurement from the minidrift detector as a function of the angle. We used a weighting algorithm to combine the two methods for all angles and obtained a position resolution that is essentially flat as a function of angle at a value of $\sim 100 \mu\text{m}$. These results were presented at the 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference and have been submitted for publication in the Conference Record of that meeting.

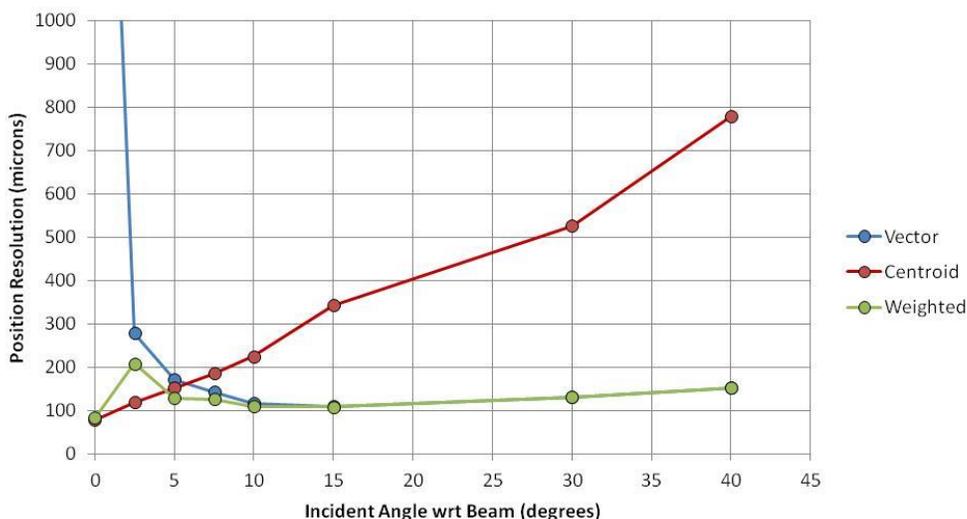


Figure 2 Position resolution of the minidrift GEM detector as a function of angle, using a simple centroid calculation (red curve), the position obtained from reconstructing a vector in the detector (blue curve), and from an algorithm that weights the two method

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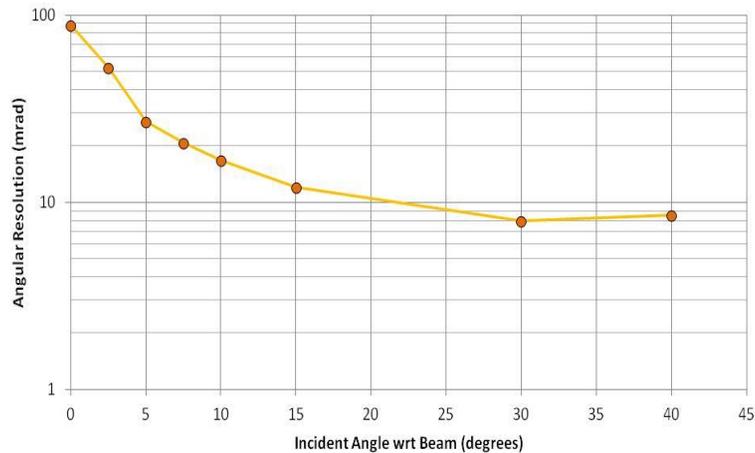


Figure 3 Error on the angle for the vector reconstructed in the minidrift GEM detector as a function of the angle of the incident particle.

Since the error on the extrapolation of the beam track is of the same order the resolution that we measured, we felt it might be possible to improve on this by repeating the test with a more precise measurement of the beam track. We therefore repeated this test at Fermilab and used a high resolution silicon telescope to measure the beam track that was located only ~ 30 cm from our minidrift detector. Figure 4 shows the setup in the MT6.1 test beam area at Fermilab. Our detector was mounted on a rotatable stage that was remotely controlled and used to perform the angle scans. The detector shown in the figure used a standard COMPASS style readout plane, but in addition, we tested a second minidrift GEM detector with a chevron readout plane which will provide information on how we might design the readout plane of our TPC.

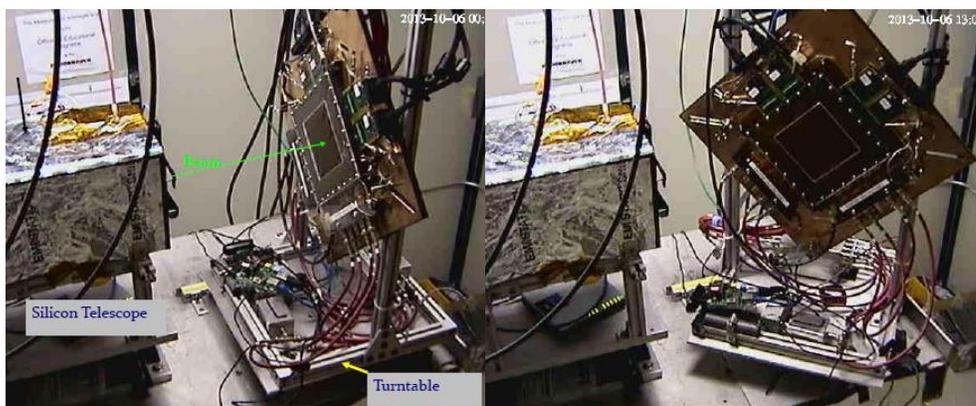


Figure 4 Setup in the MT6.1 test beam area at Fermilab. The minidrift GEM detector was mounted on a remotely controlled rotation stage and the high resolution silicon telescope was located approximately 30 cm away.

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The data from the Fermilab test are in the process of being analyzed and the initial results look encouraging. Figure 5 shows the position resolution obtained from the centroid measurement with the detector at zero degrees and again shows a resolution $\sim 100 \mu\text{m}$. However, obtaining the best resolution at all angles will require a careful alignment of the two detector systems and optimizing the use of the tracks measured in the silicon telescope.

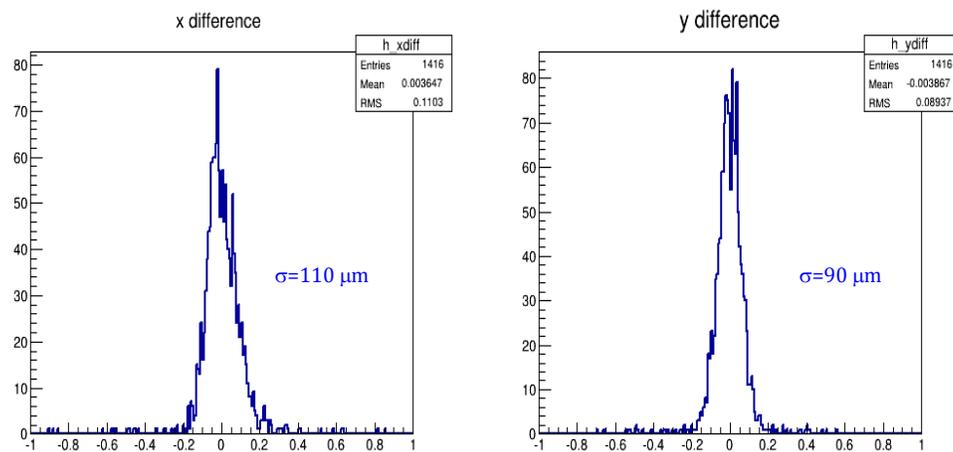


Figure 5 Preliminary results from the minidrift detector at zero degrees using the centroid measurement and tracks measured in the silicon telescope.

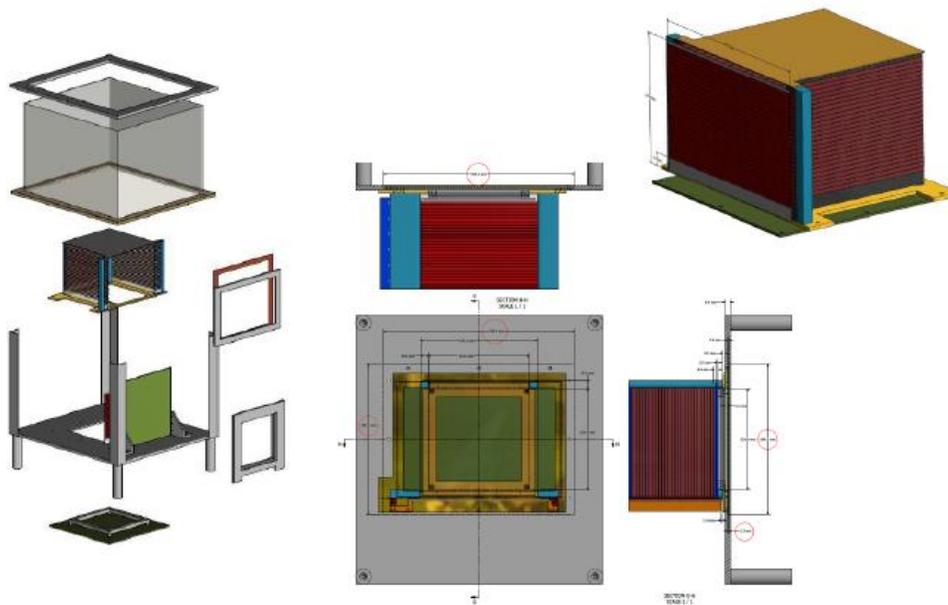


Figure 6 3D model of the prototype TPC/ Cherenkov detector.

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Progress was also made on the development of a prototype TPC/Cherenkov detector. In terms of the design, we focused on the field cage and the GEM detector for the TPC readout. The current detector model is shown in Figure 6. The TPC GEM detector and its readout plane will be removable without having to remove the field cage. We also began a full electrostatic simulation of the field cage which is shown in Figure 7. One of the main concerns with this design is the close proximity of the upper electrode of the field cage to the outermost electrode of the GEM detector that is used to detect the Cherenkov light. We plan to do a more detailed simulation of this region of the detector, but in addition, the photosensitive GEM will be on movable track so that its distance to the electrodes of the photosensitive GEM can be varied in the actual prototype.

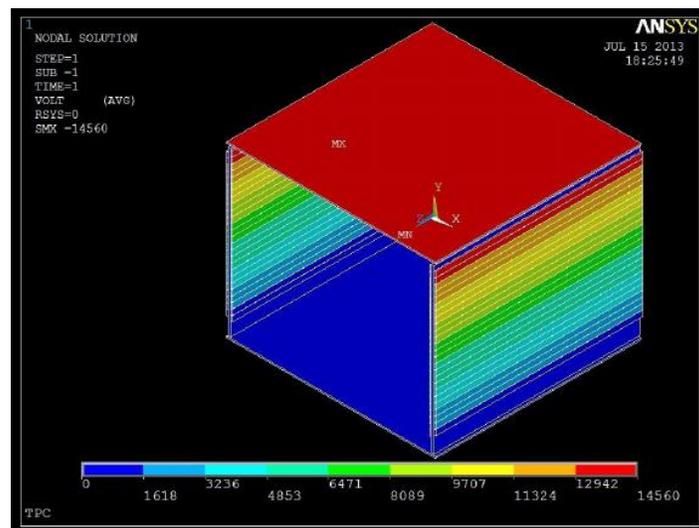


Figure 7 Initial electrostatic simulation of the field cage using ANSYS

We also carried out studies on gases that could be used for the TPC. We tested several neon based gas mixtures, which have higher ion mobility than argon based mixtures that helps reduce the problem of ion back flow in the detector. Figure 7 shows the results of some of the measurements with Ne/CO₂ and Ar/CO₂, and shows that the drift velocity in Ne/CO₂ is significantly higher than in Ar/CO₂. Also shown is a Garfield calculation of the various gas mixtures, and the measurements agree well with the calculations. We next plan to measure mixtures containing CF₄, which should result in even higher drift velocities, and will study these mixtures in terms of their ion back flow properties. Also shown in Figure 8 is a measurement of the charge attachment in a 70/30 mixture of Ar/CO₂ for a drift distance of 32 cm. We plan to also measurements the charge attachment on the other mixtures containing Ne and CF₄.

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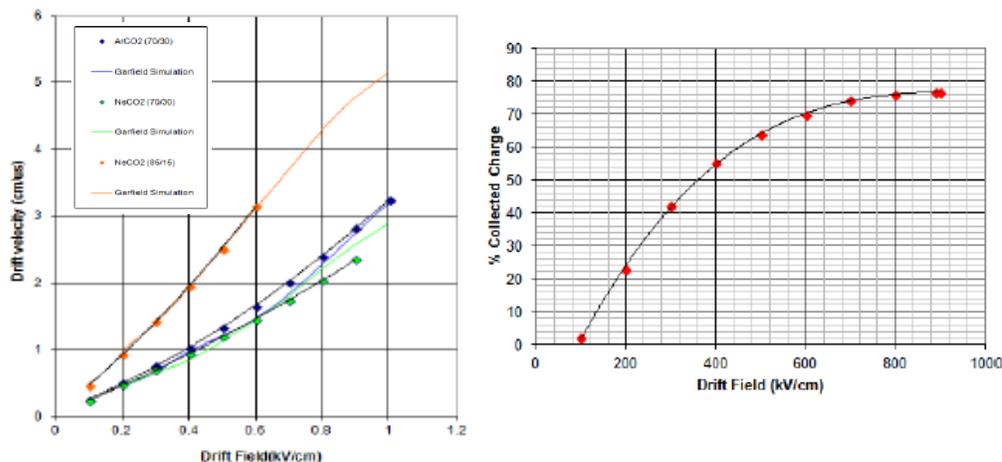


Figure 8 Left: Measurement of drift velocity in Ar/CO₂/Ne gas mixtures with a comparison to a Garfield simulation, Right: Measurement of charge attachment in Ar/CO₂ (70/30) over a 32 cm drift distance.

We also began to study ion back flow in GEM detectors that would be used to read out the TPC, since this could lead to significant field distortions at higher luminosities at EIC. While GEMs alone suppress ion back flow significantly compared to conventional wire chambers, micromegas are even more effective in suppressing ion back flow than GEMs due to the high concentration of field lines inside the gap. However, it may be more difficult to operate micromegas at higher gains, and therefore a combination of GEMs and micromegas may be able to achieve more stable operation with low ion back flow. To study this, we built a small detector consisting of an initial two stage GEM followed by a final stage micromegas and measured the ion back flow. The results are shown in Figure 9 for a 70/30 mixture of Ar/CO₂. It shows that it is possible to achieve an ion back flow as low as 0.2% by varying the ratio of the field in the transfer gap in front of the micromegas to the field inside the micromegas. These results are quite encouraging and we plan to repeat them for mixtures containing both Ne and CF₄ in order to find a gas that has both a fast drift velocity and very low ion backflow.

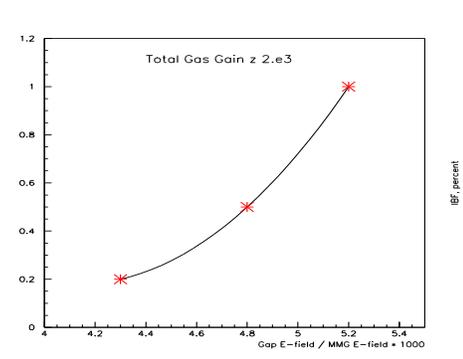


Figure 9 Measurement of ion back flow in a three stage detector consisting of a two stage of GEM followed by a final stage micromegas. The vertical axis is the percentage of ion back flow (defined as the ratio of the anode current to the current produced by the primary ionization) and the horizontal axis is the ratio of the voltage in the transfer gap between the GEM and micromegas to the field inside the micromegas. The operating gas was 70/30 Ar/CO₂.

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Florida Tech group:

Dr. Aiwu Zhang, the new EIC hardware post-doc, arrived at Florida Tech in June 2013. His involvement significantly sped up our design work for pcb's with zigzag strip readout. Aiwu and his team of undergraduates, Liz Starling and Kimberly Walton, designed four different pcb's using Altium software and had them produced in US industry. These comprise two separate designs with radial zigzag strips for 10cm×10cm GEM detectors (one with 30 strips and another with 48 strips) and a design for a 30cm×30cm GEM detector with four distinct readout patterns (one with 128 parallel 10cm-long zigzag strips, another with 30cm-long zigzag strips, and two sectors with 10cm-long radial strips). They also designed a large pcb for a 99cm×(22-45)cm trapezoidal chamber, the first full-size prototype for a cost-efficient EIC forward-tracker chamber (Figure 11).

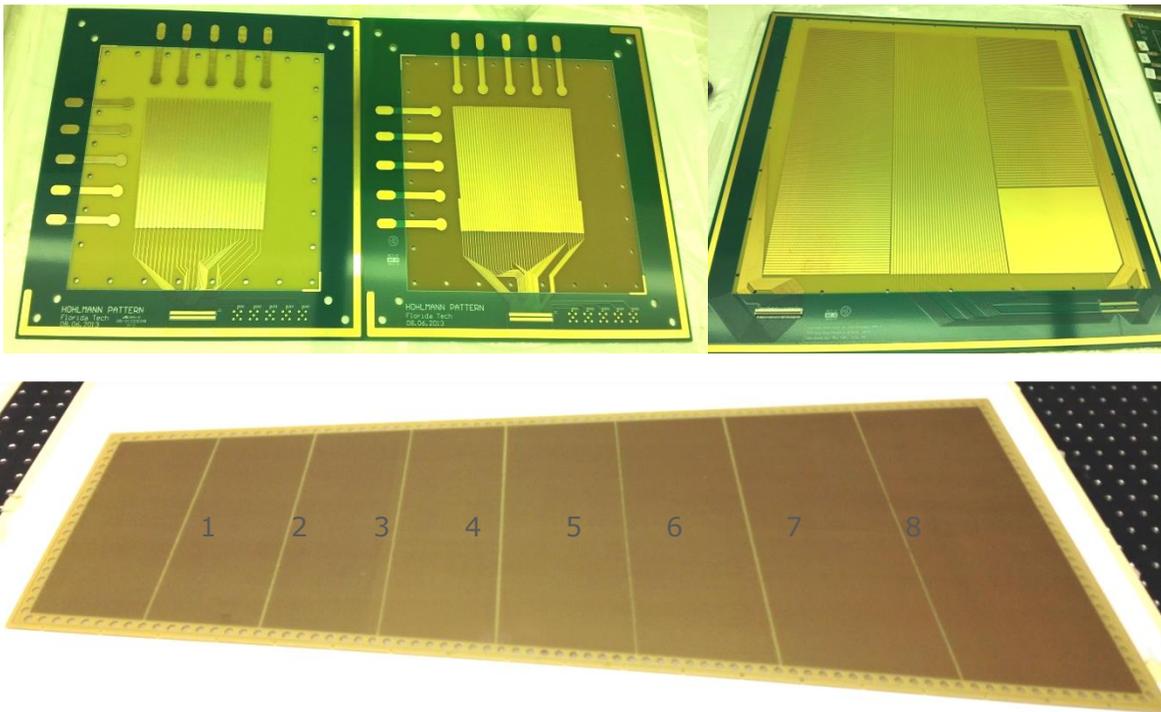


Figure 10 Printed circuit boards with radial zigzag strips designed at Florida Tech. **Top:** Boards for 10cm×10cm GEM detectors with 30 (left) and 48 (center) radial strips and for 30cm×30cm detector with four distinct strip patterns (right). **Bottom:** Printed circuit board for large 99cm × (22-45)cm trapezoidal chamber with eight numbered η -sectors. Each sector features 128 radial zigzag strips with varying pitch.

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Figure 11 Trapezoidal GEM chamber with zigzag pcb instrumented with APV hybrids. Four HDMI cables (black) linked to the SRS DAQ suffice to read out the entire chamber.

We installed all pcb's in triple-GEM detectors; the drift / transfer1 / transfer2 / induction gap configurations were 3:1:2:1 mm for the large trapezoidal chamber and 3:2:2:2 mm for all other detectors. The chambers were then commissioned on campus using an x-ray generator. In addition, we bought, assembled, and commissioned a new standard 10cm×10cm GEM detector with 2D straight-strip readout for use as a reference tracking detector. Aiwu and graduate student Vallary Bhopatkar transported all five detectors to the FNAL test beam facility, where they installed and commissioned them in the MT6.2 beam line. They were supported by undergraduate Jessie Twigger in the first week of the test. The 10cm×10cm detector was mounted in a fixed position together with three 2D GEM detectors provided by U. Virginia to form a reference tracker. The zigzag detectors were installed on a mobile stage together with the test detectors from U. Va. (Figure 12).

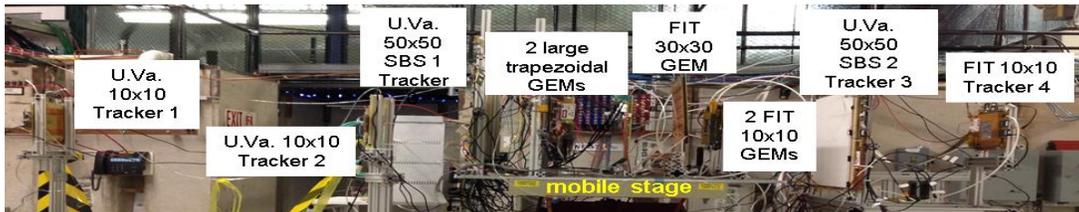
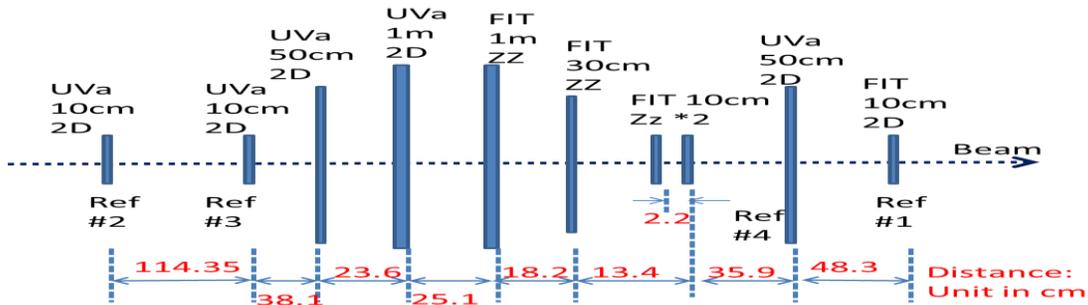


Figure 12 Top: GEM detector arrangement at FTBF by FIT and U.Va. The first two and the last two detectors were fixed on individual stands as reference; the six test detectors in between were installed on a 2D motion stage. Bottom: Photo of detectors in beam line.

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Florida Tech and U. Va. pooled their RD51 Scalable Readout System (SRS) electronics to read out all ten tracking chambers simultaneously in a common system. In total, about 8k channels were read out for each trigger in this first slice test for an EIC forward tracker and the team collected data for over three million triggers over a period of three weeks. In the last data taking period, we swapped the zigzag readout board in the large trapezoidal chamber for a standard CMS straight-strip readout board to collect some reference data. Runs included high voltage scans and position scans. We were supported in the data taking effort for two weeks by Patrizia Barria, a CMS GEM colleague from U. Brussels. With remote support from undergraduate Mike Phipps at Fl. Tech, the team adapted our DAQ software based on AMORE for monitoring the data taking and later for offline analysis.

Here, strips with induced charges five times above noise level are accepted as hit strips and grouped into clusters. The noise level is determined from the rms widths of pedestals on a strip-by-strip basis and ranges from about 4 ADC counts (0.15 fC) for straight strips to 6-10 ADC counts (0.22-0.37 fC) for zigzag strips.

We highlight first results from our ongoing offline data analysis focusing on the large trapezoidal chamber with zigzag readout. The total cluster charge distributions follow Landau distributions as expected (Figure 13 left). The pulse peaks are reasonably well centered in the $9 \times 25\text{ns}$ readout window (Figure 13 right). The most probable values from the Landau fits increase exponentially with HV as expected for a gaseous detector (Figure 14 left). The cluster widths also increase with HV (Figure 14 right). The triggered events overwhelmingly contain single clusters (Figure 15 left). The efficiency of the chamber can be determined from the fraction of triggered events with at least one reconstructed cluster and is plotted vs. HV (Figure 15 right). The efficiency of this chamber, which has a 2mm drift gap, plateaus above 3200V with a value larger than 97%. A scan of the total cluster charge across seven η -sectors shows a considerable systematic response variation at the $\pm 20\%$ level (Figure 16 left). This is consistent with previous results obtained at CERN by the CMS GEM collaboration with a chamber of the same type of construction. The non-uniformity is due to a slight bending of the drift and readout boards after the GEM foils are tensioned that produces non-uniformity in the widths of the drift and induction gaps across the chamber. We plan to address this issue with a new prototype that is constructed from pre-bent boards to compensate the bending due to GEM tensioning (for more details see section on future plans). The vertical beam profile is well measured with this chamber (Figure 16 right) giving a vertical beam width of $\sigma = 3.1$ strips or 7.3 mm for the 32 GeV beam.

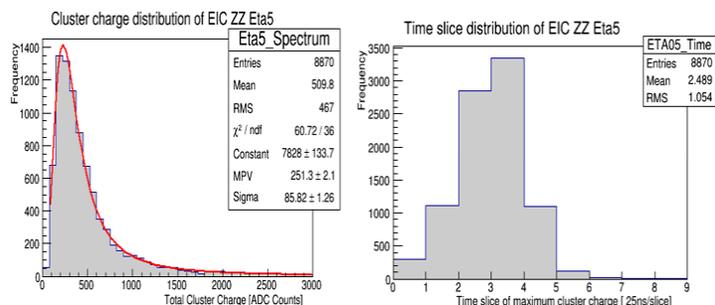


Figure 13 Cluster characteristics of large trapezoidal zigzag detector (sector 5 at 3200V for 25GeV mixed hadron beam). Left: Total cluster charge distribution with Landau fit.

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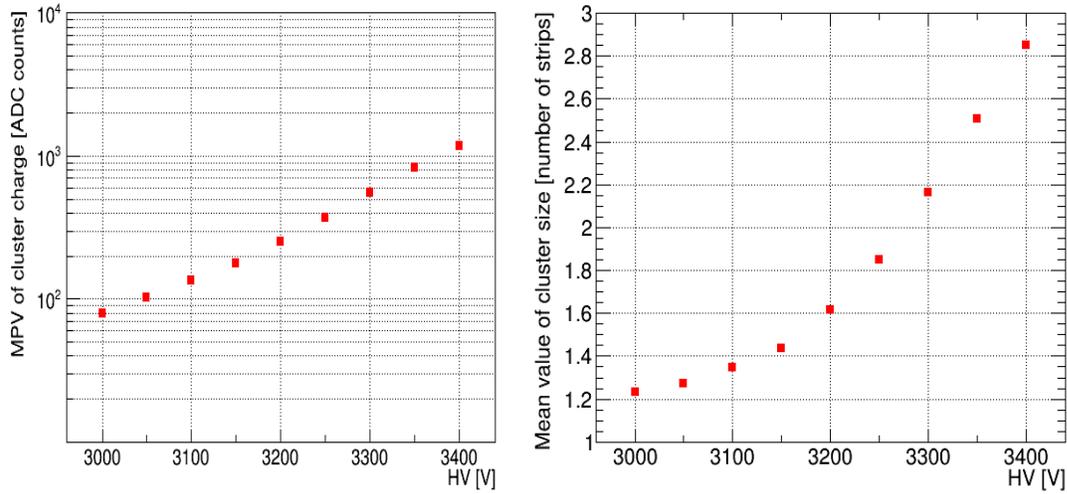


Figure 14 Results from HV scan for central part of η -sector 5 in large trapezoidal zigzag detector. Left: Most probable value (MPV) of cluster charge from Landau fit vs. HV showing exponential increase with high voltage. Right: Mean value of cluster size also increases with high voltage. Errors are smaller than marker symbols in both plots.

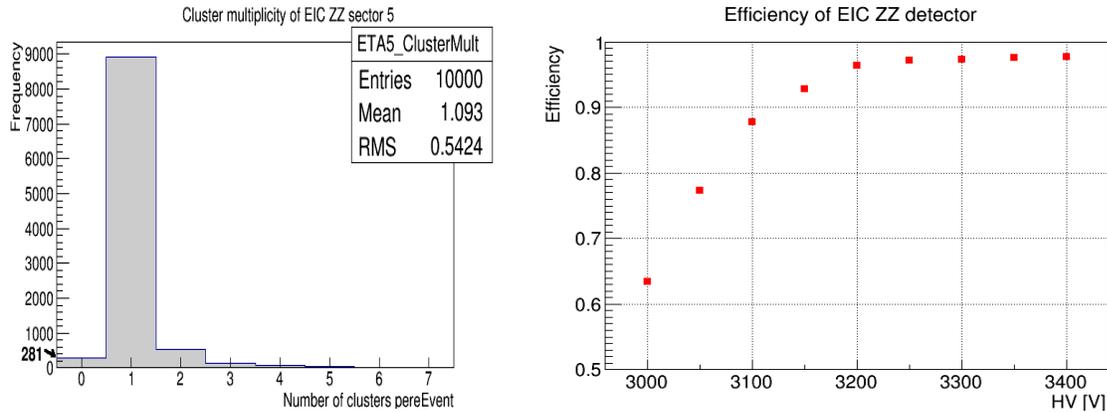


Figure 15 Left: Cluster multiplicity in η -sector 5 at 3250V in large trapezoidal zigzag detector. Right: Efficiency for central part of η -sector 5 in same detector vs. high voltage as calculated from event fraction with non-zero cluster multiplicity plateaus above 97%.

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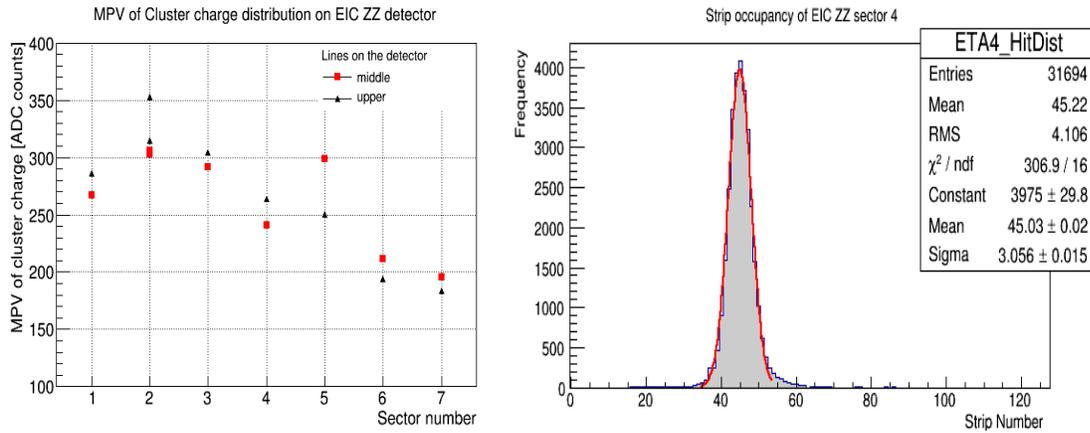


Figure 16 Left: Scan of most probable cluster charge for large trapezoidal zigzag detector in first seven sectors at 3200V. The detector was scanned along two different horizontal rows. The response non-uniformity is about $\pm 20\%$. **Right:** Strip occupancy in η -sector 4 of trapezoidal zigzag detector reflecting the beam profile along vertical y-axis.

The two 10cm×10cm zigzag detectors were positioned only 2cm apart and we expect that any beam divergence over that distance is very small. Consequently, the difference in y-hit positions, i.e. the Δy_{hit} distribution, can be used to estimate the average spatial resolution of the two zigzag detectors. A Gaussian fit of the core of the Δy_{hit} distribution for clusters with three or four strips shows a width of $\sigma=0.122$ strips or 256 μm (Figure 17 left) as the pitch for the 48 zigzag strips is about 2.1mm. Since the two detectors are of identical construction, the spatial resolution of one chamber can be estimated to be $\sigma/\sqrt{2} \sim 173\mu\text{m}$. When the same detectors are equipped with the readout boards with 30 zigzag strips, the Δy distribution for clusters of three strips is narrower with $\sigma=0.023$ strips or 76 μm (Figure 17 right); the strip pitch in this board is 3.3mm. This is unexpected as the strip pitch 30-strip board is larger than in the former and the electron avalanche is sampled more coarsely. Our hypothesis is that this is due to a systematic difference in the detailed structure of “zigs” and “zags” of adjacent strips in the two boards with the 30-strip board featuring sharper tips. Note that the 30-strip and the 48-strip boards were produced by two different pcb companies.

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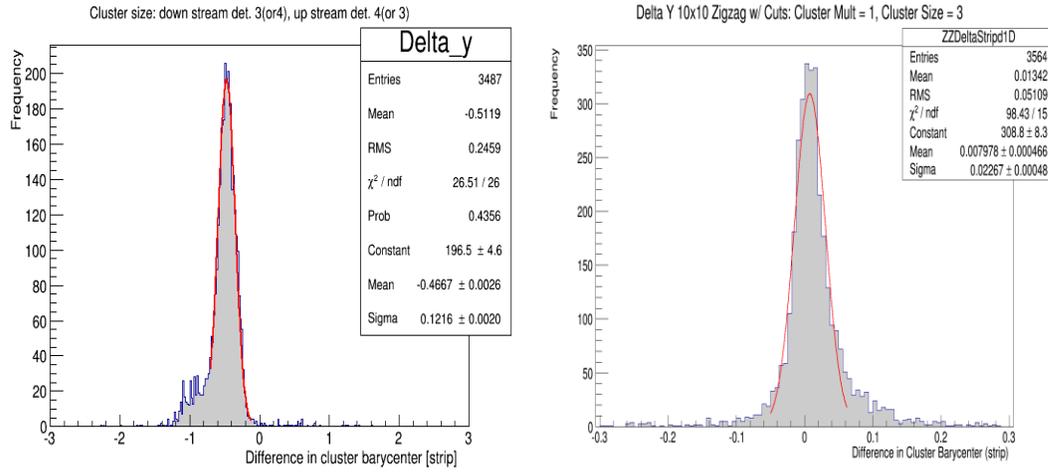


Figure 17 Left: Difference in y-positions of strip cluster barycenters measured for the same traversing beam particle using the two 10cm×10cm detectors with 48 zigzag strips at 4100V. Plot is for events with three strips in one cluster and four strips in the other. **Right:** Same for 10cm×10cm detectors with 30 zigzag strips at 4050V for events with three strips in both clusters. The distribution cores are fitted with Gaussians.

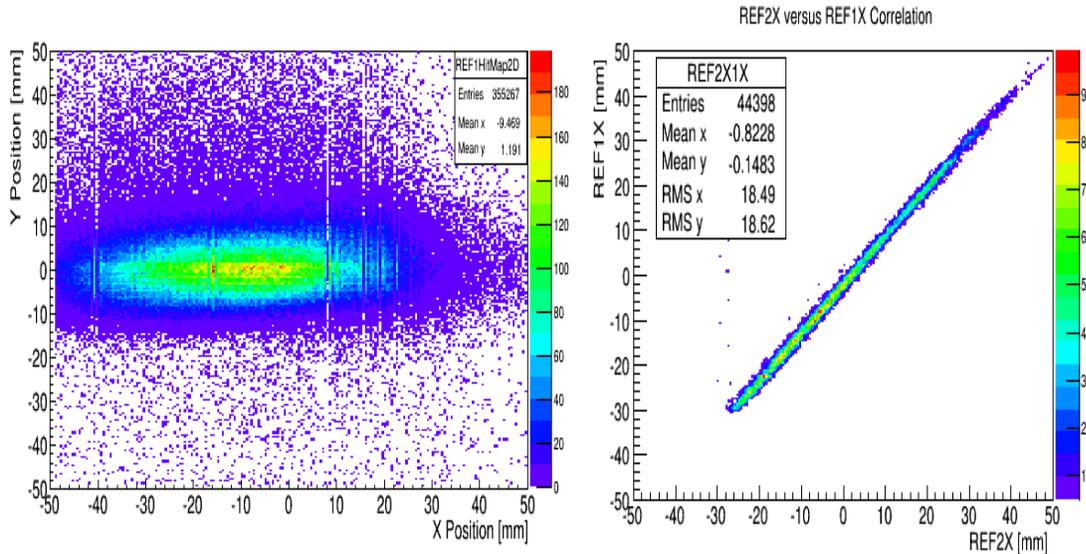


Figure 18 Left: Hit map in FIT 10cm×10cm reference detector for 32 GeV mixed hadron beam. **Right:** Correlation of x-positions of hits in this most downstream detector (“Ref.1”) with x-positions in most upstream 10cm×10cm reference detector (UVa’s “Ref.2”) after coarsely aligning both detectors, which were placed >3m apart in z, to the beam center.

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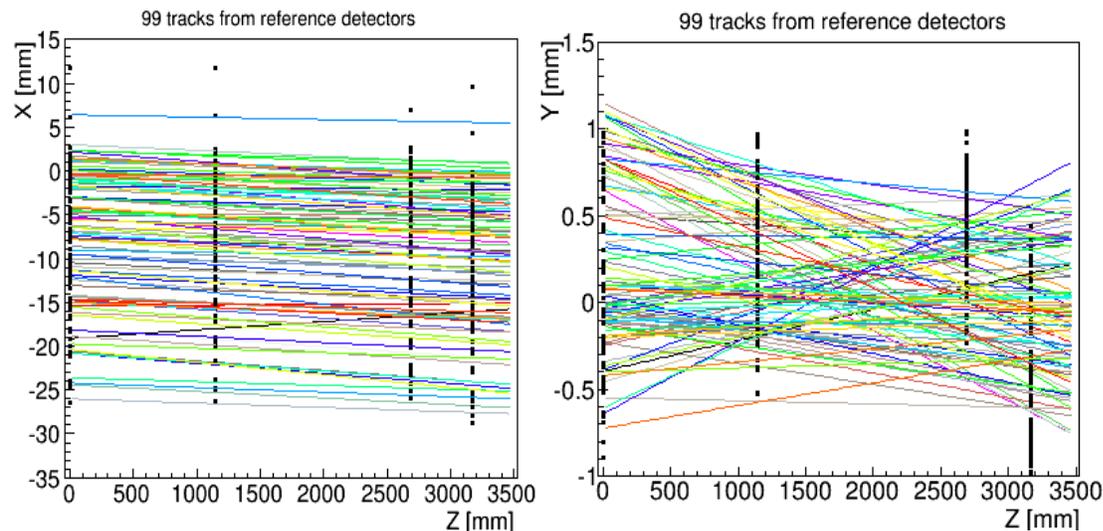


Figure 19 First example of basic track reconstruction using all four reference trackers. Shown are track fits for 99 tracks with y -hits in the range $-1\text{mm} < y_{\text{hit}} < 1\text{mm}$ from one run. Left: X-Z plane. Right: Y-Z plane. Black squares indicate hits. Note that the trackers are only coarsely aligned to the beam center for now.

The high-statistics image of the beam spot for the 32 GeV mixed-hadron beam in the Fl. Tech $10\text{cm} \times 10\text{cm}$ reference GEM detector (Figure 18 left) shows that the beam is mostly contained within the acceptance of that detector and reasonably well centered. The other three tracking reference detectors give similar beam spot images. The x -coordinate measured in this most downstream detector is highly correlated with the x -coordinate measured with the most upstream detector (Figure 18 right). The correlations with the other tracking detectors and for all the y -coordinates are similarly high. This is promising for reconstructing high-precision tracks in the four reference trackers for the ultimate determination of spatial resolutions and efficiencies in the probed detectors. We are currently working on the track reconstruction and alignment of tracking detectors. An example of first reference track fits using just a coarse alignment of the tracking detectors to the beam center is shown in Figure 19.

Stony Brook Group:

The principal goal from the Stony Brook group was to extend our knowledge of the EIC RICH detector from its performance in electron beam (wherein all beam particles have saturated their ring radius) to true identification of hadrons. The FTBF facility is ideal for this purpose since it has the ability to deliver secondary beams momentum analyzed from collisions of the 120 GeV/c proton beam impinging on a target. The FTBF facility has two targets. The upstream target delivers 8-66 GeV/c particles. Unfortunately, beams from that target are virtually devoid of Kaons due to decay in flight. The downstream target provides 1-32 GeV/c secondaries and was used for our studies.

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FTBF provides a differential Cherenkov counter for identification of the beam particles. Although this detector was out of service when we arrived, we were able to repair it and use it for our beam tests. A sketch of the device is shown in Figure 20.

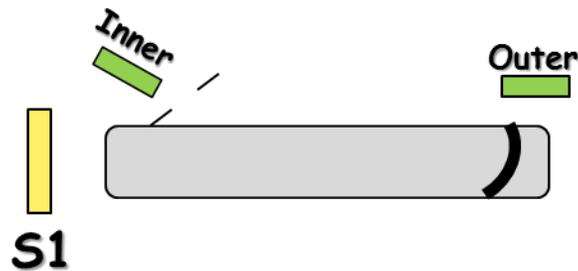


Figure 20 Sketch of the FTBF Differential Cherenkov.

We tuned the pressure in this detector so that pions would fire the “outer” detector, Kaons would fire the “Inner” detector and protons would fire neither. Despite being closer to our apparatus, the downstream target still only provided ~1% content of Kaons. For this reason, we developed a trigger on the inner Cherenkov counter to take “Kaon-only” data. Our running period was divided such that 50% of the clock time was dedicated to Kaon trigger data.

Because the current implementation of the detector pad plane has coarse segmentation (5mm hexagons), the ring radius resolution would be limited by the determination of the ring center. To overcome this limitation, we build two tracking detectors from “spare parts” available from our consortium allies. Beam spots from these trackers are shown in Figure 21.

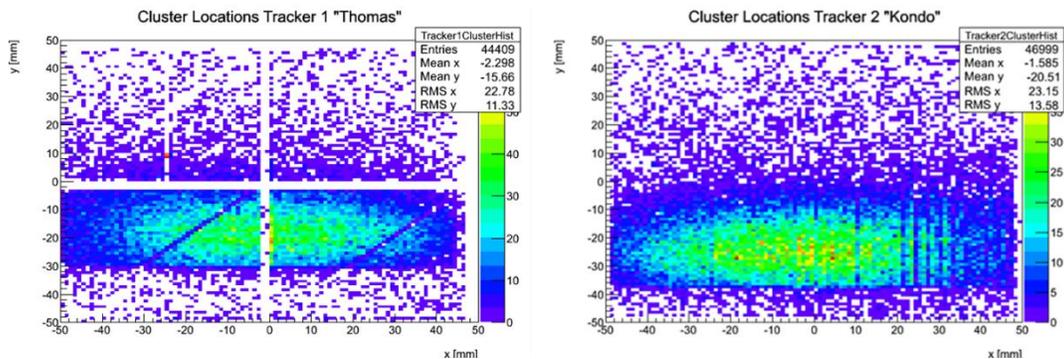


Figure 21 Beam spots in the “Cherenkov Trackers”.

For intense rings (well above the Cherenkov threshold) we are able to determine the ring center using the ring itself. An empirical alignment was determined by plotting the correspondence between the self-determined ring center with the direction vector of the tracks from the trackers (not shown for sake of brevity). Once aligned, rings are determined in two stages:

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- Hit pads are histogrammed in their apparent radius.
- A trial radius is determined by the maximum of the histogram.
- Pads are collected in a road around the peak channel.
- The collected pads are fit to a ring radius.

Shown in Figure 22 below are data from the highest beam momentum (32 GeV/c) with a variety of plots. Three histograms show the distributions of number of hit pads for pions, kaons, and protons as defined by the beamline Cherenkov detector. Pions show a mean number of fired pads at ~12 pads. The lower right-hand plot shows the number of fired pads vs the radius of the ring squared. Because Cherenkov light yield follows $\frac{dN_Y}{dL} = 2\pi\alpha \sin^2 \theta_C \int \epsilon(\lambda) \frac{d\lambda}{\lambda^2}$ and $R = f \sin \theta_C$, we expect that the photon yield will scale linearly with the radius squared, as it does.

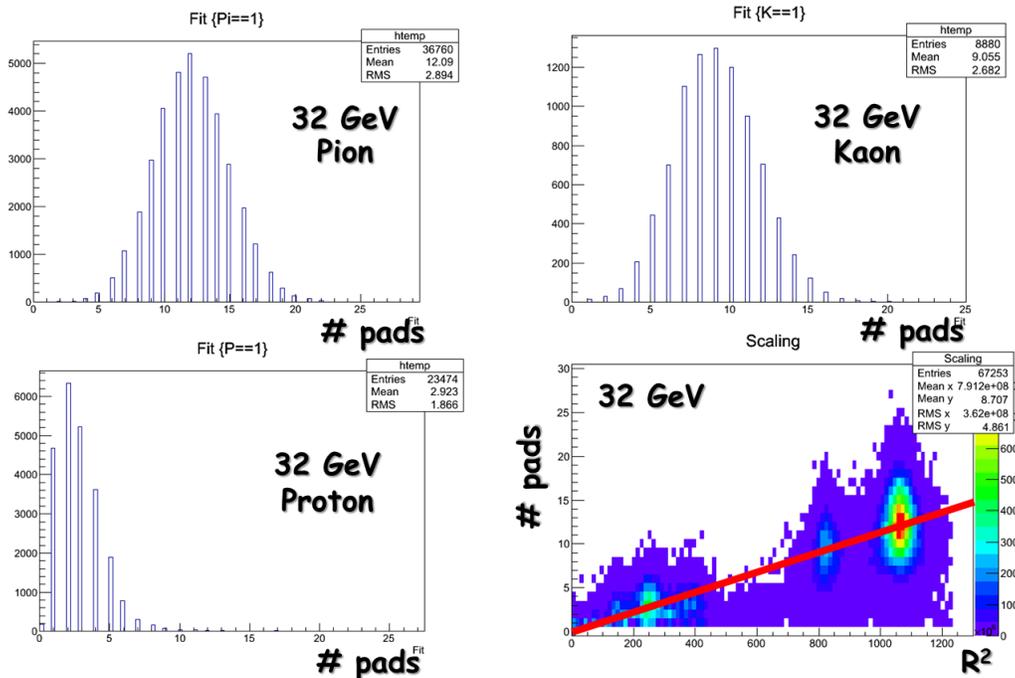
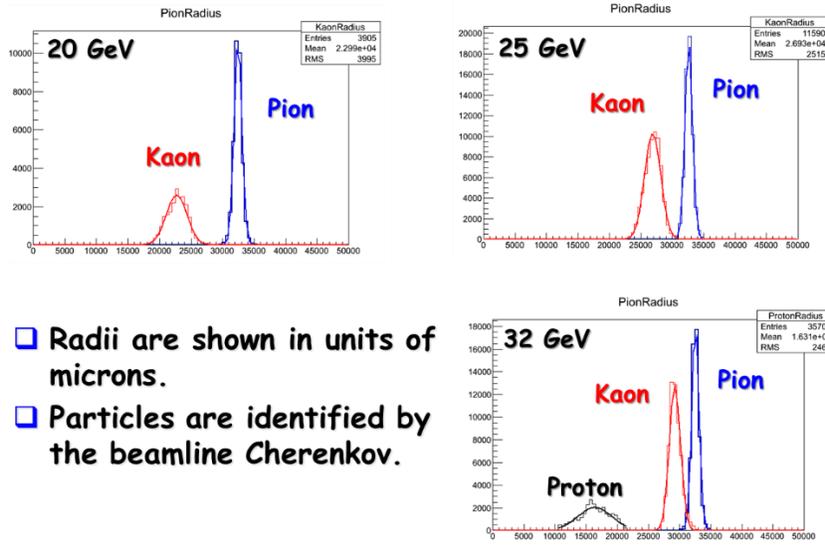


Figure 22 Histograms show distributions of the number of fired pads for various particle species. The color plot shows the dependence of the number of pads on the radius squared.

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Because the Cherenkov threshold for Kaons in CF_4 is ~ 16 GeV/c and the known tunes for the FTBF are in 5 GeV/c increments, only three beam energies are useful for collecting data: 20 GeV/c, 25 GeV/c, and 32 GeV/c. Figure 23 shows the distributions of radii for identified particles at all these radii. As is apparent the separation is superb.



- Radii are shown in units of microns.
- Particles are identified by the beamline Cherenkov.

Figure 23 Particle Identification accomplished by our RICH.

These peaks can be well understood in terms of radius and width. The radius is determined by the particle velocity. The left panel of Figure 24 shows the correlation between the measurement and the calculation with the best fit index of refraction $n=1.00055$ (in agreement with published results). The right panel of the same figure shows the expectation for the width accounting for dispersion in the gas, segmentation of the RICH, momentum bite of the FNAL beam line (fitted, but reasonable), and a constant term of 240 microns to account for all other factors. The fit is not great and is likely attributed to the assumed momentum bite of the beam line.

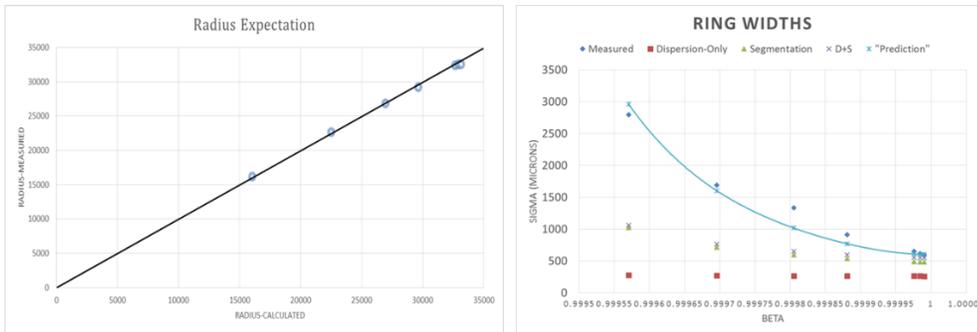


Figure 24 Analysis of radius data.

Overall, the RICH results must be considered as superb.

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UVa group:

We have successfully built 1 m long trapezoidal GEM prototype with 2D readout strips for the EIC Forward Tracker R&D. Figure 25 shows a picture of the chamber. The assembly of the chamber was completed in September 2013 and represents the largest GEM detector with 2D readout ever built.

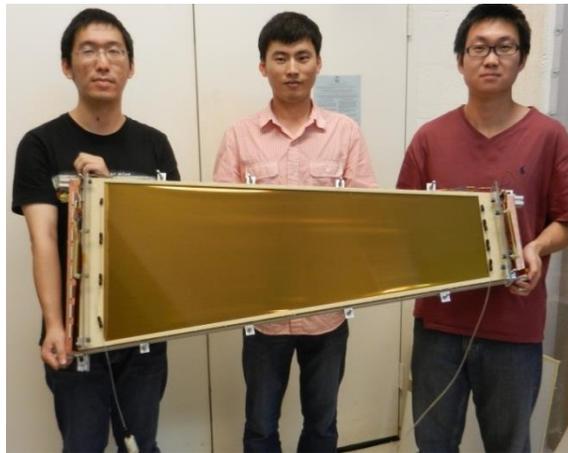


Figure 25 Large area GEM prototype for EIC forward tracker

Figure 26 shows GEM foil design (electron amplification device) with its 32 HV sectors electrodes located at the inner and outer radius sides, and the drawing of the flexible 2D u-v readout board (right) with a 12° angle between the top layer strips and the bottom layer strip. The connectors to the front-end electronics are located at both the inner and outer radius sides of the chamber.

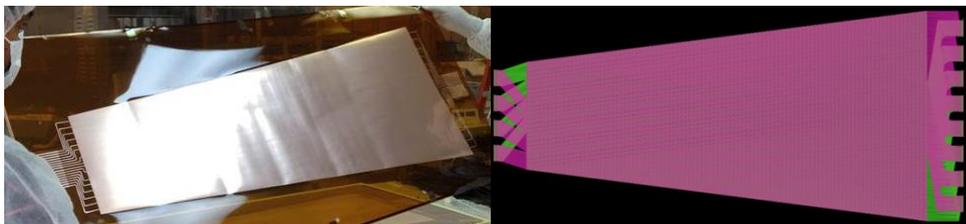


Figure 26: The GEM foil (left). The drawing of the 2D u-v strips readout board (right).

For the assembly, we fabricated a dedicated large size mechanical stretcher based on the concepts we previously developed for the $50 \times 50 \text{ cm}^2$ detector R&D for the tracking system of the Super Bigbite Spectrometer (SBS) in Hall A for the 12 GeV Upgrade at JLab. A N_2 box was also fabricated for the test of GEM foil HV sectors in dry environment (in nitrogen gas flow) before and during the assembly Figure 27 shows a picture (left) of the GEM foil on the large stretcher with the spacer frames glued onto it and the framed foil being tested in the N_2 box (right).

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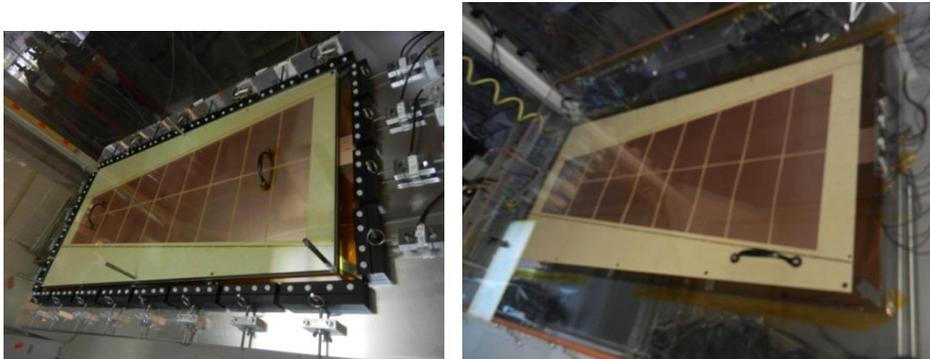


Figure 27: GEM foil with its support frame on the mechanical stretcher (left) and under test in the N₂ box (right)

The EIC GEM prototype was brought to Fermilab Beam Test Facility (FTBF) in October 2013 as part of the EIC Tracking and PID T-1037 beam test effort, together with two (50 cm × 50 cm) SBS GEM chambers and two small (10 cm × 10 cm) GEMs that we use as trackers. During the 3 weeks of the test beam, we accumulated about 1Tb of data under various configurations to study the spatial resolution, gain uniformity and detector efficiency of the GEM chambers under study. On the right picture of Figure 27 we could see the EIC GEM prototype on a mobile stage on MT6.2 beam line at FTBF together with two SBS GEM chambers and large 1 m long trapezoidal GEM detector with zigzag readout (EIC-CMS-FIT) from Florida Tech.

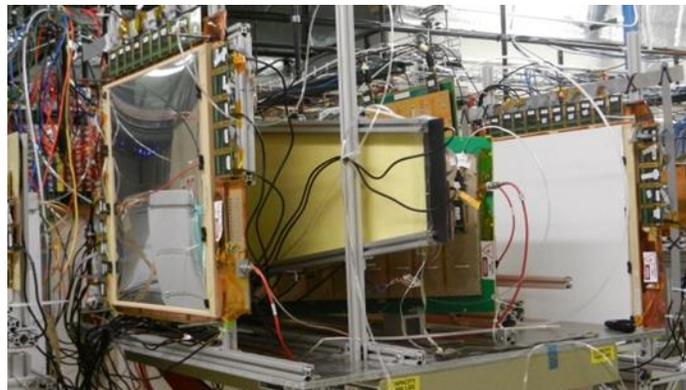


Figure 28: EIC GEM prototype on the test beam setup at FNAL (Oct. 2013)

Figure 29, Figure 30, and Figure 31 show preliminary results from the beam test data analysis. The left plot on Figure 29 is the position scan of EIC GEM chamber with 25 GeV hadron beam with a very good response uniformity of the chamber over the scanned area. On the right we could see an excellent correlation of the charge sharing between the top strips and bottom strips of the 2D u-v readout board.

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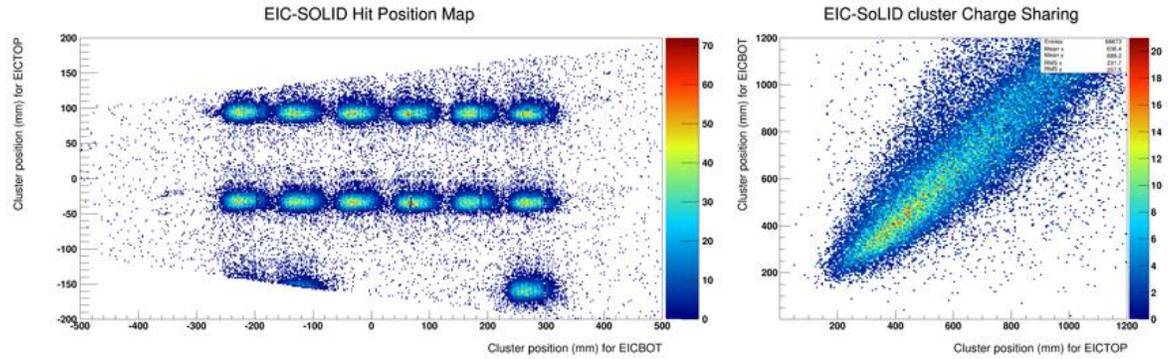


Figure 29: 25 GeV Hadron beam position scan (left); u-v strips charge sharing correlation (right).

Figure 30 shows the total cluster charge distribution on bottom layer strips and top layer strips of the chamber with the expected Landau shape by minimum ionizing particles energy deposit in the chamber.

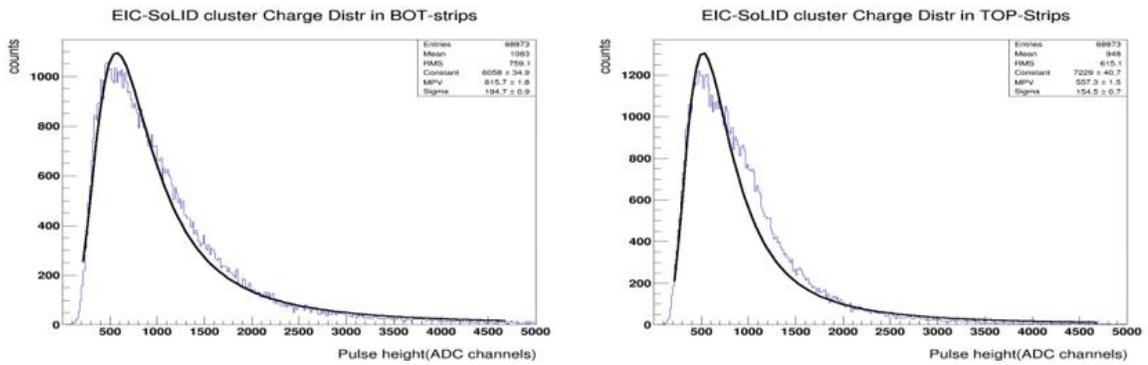


Figure 30: cluster charges distribution with Landau fit on v-strips (left) and u-strips (right).

Figure 31 plots the cluster size distribution for the top strips (u-strips) and the bottom (v-strips). A cluster is defined by all the consecutive strips with charges five times above the noise level define as the rms width of the pedestal for each individual strip.

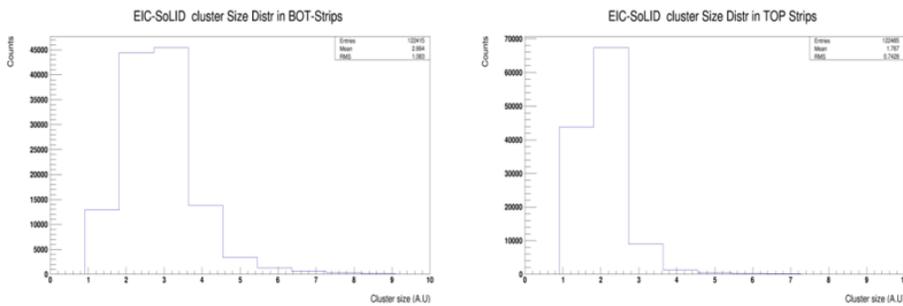


Figure 31: Cluster size distribution on v-strips (left) and u-strips (right).

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The analysis of the beam test data is still ongoing for spatial resolution and gain uniformity and efficiency studies of the chamber. The final results will be presented at conferences and published in peer-reviewed scientific journal.

Yale group:

Four chambers with 800 μm pitch 3-coordinate readout were installed in the MT6 beam and operated for 3 weeks during the month of October. The chambers were instrumented with 2024 channels of RD51 SRS readout (APV25 based system). Figure 32 shows the chambers installed in the beam at Fermilab. The second chamber was installed on a 2-axis pivoting frame so that it could be remotely rotated in both pitch and yaw directions. Data were taken at multiple high voltage settings, multiple angles (from normal incidence to 45° in both directions) and with two different gas mixes (Ar + 10% CO₂ and Ar + 5% CO₂). The run was quite successful with ~2.5 million tracks recorded. Figure 33 shows an event display of a typical event with clear hits in all chambers in all 3 coordinates.

The four 3-coordinate GEM chambers were operated for three weeks in the test beam at Fermilab in October 2013. The readout board pattern for the 4 chambers is shown in Figure 34. Figure 35 shows the chamber layout along the beam. Extra space was allowed between chamber 2 and chambers 1 and 3 to allow space for chamber 2 to rotate. Since that run we have begun to look at the data acquired there and even with a rather crude first look the spatial resolution is about as expected for normal incidence tracks (~100 μm). The test beam was operated at different momenta from 20 – 32 GeV/c tuned to transmit positive particles. At any of these momenta the contribution to track point resolution from multiple Coulomb scattering in the 3-coordinate chambers should be small.

Figure 36 shows a typical beam profile measured in one of the chambers with a 32 GeV beam setting. The units are chamber strip number (0.08 cm pitch). Figure 37 shows the beam dispersion (angle vs. position) using the position difference in the first and last chambers to measure the angle. The small positive correlation in the horizontal plane indicates the beam is slightly diverging in the horizontal (~3 mrad full width).

Figure 38 shows the residuals from tracks fitted to the hits in all four chambers in one coordinate. For these fits only the transverse alignment has been done so far (vertical and horizontal offsets corrected). Relative rotations about the beam axis are expected to be small given the mechanical tolerances in the construction of the chambers and support structure however we will measure and correct for them as the analysis proceeds. Applying the appropriate scale factor to convert residuals to resolution gives an average resolution of 107 μm for the data shown (96 – 117 μm across the 4 chambers). This is already quite reasonable for an 800 μm pitch chamber.

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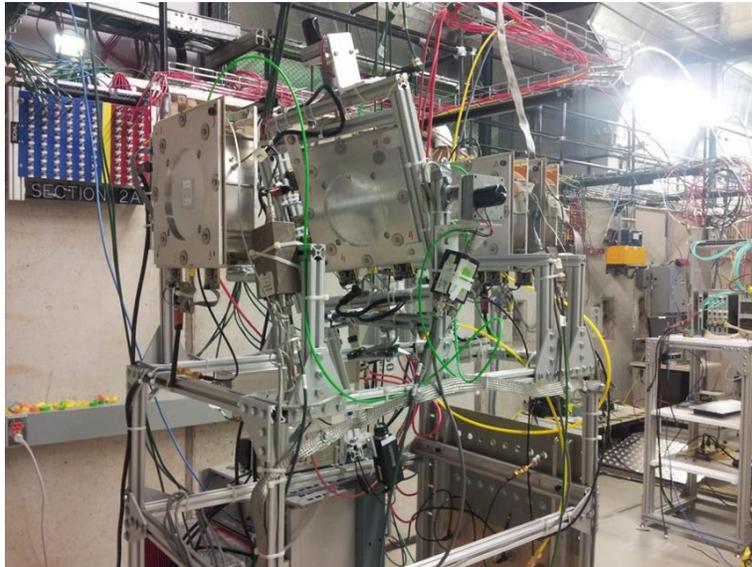


Figure 32. Four 3-coordinate GEM chambers in the test beam at Fermilab. The second chamber can be remotely rotated and is shown rotated from normal beam incidence.

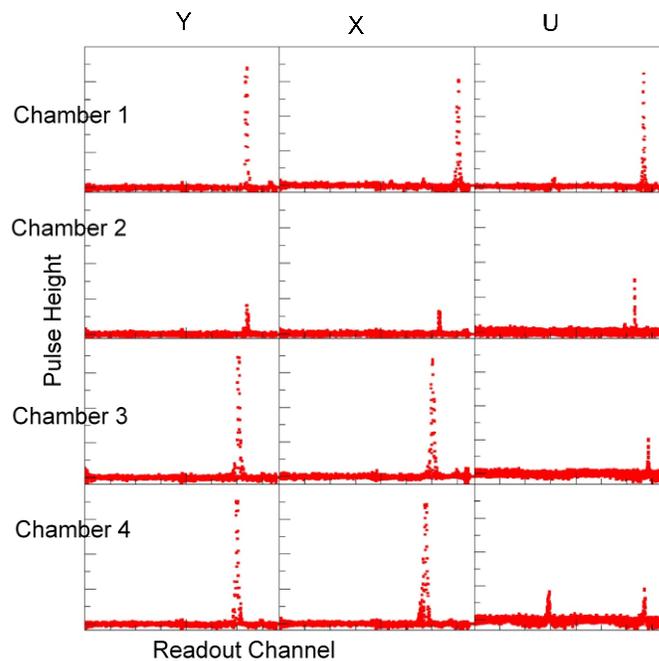


Figure 33. Typical event display showing signals from all 4 chambers and all 3 coordinates. Horizontal is readout channel, vertical is signal pulse height. (X= horizontal, Y = vertical, U= 45° diagonal coordinate). Note: all 15 time bins that were read out are plotted for each channel.

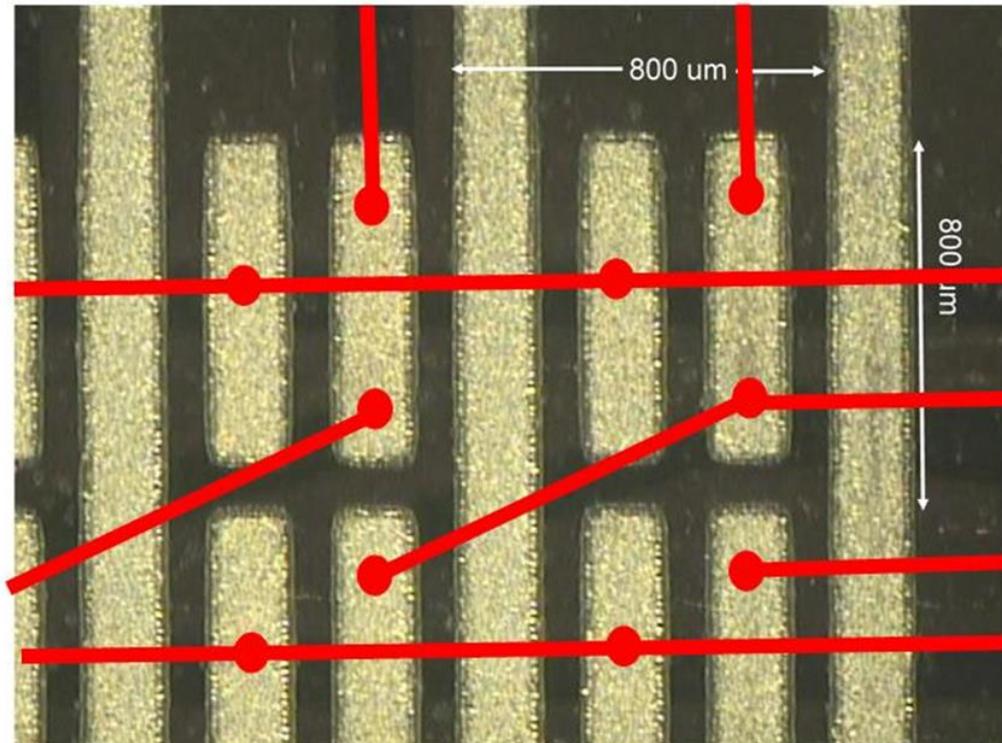


Figure 34. Image of the upper right corner of a 3-coordinate readout board. Pattern is fabricated with 5 μm copper on 50 μm polyimide film. Image shows readout side, red shows vias and routing on back side.

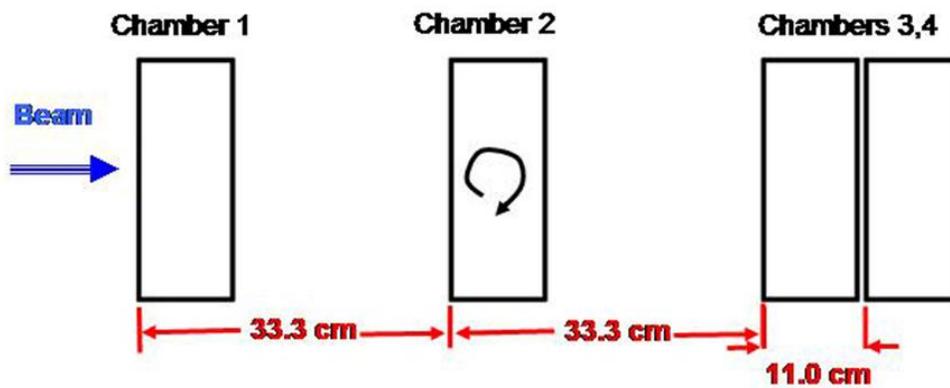


Figure 35. Layout of chambers on beam line. Chamber 2 can be rotated remotely in pitch and yaw.

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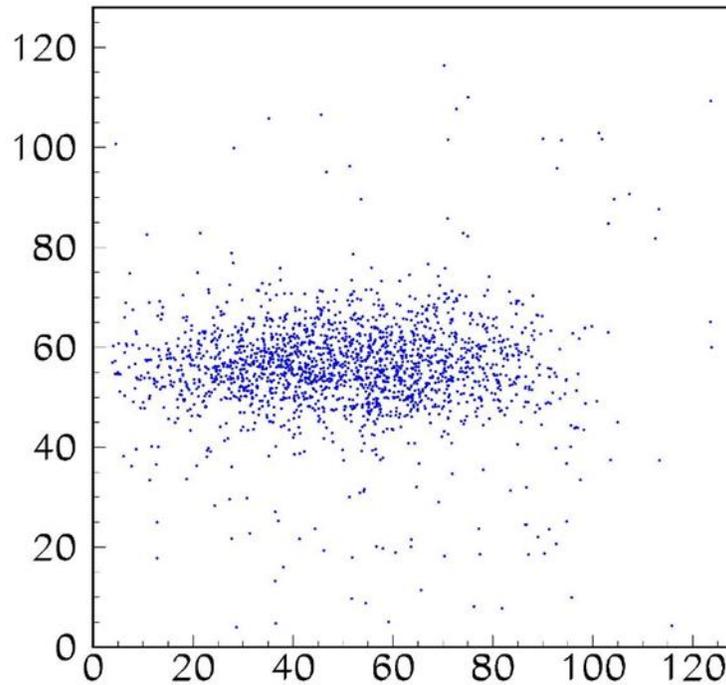


Figure 36. Typical beam profile (32 GeV/c positive beam). Scale is detector channel number = 0.8 mm per channel. Full scale is 10 cm in both horizontal and vertical.

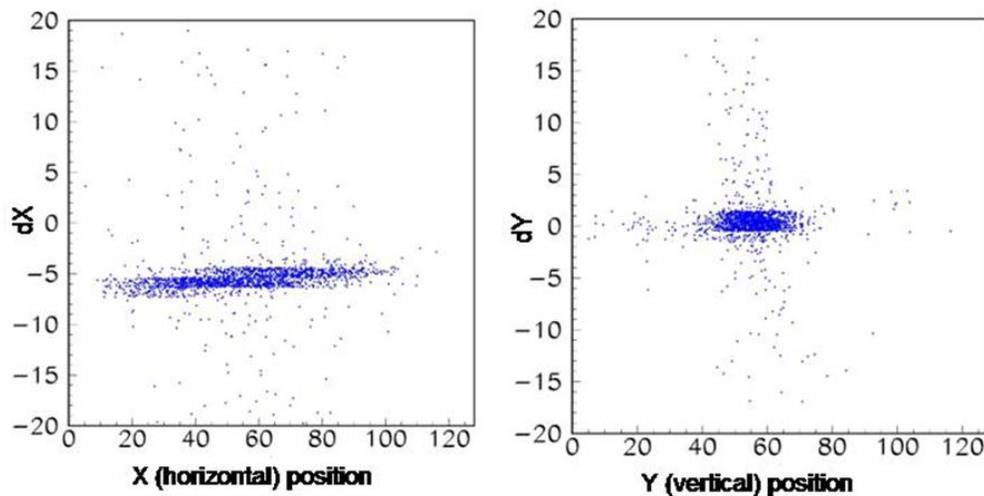


Figure 37. Beam divergence (32 GeV/c positive beam). dX , dY are position differences: chamber 4 – chamber 1. Units are detector channel number (0.8mm). Small positive correlation for horizontal indicates a small beam divergence.

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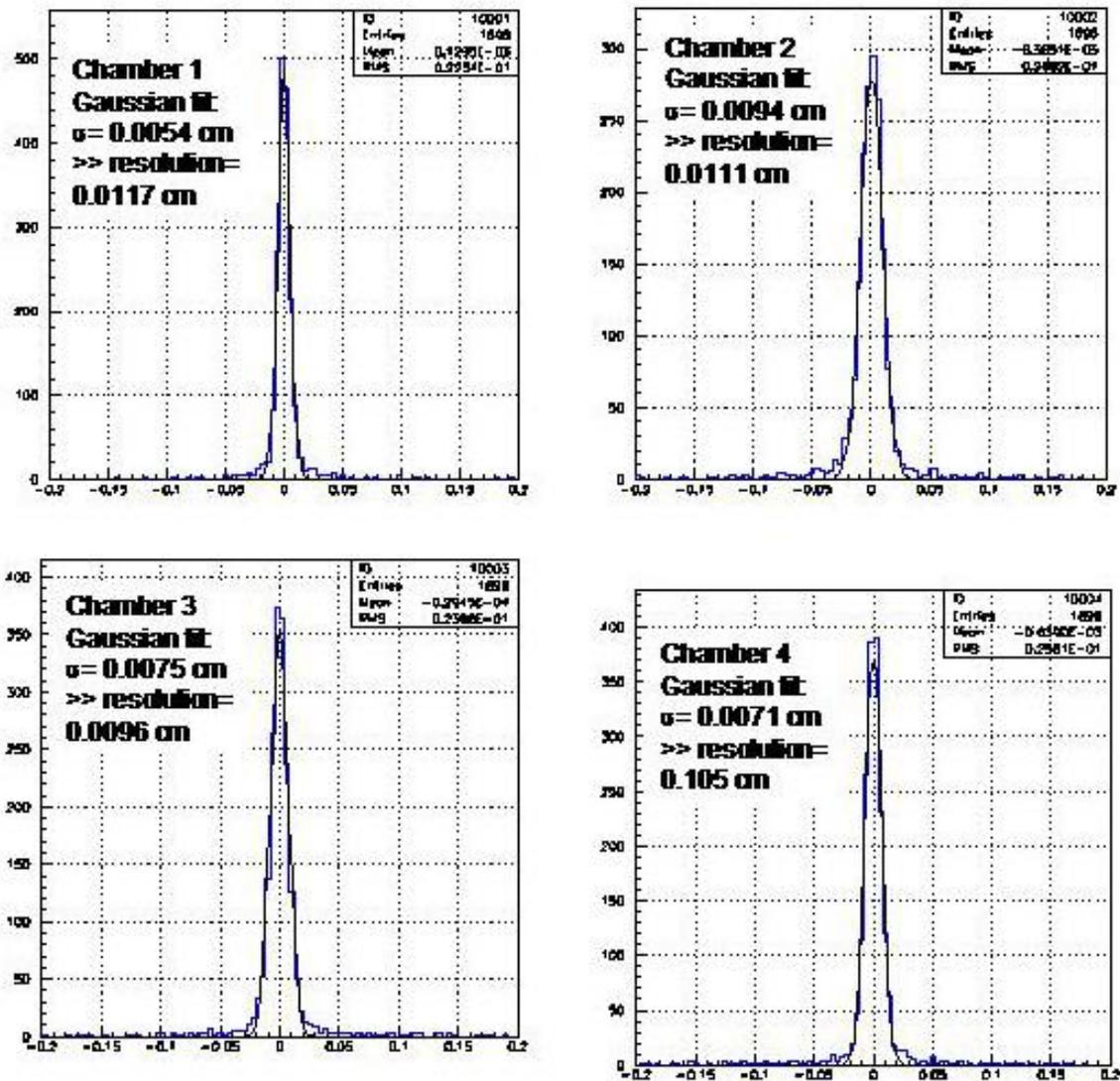


Figure 38 Residual distributions for straight line fits in one coordinate (horizontal). Units are cm. From the sigma of Gaussian fits to the distributions we apply the geometry dependent scale factor to get resolution estimates which range from 96 - 117 μm .

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WHAT WAS NOT ACHIEVED, WHY NOT, AND WHAT WILL BE DONE TO CORRECT?

BNL group:

We have just begun the analysis of the test beam data from Fermilab. It will take a careful alignment of our GEM detector with the silicon telescope in order to make a detailed study of the resolution of the minidrift GEM as a function of angle. We also feel that it is possible to improve the resolution compared to the CERN beam test by improving the algorithm that weights the centroid method and the vector method for determining the position. We will also analyse the data from the minidrift detector with the chevron readout which will provide valuable information on how to design the readout plane of the TPC.

We have not completed the 3D model or electrostatic simulation of the TPC/Cherenkov detector. We hope to have help from the Livermore group, which just joined our Tracking Consortium, in completing the field cage design. We also hope to complete the mechanical design of the detector with additional engineering help at BNL that we expect to get during the first part of next year.

We have not yet identified what readout electronics we plan to use for the prototype. There are several possibilities (e.g., the S-ALTRO chip or the AFTER chip), but we have not really begun to explore which of these are best suited and would be easiest to implement. There is also TPC electronics available from Livermore that we plan to investigate.

Florida Tech group:

With this first slice test at the FTBF, the main goals for this R&D period were achieved.

Stony Brook group:

We have achieved all goals for this period.

UVa group:

With the construction of the large EIC GEM prototype and the successful beam test at FNAL, the two main goals of the current R&D period were achieved and preliminary results demonstrated that large size GEM with 2D u-v strips readout is a viable option for EIC forward tracking system.

Yale group:

It was hoped to also have a set of 600 μm pitch chambers ready for the test beam run at Fermilab however due to late arrival of the readout boards this was not accomplished. It appears there are some yield issues, particularly with the diagonal coordinate that relies on many vias along each trace to have a good connection. Indeed this was one issue to be explored for this R&D. We will continue detailed electrical tests on the 600 μm boards with plans to still assemble and test those chambers if possible.

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WHAT IS PLANNED FOR THE COMING MONTHS AND BEYOND? HOW, IF AT ALL, IS THIS PLANNING DIFFERENT FROM THE ORIGINAL PLAN?

BNL group:

Complete the analysis of the Fermilab test beam data. With this data and improvements to the position finding algorithms, we hope to be able to improve on the resolution we measured in the CERN beam test. We will also analyze the data from the minidrift detector with the chevron readout which will help us in the design of the readout board for the TPC.

Complete the 3D model of the TPC/Cherenkov prototype along with the electrostatic simulation of the field cage and proceed to constructing the actual detector. The main items remaining are to finish the design of the GEM assembly and readout board for the TPC and to incorporate the photosensitive GEM detector into the final assembly.

Begin to study different readout electronics for the TPC prototype.

Make additional measurements of the drift velocity and ion back flow with various gas mixtures.

Upgrade the beam optics of our VUV spectrometer in order to improve its sensitivity and resolution in the deep UV (below 140 nm). The spectrometer will be used to measure mirrors and other components of the Cherenkov detector being developed at Stony Brook and also to measure the UV transparency of gases that we plan to use in our TPC/Cherenkov detector.

Florida Tech group:

Our immediate task is to develop full track reconstruction for the beam test data and produce results using high-precision tracks. We plan on presenting final beam test results for the zigzag detectors at conferences and will prepare a corresponding journal publication.

We would like to upgrade our x-ray test setup by enlarging our shielded chamber enclosure so that we can irradiate an entire 1-1.2m GEM chamber with our x-ray source by placing the source farther from the chamber. On the electronics side, we plan on calibrating our APV's to each other by determining their response variations. To make our x-ray tests more efficient, we would like to increase the speed of our SRS DAQ by procuring a Scalable Readout Unit (SRU) of the type that was provided by U. Va. for the FNAL beam test. This should allow us to acquire x-ray data with speeds close to 1kHz.

On the detector side, we want to address the response non-uniformity observed in the large trapezoidal chamber. After some additional response uniformity measurements for that chamber with our local x-ray source, we plan on building a second improved prototype. We have parts for such an improved chamber prototype with pre-bent drift board and pre-bent straight-strip readout board in hand. We will mount the existing readout board with zigzag strips on that chamber if it fits or develop a new one. CERN is developing an improved construction technique for the 1m trapezoidal GEM chambers with the goal of eliminating any bending of pcb's due to GEM tensioning. We have ordered parts for one such chamber and will outfit it also with a zigzag readout board and then test it with x-rays. CERN plans on developing 120cm long chambers in

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2014. We plan on procuring parts for such a prototype and developing a zigzag readout for this longer chamber and testing it with x-rays or possibly in a second beam test at Fermilab.

In this process, we would like to optimize the zigzag board design by improving the interleaving of “zigs” and “zags” of adjacent strips since the test beam data suggest that this is critical for the spatial resolution performance of the chamber. We will work with industry to find the optimal zigzag pattern that can be produced on a 1-1.2m scale.

Finally, students are refurbishing a table-top electromagnet that can provide up to 1.5T magnetic field and that can accommodate 10cm×10cm GEM detectors between its poles. Using this magnet we plan on studying the performance of GEMs with straight strips and zigzag strips in a strong magnetic field.

Stony Brook group:

The RICH in its current form has proven to be highly successful. The high momentum reach of the current device is limited (as expected) by the position resolution of the individual photons coming from the large pads. We propose for the next funding period to begin work on a resistive charge division scheme to allow high precision single photon position resolution measurements.

In past funding periods, we have placed low priority on the development of in-house mirror coating. We plan to begin this development in earnest in the first half of FY14. These funds were approved in June 2013 and the statement of work for these funds is already in process.

UVa group:

There are two main ideas that we would like to explore in the coming month on the new EIC trapezoidal GEM prototype that we think will represent a major upgrade to the current prototype:

New design of the GEM foils and support frames for a larger GEM

The largest GEM chamber for the EIC forward tracker would be 1.5 m long. A chamber of that dimension requires some fundamental R&D effort both in term of the GEM foil design and readout board approach. We propose for our second prototype to be a 1.2 m GEM chamber with some minor but crucial changes on the design of the support frame to improve the stretching of the foils and reduce the dead area inside the chamber by reducing the number of spacer ribs.

New design for the 2d u-v readout board

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R&D on 2D readout board for 1 m trapezoidal GEM for EIC forward tracking R&D

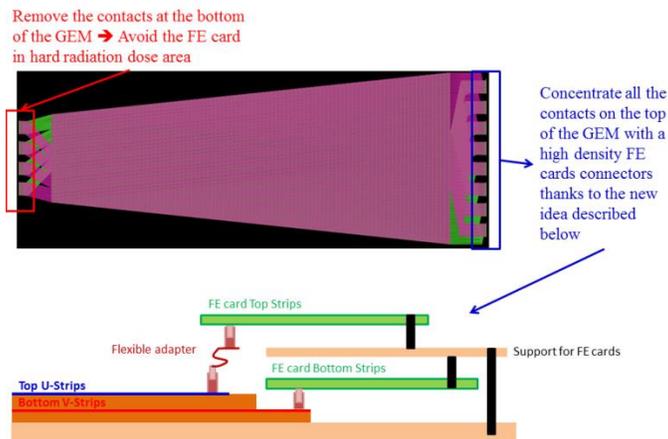


Figure 39: New 2D u-v strips readout board design for EIC GEM

On the current EIC GEM prototype, the Front-End (FE) readout electronics are connected the 2D readout board of the chamber at both the inner radius and the outer radius sides of the chamber. This option was chosen to avoid having to connect FE cards on the sides of the chamber in order to minimize the dead area when the GEM modules are arranged together into a disk layer of the forward tracking detector. But FE cards at the inner radius of the chamber will be exposed to a very high radiation dose because of the proximity to the beam line. We propose to explore a new idea to enable all strips of both u and v strip layers to be read-out from the outer radius side of the chamber. The proposed concept illustrated in (Figure 39), calls for two layers of EF cards at the outer radius side of the chamber. The upper cars would be connected to the readout board using a flexible adapter board. It would require a redesign of the current readout board and the production of flexible PCB adapter board and support pieces for the FE cards.

Yale group:

The major activity for the next period and following will be analysis of the data collected in the test beam run at Fermilab. These data should provide an extensive characterization of the chambers. Analysis activities going forward we will include:

Finalizing chamber alignment procedure including rotations

Optimizing clustering algorithm

Optimize threshold cuts on signals included in a cluster

Optimize use of pulse shape information

Once we have optimized the cluster finding and hit position calculations we will characterize the chamber performance under all the various conditions – high voltage setting, incident angle, gas mix – and to characterize the performance of the diagonal coordinate. Further, we will make a detailed comparison with

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our detector simulation to vet/tune this tool. This extensive set of data and simulation will lead to a publication.

We also intend to continue detailed electrical measurements of the 600 μm boards to make a determination of whether this technique at this pitch is scalable to large readout boards.

Additionally, we propose new research as described below:

Proposal to investigate the properties of combined Micromegas and GEM gain structures for use in PID and tracking detectors.

Micropattern gas detectors (Gas Electron Multipliers (GEM), MicroMegas (MMG)) will be a key element of EIC detectors. Multi-GEM and MMG detectors have demonstrated high gas gain; good space, energy and timing resolution; low ion back-flow (IBF) and the ability to work with many different gas mixtures. We propose to investigate the properties of combined GEM and MMG structures through simulation and a series of prototype detectors.

Cherenkov Photodetector.

The combination multi-GEM+CsI photocathode was successfully utilized in PHENIX for a hadron blind Cherenkov detector and also tested in this R&D collaboration in a ring imaging Cherenkov (RICH) detector. To be sensitive to single photo-electrons the detector gas amplification should be $>10^4$. For stable operation this requires ≥ 4 GEM foils.

As an alternative approach we would like to test GEM+MMG to exploit the positive properties of both technologies. A GEM+CsI photocathode has been shown to be a high quantum efficiency photo-detector with ~ 10 -20 gas amplification and good efficiency to transport electrons to the next amplification stage. Using a MMG as the next stage with a gain of 500-1000 meets the requirements of high gain while at the same time allowing operation of both stages (GEM and MMG) at quite modest gain to minimize sparking and instability. This combination provides a simpler structure allowing simpler operation (only 2 elements requiring HV bias). Both GEM and MMG have demonstrated the capability to operate in a wide variety of gases and gas mixes and so both are amenable to use in a photo-detector. We propose to first carry out a detailed simulation including all aspects of the Cherenkov detector to determine the optimum readout structure (pad pitch, size) and then to build and test a small prototype detector.

TPC Detector

A key problem for TPC tracking detectors is the backflow of positive ions (IBF) produced in the gain structure into the main TPC drift region. Since these ions drift very slowly they can accumulate in the main TPC volume leading to distortion of the main TPC electric field and hence distortion of the track images. For the present generation of TPC's with MPWC gain structures this problem has been overcome by introducing a wire grid in front of the MPWC with alternating wires set to different voltages. The voltages on the grid wires are set either to allow transmission of charged particles or to block the transmission. This gating grid is normally set to block transmission. The

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TPC is operated with a trigger and when a trigger is received the gating grid is opened for long enough to allow the ionization electrons from the main TPC volume to drift into the MPWC and be multiplied there. The positive ions produced in the avalanches at the MPCW wires drift very slowly back toward the gating grid. The grid is closed before the positive ions reach it so they are blocked from entering the main TPC volume. To block these ions the grid must remain closed for the time required for the ions to drift from the MPWC anode wires to the grid. This is typically about 100 μs and represents an intrinsic dead time for this method.

GEM's and MMG's both have intrinsically low ion feedback and offer the possibility to construct a TPC that can operate continuously (no gating grid). Recent measurements by the ALICE group have demonstrated that with 4 GEMS, two with hole pitch twice as large as the other two, IBF as low as 1% can be reached. To achieve this low IBF the transfer field in some of the gaps between GEM foils must be set almost to the limit where gain would occur in those gaps. Also, even with IBF as low as 1% at a gain of 2000 this means the IBF is 20 times the initial ionization in the TPC drift volume. MMG have quite low IBF due to the very high ratio of field in the MMG amplification gap to the drift field above the mesh. However because of the small amplification gap and the very high field there is very little spreading of the avalanche electrons on the readout structure. To obtain good spatial resolution the charge must be spread across at least two readout elements. Thus one would need a very fine pitch readout structure giving high channel count and high cost for the electronics. This is especially the case for compact TPC's using fast, low diffusion gas. To alleviate this problem a resistive coating on the readout plane can be used but this adds significant complexity to the manufacture of the MMG and also slows down the signal.

By combining GEMS with MMG for a TPC gain structure one can have some charge spreading from the GEM layers and the additional benefit of operating all gain elements at very modest gains. We have performed an initial simulation that shows that combined with a chevron style pad structure for the readout plane (charge sharing is insured by the geometry of the pads) one can preserve excellent spatial resolution with reasonable pitch and channel count. We have borrowed a small (10 cm x 10 cm) MMG and combined it with two standard GEM foils to make an initial measurement of the IBF. Figure 40 shows the setup used for this and Figure 2 shows the measurements. Measurements were done using ArCO_2 (70%/30% and 90%/10%) with the GEM foil voltages always set to give a total GEM+MMG gain of 2000. The MMG voltage was varied to change the ratio of MMG field to induction field (see Figure 40). The ratio of cathode current to anode current in the presence of a radioactive source vs. the ratio of MMG field to induction field is plotted in Figure 41. These results are reproduced with the two different gas mixes. At each setting the gain was adjusted and resolution checked by measuring the PH spectrum at the anode (read out plane) with a standard CSP/shaper and ADC with the chamber illuminated with a ^{55}Fe source.(Figure 42). IBF as low as 0.2% is reached without any further optimization.

We propose to build 4 prototype GEM + MMG chambers to investigate and optimize this structure. Two chambers will be built with different MMG mesh pitch (one "normal" 400 LPI, one at least 600 LPI). We expect finer pitch MMG should give lower IBF. For each of these chambers we will

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investigate different GEM configurations to find the optimum configuration for minimum ion feedback. After optimizing the configuration we will use a detailed simulation to determine the optimum pitch for a TPC readout plane and for a RICH focal plane for the optimized configuration and build small prototypes that can be combined with our prototype TPC and RICH detector to verify the performance.

In summary we propose to build and characterize a series of GEM + MMG chambers to find the optimum configuration for use in a RICH detector and a TPC. The budget for this research is shown in the next section.

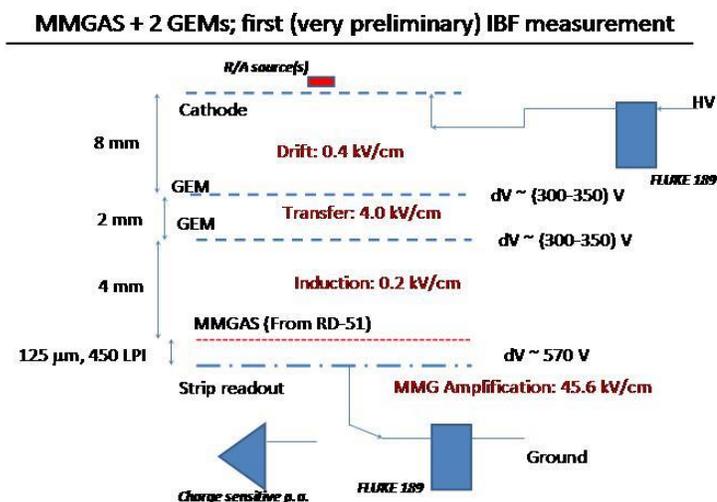


Figure 40. Setup used for preliminary IBF measurement of combined GEM + MMG. Measurements were performed using ArCO₂ mixes (70%/30% and 90%/10%) for three MMG voltages (field) settings with GEM voltages adjusted to keep overall gain at 2000.

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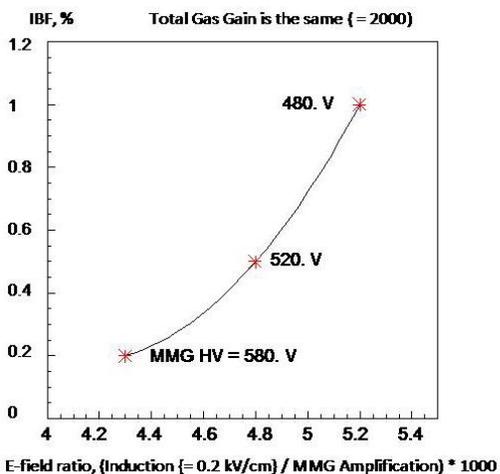


Figure 41. Preliminary IBF measurement for 2 GEM + MMG. Horizontal scale is ratio of MMG field to induction field (see Figure 40). Vertical scale is ratio of anode current (strip readout plane) to cathode current.

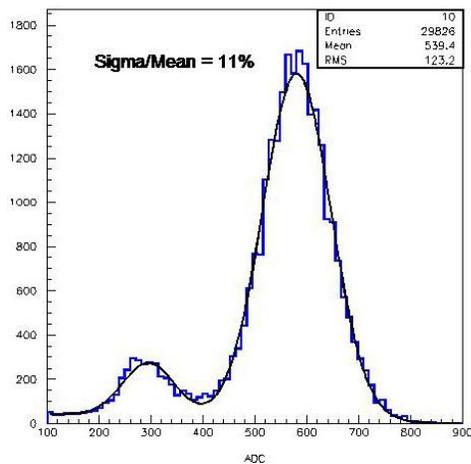


Figure 42 Typical PH spectrum from MMG anode of 2 GEM + MMG chamber irradiated with ^{55}Fe source.

TPC Sub-Consortium (LLNL, WIS)

As noted above, our group has grown significantly with the inclusion of groups from LLNL and WIS. The intent of these groups is to work on development of a TPC for the EIC and will complement the ongoing work in our group. Because this effort is a new and emerging one, the time between now and the next report will be spent formulating the details of how this work should proceed. As such, funding requests for this work will be made in May 2014. We currently expect that funds of roughly \$100,000 in the second half of FY14 will be required and that a detailed and targeted request will be forthcoming in December 2014 regarding FY15 funds.

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WHAT ARE CRITICAL ISSUES?

BNL group:

Determining the best possible position resolution for the mindrift GEM detector.

Competing the electrostatic and mechanical design of the TPC/Cherenkov prototype and building the actual detector.

Identifying suitable readout electronics for testing the prototype.

Florida Tech group:

Improving the spatial resolution by interleaving “zigs” and “zags” of adjacent zigzag strips more tightly.

Eliminating response non-uniformity by minimizing any bending of drift and readout boards in the large trapezoidal chambers.

Stony Brook group:

Determining a charge division scheme to improve the single photon position resolution.

UVa group:

We really need to move the front end electronics away from the inner radius part of the chamber and move all electronic channels to outer radius side. This requires a complete re-design of the readout board with new approach to be tested.

A second critical part is to optimize the GEM foil and the support frames in order to ensure a better stretching of the foils and to improve the gain uniformity over the entire area of the chamber.

Yale group:

As discussed above the critical issue is the reliability of fabrication of the finer pitch boards and the whether it is possible to scale this technique to larger readout boards.

TPC Sub-Consortium

Critical issues will be determination of the specific design performance parameters and how these influence the targeting of initial funding.

RD6 TRACKING & PID CONSORTIUM

Funding Request

For clarity our budget requests will be laid out in fiscal year and we will begin with an executive summary. We request salary funding that should be awarded in a timely manner so that there is no gap (NOTE that there is typically a 6 month delay between approval of funds and delivery to remote institutions). We further request that FY14 funds for hardware be distributed in two allocations (those requested in Dec-2013 and those to be requested in May-2014).

RD6 Tracking Consortium FY14					
	Salaries	Dec	May	Totals	Explanation
SBU		50	43	93	\$83k for mirror work and \$10k for resistive charge division
FIT	89	36	50	175	Salary for Aiwu Zhang. \$35k chamber w/ improved uniformity
BNL Woody		60	60	120	TPC/Cherenkov Small Prototype Development
BNL Elke	180			180	Salary for Alexander Kisilev
Uva		45		45	Development of tracker with readout away from beam pipe.
Yale		35		35	Micromega and GEM hybrid work.
TPC			100	100	Start-up funding to be detailed in May 2014
TOTAL	269	226	253	748	

These requests are detailed below

BNL-Woody:

BNL FY 14 Budget Request			
	Dec	May	Total
TPC/Cherenkov prototype detector			
Mechanical design	10	5	15
Technical support	5	10	15
Detector components	5	15	20
Electronics development	5	5	10
Gas system supplies & materials	5	5	10
VUV spectrometer optics	10		10
	40	40	80
Overhead	20	20	40
Total	60	60	120

All numbers are listed in \$k.

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Florida Tech group:

Florida Tech FY 14 Budget Request			
	Dec-13	May-14	Total
<i>Forward tracking: Large-area GEM detectors</i>			
Fully loaded personnel (Post-doc Aiwu Zhang)	89	-	89
Undergraduate summer support	4		4
GEM chamber parts and readout boards	18	20	38
SRS electronics development	5	10	15
Travel	3	9	12
Supplies & Materials	3.1	5	8.1
Overhead	2.8	6.4	9.2
Total	125	50	175

All

The salary request for post-doc Aiwu Zhang covers the 12-months period from June 2014 to May 2015. Given the usual delay of several months until funds arrive at the institution after budget approval it is critical that these salary funds be allocated in Dec 2013 so that they arrive in time for renewal of Aiwu's contract. Similar reasoning applies to the support for one undergraduate for summer 2014.

Stony Brook group:

	Dec	May
Large Evaporator Refurbish		
E-gun w/ 4 pockets, 5kW PS, XY sweep, Indexer		43
Replacement Flanges	20	
Replacement O-ring	1	
Turbo Pump Flange Adapters	15	
Thickness Monitor	4	
TOTAL	40	43
Resistive Charge Division		
Circuit Cards	5	
Coatings	3	
Gas Flow Controller Module(s)	2	
TOTAL	10	
Grand Total	50	43

RD6 TRACKING & PID CONSORTIUM

UVa group:

Item	Item cost (\$)	Quantity	Total (\$)
GEM foils	2000	4	8000
Readout board	3000	1	3000
Spacer frames	3000	1 set	3000
Material and supplies (Gas, cables, mounts, shipping goods ...)	3000	1 set	3000
Mechanical Stretcher	5500	1	5500
Engineering & Technical support	7500		7500
Travel to CERN	5000		5000
Overhead	7250		7250
Fringes	2500		2500
Total			45000

Yale group:

The Yale group are leading participants in the TPC/HBD development and as such will benefit from the BNL funds listed above. No funds are required to be sent directly to Yale for that work.

The Yale group additionally proposes new micromega/GEM hybrid work described above.

	Unit cost	Number	Total direct	Indirect *	Total
MMG chamber	\$ 3,000	4	\$ 12,000		\$ 12,000
GEM foils and frames	\$ 300	12	\$ 3,600		\$ 3,600
Fine pitch mesh	\$ 1,200	1	\$ 1,200		\$ 1,200
Gas system	\$ 5,000	1	\$ 5,000		\$ 5,000
Gases	\$ 2,400		\$ 2,400	\$ 624	\$ 3,024
Domestic Travel including Test beam	\$ 8,100		\$ 8,100	\$ 2,106	\$ 10,206
Total			\$ 32,300	\$ 2,730	\$ 35,030
* Yale off campus rate = 26%					

RD6 TRACKING & PID CONSORTIUM

TPC Sub-Consortium

Currently there is tremendous activity of multiple groups becoming interested in the development of a fast TPC for EIC. As this work is in the early stage, we do not request any funds for the first half of FY14. Nonetheless, it is quite clear that these groups will need seed funding to be able to present a worthy and targeted proposal in December 2014 for the allocation of FY15 funds. Because it is important for future planning, we take the opportunity here to request \$100,000 in May 2014 as a placeholder.

	Dec	May	Total
TPC	0	100k	100k