EIC Detector R&D Progress Report:
from December 2015 to July 2016

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

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Date: June, 2016

Introduction

The EIC Tracking R&D program within eRD6 is approaching a stage where it considers to finalize its generic R&D projects and prepares to move to the next step which has targeted detector R&D as its goal. Previously, the EIC received highest priority for new construction in the recent NSAC long-range plan and various detector concepts have been shaped to a level that requires detector R&D which is investigating the realization of their sub-detectors.
In the context of changing priorities, we can announce to have two more high-caliber institutes joining our efforts, INFN Trieste and Weizmann Institute of Science. They will be joining for pursuing detector R&D which focuses on targeted detector R&D.
In a separate document we elaborate further how the transition will take place and how eRD3 and eRD6 will merge for forming a new group as a consequence.
We can also announce that the international advisory committee for the bi-annual MPGD-conference after our bid just awarded the members of eRD3 and eRD6 to host the MPGD 2017 conference at the Temple University. This also shows the interest of the international gas detector community and success of our consortia in the field of detector R&D that we are pursuing.

Past

What was planned for this period?

Brookhaven National Lab:

The primary goal for this period was to prepare the TPC/Cherenkov (TPCC) prototype detector for a test beam measurement at the Fermilab Test Beam Facility (FTBF), perform the beam test, and analyze the data. This work was done in collaboration with the group at Stony Brook University. Preparing the detector for the beam test involved making the field cage robust against sparks, and performing various lab measurements, including reconstructing TPC tracks from cosmics, and measuring drift velocity, gain, charge spread, and charge attachment measurements in pure CF_4, which was the gas chosen for operating the TPCC. We also planned to make the photocathode for the Cherenkov portion of the detector, consisting of a GEM coated with CsI, using a sophisticated evaporator system at Stony Brook. We planned to transport the fully assembled detector from Stony Brook to FNAL while under gas flow for the purpose of keeping the CsI quantum efficiency intact. Approximately two weeks was allotted for the beam test, during which time we planned to measure the performance of the TPC portion of the detector with charged hadrons from a few GeV/c up to 120 GeV/c, and the detection efficiency for electrons and high momentum hadrons in the Cherenkov portion of the detector. During this same time period we also started to design several variants of a new chevron readout pattern aimed at improved resolution performance, and hoped to have one particular design fabricated in time for use in the TPC portion of the prototype.

Florida Institute of Technology:

Finish our second paper on EIC R&D results and submit it to a peer-reviewed journal. The topic is a study of the geometric-mean method for determining the spatial resolution of tracking detectors in the presence of multiple scattering.
Analyze the BNL scan data for the zigzag readout boards obtained in Nov 2015.
Before producing the new large zigzag readout board or foil for the next Forward Tracker (FT) GEM prototype, demonstrate that the re-designed zigzag strips have a more linear response. To that end, produce new radial zigzag boards for a 10 cm × 10 cm GEM detector with the re-designed zigzag pattern and scan them at BNL.
Start producing the large common GEM foils and send out the designs for drift and readout foils and the various frames for quotes. Attempt to get them produced if feasible in the current 6-month time period. Investigate stiff carbon fiber frames for assembling the next EIC FT GEM prototype.

INFN Trieste:

N/A

Stony Brook University:

It was planned to refurbish the Big Mac evaporator after finalization of design consideration so that the necessary equipment for the mirror production can be purchased. The diameter of the vessel is about 7 feet and therefore would allow the insertion of large sized mirror blanks for evaporating with MgF_2.

Another project was to design a pad readout board with snowflake pattern, locally at Stony Brook with engineers and aiming for placing an order to our previous PCB vendor.

University of Virginia:

Continue the tests of the Cr-GEM detector in x-ray box to study the performance under severe background conditions.

Complete the design of the zebra-to-Panasonic adapter board and of the GEM frames and mechanical structure of the triple-GEM chamber.

The new 2D U-V strips readout design with narrow strips present several advantages that are beneficial for EIC tracking detectors. However, a few new ideas such as etching the top and bottom strips contacts on the same Kapton support and the zebra connectors for electrical contacts need to be tested before we produce the EIC-size board for the second prototype. We plan to develop a small ($10 \times 10\ cm^2$) 2D U-V strips readout board with the new zebra-based connection scheme and zebra-to-Panasonic adapter and perform validation tests.

Weizmann Institute of Science:

N/A

Yale University:

3-Coordinate GEM

During the past period it was planned to complete the analysis.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas (2-GEM+MMG)

During this period, it was planned to submit a paper on the results achieved to date. It was also planned to continue study of 2-GEM+MMG with resistive planes. Further study to understand the corona like discharge at high intensity was planned.

Multi-element stacked gated grid

Continued setup and characterization of the stacked gated grid was planned

What was achieved?

<u>*Brookhaven National Lab:*</u>

Beam Test Preparation

In order to minimize potential high voltage problems and to optimize the performance of the prototype detector for the test beam, the following modifications were made to our previous detector configuration that was described in the last report:

1. Installed a new Kapton foil field cage with larger gaps between neighboring electrodes
2. Installed 12 way segmented GEM foils with a voltage divider to minimize capacitance and stored energy in case of sparking
3. Installed quadruple GEM stacks for both the TPC and Cherenkov detectors to minimize the required gain per stage.

The use of CF_4 as an operating gas provided both a high N_0 for the Cherenkov detector as well as a high drift velocity for the TPC detector. By operating the field cage at a relatively modest field of 0.4kV/cm, we obtained a drift velocity of about 7.5cm/µs, thus enabling the APV25/SRS readout electronics to collect virtually all of the charge deposited in the ~10cm drift length of the TPC within the limited ~700ns wide DAQ capture window.
For the Cherenkov detector a thin layer of CsI was deposited onto the top surface of the top GEM at Stony Brook using the evaporator system pictured below in the left side of Figure 1. Following the evaporation, the GEM photocathode was carefully installed onto the vertically oriented GEM stack seen in the right picture of Figure 1. After completing the final assembly of the detector and verifying that all of the detector components were fully operational, the detector was transported by truck under argon gas flow to the FTFB.

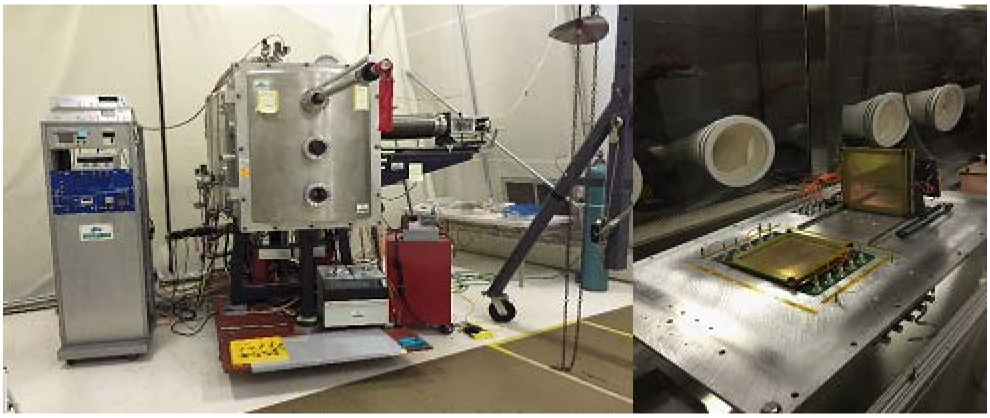

Figure 1 Picture of the vacuum CsI evaporator at Stony Brook Univ. (*left*), and a CsI coated gold GEM foil, standing vertically inside a glove box with low water levels to keep the CsI intact (*right*).

Test Beam at FNAL

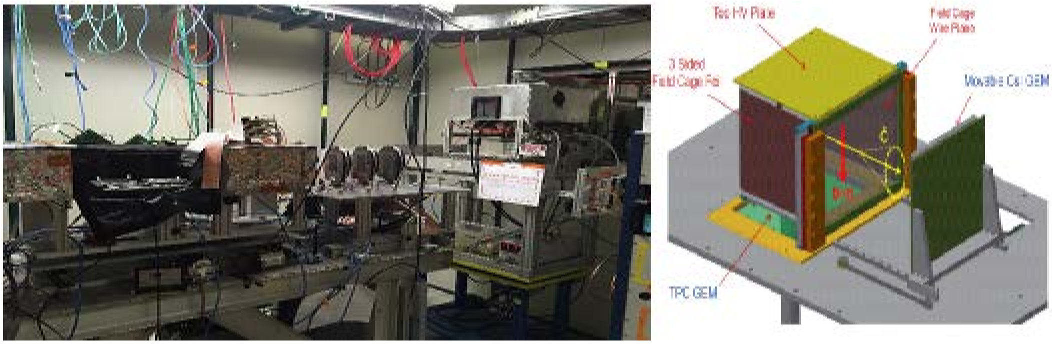

Figure 2 Right: detector setup at Fermilab test beam facility. Left: sketch of detector configuration, showing both the cubical TPC drift volume, and the vertically oriented Cherenkov detector.

The purpose of the beam test of the TPCC prototype at the FTBF was to perform a proof of principle study to test the concept of particle tracking and effective particle id within a common gas volume. The detector was exposed to a primary 120GeV/c proton beam and to secondary mixed beams consisting of electrons, pions, kaons, and protons at energies ranging from 4 to 12GeV/c. The prototype was placed just downstream of an 11 layer Si telescope which was used to provide high resolution reference tracks for comparison with tracks measured in the TPC. The test beam run was just completed in mid-April of this year and therefore all of the results obtained so far are preliminary and should improve with further analysis.

Cherenkov detector

The Cherenkov portion of the detector was operated in threshold mode where the main objective was to measure the light yield for electron tracks and to investigate the electron id performance.   Cherenkov light produced along the track passing through the gas volume was detected by the CsI photocathode, converting it to photoelectrons which were then amplified by the GEM. The charge was collected onto an array of relatively large (3.3cm x 3.3cm) pads which contained the full Cherenkov cone. The field within the 2.3mm drift gap of the GEM stack was adjusted to optimize the collection of photoelectrons while maximizing the rejection of the signal from direct ionization charge deposited in the gap. A positive drift field (which we denote forward bias) collects the direct ionization charge while a negative drift field (reverse bias) suppresses the direct ionization charge. Figure 3 shows the results of a drift field scan using 120GeV/c protons. The optimal field for operating the drift gap was found to be -0.05kV/cm.

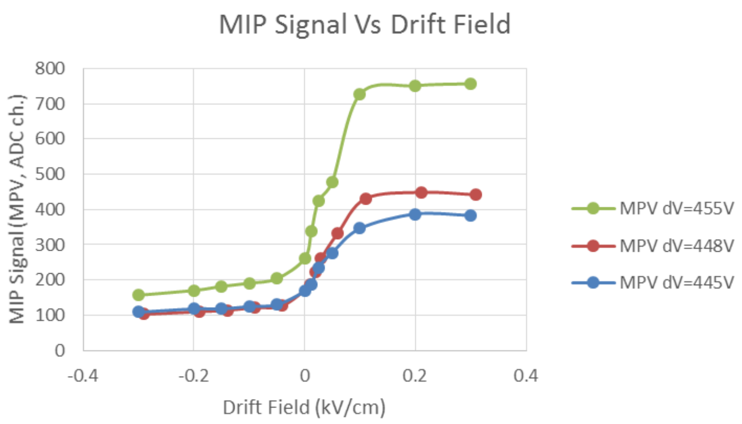

Figure 3 Response of Cherenkov detector to 120GeV/c proton beam as a function of drift field.

Using the known dE/dx in CF4 we were able to get a good estimate of the absolute gain of the Cherenkov GEM. Figure 4 shows the absolute gain curves for the Cherenkov GEM for the forward and reverse bias conditions.

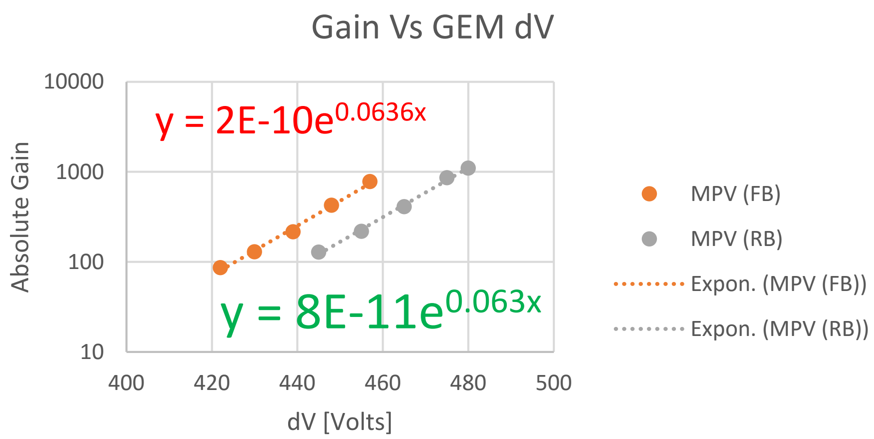

Figure 4 Gain curves measured in 120GeV/c proton beam with the Cherenkov detector in forward bais (FB = 0.7kV/cm), and reverse bias (RB=-0.05kV/cm).

Figure 5 shows preliminary results for the Cherenkov signal produced by electrons and pions which were above the Cherenkov threshold compared with the residual ionization charge produced by kaons and protons which were below threshold. A clean separation is observed at all three voltages. Using the absolute gain curves shown in Figure 4, we were able to estimate the number of photoelectrons corresponding to the Cherenkov peaks shown in Figure 5. The peaks correspond to ~ 9 p.e., which is in good agreement with our expectation for the 29 cm path length for the track in the radiator gas. Additional data was also taken for radiator path lengths between 10-29 cm that will allow us to study the photoelectron yield as a function of the radiator path length.

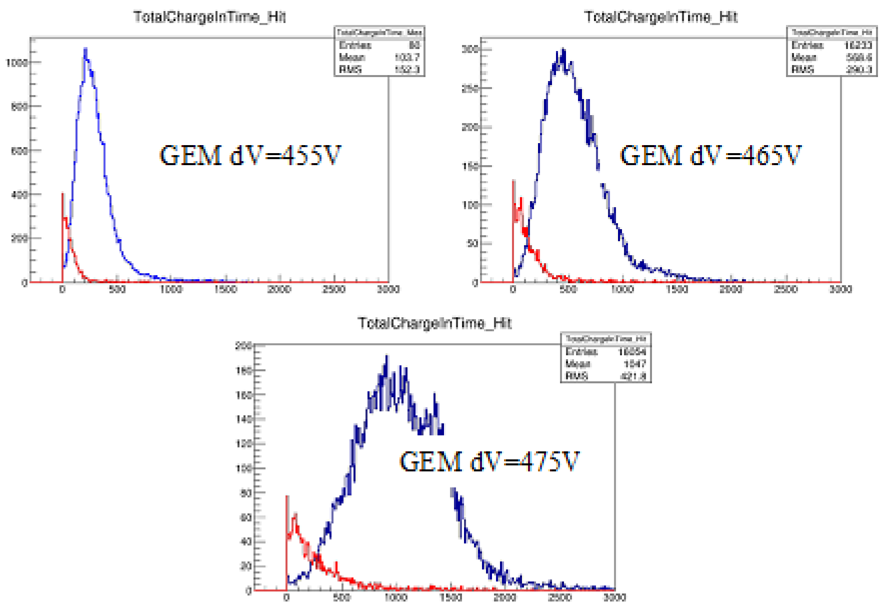

Figure 5 Cherenkov detector pulse height distributions for 12GeV/c particles above and below the Cherenkov threshold for varying GEM voltages. The blue curve corresponds to electrons and pions, which are above the Cherenkov threshold and the red curve corresponds to kaons and protons.

TPC detector

The objective of the measurements done with the TPC portion of the detector was to reconstruct particle tracks and look for hit correlations with the Cherenkov detector. Examples of single event particle tracks in both the X-Y, and Y-Z planes of the detector (where Y is the dimension along the beam axis) are given below in Figure 6.

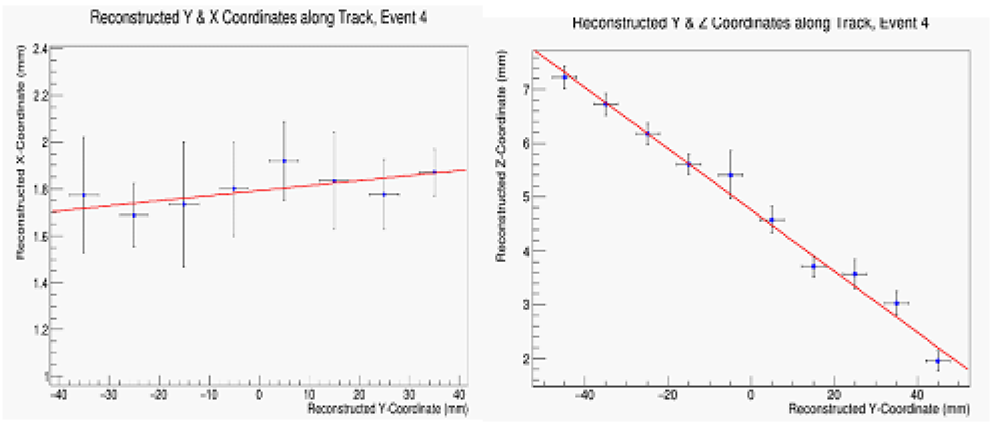

Figure 6 Reconstructed tracks in the TPC in the X-Y and Z-Y planes.

Figure 7 shows the correlation for tracks found in the TPC with those found using the Si telescope, separately for the X and Y coordinates. There is a tighter correlation in the Y coordinate, which is the precision coordinate for the chevron pads. The uncorrelated events that are off the diagonal in both of these plots are mostly due to unsynchronized events between the Si telescope data acquisition system and our DAQ system. We expect to improve the correlation in both coordinates with further analysis and better alignment of the two detector systems.

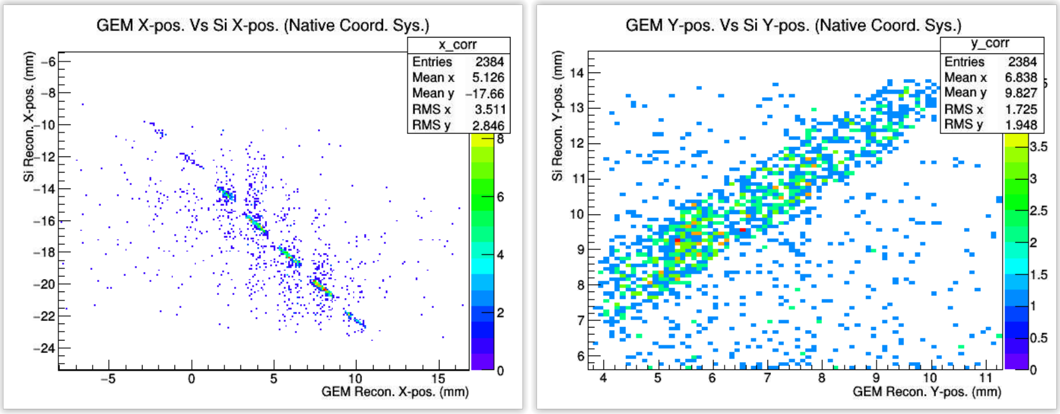

Figure 7 Correlation plots for X and Y track coordinates, respectively for the TPC and Si detectors derived from vector reconstruction.

Figure 8 shows the hit correlation between the Cherenkov and TPC detectors from several event displays. A clear correlation is seen between the track found in the TPC and the pads hit in the Cherenkov detector. This correlation will be studied in more detail in future analysis, but we feel that this clearly shows the main objective of the test, namely, to demonstrate that both particle tracking and Cherenkov id could be accomplished in the same detector, was achieved.

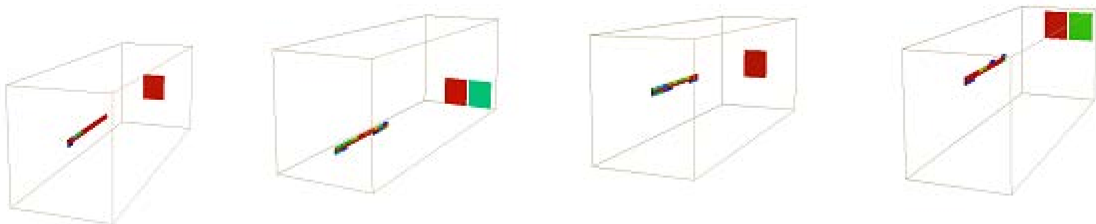

Figure 8 3D event displays demonstrating the hit correlations between TPC tracks and the corresponding hits in the Cherenkov detector in the vertical plane (red: below threshold, green: above threshold).

Florida Institute of Technology:

Publishing and Presenting R&D results

We submitted our paper "Accuracy of the geometric-mean method for determining spatial resolutions of tracking detectors in the presence of multiple Coulomb scattering" to the Journal of Instrumentation (JINST) and posted it on the e-print arXiv (1604.06130). The paper has been accepted for publication by JINST. This is our second paper that is an outcome of the first eRD6 beam test at FNAL.
We also submitted an abstract on the "Study of non-linear response of a GEM read out with radial zigzag strips" to the 2016 IEEE NSS/MIC conference in Strasbourg, France.

Results on non-linearity of zigzag strip readouts from X-ray scans

We scanned two zigzag-strip readout boards using a standard 10 cm by 10 cm triple-GEM detector and a collimated X-ray gun on a 2D motorized stage at BNL and analyzed the data. The patterns of the zigzag strips on these boards are identical to those implemented in the readout PCB of the first large 1-m GEM detector that we had tested at Fermilab and reported on earlier. The objective was to gain more information on the non-linear behavior of this readout type that was observed in the Fermilab data so that the design can be modified to produce a more linear behavior.

As shown in Figure 9, one board has 30 strips and the other one has 48 strips. The strips run radially with an azimuthal angle pitch of 1.37 mrad and they measure the azimuthal phi-coordinate of incident particles. The difference between the two boards is that the radial zigzag strips are located at different radii. Specifically, the radial range for the 48-strip (30-strip) board is about 1420-1520 mm (2240-2340 mm) corresponding to the narrow (wide) end of our first large-area prototype chamber.

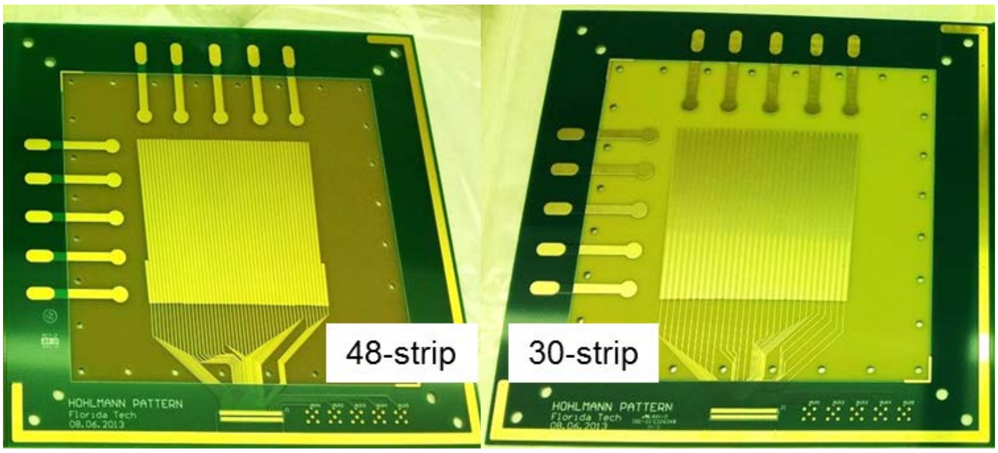

Figure 9 The first batch of small zigzag boards studied in X-ray scans by our group. The boards are suitable for reading out standard CERN 10×10 cm^2 GEM detectors.

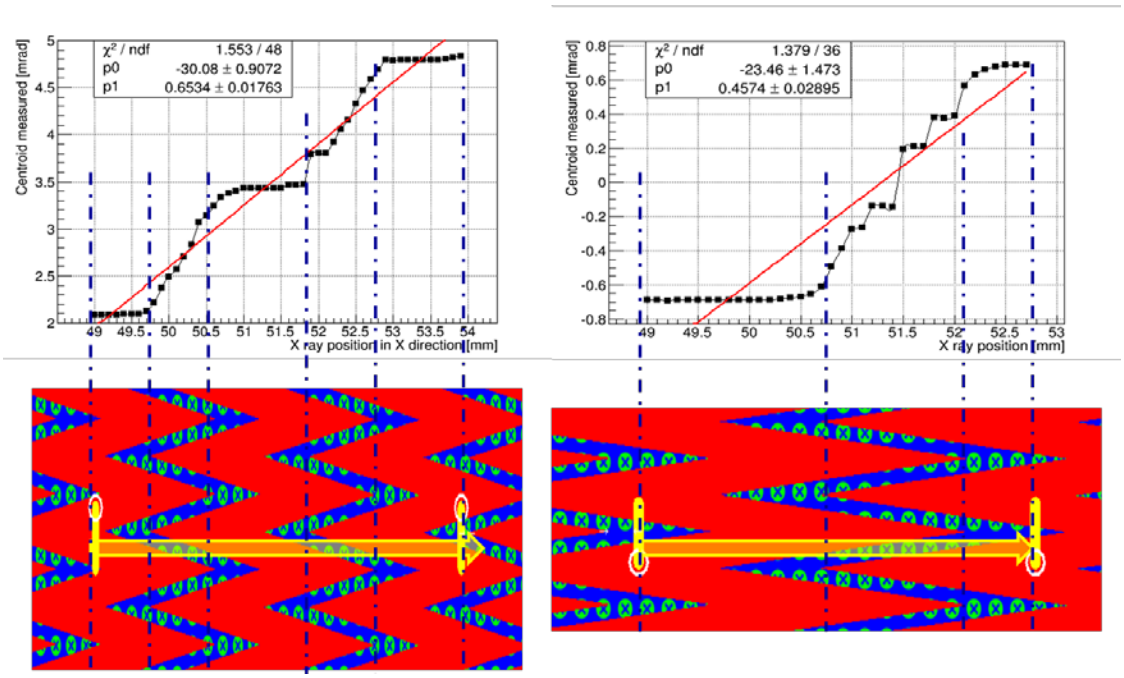

Figure 10 Results of X-ray scans across zigzag strips for boards in Fig.1. *Top:* Measured hit position vs. X-ray reference position for the 48-strip board (left) and the 30-strip board (right). *Bottom:* Zigzag design of scanned regions on the two boards. The vertical dashed lines show the locations of the zigzag tips on the boards indicating regions with and without overlap of strips. These regions correspond to different correlations of measured strip cluster centroids with the position of X-ray incidence.

Figure 10 (top) shows the measured hit position versus the position of incident X-rays for the two boards from the scans across zigzag strips. We observe in the scans that the measured hit position is not linearly related to the X-ray gun position, i.e. there is a non-linear response of the zigzag strips. In particular, the curves have some flat regions where the readout is not very sensitive to the incident particle position because only one strip is fired in those regions; the obtained hit position is then just the center of the strip as no charge is shared between strips. This is confirmed by inspecting the scanned positions on the boards (Figure 10, bottom) as well as by checking the strip multiplicity of the charge clusters (Figure 11).

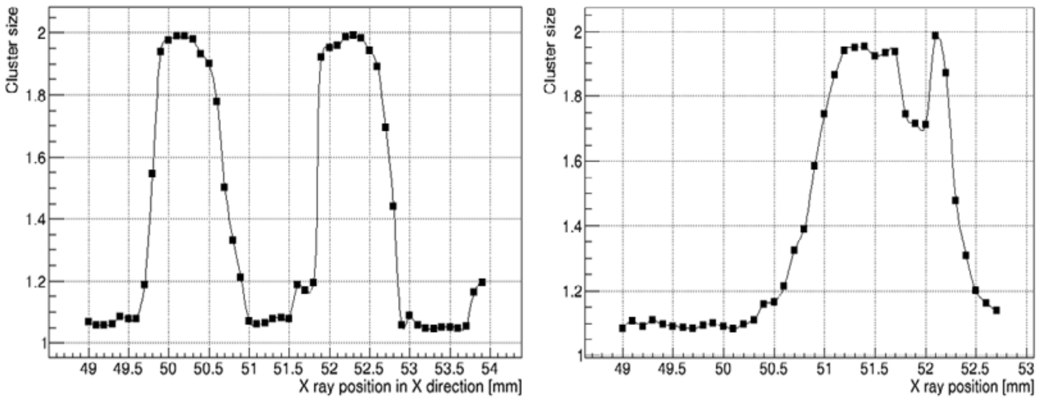

Figure 11 Mean cluster size vs. X-ray position for the 48-strip board (left) and 30-strip board (right) from the X-ray scans across zigzag strips.

We correct the non-linear response offline using the data. For example, for the 48-strip board, we plot the residuals of the linear fits in Figure 10 vs. X-ray position and get global correction functions by fitting the resulting profiles (Figure 12, top left). Plotting globally corrected residuals vs. X-ray position (Figure 12, bottom left), we observe that the overall residual distribution improves (Figure 12, right). For example, if we select events at X-ray positions larger than 51.5 mm, the observed residual sigma is about 128 μrad (Figure 12, bottom right).

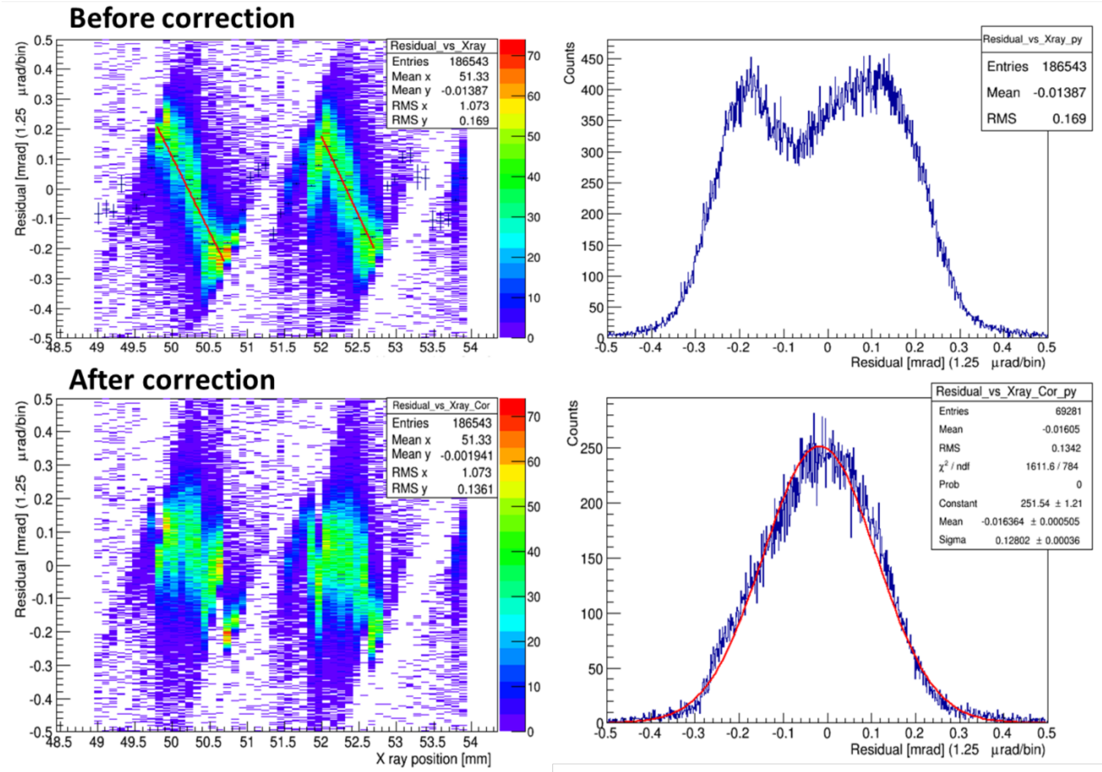

Figure 12 Correction of non-linear response for the 48-strip board using data from the scans across zigzag strips. *Left:* Residuals vs. incident X-ray position before and after correction. *Right:* Residual distributions before and after correction. The bottom right residual distribution is for events with X-ray position > 51.5 mm and the sigma is 128 µrad.

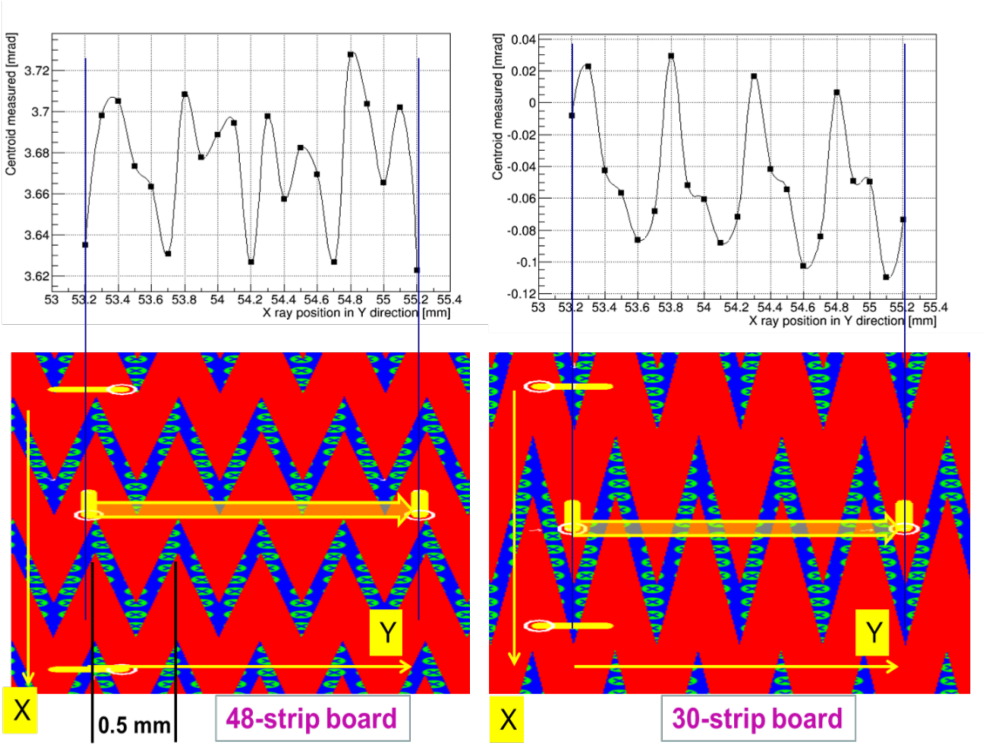

Figure 13 Results from scans along a zigzag strip. Plots on the top are measured hit position vs. X-ray position for the 48-strip board (left) and the 30-strip board (right). Figures on the bottom show the corresponding scanned regions on the boards.

We also scanned the boards along the zigzag strips and the results are shown in Figure 13. For the 48-strip board the scan was done close to a strip center; for the 30-strip board the scan was done in between two strips. Looking at measured hit position vs. X-ray position, we notice systematic comb-like variations as the X-ray moves along the strips; the variations are of similar magnitude as the residual width in Figure 12: 100 μrad for the 48-strip board and 120 μrad for the 30-strip board. This implies that the incident position along the strips does not introduce a significant bias on the measurement of the position across the strips. This is of course the intention of this zigzag design, which has a tip-to-tip pitch along a strip (0.5 mm) that is considerably smaller than the strip-to-strip pitch across the strips (~2 mm).

Readout boards with improved zigzag strip geometry

In the particular designs of the original two zigzag boards discussed above, the “zigs” and “zags” of a strip interleave with its neighboring strips only to a certain extent (Figure 14). Much of the center region of each strip is not covered by adjacent strips and this explains that only one strip fires when a particle hits that region (Figure 11). In the actual physical PCB implementation of this design, this flaw is exacerbated due to a rounding of sharp tips and troughs in the etching process (Figure 14, right).

In order to reduce the non-linear response of the zigzag strips due to this flaw in the strip geometry, we have modified the geometry of the zigzag structures so that the tips of the “zigs” and “zags” of a strip reach all the way to the centers of its neighboring strips (Figure 15, left). At the same time, the tip-to-tip pitch of 0.5 mm is maintained. However, it appears that PCB industry has some difficulties to produce exactly what we have designed. The “zigs” and “zags” of the actual physical strips on the PCB do not fully reach the centers of neighboring strips (Figure 15, right). Also, the strips come out much thinner than in the design.

Consequently, we made a third design where the “zigs” and “zags” go even beyond the centers of neighboring strips (Figure 16, left) in the hope that this would compensate for the production process and give us a PCB with the desired design. The resulting PCB produced by the same company comes close to the desired interleaving of zigs and zags; interestingly, the compensation in the design resulted in a slight overcompensation on the actual PCB (Figure 16, right).

However, strips are still coming out much thinner than designed. The company has suggested that this problem might be overcome by using a thinner copper layer on the PCB that requires less etching. We will continue working with the company to see if they can produce a PCB as we have designed it.

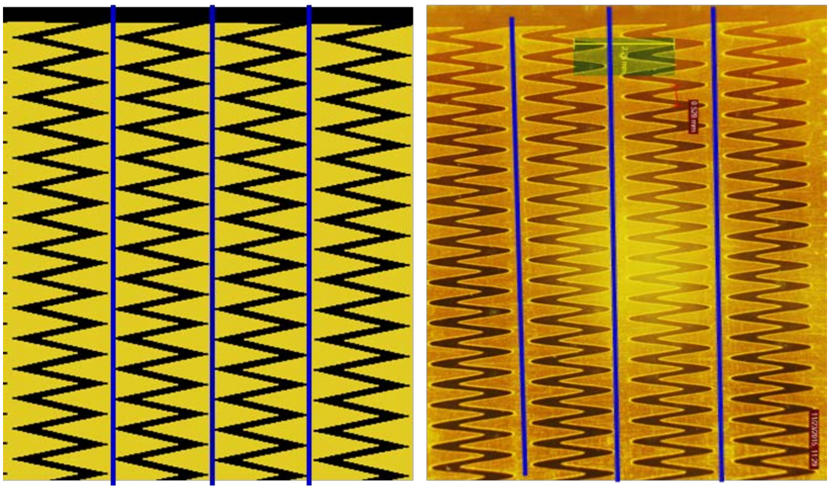

Figure 14 *Left*: Zoomed view of a few readout strips in our original zigzag design. *Right*: Actual zigzag strips produced by a PCB factory. Blue lines indicate strip centers.

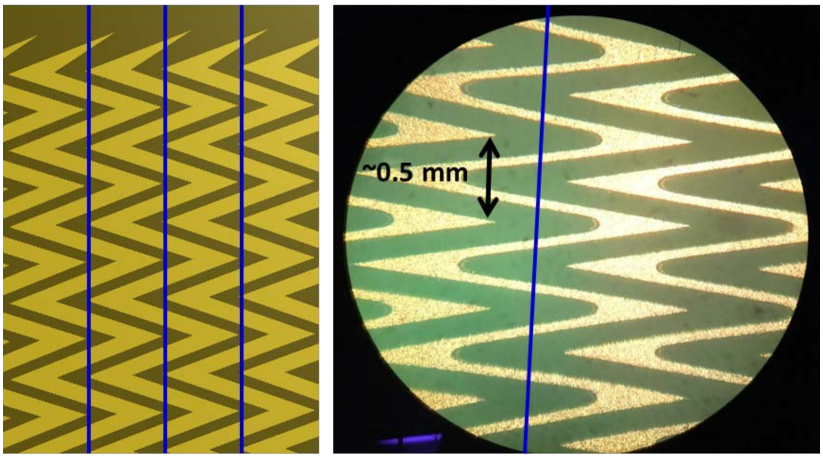

Figure 15 *Left*: Zoomed view of the first modified zigzag structure design. *Right*: microscope image of actual zigzag strips produced by a PCB factory. Blue lines indicate strip centers.

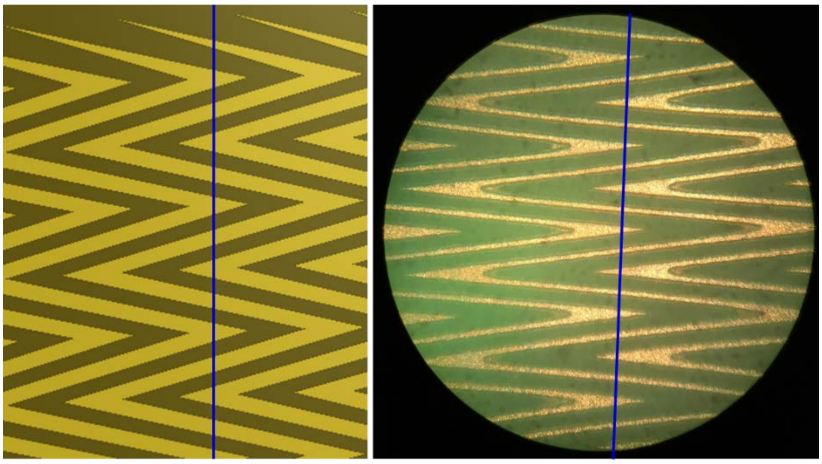

Figure 16 *Left*: Zoomed view of the second modified zigzag structure design with overcompensation. *Right*: microscope image of actual zigzag strips produced by the same PCB factory. Blue lines indicate strip centers.

Looking ahead, in our next 1-m EIC FT GEM prototype the optimized zigzag readout pattern will actually have to be produced on a flex-circuit instead of on a rigid PCB. Given our experience with industry, we have ordered a 10cm × 10cm test readout foil mounted on a honeycomb backing from Rui de Oliveira's workshop at CERN to see how well he can reproduce our design pattern; production of the test board at CERN is finished and we expect to scan it at BNL in the next few weeks.

The new readouts we have gotten were scanned at BNL with the X ray gun in late May 2016. We'll summarize all the results and conclusions in our next report.

Status of the next 1-m-long EIC FT GEM prototype chamber

- Common GEM foils:

We placed an order of four 1-m-long common EIC FT GEM foils of our design with the CERN workshop in February 2016. Production of these foils at CERN is finished. Delivery is expected in late June 2016. We will need to validate the foils by measuring leakage currents once they arrive in Florida.

- Readout foil and drift foil:

We have completed the zigzag strip readout design; the spacing and width of traces is around 70 µm. We sent Gerber files to four different US PCB factories for quotes. Unfortunately, none of these factories is able to produce 1-meter-long flex PCB with the precision that is required. Then we approached the CERN workshop again and found that Rui Oliveira is able to produce this readout foil for us. We worked with his design team to tune and finalize the design. As mentioned above, in order to make sure that we can actually get produced what we have in the design, we asked Rui to first produce a small board for testing purposes. If the small CERN foil can be validated for our purposes, we will place the order for the full-size readout foil. We would then expect to receive that foil in August 2016. The much more straight-forward drift foil design is also finished. We have obtained quotes for both readout foil and drift foil from Rui.

- Mechanical aspects of chamber construction and assembly:

As described in previous progress reports, we have adopted a modified mechanical stretching method without spacers that the CMS GEM collaboration has been using for large GEM chamber construction. In order to reduce material in the active detection area of the EIC FT prototype, we make a stack from five foils (three GEM foils, one drift foil, and one readout foil), sandwich it between two support frames made from some stiff material, and stretch the stack against so-called pull-out posts that are fixed on the support frames.

We completed the details of the 3D mechanical design for the prototype chamber in Autodesk Inventor by adding screws and nuts into the design. We are currently studying the expected deformations of this design with finite-element analyses using Autodesk Inventor and ANSYS. The reason to use ANSYS is that we found that Inventor cannot handle a stress analysis for thin foils. With help from our mechanical engineering department we have gained access to an ANSYS research license. We use these tools to define the required mechanical strengths and dimensions of support frames, screws, and other mechanical elements. We also study the expected deformation of the foils after stretching, e.g. under gravitational load (Figure 17), so that we can optimize the force loads that are applied in the stretching process.

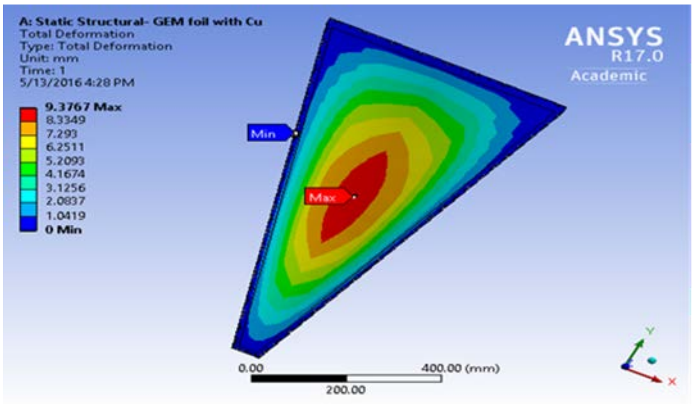

Figure 17 Simulated deformation of the common EIC GEM foil (no GEM holes) in horizontal position due to gravitational sagging when all four edges are constrained to be at the same height.

We are not yet able to simulate the entire detector with all components in ANSYS because that requires a very large number of mesh nodes in the model, which currently overloads the PC we use. We are working on optimizing the meshing in ANSYS to get around this problem. For now, we simulate a less complex subassembly in Autodesk Inventor, i.e. the drift and readout support frames assembled together with posts that will hold the tension load of the foils (Figure 18, left). In the simulation, we apply forces on the posts pointing into the detection area (Figure 18, right), which by Newton's third law are equal and opposite to the forces exerted by the posts on the foil stack that stretch the foil stack.

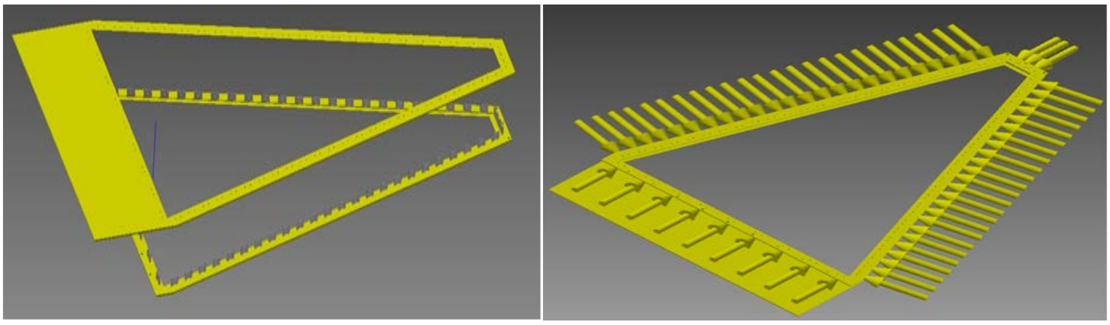

Figure 18 *Left*: Exploded view of chamber frame assembly with readout support frame shown above drift support frame. The two frames are held together by 60 pull-out posts (gray) that are also used for attaching and stretching the foil stack. *Right*: Inventor simulation of tension forces from stretched foil stack applied to posts in assembled frame; forces point towards the foil stack and are perpendicular to the post faces.

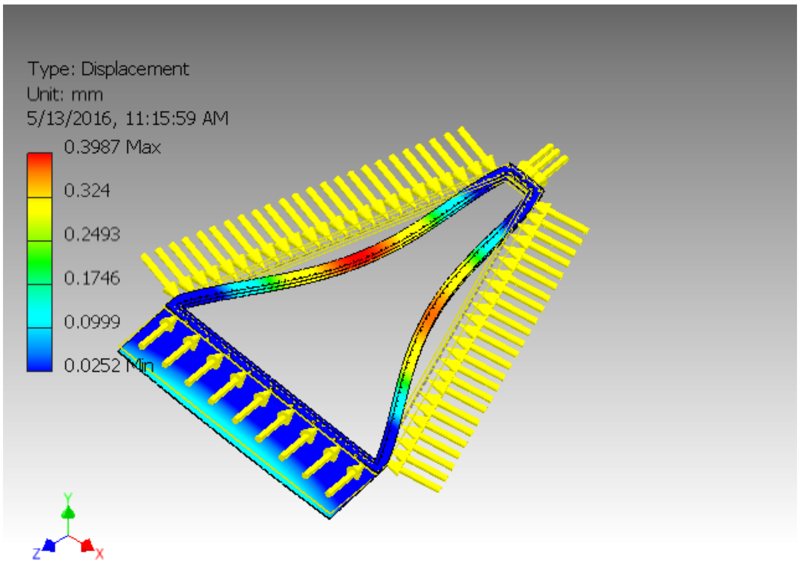

Figure 19 Simulated deformation of frame assembly for 10 N of stretching force applied to each pull-out post. The frame material here is carbon fiber M55UD.

With this configuration, we varied frame material and thickness as well as force magnitude to study the expected deformation of the frames due to the stretching forces. Table 1 lists the maximum deformation of the frames for a 10 N force on each post for different frame materials. The mechanical properties (density, Young's modulus, Poisson ratio, shear modulus, tensile modulus) of the materials used in the simulation are researched from internet sources, e.g. ref. [1] for carbon fiber materials. We find that for standard PCB material, i.e. FR4, the deformation is about 4.6 mm, which is presumably too high for our application. With unidirectional (UD) M55 carbon fiber material we expect a much smaller maximum deformation of about 0.4 mm. With ceramic (silicon nitride) the deformation could be even less than 0.3 mm. We will research more carbon fiber composites to find one that can minimize the deformation.

Table 1 Maximum expected inward bowing of frames from simulation for different frame materials. A force of 10N is applied to each post (Figure 18, Figure 19); frames are 3 mm thick.

Frame material	Carbon fiber (M55UD)	Carbon fiber (UD std.)	Ceramic (Silicon Nitride)	FR4
Max. deformation (mm)	0.399	1.068	0.282	4.565

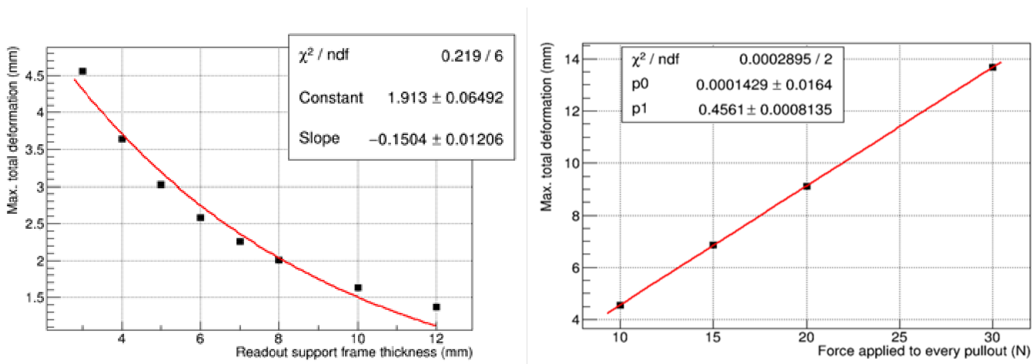

Figure 20 *Left*: Maximum deformation of FR4 frame assembly from simulation as a function of the readout support frame thickness for 10 N force per post. *Right:* Maximum deformation of 3 mm thick FR4 frame as a function of force applied to each post.

Figure 20 (left) shows the maximum deformation of the frames as a function of readout frame thickness for 10 N forces per pull-out post and as a function of applied force per post for 3 mm frame thickness (right). We find that the deformation is roughly an exponential function of frame thickness, and it is linear with respect to the force magnitude.

Participation in the Cherenkov/TPC beam test campaign

In addition to the originally planned efforts, A. Zhang participated for one week in the Cherenkov/TPC beam test campaign at FNAL organized by the eRD6 consortium and led by the BNL and Stony Brook U. groups. The beam test successfully demonstrated the concept of a GEM Cherenkov/TPC. This effort is described in more detail in the report sections provided by the BNL and SBU groups.

Reference

[1] Carbon fiber mechanical properties, http://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp

INFN Trieste:

N/A

Stony Brook University:

After careful calculation and consideration, it was decided to not to pursue the refurbishment of the evaporator called *Big Mac* since the complexity of the redesign would be too costly and complicated. If choosing a simpler solution one would risk not to achieve the required vacuum to perform the evaporation to the desired level.
Instead, we will be using the existing evaporator (Figure 21) that is routinely used for evaporating CsI on GEMs for HBD like readout structures, see also the report from BNL. For preparing this evaporator we are in the process to purchase an electron gun so that the cover material of the mirror, MgF_2 can be reliably attached to the surface of the prepared mirror blank plus aluminum. The latter process requires the protection of areas that are serving as insulator between conducting elements within the evaporator. At the write-up of this report the purchase of items and preparation is ongoing.

Figure 21 Evaporator in the clean room of SBU. Left: side view. Right; View inside the evaporator.

In collaboration with BNL we produced the Cherenkov-GEMs and prepared for the BNL TPCC effort. We have participated in the test beam campaign in April 2016 which was described in the BNL portion of this report.

<u>*University of Virginia:*</u>

High particle rate study of the Cr-GEM

The Cr-GEM concept would allow the reduction of GEM detector material thickness by a factor of two. Our results indicate that the Cr-GEM detectors work very well under low particle rate, while extreme particle fluxes appear to damage some components of the detector. Our observations show that a similar detector with some re configuration may be able to function well under high fluxes.

The study consists of a uniform exposure of the Cr-GEM in the high intensity x-ray source to analyse the response of the chamber such as uniformity and efficiency for various particle rates. For each measurement, the total charge (Coulombs) integrated over 24 hours is used as a measure of the particle rate. The top left hit map plot of Figure 22 shows no degradation of the chamber after an exposition to moderate particle rate an integrated charge of about 0.17 C. With an increase of the intensity of the x-ray source corresponding to an accumulated current of 0.35 C in 24 hours, we observe the appearance of a small dead area spot as shown on the top right plot. The dead area size increases dramatically with increasing rate as shown on the bottom two plots of Figure 1, with almost half of the active area of the chamber dead when the rate increases up to 0.7 C a day.

We opened the Cr-GEM prototype in the clean room to inspect the individual GEM foils after the intense high rate test and subsequent efficiency drop. Preliminary visual inspection shows that the first two GEM foils seem intact with no noticeable damage due to the high rate irradiation.

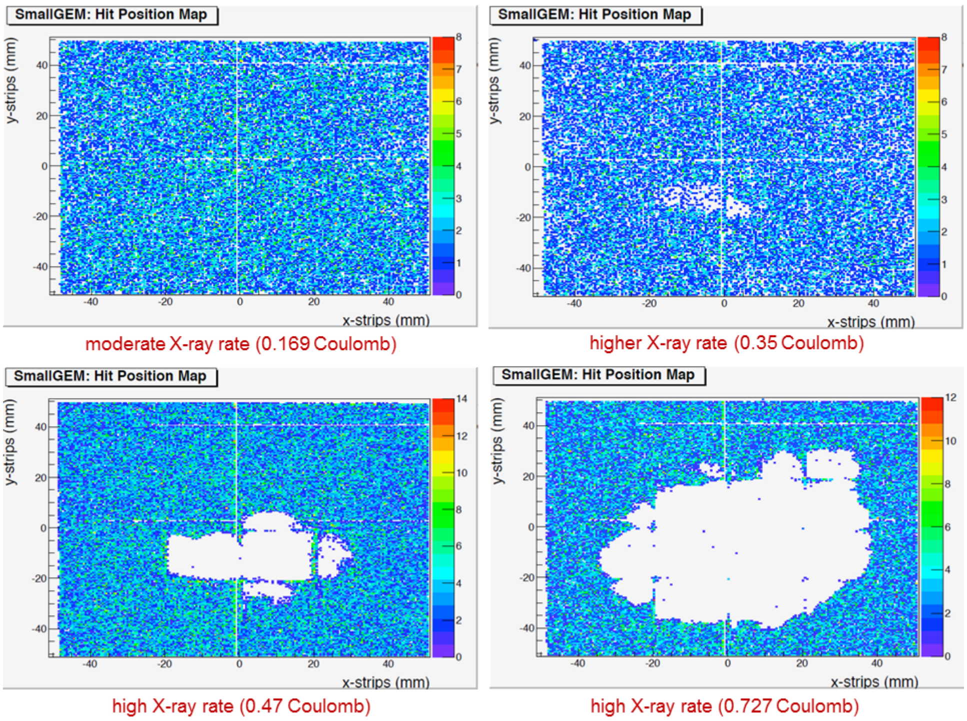

Figure 22 ***Degradation of Cr-GEM prototype in high particle rate environment with X-ray source.***

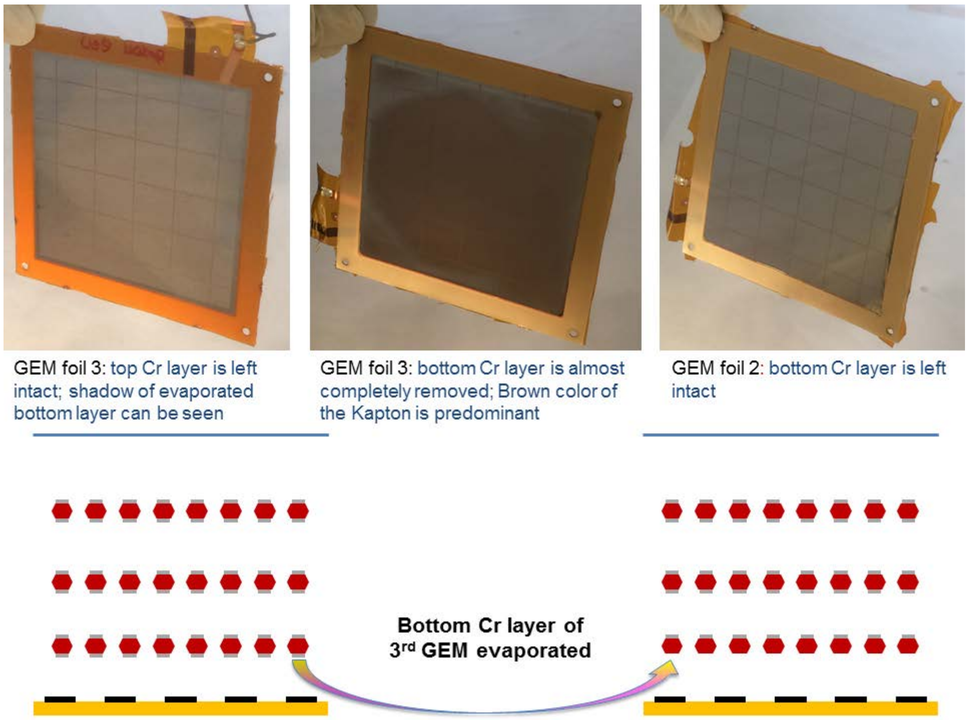

Figure 23 *Picture of the Cr-GEM foils with the thin Cr layer removed from the bottom side of the GEM foil 3.*

HV test of these foils also did not reveal anything unexpected. The foils seem to be functioning perfectly well. The third GEM foil however displays a somehow surprising effect with the top Cr electrode layer intact with no apparent sign of discharges or spark as one can see on the left picture of Figure 23, however on the bottom side, the Cr layer has been almost completely "evaporated" leaving dark brown color of the Kapton. There is no evidence of short circuit developing between top and bottom layer as is often the case when a high energy discharge develops in the GEM foil. But all evidences point to the fact that small discharges are sufficient to locally evaporate the Cr layer and actually preventing big discharge to develop and destroy the foil and propagate to upper GEM foil. By comparison, the left picture shows the bottom side of GEM foil 2 (the middle foil) with the thin Cr layer left intact.

The disappearance of the thin Cr-layer at the bottom of GEM foil 3 is the result of the high concentration of charges present at the bottom of GEM foil 3 under high rate condition. From this preliminary study, we see strong evidence that the removal of the Cr-layer is not caused by "ageing process" of the Cr-GEM foil but rather by some small scale discharge evaporating of the Cr without damaging the Kapton or top Cr layer. We plan in the next study to take data with the Cr-GEM prototype over a long period of time (several month) under moderate X-ray flux in order to study the ageing process of the Cr-GEM foils. We are ordering new Cr-GEM foils from CERN to replace the damaged one for this study.

1. Large GEM prototype:

The common GEM foil designed for UVa, Florida Tech and Temple University has been completed and is under production at CERN. We expect delivery of the UVa version of the foils by early June. Preliminary works on the design of the zebra-to-Panasonic adapter used for the connection of the U-V readout board to the front end electronic has started with the collaboration with CERN PCB workshop experts. The final design is still being implemented.

2. Small scale triple GEM with U-V strips readout:

We submitted the initial design for a small size (10 cm × 10 cm) U-V strip readout board that we are planning to assemble with our spare (10 cm × 10 cm) GEM foils and test together with the zebra-Panasonic adapter scheme to validate the process before we move to the production of the full size readout board. We expect delivery of the small readout board before the end of July.

Weizmann Institute of Science:

N/A

Yale University:

3-Coordinate GEM
Experienced personnel were added to this effort and the analysis is near completion. The final pad response functions are being extracted to develop the required corrections.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas
A paper on the results to date has been submitted to NIM and is available at:
http://arxiv.org/abs/1603.08473
Results and status were also presented at
RD51 Collaboration Meeting (08-11 March 2016), CERN, Combined of Gas Electron Multipliers and Micromegas as Gain Elements in a High Rate Time Projection Chamber
and
ECFA LC workshop, May 30th – June 5th, 2016, Santander (Spain);
Invited report; Combined of Gas Electron Multipliers and Micromegas as Gain Elements in a High Rate Time Projection Chamber

Consulting with other groups it was determined that the high intensity corona-like discharges seen in the resistive layer MMG's are a problem with the manufacture of the resistive layers for the particular chambers we have. We will submit these for rebuild.

Multi-element stacked gated grid
Initial measurements to determine voltages needed for transparency and ion clearing are completed.

What was not achieved?

Brookhaven National Lab:

We had planned (and also started) the design of a new chevron readout board which we feel would have provided better spatial resolution than the one used for the TPC in the Fermilab beam test but it was not possible to complete the design and have the board fabricated and tested in time for the beam test. However, this was only one of several designs that we wish to test, and we plan to include these as part of our future R&D effort for the next FY. This will also include additional calculations, simulations and laboratory measurements as described below.

Florida Institute of Technology:

We achieved most of what we had planned for this period.

We were slowed down somewhat on the production of the zigzag readout for the large FT GEM prototype because the production of test boards with proper zigzag strips to understand the non-linear response is more difficult than anticipated. We are addressing this issue with the PCB company and with the CERN workshop.

We have not yet been able to experimentally investigate stiff chamber frames, e.g. made from carbon fiber; we have just started investigating this issue in the finite-element simulations.

INFN Trieste:

N/A

Stony Brook University:

As described above the evaporator *Big Mac* was not refurbished and instead the redesign of the existing CsI evaporating facility is ongoing.
The design of a snowflake readout pad had been postponed due to the support activity of the TPCC effort of BNL.

University of Virginia:

It has taken longer than expected to get funding transferred from BNL to UVa. The final paperwork for fund transfer has been submitted to BNL and we are now waiting for funds to arrive at UVa.
The design of the support frames for the GEM foils and the mechanical structure of the detector is a few months behind schedule. This was in part due to our other commitment to the PRad experiment run at JLab that just started in May 13, 2016. Our detector group at UVa was in charge of the construction, commissioning and installation in Hall B a JLab and operation of the large PRad GEM chambers as well as its readout electronics. Preparation for the PRad experiment required that we focus our resources for the last 6 months or so on the PRad GEM detectors. We will resume the drawing and design of the frames in the coming weeks.
For the same reasons as state above, our plan to test the small size U-V readout board with zebra connection has been delayed as well. We have just managed during this cycle to finalize the drawings and place the order. We expect to receive the board in about a month for now and we would then start the validation test of the new ideas.

Weizmann Institute of Science:

N/A

Yale University:

3-Coordinate GEM
Submission of a paper on the final analysis remains to be completed.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas
Study of the resistive layer 2-GEM+MMG was delayed by an apparent problem with the manufacture of the MMG we have.

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 planned activities during the next funding cycle are as follows:

- *Complete the analysis of the TPCC test beam data and publish the results in IEEE TNS*: The anticipated outcome from this test is that we will demonstrate a proof of principle of the concept behind this hybrid detector, and include several import performance specifications such at the track position resolution of the TPC, and the light yield and particle id performance of the Cherenkov portion of the detector.
- *Simulation/Design/Testing of new chevron patterns:* We are currently developing the software tools to fully simulate the propagation of charge through the TPC, from the point where the primary charge is deposited in the gas volume to the point where the shaper response of the readout electronics is analyzed from each chevron pad. The effects of diffusion, the avalanche process, and the specific electric field shape in the GEM holes and near the readout electrodes are all taken into account in a 3D simulation in an effort to accurately simulate the response of a variety of readout patterns. This work has already been started and preliminary results were given in the previous R&D report in January 2016. These results will be used to guide the design of the electrode structures for the new readout boards, such as the periodicity and pitch of the chevrons, in order to optimize the resolution and segmentation. We plan to test various versions of the improved chevron designs in the lab using our precision X-ray source (which has also been used by the FIT group to study similar patterns), and carry out systematic studies of their position resolution using different gases. We also hope to be able to test these new designs using our existing TPC prototype detector using a beam of 1-2 GeV protons at the NASA Space Radiation Laboratory at BNL if suitable arrangements can be made to avoid excessive charges for the use of this facility.
- *Working with Stony Brook to build a TPC prototype field cage :* Stony Brook has initiated designing and building a portion of a prototype TPC field cage for use at RHIC and EIC. The BNL group plans to work with the Stony Brook group in this effort in order to complete the design and construct the actual detector.
- *Ion Back-Flow (IBF) measurements:* A critical component for the successful operation of the TPC is to understand the magnitude of ion back flow to be expected in the TPC and to minimize it. A great deal of effort has already been carried out on this subject by the ALICE experiment and we plan to build on that experience. Our measurements will focus on various ways of minimizing ion feedback by optimizing the GEM electrode structures and operating parameters, using hybrid structures such as a combination of GEMs and micromegas, and studying various types of operating gases. We plan to carry out these measurements in collaboration with Stony Brook, the Weizmann Institute and Yale University.

- *Measure the reflectivity of VUV mirrors:* Stony Brook plans to produce high quality Al/MgF_2 coated mirrors for future RICH detectors. We plan to use our VUV spectrometer at BNL to measure the reflectivity of these mirrors. However, the spectrometer requires new hardware, commissioning, and possibly new software before these measurements can be performed.

Florida Institute of Technology:

We will finish the tests of small zigzag boards to find the zigzag geometry with the most linear position response. We plan to present the results from this study in the 2016 NSS IEEE conference and to publish them in TNS or NIM. We will also apply that optimal geometry to the design of the large readout foil for the FT GEM prototype chamber and then have that foil produced at CERN.
We will measure leakage currents of the large common GEM foils once we receive them to assure the foil quality.
We need to finish the static structural FE analysis for the mechanical aspect of chamber assembly, specifically with respect to any potential for buckling of the frames under stretching forces, choose proper materials (frames, support boards, etc.), and then identify companies in industry that can produce them for us.
We expect to have the second FT GEM prototype chamber assembled by early 2017 so that we can test it in a beam at Fermilab in 2017.

INFN Trieste:

Further development of hybrid MPGDs for single photon detection synergic to TPC read-out sensors.

The concept of the hybrid MPGD detector of single photons has been developed in an eight-year R&D program; the reference figures for the present optimization are the requirement for the upgrade of the gaseous RICH counter of the COMPASS experiment at CERN SPS. The resulting detectors are presently built and installed, while the commissioning will start in the late Spring 2016. The detector architecture (Figure 24) consists in three multiplication stages: two THick GEMs (THGEM) layers, the first one coated with a CsI film and acting as

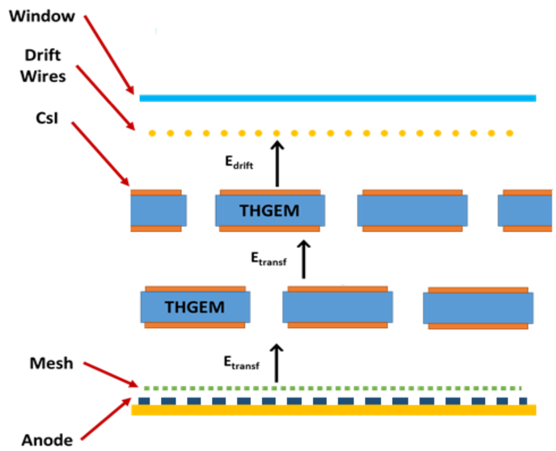

Figure 24 Schematic architecture of the hybrid MPGD detector of single photons (not to scale).

photocathode, followed by a MicroMegas (MM) multiplication stage. The two THGEMs are staggered: this configuration is beneficial both to reduce the Ion BackFlow (IBF) and to increase the maximum gain at which the detector can be operated exhibiting full electrical stability. These photon detectors can operate at gains of at least 5 x 10^4 and exhibit an IBF rate lower than 5%. The gas mixtures used are by Ar and CH_4, with a rich methane fraction in order to maximize the photoelectron extraction.

An original element of the hybrid MPGD photon detector is the approach to a resistive MM by discrete elements (Figure 25), which has been triggered by the resistive MM developed for the ATLAS experiment at CERN LHC [The ATLAS Collaboration, "Technical Design Report for the New Small Wheel," CERN-LHCC-2013-006 / ATLAS-TDR-020, June 2013], but presents substantial differences. The anode elements (pads) facing the micromesh are individually equipped with large-value resistors and the HV is provided, via these resistors, to the anode electrodes, while the micromesh is grounded. A second set of electrodes (pads parallel to the first ones) are embedded in the anode PCB: the signal is transferred by capacitive coupling to these electrodes, which are connected to the front-end read-out

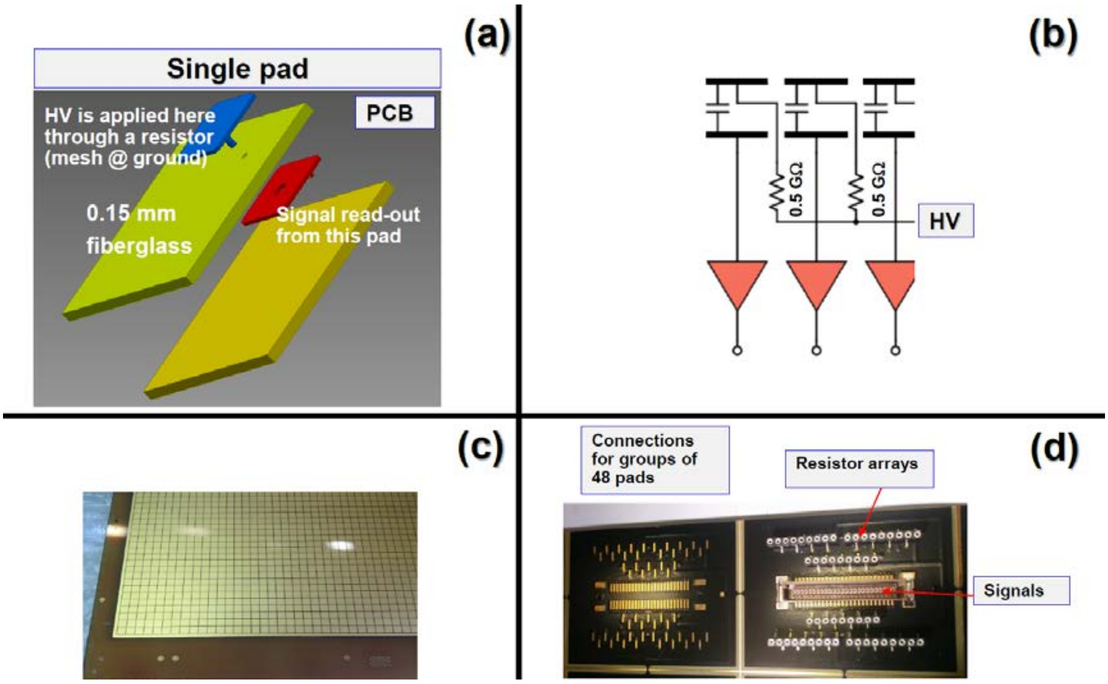

Figure 25 The resistive MM by discrete elements. (a) The principle is illustrated by a single pad; the different layer of the PCB forming the MM anode are schematically shown: the blue pad is the anode electrode of the MM kept at positive voltage; it directly faces the micromesh; the red pad is embedded in the PCB and the signal is transferred from the blue to the red pad by capacitive coupling. (b) The principle is illustrated by the electrical scheme: the top elements of the capacitors are the pad forming the MM anode (blue pad in (a)), the bottom elements of the capacitors (red pad in (a)) are connected to the front-end electronics. (c) Picture of the MM anode PCB in the present version, front view: the pad size is 8 x 8 mm^2. (d) Picture of the MM anode PCB in the present version, rear view, detail: the connectors serving 48 pads are grouped together; both the signal connectors and the supports of the resistor arrays are present.

electronics. The advantages of the design shortly described above are several:

- As in ATLAS resistive MM, applying the HV to the anode instead of to the MM cathode results in larger amplitude signals;
- In case of local defects of the MM, a single electrode can be isolated resulting in a dead area as large as the electrode itself, while the large majority of the detector is still active;
- No resistive coating is present inside the detector volume;

- The absence of a resistive layer on top of the anode electrodes is limiting the degradation of the dE/dx information in the collected signals.

The hybrid detector concept can be further improved in order to match the requirements of high momenta hadron identification at EIC; this challenging task requires:

i. Limited radiator length of the order of 1 m: here one of the most promising approaches is the window-less RICH concept [M. Blatnik et al., IEEE transaction on Nuclear Science 62 (2015) 3256];
ii. Fine space granularity to cope with the modest lever arm related to the radiator length;
iii. Control of the IBF rate in order to guarantee stable detector performance over time;
iv. Further improvement in the engineering aspects in order to simplify the construction and control the costs;
v. The comparison between hybrid detectors where THGEMs or GEMS in view of an overall optimization of the detector principle.

The R&D program proposed here is meant to match the requirements listed above. It spans three years of activity and it includes five tasks:

1. test of novel materials for THGEM substrate to simplify the detector construction, increase the yield of valid large-size THGEMs and, thus, control the detector costs (related to requirement iv);
2. the development of resistive MM by discrete elements with miniaturized pad size (present size: 8 x 8 mm^2) in order to obtain finer space resolution (related to requirement ii);
3. comparison of THGEM vs GEM photocathodes in order to select the best architecture for the photon detectors of the EIC RICH (related to requirement v);
4. further studies in order to enhance the IFB suppression in hybrid MPGDs (related to requirement iii);
5. operation of hybrid MPGDs (THGEMs + MM) in fluorocarbon-rich gas mixtures (related to requirement i).

The overall timelines are provided in Figure 26.

It is relevant to underline that the further development of the hybrid detector concept, in particular with finer space resolution and low IBF rate is synergic to another sector of great relevance for the future experiments at EIC, namely the read-out sensors for the TPC. A hybrid MPGD approach to TPC read-out has already been proposed making use of traditional non-resistive MMs [A. Aiola et al., “Combination of two Gas Electron Multipliers and a Micromegas as gain elements for a time projection chamber”, http://arxiv.org/abs/1603.08473, submitted to Nucl. Instr. Meth. A]; our approach to resistive MM can offer a detector which exhibits robust electrical stability while preserving a good dE/dx resolution.

		FY 2017				FY 2018				FY 2019			
TASK no	TASK	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter
1	test of novel materials for THGEM	■	■	■	■								
2	resistive MM by discrete elements with miniaturized pad size			■	■	■	■						
3	comparison of THGEM vs GEM photocathodes					■	■	■	■				
4	enhancement of the IFB suppression in hybrid MPGDs							■	■	■	■		
5	operation of hybrid MPGDs (THGEMs + MM) in fluorocarbon-rich gas mixtures									■	■	■	■

Figure 26 Timelines of the R&D

Stony Brook University:

The finalization of redesigning the evaporator for producing large mirrors is expected to be performed at the beginning of the new funding cycle. The plan is to provide a large surface equipped with smaller mirror blanks at each corner and in the center. The samples will then be evaluated with the VUV spectrometer from BNL. This should represent a good measure of the properties of a large mirror evaporation.
Furthermore, data analysis for the TPCC beam test data from April will be performed.
In collaboration with the BNL group we are planning to work on the understanding of the magnitude of ion back flow in a TPC and plan to purchase necessary equipment and test it under test beam condition. Ion back flow is problematic for TPC performance in a specific environment and we are working on providing a TPC that does not need to be gated. TPCs in future applications will profit from a gate-less operation and this will be the trend for future TPCs wherever they will be used in collision experiments. A TPC is also planned to be part of ePHENIX, one of the detectors that is foreseen to be a day-1 detector to perform EIC physics. This is targeted detector R&D specific to one or more of the EIC detector concepts. All EIC detector concepts that will have a TPC as central tracking device will profit from operating with a gate-less device.
As we have showed with our RICH prototype in the SLAC testbeam (see publication IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 6, DECEMBER 2015) the top GEM can be operated as a device with gain one and it will be suited to act as a gate-less ion back flow blocker in a GEM-readout for a TPC.

University of Virginia:

For the coming cycle from June 2016 to December 2016, we plan to:

1. Continue the study of Cr-GEM detector with x-ray source. Take data under moderate particle rate for several months to study the long term stability and ageing of such thin Cr-GEM structures.
2. We plan to validate the new ideas such as etching the top and bottom strips contacts on the same Kapton support and the zebra connectors for electrical contacts developed for U-V strips readout of EIC GEM prototype II, on a small scale (10 cm × 10 cm) readout prototype before we move ahead with the full size detector.
3. Upon reception of the UVa version of the EIC common GEM foils from CERN, we plan to perform HV tests of the foils for quality control. In the meantime, we would have completed the design of the frames and mechanical structure and the fabrication of the full size U-V readout board is expected to be launched

Weizmann Institute of Science:

The group conducts research on the multilayer micropattern detectors in order to increase the detector performance. This research has direct implications for a TPC foreseen to be used in the ePHENIX detector.

The first direction involves optimization of the multi-GEM stack for improving the space charge problem in the TPC, or to improve the IBF characteristics. There are several steps in the plan how that can be achieved beyond the parameters previously measured by the ALICE research groups:

1. Choosing different gas mixtures. The gas system allows testing any gas combination by readjusting gas flow meter settings.
2. Changing the field configuration inside the GEM stack. Both items 1 and 2 were thoroughly studied by the ALICE collaboration, and mentioned here are tools for additional studies.
3. Adding GEM layer. Addition GEM should further suppress the IBF and if properly configured with the electric field to be in gain=1 regime can further suppress the IBF
4. Using additional mesh instead of GEM and changing drift/transfer field ratio.
5. Using GEMs with so-called “cobra” pattern that allows more effectively redirect ions onto GEM electrodes.
6. Altering GEM pitch, using so-called small pitch (90um) and large pitch (200um) GEMs.
7. Explore a possibility to effectively misalign holes in the construction of the GEM stack of the same pitch to improve the IBF suppression due to geometric factor.

The second research direction is the design of a GEM readout module prototype. The prototype uses different concept compared to previously built multi-GEMS readout elements. The concept is shown in Figure 27.

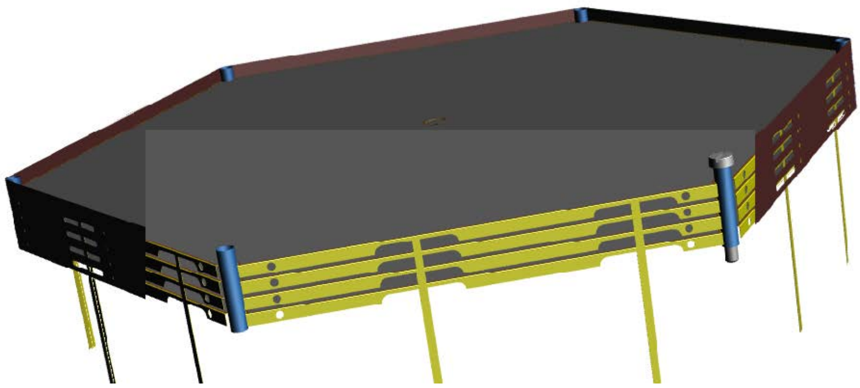

Figure 27 A four-layer GEM read-out element assembly view. Some elements are to be removed in the assembly procedure. The voltage divider (not shown) is integrated in the element structure.

The readout element is a standalone module, which has several crucial advantages:

1. Almost frameless design (approximately 600um between holes of adjacent modules) allows reducing inactive areas in the detector to a percent level. Residual areas that never fully shadow one single pad would result in a signal reduction rather than in a signal loss. Thus, this design, then proven to work, can be considered virtually a “no dead area” design.
2. Geometry of the GEM elements can be tailored to fit the entire fiducial area.
3. Loss of a single element has small impact on the TPC performance.

4. Each element is build out of approximately 100cm^2 GEMs. Such GEMs can be produced in large quantities at lower cost compared to larger GEMs of the equivalent area.
5. Uniformity of small GEMs is typically better than that of the large GEMs due to less demanding tolerance during the manufacturing stage.
6. Small size of the element may, in principle, allow to (miss-)align holes in different GEM layers for better IBF suppression.
7. Production, and more importantly, testing of GEM elements can be effectively done in parallel by several groups to keep up on the scheduler and to ensure the highest quality of the final detector.
8. Since the element is assembled in its final configuration already at the testing stage it can be fully calibrated before being mounted onto TPC.
9. Low cost of individual element allows pre-selecting the best elements to be used in the experiment and keeping the rest as a contingency.
10. Such element better suites to be used in future HBD-like detectors, there GEMs need to be coated with CsI. Pre-tested and coated element can be installed into its final position avoiding intermediate assembly required in a layer-by-layer procedure.

Equipment

The group at the Weizmann Institute possesses a fully equipped clean room with the area of ~50 m^2 shown in Figure 28.

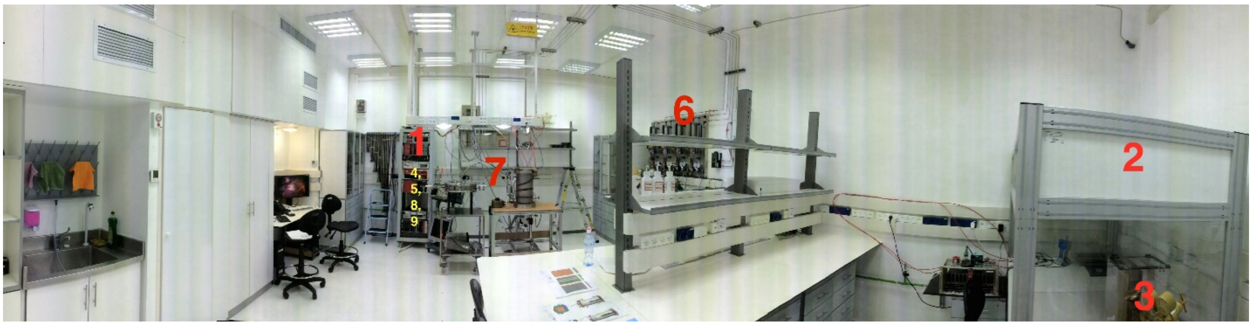

Figure 28 The gaseous detector laboratory at the Weizmann Institute. The numbers on the photograph correspond to the numbers in the text.

The clean room has the following equipment:

1. Rack with the NIM crates and various logical and service modules, the oscilloscope.
2. Laminar Flow Table (LFT) for GEM assembly.
3. Olympus BXFM optical system for visual inspection of the GEM foils and GEM stacks. (This system is not visible in the photo in Figure 10 at location 3)
4. CAEN mainframe with 12 channels HV module up to 5 kV. The system is expandable to 60 HV channels.
5. Glassman HV power supply for up to 40 kV.
6. Fully automated, computer controlled gas flow system capable of mixing up to 4 different gases with the precision of 2%. The system has three gas flow lines which can be operated independently. The system integrates flow, pressure, humidity and oxygen content control devices.
7. Test cells for micro-pattern gaseous detector testing and gas studies:
    a. For 10 cm × 10 cm size detectors with 30 cm gas drift volume;
    b. For 20 cm × 30 cm size detectors without drift volume;

   c. Cells are connected to the turbo-pump based gas evacuation system;
   d. Cells are equipped with ionization source, MINI-X X-ray tube, and the UV-laser system for gas ionization;
   e. Cells are connected to 10ch and 3ch floating picoampermeter system for measuring currents in the micropatern detector layers.
8. Data acquisition system for 512 channels, expandable to up to 4096 readout channels.
9. Alternative DAQ with smaller number of channels.
10. Standard laboratory equipment.

The cleanness of the air in the room outside the LFT working volume corresponds to Class ISO-8 clean room standards for particles less than 1 μm and exceeds that for larger particles. The cleanness of the room can be elevated; however, the detectors are normally not exposed to the room air outside the LFT volume. The clean room is considered as the main working place for the project. Additional rooms can be provided by the Institute infrastructure, if required.
The resources which are available at the Weizmann Institute of Science and which will be used in order to perform the efforts for this project are listed below:

- Instrumentation design unit.
- Machine shops.
- Electronic shop.
- Electronics & Data Acquisition unit.
- Instrument Control, Algorithms & Numerical Simulations unit.

The Institute Campus is situated near the Itzhak Rabin Scientific Park area, where many high-tech and research companies are located. Many can also be reached routinely if needed.

Yale University:

3-Coordinate GEM
In the coming period we will submit a paper on the final analysis.

Hybrid Gain Structure for TPC readout
We expect to have fully functional MMG with resistive layers and continue to characterize their behavior.

Multi-element stacked gate grid.
We will develop the switching circuit and continue investigation of the extended gating grid concept.

What are critical issues?

Brookhaven National Lab:

Our first priority will be to complete the analysis of the test beam data and to publish the final results. We have already gotten off to a good start on this effort and anticipate that this will take a few months to finish. Our second priority is to complete the new designs of the chevron patterns that we started several months ago and then have the corresponding readout boards fabricated and tested. One important concern is that the quality of the readout electrodes depends very strongly the manufacturing technique used to make the PC board. Our experience has shown that some PCB manufacturers were not able to match the point resolution specified in the design. However, we feel we have identified a particular vendor (Somacis) that is capable of producing these high resolution boards which we plan to use for our initial tests. We also plan to continue with additional calculations and simulations for new and better types of readout electrode patterns that we will then have fabricated and tested in our lab.

Reducing ion back flow is also very critical for the operation of a TPC, and we therefore plan to start a series of measurements on how to suppress IBF using various techniques.
These measurements will be coordinated with our collaborators from Stony Brook, Weizmann and Yale in order to make a comprehensive study of the various options available. We also believe that designing and constructing a practical field cage for an actual TPC for an EIC experiment is a long term project that is on a critical path, and we plan to work with the Stony Brook group on continuing this effort.

Finally, identifying electronics suitable for the TPC readout is still an open and critical issue. However, we feel at this point, some version of the SAMPA chip used at STAR will eventually become a viable solution.

Florida Institute of Technology:

The most critical issue specifically for Florida Tech is the continued availability of post-doc Aiwu Zhang throughout construction and testing of the second EIC FT detector prototype, for which funding was initiated following the June 2015 review. The significant progress described in the “What was achieved?” section above, in particular getting publications out and designing the next FT detector prototype, is to a very large extent due to Aiwu’s comprehensive work on the project. He has been simultaneously filling the roles of physicist (data taking and analysis, publication), mechanical engineer (CAD design and FE analysis), and PCB designer (Altium board design) on the project. Due to his involvement on all fronts of the development process, Aiwu’s continued work is absolutely critical for completing the project in 2017. Without him, the EIC R&D effort on the second FT detector prototype at Florida Tech would die instantly.
Due to the low overhead rates at Florida Tech, his employment is also a very cost-effective investment for the consortium. Consequently, we request that funding be provided to renew his position for another year in FY17 so that he can see the design, production, and performance testing of the previously funded FT prototype through to the publication of the performance results.

On the technical side, most PCB factories are apparently not able to produce zigzag strips on flexible PCB due to the fact that trace width and space are less than 3 mils in our design. The CERN workshop claims that they can do it, but we will have to validate the foil quality first.

INFN Trieste:

N/A

Stony Brook University:

The implementation of the ordered equipment and working mode for modifying the vacuum evaporator is the critical issue to finalize the evaporation of a large sized mirror.

University of Virginia:

The production and tests of the new readout design on a smaller scale is a critical step before we can confidently go for the large size prototype. This is an area we would like to investigate in the next six months.

Weizmann Institute of Science:

N/A

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).

Workforce

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. It includes one Senior Scientist (0.2 FTE), one Physics Associate (1.0 FTE), one Assistant Physicist (0.1 FTE) and one Technician (0.3 FTE). All personnel are paid by the BNL Physics Department.

Florida Institute of Technology:

Marcus Hohlmann, P.I., 0.25 FTE, not directly funded under this R&D program.
Aiwu Zhang, post-doc, 1 FTE, fully funded under this R&D program, located at Florida Tech and supervised by M. Hohlmann.
Several undergraduates; unfunded.

INFN Trieste:

The proponents are part of the group from INFN-Sezione di Trieste and Trieste University presently active in the COMPASS experiment at CERN SPS. The group has two main lines of interest: hadron physics items and COMPASS data analysis and in hardware items, including R&D and detector construction; in particular, the Trieste group has designed COMPASS RICH-1, a large acceptance gaseous focusing RICH, has coordinated the project and built most of the counter components. Presently, the group has completed the construction for an upgrade of the RICH based on novel photon detectors by MPGD technologies. Therefore, the group competence in hardware is the field of RICHes and MPGDs. The group is formed by 12 units, including 5 staff ones; about half of the group is directly involved in the R&D proposed for the next three years:
S. Dalla Torre (INFN, Staff)
S. Dasgupta (Trieste University, PhD student)
G. Hamar (INFN, postdoc)
S. Levorato (INFN, Staff)
F. Tessarotto (INFN, Staff)
The contribution of technical personnel from INFN-Trieste is also foreseen according to needs.
The manpower for this activity will be enriched by one more postdoc unit specifically enrolled for this R&D, working in Trieste under the supervision of S. Levorato and F. Tessarotto; financial support for this postdoc position is included in the requested founds.

Stony Brook University:

None of the labor at SBU is funded by EIC R&D. The workforce is
K. Dehmelt, Research Scientist, 0.4 FTE, T. K. Hemmick, Professor, 0.1 FTE, N. Nguyen, Undergraduate student, 0.25 FTE

University of Virginia:

None of the labor at UVa is funded by EIC R&D. The workforce is
N. Liyanage, Professor, 0.1 FTE, K. Gnanvo, Research Scientist, 0.4 FTE, V. Nelyubin, Senior Research Scientist, 0.05 FTE, H. Nguyen, Post-doc, 0.05 FTE, X. Bai, Graduate Student, 0.05 FTE, R. Wang, Graduate Student, 0.05 FTE

Weizmann Institute of Science:

The Heavy Ion research group at the Weizmann Institute includes the PI, one senior scientist working part time, 3 post-doctoral researchers, 2 PhD students, visiting scientist and part time graduate and undergraduate students. Personal focused on the detector research are
Prof. Alexander Milov, part time, Prof. Vladimir Peskov, full time, Dr. Lior Arazi, part time, PhD student, part time

For short-term projects and critical research steps the manpower of the group can be focused on the detector studies. The group has long term well established relations with other research groups involved in the detector construction. The detector research group of Prof. Amos Breskin, the ATLAS High Energy group involved in the New Small Muon Wheel upgrade, the group of Dr. Shikma Bressler working on the ILC.

Yale University:

None of the labor at Yale is funded by EIC R&D. The workforce is
R. Majka, Senior Research Scientist and Scholar, 0.1 FTE, N. Smirnov, Research Scientist and Scholar, 0.5 FTE, Undergraduate Student, 0.25 FTE

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 currently no other external funding for the R&D effort at BNL on the TPC/Cherenkov detector.

Florida Institute of Technology:

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.

INFN Trieste:

A request for financial support from INFN will be placed either starting in year 2017 or in year 2018, according to the indications of the INFN management and the general consolidation of the EIC project.

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 R&D 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.

Weizmann Institute of Science:

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

Yale University:

None.

Budget Request for new EIC R&D funds.

Brookhaven National Lab:

We anticipate the following funding request for the next round of EIC R&D funding in FY17.

1. Expendable materials and supplies for gas detector lab - $10K
2. Travel - $5K
3. Design and materials for new chevron readout patterns - $10K
4. Parts and materials for investigation of GEM/Micromegas operation - $10K
5. New optics for VUV spectrometer - $10K

Total without overhead - $45K
Total with overhead - $67.5K

Florida Institute of Technology:

The budget requested by Florida Tech for FY17 is listed in the following table. All amounts are fully loaded with fringe and overhead.

Forward tracking: large-area GEM with zigzag strip readout		
Personnel (post-doc, Aiwu Zhang)	$100k	12 months, fully loaded
GEM readout foil	$9k	From CERN
GEM assembly parts	$6k	Frames, O-ring, connectors, etc.
Supplies & material	$2k	Gas, T/P monitor, etc.
Travel	$7k	Beam test(s); conference, consortium meetings
Total	$124k	

INFN Trieste:

The funding request for this R&D activity is presented in table 1, where the bare requests are listed and also the overhead is included assuming the typical INFN rate of 20%. The request includes 3 main chapters:

- the financial support for a postdoc fully dedicated to the project: the contribution of a dedicated personnel unit will offer a crucial boost to the R&D program; $33k corresponds to one-year postdoc salary in Italy;
- traveling resources, mainly to have the possibility of closer interaction with the whole RD6 Consortium and to follow the evolution of the EIC project: 3 trips to US per year require about $9k; a minor support is requested for material procurement, to interact with the producers when non-standard components are needed and for the construction of specific detector elements that must be produced at CERN: this needs is estimated to be $3k per year;
- Consumables have to cover prototype components and prototype operation costs; the needs for the first year are already well defined and are listed in the following, while the request for the following years indicate a reasonable envelop and the details will be spelt out year by year.

Consumables for FY2017 include:

- Material and fabrication of novel substrate THGEMs: $6k;

- Mechanics and equipment (connectors, gas connections, mechanical frames) to test the prototypes forming 2 dedicated chambers: $4k;
- 2 PCB for MMs with miniaturized pad-size: $4k;
- Production of two bulk MMs with miniaturized pad-size: $5k;
- Mechanics and equipment (resistors, connectors, gas connections, mechanical frames) to test the MM with miniaturized pad-size, 1 dedicated chamber: $5k;
- Gas bottles to operate the detectors: $3k;
- Miscellanea of small items: $3k.

No funding for equipment is requested because, thanks to the long tradition and activity in the field of MPGDs and RICHes, the home laboratory of the Trieste group has a rich general purpose equipment and specific tools and instrumentation dedicated to the development of gaseous detectors and photon detectors. In particular:

- SRS read-out set-up with APV25 front-end chip and related DAQ system;
- Small- and large-size glove boxes;
- Gas mixing units with mass flowmeters;
- X-ray station (source: AMPTEK miniature X-ray tube) with the capability to illuminate also large surfaces of the order of 0.25 m^2;
- High purity nitrogen generator (O2 contamination below 15 ppm, rate: 5l/min);
- Clean room, 6 m^2 (overpressure, constant flow of filtered air);
- Reference table (60 * 50 cm^2);
- HV systems by Caen;
- HV control system for voltage regulation to compensate for temperature and pressure variations, custom, home-made;
- A large set of fully floating pico-ampmeters, custom, home-made;
- Set-up for surface polishing including a large-size ultrasonic bath;
- UV light sources including a Continuous High Intensity Deuterium Lamp UV system and a pulsed source Picoquant picosecond Pulser PDL 800B with 265 nm and 255 nm UV light sources.

	requested founding (k$)	(k$)	(k$)	total (k$)
year	**2017**	**2018**	**2019**	
item				
manpower (1 unit for the 3 years of the project duration)	33	33	33	99
travelling (3 trips to US per year + trips for material procurement and construction)	12	12	12	36
consumables (specific for each year, according to the project time-lines)	30	30	30	90
total	**75**	**75**	**75**	**225**
total adding overhead (at 20% level)	**90**	**90**	**90**	**270**

Stony Brook University:

1. Purchase of IBF-GEM foils - $5k
2. Expendable materials and supplies - $5k
3. Support for beam test - $10k
4. Travel - $5k

Total without overhead - $25k
Total with overhead - $40k

University of Virginia:

We anticipate the following funding request for the next round of EIC R&D funding in FY17.

1. Materials and Production of (U-V strips) readout board including the Zebra-Panasonic adapter boards - $10K
2. Design and materials and production of GEM support frames - $4K
3. Expendable materials and supplies - $3K
4. Support for undergraduate student $5K
5. Travel - $3K

Total without overhead - $25K
Total with overhead - $30k

Weizmann Institute of Science:

GEM foils. Since currently the producer of GEMs is CERN, the cost of a single framed foil costs approximately $450. A non-standard GEM costs $600-$700 depending on design. Additional expense may include tooling ($300) and design work ($300). Depending on the research we would ask $10k to be spent on design and production of GEMs.

Another budget item is running the lab, which includes consumables such as gases, cleaning materials, IT service, small tooling and similar. Typical cost is $700 per month, $8.4k per year.

Expense	Amount
Design and production of GEM elements and tooling	$10k
Operation of the detector lab (consumables, tooling, IT support, etc…)	$8.4k
Total w/o overhead	$18.4k

Yale University:

None.

Publications

Please provide a list of publications coming out of the R&D effort.

Brookhaven National Lab:

1. B. Azmoun et al., "A Study of a Mini-drift GEM Tracking Detector", submitted August, 2015 to the IEEE Transactions on Nuclear Science, accepted for publication in April 2016 and to be published in June 2016.
2. Requested an oral presentation at the IEEE NIS/MIC conference in Strasbourg, France in November 2016 on the TPC/Cherenkov hybrid detector and expect to publish the final results in the IEEE Transactions on Nuclear Science
3. C.Woody et al., "A Prototype Combination TPC Cherenkov Detector with GEM Readout for Tracking and Particle Identification and its Potential Use at an Electron Ion Collider", Proceedings of the 1015 Micropattern Gas Detector Conference, Trieste, Italy, Oct. 12-17, 2015 (publication in process)
4. M.L. Purschke, "Test Beam Study of a Short Drift GEM Tracking Detector" Conference Record Proceedings of the 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference, October 27-Nov 2, 2013, Seoul, Korea

Florida Institute of Technology:

1. A. Zhang and M. Hohlmann, "Accuracy of the geometric-mean method for determining spatial resolutions of tracking detectors in the presence of multiple Coulomb scattering," accepted for publication in JINST and posted on arXiv (1604.06130).
2. A. Zhang et al., "Study of non-linear response of a GEM read out with radial zigzag strips," abstract submitted to the 2016 IEEE NSS/MIC conference in Strasbourg, France.
3. A. Zhang et al., "Performance of a Large-area GEM Detector Read Out with Wide Radial Zigzag Strips," Nucl. Instr. Meth. A811 (2016) 30-41, doi: 10.1016/j.nima.2015.11.157
4. A. Zhang et al., "R&D on GEM Detectors for Forward Tracking at a Future Electron-Ion Collider," 2015 IEEE Nuclear Science Symposium Conference Record, Nov 1-7, San Diego, CA.

INFN Trieste:

N/A

Stony Brook University:

1. M. Blatnik et al., "Performance of a Quintuple-GEM Based RICH Detector Prototype", IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 6, DECEMBER 2015.
2. M. Blatnik et al., "Performance of a Quintuple-GEM Based RICH Detector Prototype", Nuclear Science Symposium Conference Record, 2015, IEEE

University of Virginia:

1. 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). DOI: *10.1016/j.nima.2015.02.017*

2. K. Gnanvo et al., "Performance in Test Beam of a Large-area and Light-weight GEM detector with 2D Stereo-Angle (U-V) Strip Readout", Nucl. Inst. and Meth. A808 (2016), pp. 83-92. DOI: *10.1016/j.nima.2015.11.071*.

Weizmann Institute of Science:

N/A

Yale University:

A paper on the results to date has been submitted to NIM and is available at: http://arxiv.org/abs/1603.08473

Combined Budget Request

Institute	Total Request (in k$)
BNL	67.5
Florida Tech	124
INFN	90
Stony Brook	40
UVa	30
WIS	18.4
SUM	369.5