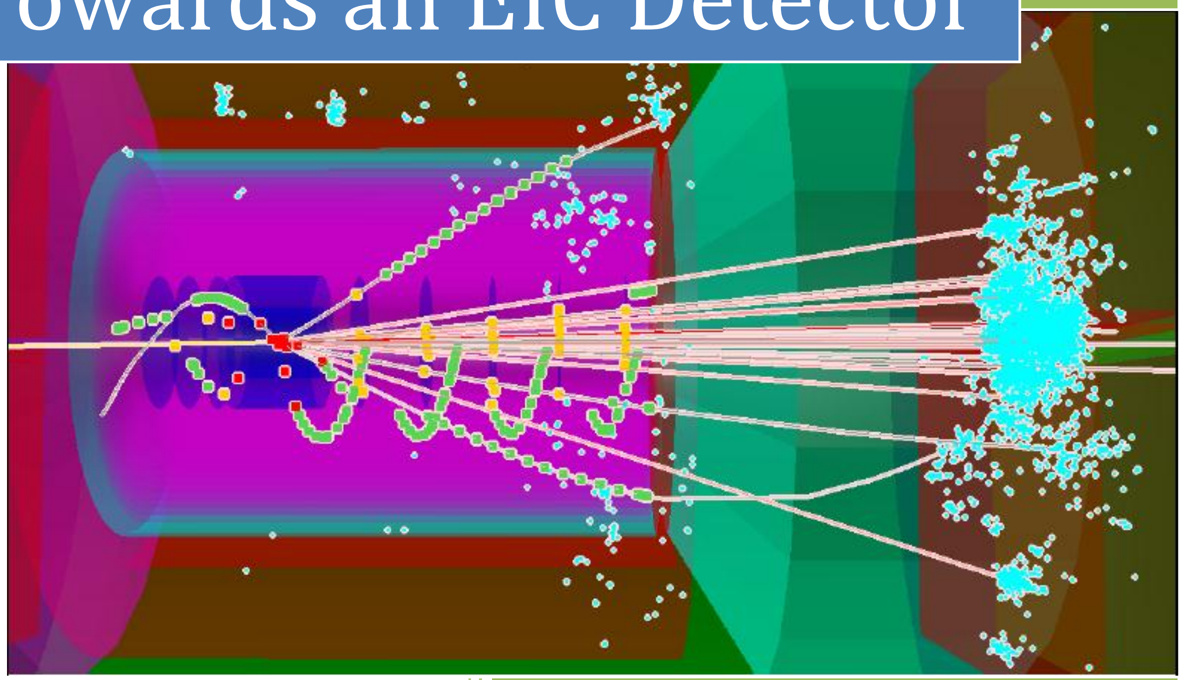
2012

Proposal for Detector R&D Towards an EIC Detector



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Introduction

This proposal is a follow-on to the Letter of Intent entitled "Letter of Intent for Detector R&D Toward an EIC Detector" sent to BNL in Spring 2011. At that time, we announced the formation of a new collaboration intending to work together on simulations to determine the required performance parameters of an EIC detector and also a list of 5 immediate R&D tasks that we deemed to be of sufficient generic interest to warrant immediate investigation. The Letter of Intent promised a full and focused R&D proposal to be submitted to BNL in Spring 2012. In Fall 2011, the authors of this proposal, under collaboration letterhead and a separate request, sought and received additional funding in the areas of simulation, test beam support, and engineering support for cylindrical GEM tracker designs.

This document is the result of the first year's research and emphasizes three fundamental areas of investigation for the coming two year's effort:

- Development of a fast TPC/HBD detector to provide ultra-low mass central tracking, hadron ID via dE/dx, and moderate electron ID via detection of unfocussed Cherenkov blobs.
- Development of large area planar GEM detectors for endcap tracking.
- Further development of Cherenkov detectors for the forward direction, with particular emphasis on high momentum hadron ID and development of large area low cost VUV mirrors.

This document will report on the [1]collaboration status, [2]progress made with the year-1 funding, [3]analytical estimates of Golden-Measure-driven tracking specs, [4]detailed simulations demonstrating adequacy of and justification for the proposed research, and [5]cost estimates for the coming two years. In keeping with the guidelines of the call for proposals, the research is generic enough that it is site non-specific. However, this research should not be considered as generic detector R&D. We are specifically targeting prototypes to the appropriate scale of EIC or whose scaling is not the technical challenge. Simply put, we are serious about doing EIC physics and we hope this fact shows through in our proposal.

Collaboration Status

In addition to simple collaboration membership issues, a more important aspect of our development is the trend toward a singular effort. Our first Letter of Intent was, not surprisingly, markedly divided in its various efforts along institutional lines. The five development efforts mapped cleanly onto five distinct institutions: Fast TPC development @ BNL, Zig-zag readouts for large area GEM detectors @ FIT, Electronics gap minimization for GEM detectors @ UVa, Csi Photocathodes @ SBU, and 3-coordinate readout geometries @ Yale. Although such a division was a natural starting point for our collaboration, these lines should and have blurred. In Fall 2011 we listed these cross-institutional efforts:

- TPC developments @ BNL include experience/expertise from Yale.
- Stony Brook engineer Chuck Pancake designed layouts for Zig-zag TPC & GEM readout boards using input on the specifications from BNL and FIT to test a variety of zig-zag pad geometries. The system is designed to directly couple to the SRS readout system used by BNL, FIT, and UVa.

- Kondo Gnanvo has moved from a post-doc position at FIT to a research position at UVa to implement SRS readout systems for system tests including those already performed at Mainz and those upcoming at JLab.

- Stony Brook, Temple, BNL, and UVa have combined forces to mount the Cherenkov test beam effort in Hall A of Jefferson Lab, using the UVa tracking coupled to the SBU Cherenkov detector.

- Stony Brook PhD student Huijin Ge has begun simulations of the three-coordinate readout system to determine the performance of this scheme as a function of particle multiplicity.

- Postdocs from SBU and ISU are contributing to the previously BNL-exclusive effort.

- Simulation efforts from BNL and Yale have merged to produce results for this document.

We view this trend toward commonality of efforts not only as highly efficient, but also healthy for developing the spirit and mindset of a single collaboration. In the current proposal, the lines have further blurred. Indeed, there are few efforts that have not taken advantage of the resources of our collaboration as a whole. Collaboration includes sharing of physical resources during beam tests, and also intellectual resources such as coupling the gas simulation codes for the TPC research to Cherenkov R&D. In the current proposal, it is no longer a simple task to map tasks onto institutions. For this reason, we shall present our budget tables in two variants: one itemized by task and a second itemized by institution.

We have grown overall in personnel since last fall. This is principally but not entirely by the involvement of additional postdoc and graduate students efforts. Although Z-E. Meziani from Temple has decided to drop involvement during the next funding cycle, Temple University remains a strong collaborator through the efforts of B. Surrow. Surrow has hardware funding through a separate proposal, but plans to be involved in the simulation efforts of this work. A. Camsonne from Thomas Jefferson Laboratory has joined our efforts. Camsonne brings expertise in detector electronics and DAQ. His efforts will help to ensure that future developments of the VMM1 chip at BNL instrumentation are maintained close to our needs for EIC.

Physics-Driven Detector Considerations

In our Letter of Intent, we identified two “Golden EIC Measurements” that drive the detector design and performance characteristics. These are:

- F_L in eA and ep collisions
- Semi-inclusive kaon measurements, e.g. Δs for positively identified kaons.

In this section we will consider separately each of these two “Golden Measures” and how they drive the momentum/position resolution and PID capability. We will further add a brief discussion of additional general constraints driving physics that have been used to shape our detector concept. We will introduce the detector concept itself in the subsequent section.

Golden #1: Semi-Analytical Calculations for F_L Measurements

The reduced cross section, σ_{red}, is commonly expanded as:

$$\sigma_{red} = F_2(x, Q^2) - \frac{y^2}{1-(1-y)^2} F_L(x, Q^2)$$

$F_L(x,Q^2)$ is determined by performing a series of measurements of the reduced cross section with varying beam kinematics so that at each (x,Q^2) the set of measurements spans a reasonable range in inelasticity (y). F_L is challenging to the physics program as a whole since it requires a well-devised long term run plan and excellent control of systematics across a long time period. The latter point indicates the need for robust detector technology. Furthermore, as the beam kinematics are varied, the scattered electrons at any given (x,Q^2) will utilize different parts of the detector.

One approach, which is somewhat old school, yet rather robust, is to solve for the desired detector resolutions analytically. The basic measurement of the reduced cross section involves counting events in a particular bin of area $\Delta\log(x)$ by $\Delta\log(Q^2)$ or more conveniently $\Delta\ln(x)$ by $\Delta\ln(Q^2)$.

$$d^2N = \mathrm{L}\frac{d^2\sigma}{dxdQ^2}dxdQ^2 = \mathrm{L}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)\frac{2\pi\alpha^2 Y_+}{Q^4 x}dxdQ^2$$
$$= \mathrm{L}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)\frac{2\pi\alpha^2 Y_+}{Q^2}dln(x)d\ln(Q^2)$$

so that

$$\frac{d^2N}{dln(x)dln(Q^2)} = \mathrm{L}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)\frac{2\pi\alpha^2 Y_+}{Q^2}$$

Multiple challenges disturb the measured yield into a bin of $\Delta\ln(x)$ by $\Delta\ln(Q2)$. However, these can be separated into two types: those for which improved tracker performance helps (bin migration) and those for which it does not (initial state radiation). To determine a limit on the detector performance we require that errors on the yield due to bin migration be held below some acceptable level.

We take as an ansatz that 1% yield measurements are possible when the total yield error due to bin shifts is held below 20%.

Defining the measurement M as:

$$\frac{d^2N}{dln(x)dln(Q^2)} = \mathrm{L}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)\frac{2\pi\alpha^2 Y_+}{Q^2} \equiv \mathrm{L}M(x,Q^2) \equiv \mathrm{L}\bar{M}(p,\theta)$$

Whereby we determine the fractional error as:

$$\frac{\delta\left(\frac{d^2N}{dln(x)dln(Q^2)}\right)}{\frac{d^2N}{dln(x)dln(Q^2)}} = \frac{\frac{\partial\bar{M}}{\partial p}\delta p}{\bar{M}} \oplus \frac{\frac{\partial\bar{M}}{\partial\theta}\delta\theta}{\bar{M}} \oplus \frac{1}{\sqrt{\mathrm{L}\bar{M}(p,\theta)\Delta\ln(x)\Delta\ln(Q^2)}}$$

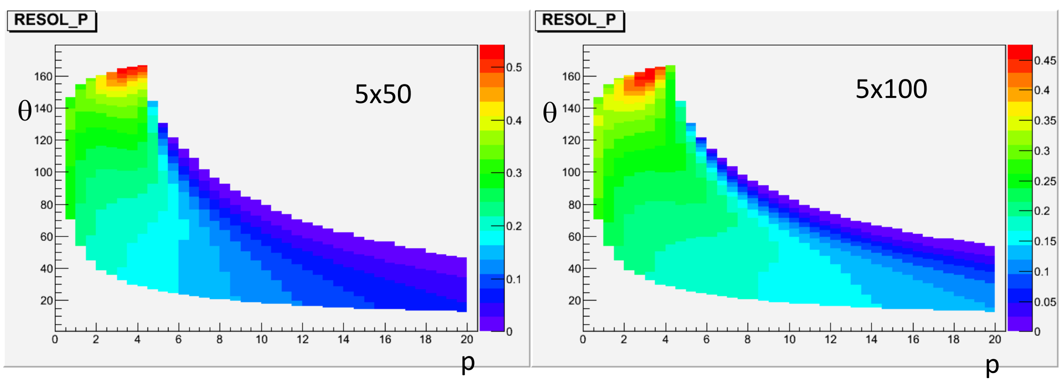
This expression is the quadrature sum of terms driven purely by the momentum resolution, δp, the angular resolution, $\delta\theta$ and a statistical term. Setting the first two terms here equal to the allowable error (ε = 0.20) allows us to analytically solve for the required detector resolutions:

$$\frac{\delta p}{p} = \varepsilon\,\frac{1}{p}\left(\frac{\partial\ln(\bar{M})}{\partial p}\right)^{-1}$$

and

$$\delta\theta = \varepsilon\left(\frac{\partial\ln(\bar{M})}{\partial\theta}\right)^{-1}$$

It is good to note that the only external input to these expressions are the structure functions F_2 and F_L. The rest is simply kinematics. Using the MRST2002 (NLO) parameterization for the structure functions we derive the resolution requirements necessary to satisfy the 20% ansatz. These are shown in the figures below:



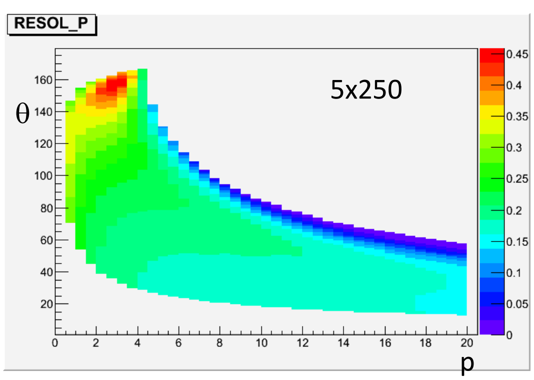


Figure 1: Plots of required momentum resolution as a function of lab angle and momentum. Colors represent $\delta p/p$

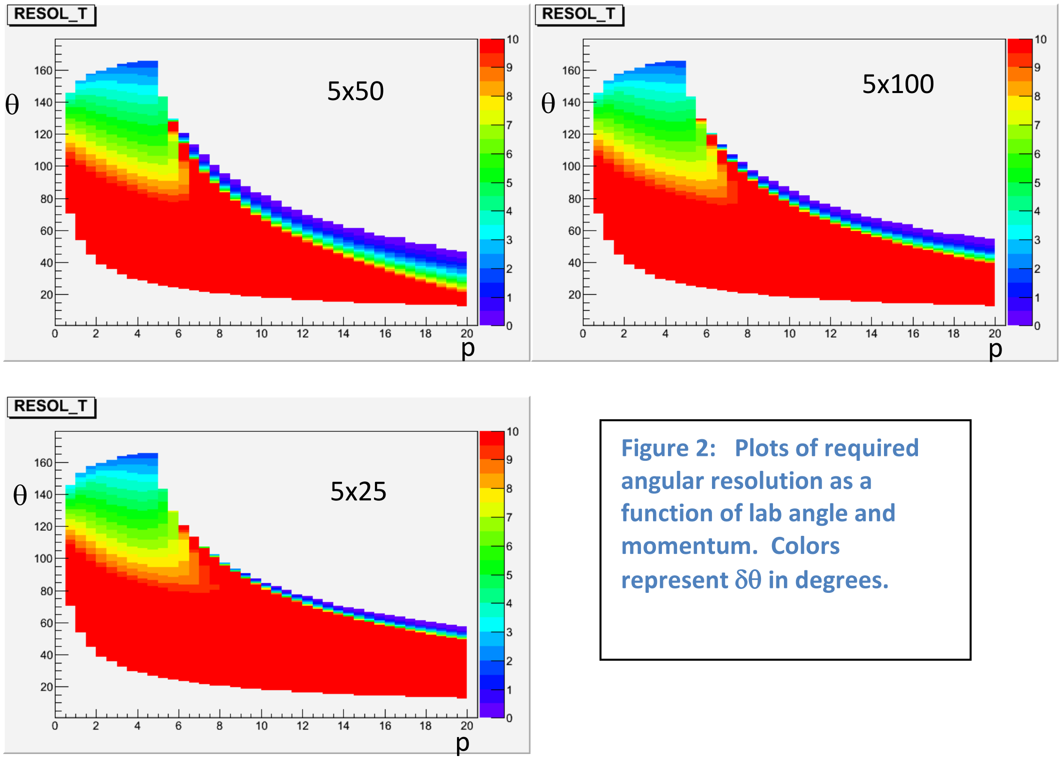


Figure 2: Plots of required angular resolution as a function of lab angle and momentum. Colors represent δθ in degrees.

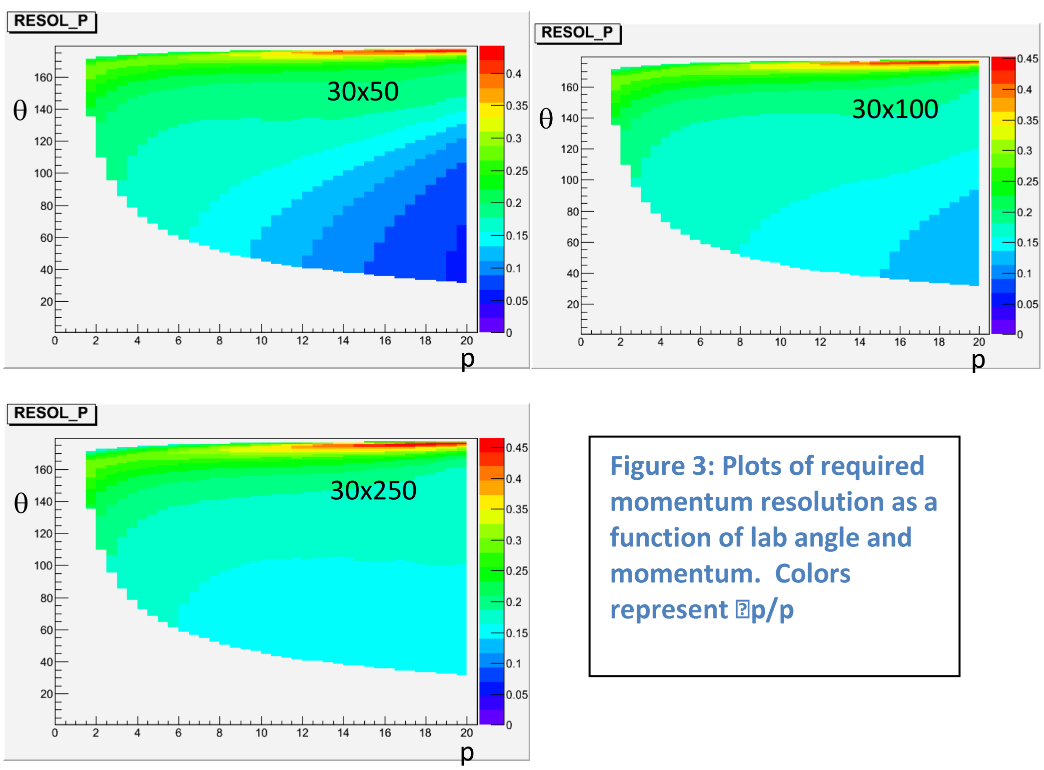


Figure 3: Plots of required momentum resolution as a function of lab angle and momentum. Colors represent [illegible]p/p

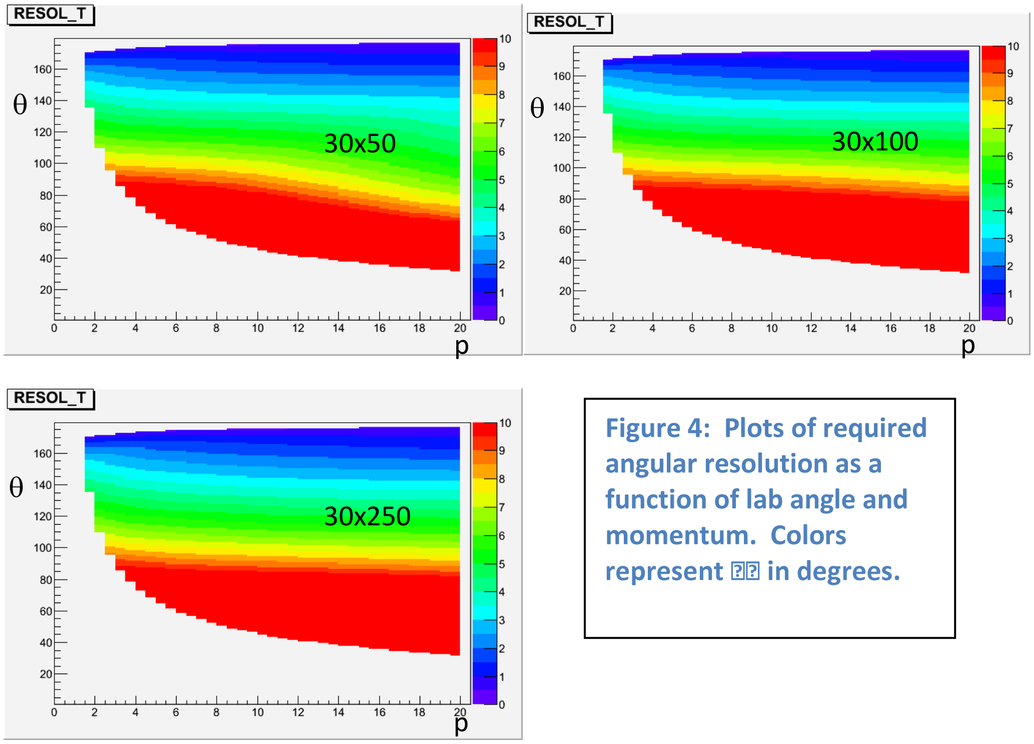


Figure 4: Plots of required angular resolution as a function of lab angle and momentum. Colors represent [illegible] in degrees.

These plots can be used as guidelines for evaluating spectrometer designs and whether they will provide the necessary performance. They also serve to explicitly demonstrate why the 5 GeV (initial stage) EIC machine and the eventual 30 GeV version present the detector system with dramatically different constraints. Nonetheless, these constraints can be met following appropriately directed R&D efforts as will be shown below.

Neither the momentum nor angle, are unique contributions from the tracking system. The vertex silicon and calorimeters will play important roles in each. The "constraint plots" above should be compared to a full simulation. The critical parameters of which are clearly position resolution and low mass in the tracking system, separate contributions to energy measurements from EMC and tracking. Furthermore, it is necessary for the EMC to be complemented in electron ID to achieve that 1/1000 requirement.

Golden #2: Constraints on Kaon Identification to measure Δs

The second so-called "Golden Measurement" identified last year is the measurement of spin structure of the strange quark, Δs. Current expectations would indicate that Δs could be roughly 1/10 $\Delta u/\Delta d$.

Figure 5 shows the expected kaon asymmetries using as input GRSV as polarized parton distributions. The K^+ asymmetries are of equal size as the π^+ asymmetries as the asymmetry is dominated by the u-quark polarization. Only the small differences between both asymmetries are due to the antistrange polarization. The K^- asymmetry at lower center-of-mass energy energy is similar to the π^- asymmetry. At higher center of mass energies it is smaller than the π^- asymmetry. This relation is a pure extrapolation from the currently very limited knowledge of polarized sea quark distribution functions. Therefore to measure the strange-quark polarizations it is extremely important to have cleanly identified kaons. This becomes even more challenging because of the relative abundances of pions compared to kaons and the fact that for many rapidity bins protons are as frequent as kaons. For details see Figure 6.

Therefore it is extremely critical to positively identify kaons and not use kaons defined to be "that which is not a pion".

A reasonable ansatz is that:

The kaon sample should have a purity of 95% in all interesting kinematic regimes.

95% purity of the sample can only be achieved if the detection system makes a "positive tag" of each kaon. Thus any Cherenkov detectors (e.g. RICH or DIRC) must be complemented by another means of particle ID at the momenta below which the kaon radiates. Furthermore, as indicated in Figure 6, the required thresholds for the Cherenkov detectors themselves depend strongly on the η of the detector coverage. Finally, the choice of Cherenkov detector technology must feed back to the momentum resolution calculation. Particularly in the forward direction, the capabilities offered by precise ring reconstruction can only be fully exploited if the momentum resolution does not become the limiting constraint.

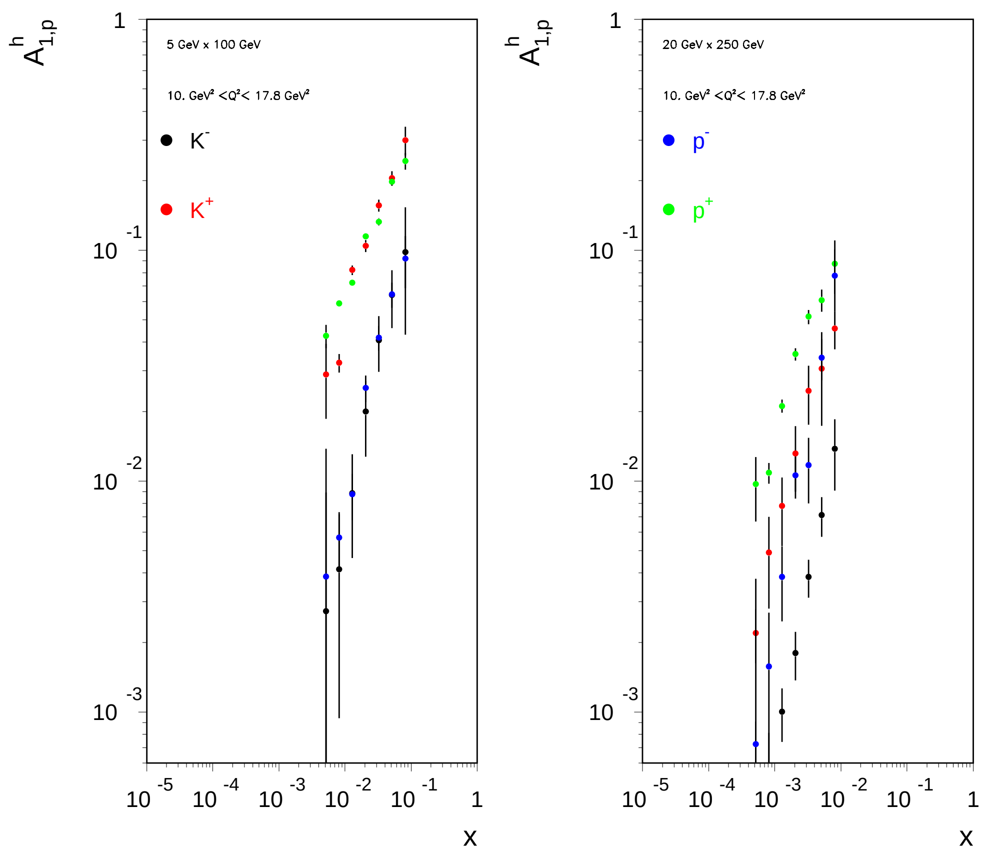


Figure 5: Expectations for the asymmetries of kaons and pions as function of x for one Q2-bin. The asymmetries are calculated using the GRSV polarized parton distribution functions.

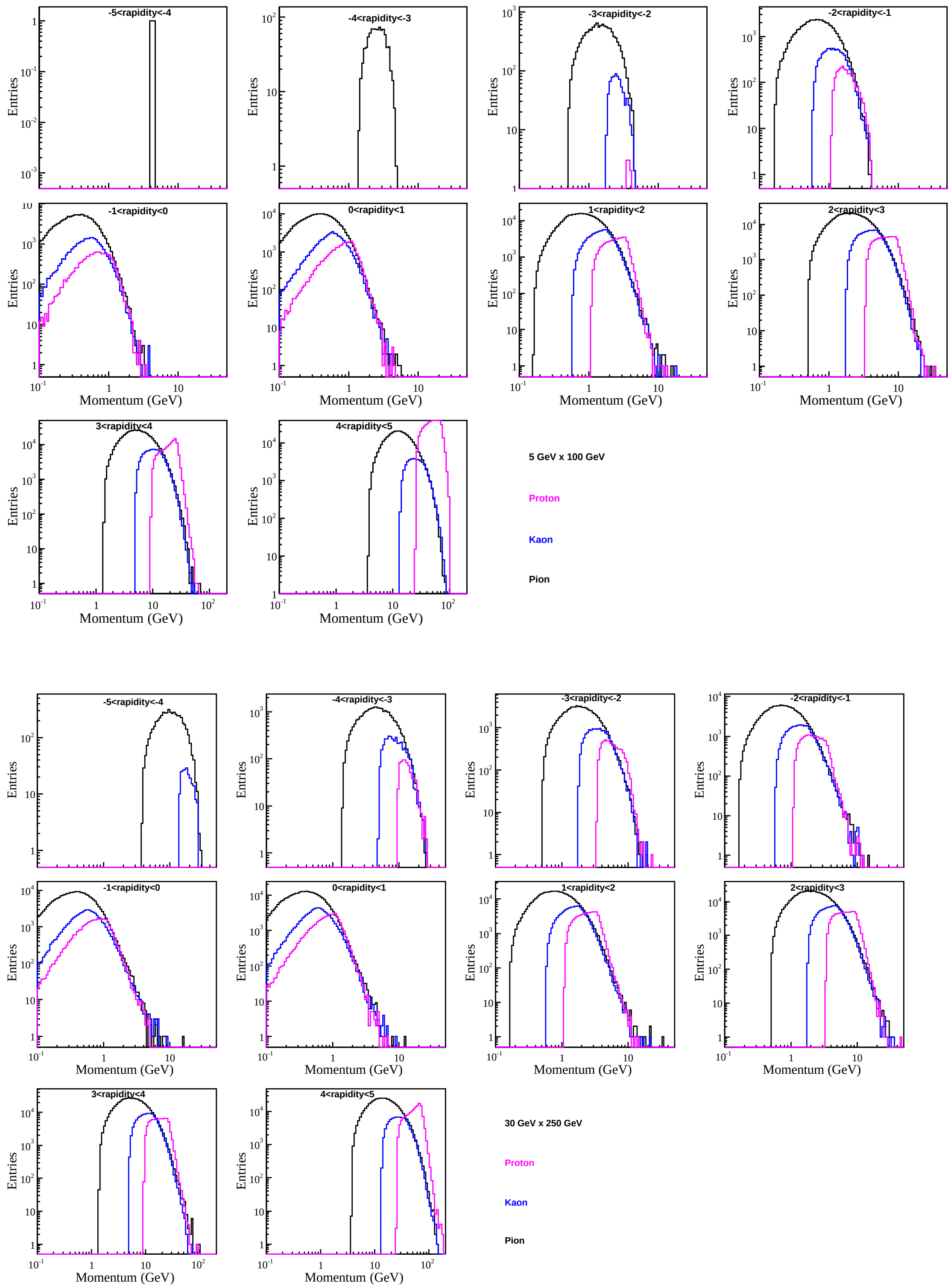


Figure 6: Particle densities for pions, kaons, and protons vs momentum for different rapidity bins. Kaons are in general suppressed by a factor of 3 compared to pions and protons are of similar strength. Therefore it is extremely important to positively identify kaons for measurements of polarized or unpolarised strange quark distributions.

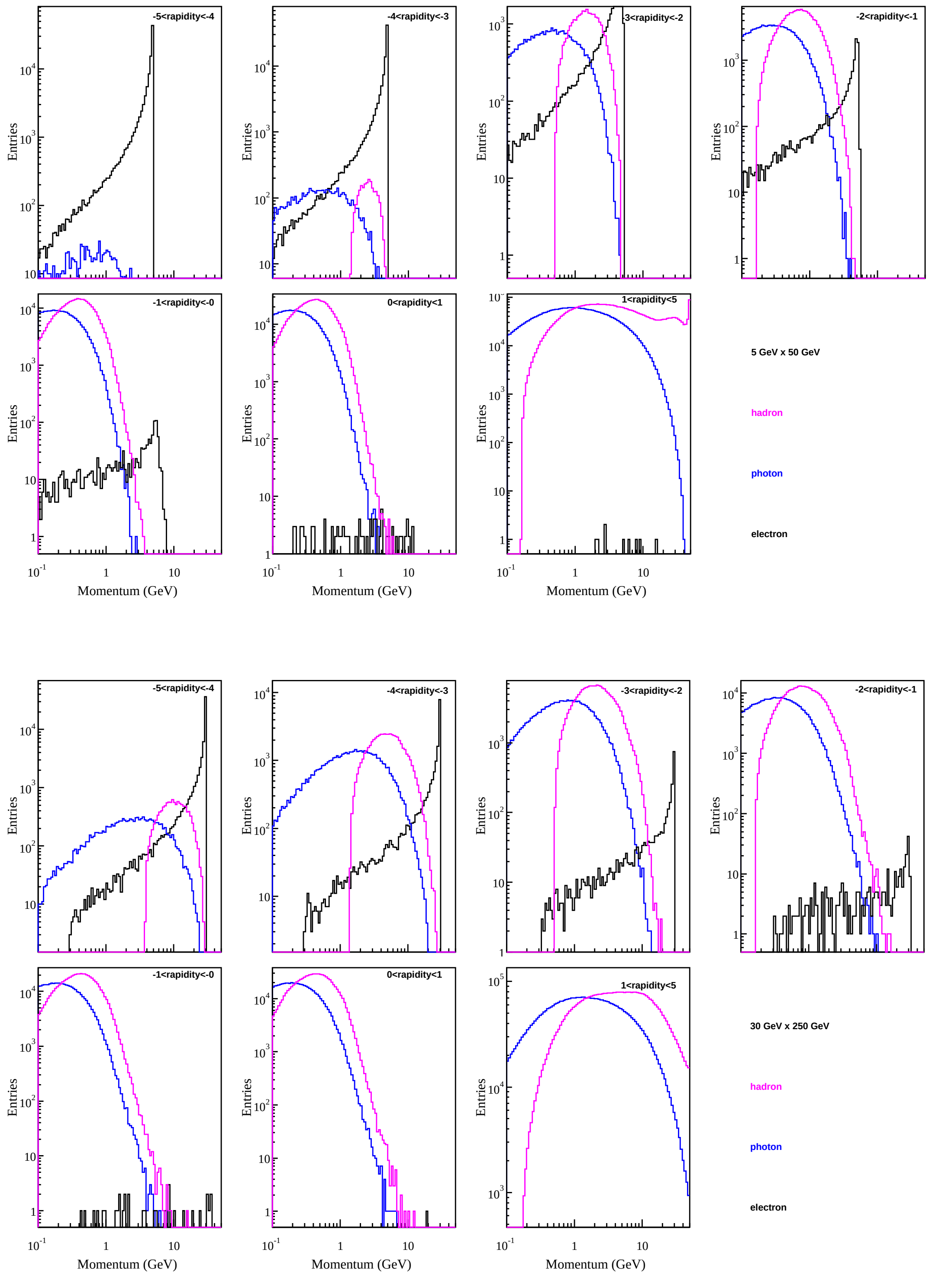


Figure 7: Electron, hadron and photon multiplicities as function of momentum for different rapidity bins. With increasing center of mass energy more hadrons are boosted more and more backwards.

Figure 7 shows how the hadron/photon suppression factor is changing for different rapidity bins increasing the center-of-mass energy.   For many rapidity bins a minimum suppression factor of 100 is needed over most of the lepton momentum.

General considerations:

Other physics processes that drive aspects of the detector design include exclusive reactions such as deeply virtual Compton scattering (DVCS), rapidity gap events, which both constrain the desired acceptance and/or calorimeter performance. Charm/Bottom physics drives the design of vertex detectors as well as our overall acceptance for the cases wherein complete reconstruction of the heavy flavor meson final state is required.

The detector technologies should be designed to match the machine parameters including interaction rate, machine backgrounds such as synchrotron radiation and beam-gas, as well as the simple considerations of occupancy and radiation dose.

Finally, magnetic spectrometers, must give equal consideration to the field shape as to the single point resolution. The “default collider” configuration of a simple solenoidal field is far from optimal at the small scattering angles where much of our physics lies. For this reason, our R&D going forward must have a component of smart magnetic field design so as to relax the position constraints on the tracking detectors while simultaneously avoiding configurations which would disturb the hadron beam polarization.

Emerging detector concept

Figure 8 shows our most recent variant of the emerging detector concept. As noted above, detector systems create coupled constraints (e.g. Cherenkov detectors require good momentum measurement for PID, EMC should assist tracking at high momentum, magnetic field shaping can relieve single-point –resolution constraints). For this reason, even a proposal targeted at only a few subsystems must consider the detector concept as a whole in developing the detector performance parameters.

As is typical for a collider experiment, we divide phase space into a barrel for $|\eta|<1$ and pair of endcaps for $|\eta|>1$.

The Barrel:

Central to the detector is a silicon vertex detector based upon MAPS technology. The technology choice is driven primarily by the need for making the detector as thin as possible to minimize the impact of Bremsstrahlung losses on scattered electrons. This “lowest mass” silicon detector is followed by the “lowest mass” gas detector, a TPC. These paired detectors are both “slow”. The TPC piles up events during the drift in the gas (along the collision axis) and the MAPS pixels are active as the charge is pumped along them, also piling up events. Although one can arrange to create mis-matches in these detector latencies (e.g. have the MAPS “drift” its charge perpendicular to the TPC), it is wise to follow the slow detectors with a single fast detector such as a Silicon strip layer or a GEM layer. This will dramatically reduce event ambiguities without extraordinary cost or complexity.

Electron ID in the barrel will be provided at the lowest momentum via dE/dx and via energy-momentum match in the EM Calorimeter at the highest momentum. Further studies are needed to determine the necessity of additional electron ID that could come in the form of Cherenkov (if the TPC used CF_4 gas, its outer layer could be configured as an HBD) or some form of pre-shower in the EMC.

Hadron ID should be provided by either DIRC technology or proximity-focused RICH. Either option must be made compliant with operation in a strong magnetic field.

Endcaps:

Different from the HERA era, the EIC collider's dramatic range in beam kinematics will send hadrons into both the forward and backwards arms. Thus the arms should be designed to be nearly the same. Silicon MAPS technology for very high pseudo-rapidity (4-5) and Planar GEM trackers filling in the gap to $|\eta|<1$. Hadron PID will require a RICH with at least two radiators: low index for the highest momentum and higher index (aerogel+gas or liquid+gas) for the lower momenta. The specifications of the RICH PID requirements will place additional constraints on the momentum measurement beyond those discussed earlier.
Electron ID is needed in the backward (electron beam direction) endcap to detect with high efficiency the scattered lepton at high momentum again via energy-momentum match in the EM Calorimeter. At the lower momentum an additional method, i.e. dE/dx, a Cherenkov detector, is needed to supplement E/p to find the scattered lepton, especially at the high-energy option of an EIC.

Some Simulation Results

One possible variation of this detector concept has been implemented in a GEANT simulation and has produced encouraging preliminary results. Figure 8 shows the detector with an event present in its volume along with the detector technologies.

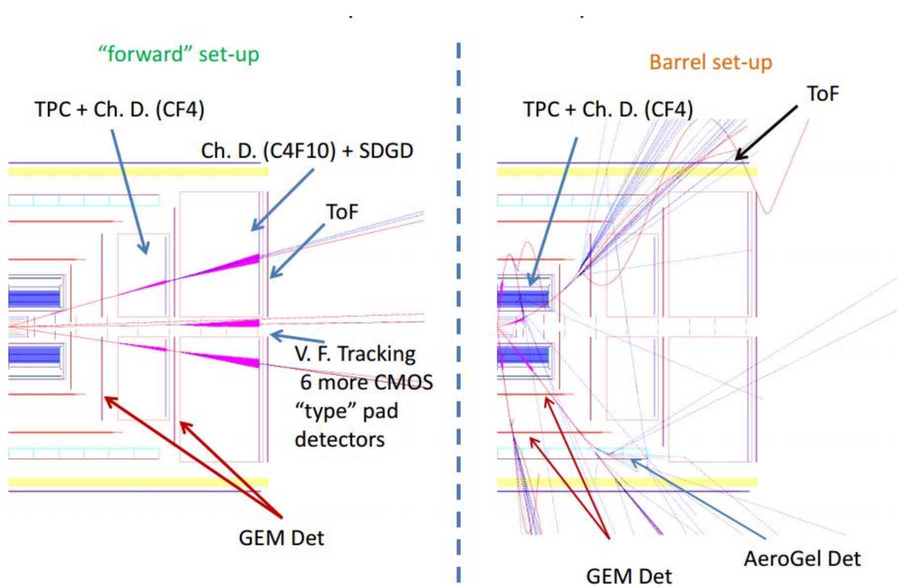


Figure 8: A GEANT implementation of one variation of the detector concept.

The resolution achieved by this detector with reasonable estimates for the individual detector layers is shown in Figure 9. The leftmost panel shows the detector performance with a nominal field of B=2 Tesla and the right most shows the result of increasing the field to 3 Tesla. Comparison with the earlier figures shows that this design fits the criteria required for our Golden Measures of tracking resolution.

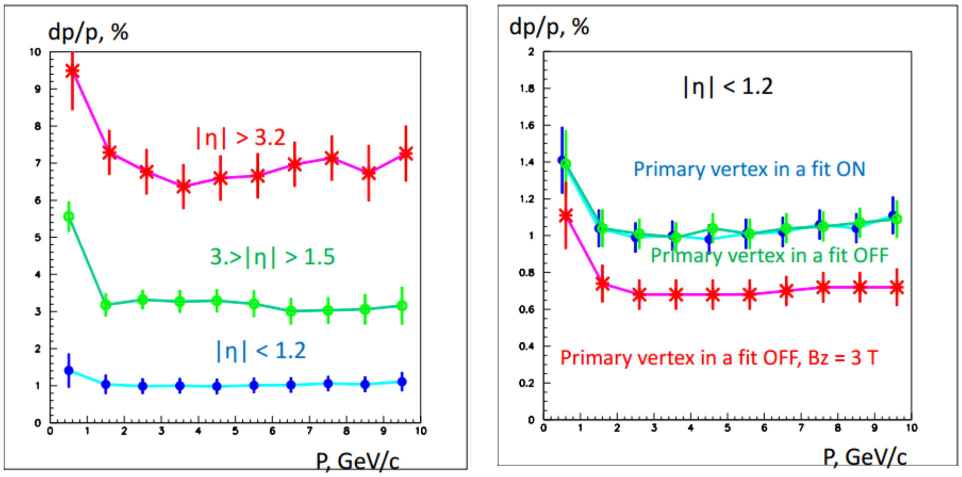


Figure 9: Momentum Resolutions.

Additional and extensive studies of the PID have been performed. For brevity we present here the result of a dual-aerogel radiator in the barrel section demonstrating that we meet our goals for kaon purity and positive ID from 1.5 < p < 4.5 GeV/c with only minor losses in efficiency above 3.5 GeV/c, which does not constitute any physics impact.

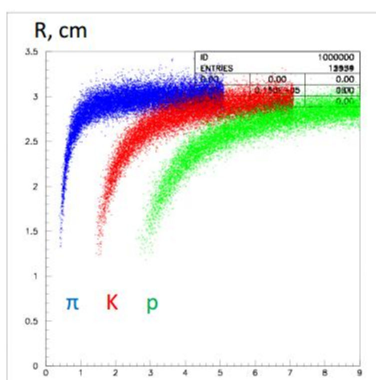


Figure 10: Particle ID from a dual aerogel central barrel detector.

The result of this work is that we have identified three items of R&D that are necessary for EIC physics:

1. Forward Planar GEM Tracking.
2. Central Barrel Fast TPC (/HBD?)
3. Forward dual radiator RICH.

The sections that follow discuss our detailed research strategy in each of these three areas.

Tracking Working Group - Introduction

Fast, low mass, high resolution tracking is needed for future EIC experiments. The tracking requirements naturally divide into two regions: barrel ($|\eta|$~ 0-1) and forward ($|\eta|$>1). Typically a TPC is the detector of choice for the barrel region because of the low mass, enhanced pattern recognition and PID capabilities at least for low momentum particles. Particle ID can be extended by adding Cherenkov capability. We propose to investigate to what extent tracking (TPC with GEM readout) and Cherenkov (UV transmitting gas and photo detector) can be made compatible and thus incorporated in the same detector.

For forward tracking, planar detectors are generally preferred. We propose investigating planar low-mass and large-area GEM detector modules of trapezoidal shape that would be arranged in rings around the beam pipe and placed in the forward region of the EIC detector. We also propose investigating the possibility of adding a very short (1 – 3 cm) drift section (micro-drift) to the forward detectors to improve the spatial resolution and get vector information from a single station.

In the very forward region up to $|\eta|$ of ~4-5 a silicon tracking system could be of future R&D interest, but is currently not within the scope of this proposal.

As a result of previous collaborative efforts carried out under the LOI program in the first year of this project, the groups from BNL (C. Woody) and Yale University (R. Majka) are planning to jointly carry out the TPC and micro-drift R&D, while the groups from the Florida Institute of Technology (M. Hohlmann) and the University of Virginia (N. Liyanage) are planning on merging and focusing their R&D towards planar large-area GEM detectors.

Compact TPC combined with RICH PID.

A barrel TPC provides a low mass solution to precision tracking in the central region. Large volume TPCs suffer from event overlap and space charge (positive ion) build up at high rates so considerable effort has been devoted to developing compact, fast TPCs for use as central trackers. [T.Matsuda, JINST 5 P01010 (2010) and references therein] For the EIC, electron ID is a key requirement. Several techniques can be used, however it is important to minimize the overall mass along the electron path. Therefore it would be extremely useful to combine tracking and electron ID in the same detector. A conceptual design for a combined TPC/Cherenkov counter was developed for PHENIX around 2001. Figure 11 illustrates this concept. It consisted of a fast, compact TPC with a drift distance of 35 cm to GEM readout detectors on each end with a drift time ~ 4 μsec. It had a momentum resolution of $\Delta p/p$ ~ .02p using the PHENIX magnet and provided particle id by dE/dx. The Cherenkov portion was a proximity focused Cherenkov detector that was read out on the outer radius with photosensitive GEM detectors with CsI photocathodes that provided electron id and had a minimal response to hadrons, thus making it essentially “hadron blind”.

The R&D proposed here is aimed at developing a similar fast compact TPC that can operate with Cherenkov gases at the EIC. Such a combined TPC/Cherenkov detector would combine low mass tracking, multiple high resolution space point measurements with particle id by dE/dx and detection of Cherenkov light. The design would separate the TPC charged particle tracking readout (at the end planes) and Cherenkov photon detection (at the outer barrel surface). The R&D is aimed at finding a single gas mixture that will work as a drift gas, radiator gas and working gas for the GEMs.

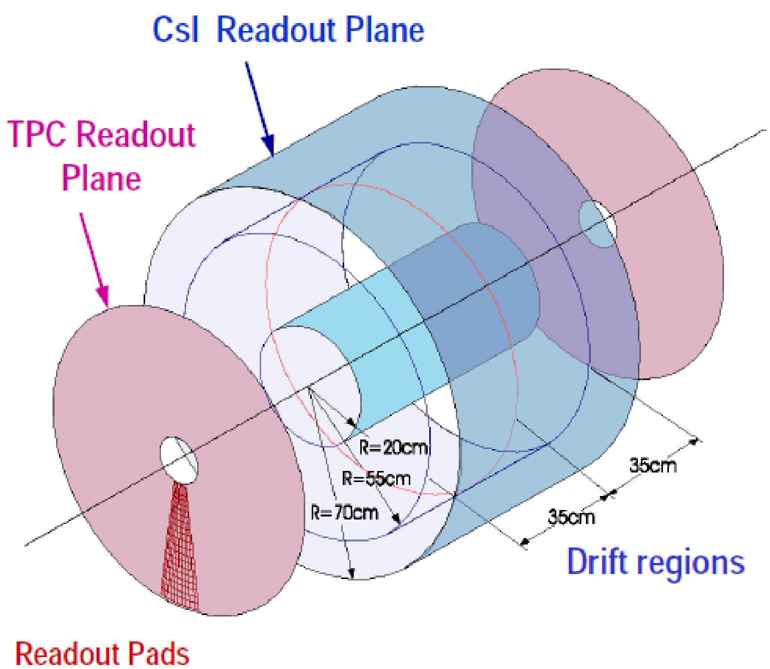


Figure 11: Conceptual design for a combined TPC and Hadron Blind Detector (HBD) proposed for PHENIX ~ 2001. The TPC provided tracking and particle id by dE/dx. The HBD was a proximity focused Cherenkov detector that identified electrons and had minimal sensitivity to charged hadrons. .

Work Plan.

Initial tests to study the TPC features of this detector will be done using an existing drift cell at BNL, shown in Figure 12, that can provide a drift distance up to 30 cm with a GEM detector readout at the end. This cell can be used to measure some of the basic properties of a compact drift structure and its readout.

We propose a series of steps to select candidate gases and test their performance studying both the TPC and Cherenkov features independently and eventually as a combined detector.

These steps include:

- Study different drift gases, measure drift velocities, diffusion, etc. using the existing test drift cell.
- Check the scintillation yield of candidate gases using another existing test chamber at BNL
- Build a small area TPC using existing 10 x 10 cm^2 GEM foils and readout structures and test the performance of candidate gases in a TPC with a GEM readout.
- Build a ~ 25 x 27 cm^2 TPC using existing GEM foils from the PHENIX HBD. (This is approximately the size needed for a sector of a compact TPC). Test the field cage design with one side “open” (likely using wires) for Cherenkov light to reach the photo-detector

- Add a CsI GEM detector to the open side and try and operate as a Cherenkov detector in the same gas as the TPC at the same time.
- Study different readout planes for both the TPC and photo-detector.

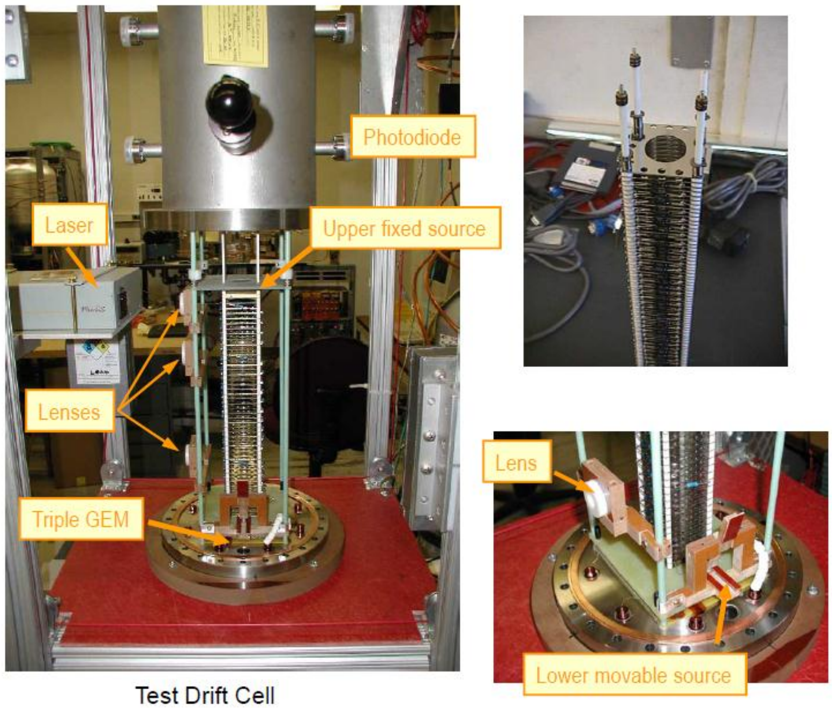


Figure 12: Test drift cell for studying TPC drift gases

There a number of items that need to be studied in order to develop a design for fast, compact TPC. These include:

- Simulations
- field cage design
- space charge calculations
- electronics development
- estimated performance in a magnetic field
- detailed beam studies

The simulations required for the TPC and Cherenkov detectors are highly coupled to the overall tracking and particle id strategy to be used at the EIC and have been discussed previously. In particular, the low mass requirements, momentum resolution, rate capabilities, occupancies and multiple track resolution must all be studied, both as a stand alone detector, and in combination with other detectors in the final EIC spectrometer.

Preliminary work has already begun on some of the items listed above. Initial field cage calculations were done for the original PHENIX TPC/HBD detector and a conceptual design is shown in Figure 13. It uses a series of field shaping electrodes along the drift direction in a double layer structure in order to achieve a highly uniform drift field. It was envisioned that the top electrode could also be made out of wires, creating an open geometry that would allow Cherenkov light to pass through to the photosensitive GEM detectors at the outer surface. However, no prototype for this detector was ever built or tested. We therefore plan to construct something similar to this design during the course of this R&D and test its performance using both cosmic rays and in a test beam.

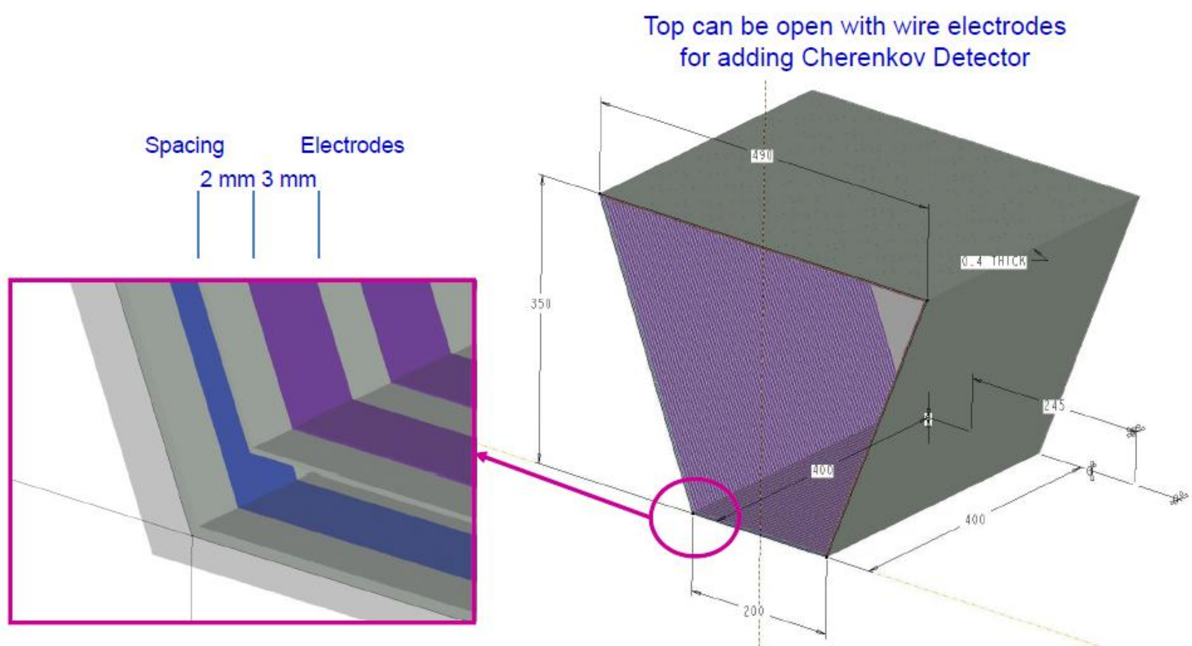


Figure 13: Preliminary design studies for a field cage for a combined compact TPC/RICH as originally proposed for PHENIX.

Estimates were also made on space charge effects for the PHENIX TPC, but these were carried out mostly for heavy ion collisions. These calculations should therefore be redone for the conditions expected at the EIC. There was also an investigation into what type of readout electronics would be required for the PHENIX TPC detector, but the technology has changed considerably since that time. As described below, we plan to utilize the Scalable Readout System (SRS) electronics currently available through the RD51 collaboration to perform the initial studies of the TPC, as well as other detectors, and later utilize a new ASIC being developed for the ATLAS muon system (as described below) for further studies. However, the development of a readout system suitable for a TPC in an actual EIC detector is not part of this R&D effort at this time.

The R&D for the Cherenkov part of the detector will build on the experience gained by the PHENIX Group with the Hadron Blind Detector. This device used ten triple stage GEM detectors, each having a photosensitive CsI photocathode on the top GEM, to detect Cherenkov light produced by electrons, while remaining essentially insensitive to charged hadrons. This was accomplished by operating the GEMs in “reverse bias” mode, where the ionization produced by charged tracks passing though the gas layer above the top GEM was drifted away from the amplification region, while photoelectrons produced on the photocathode by Cherenkov light were collected into the GEM structure and amplified. The HBD was operated using pure CF_4 as both the radiator gas and as the working gas for the GEMs. It achieved a remarkably high figure of merit for a Cherenkov detector (N_0 = 322 cm^{-1}) and performed well under actual beam conditions [W.Anderson et.al., NIM A646 (2011) 35-58]. Pure CF_4 also has a very high drift velocity (up to ~ 12 cm/μsec at high drift fields), as do various mixtures of CF_4 with other gases such as argon. This makes CF_4 a prime candidate for study as a drift gas for a fast TPC. However, CF_4 also has a very high scintillation light yield which can cause significant amounts of background for the photosensitive GEM detectors. We therefore plan to study CF_4, both pure and in combination with other gases, as potential gases for use in both the TPC, the Cherenkov detector, and in combination with each other.

Micro-drift Chamber

While GEM tracking detectors provide excellent spatial resolution (~ 50-75 μm under ideal conditions) for tracking applications, their resolution can deteriorate significantly for tracks passing through the detector at larger angles. In addition, each tracking detector typically provides only a single space point, and imposes a certain amount of material along the track. A micro-drift detector, as shown in Figure 14, can both improve the spatial resolution for inclined tracks and reduce the amount of material for a given number of ionization samples along the track. It consists of a short drift region (~ 1-3 cm) where the charge is drifted in to a multistage GEM detector, amplified and read out on a set of strips or pads. Both the amount of charge and the arrival time of the charge are measured for each strip or pad, providing not only a centroid value for the position but also a vector for the direction of the track as it passes through the tracking detector.

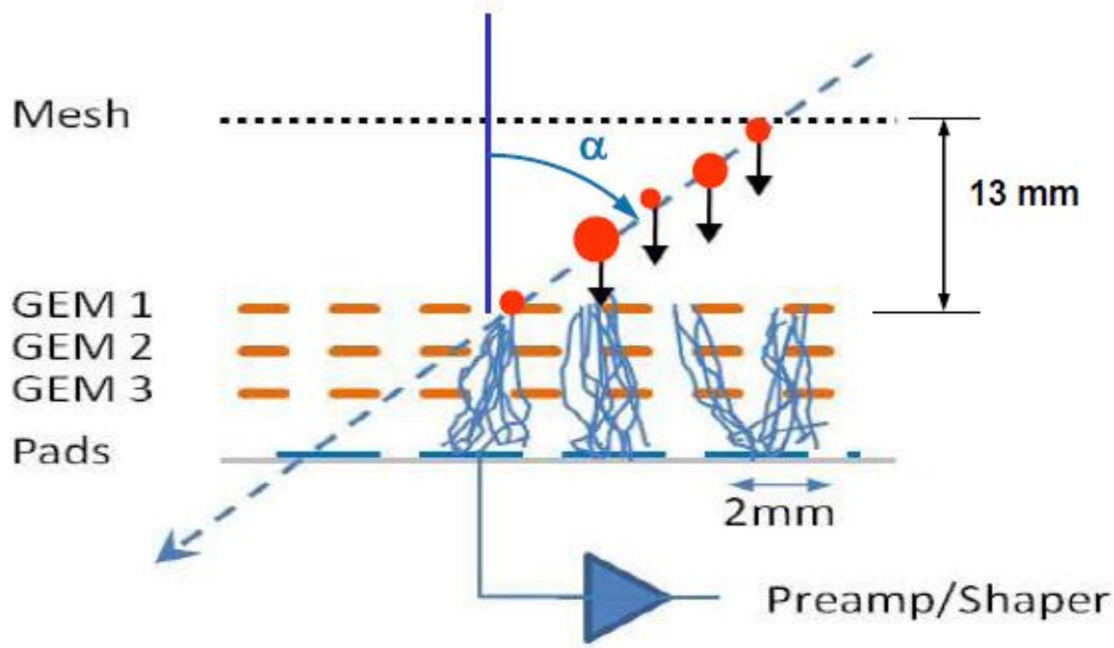


Figure 14: Illustration of micro-drift GEM detector with pad readout.

One problem with this type of micro-drift detector is that there are rather large fluctuations in the ionization along the track, which can lead to uncertainties in determining the centroid position using only the charge information. This is illustrated in Figure 15, which shows a simulation of a micro-drift GEM detector on the left hand side, where the small red lines indicate the actual charge clusters deposited in the gas, and the solid curve shows the amplitude of the charged measured on the strips after diffusion, amplification and electronic signal processing. The right hand side of Figure 15 shows actual data from a micro-drift GEM detector measured in our lab using a Sr-90 beta source which clearly shows the effect of different size clusters arriving at different times. The large fluctuations in the number of ionization clusters would be expected for δ rays produced along the track and would result in poor resolution. However, for multiple measurements along the track, one can reject large pulse height signals from the track fit to potentially improve the spatial resolution. If in addition, one also measures the arrival time of the charge clusters, one can determine the position in the drift gap where the cluster was produced and therefore compute a vector for the track as opposed to a single space point. This allows one to correct for the angle of the track, improving the resolution, and also obtain multiple space points from a single detector.

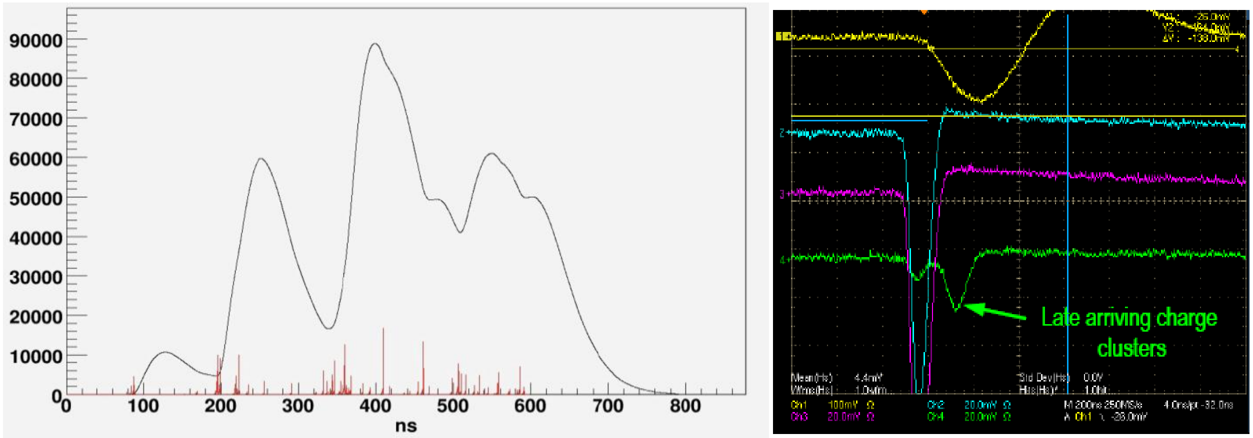


Figure 15: Left: Simulation of charge deposited in a micro-drift GEM detector with a 1.3 cm drift gap. Small red lines are the actual charge clusters deposited in the gas and the solid curve is the detector response after diffusion, amplification and electronic signal processing. Right: Actual data measured with a micro-drift GEM detector with a 1.3 cm drift gap using a Sr-90 beta source showing late arriving charge clusters of varying amplitudes arriving at different times. (The simulation was carried out by T.Cao from the Biomedical Engineering Department at Stony Brook University)

The ATLAS Muon Trigger Group has tested a micro-drift detector using a micromegas to provide the gas amplification. The results of one of their measurements are shown in Figure 16 [V.Polychronakos, 6th RD51 Collaboration Meeting, Bari, Italy, October 2010]. They achieved an angular resolution between 4-6 mrad for tracks at incident angles between ~ 0.1-0.3 rad. Simulations carried out by our own group confirm that this level of resolution is achievable. Figure 17 shows a simulation of a micro-drift GEM detector with a 3 cm drift gap and a strip-pad readout with 400 µm pitch, and indicates that the measured uncertainty in the track angle is less than about 10 mrad (sigma).

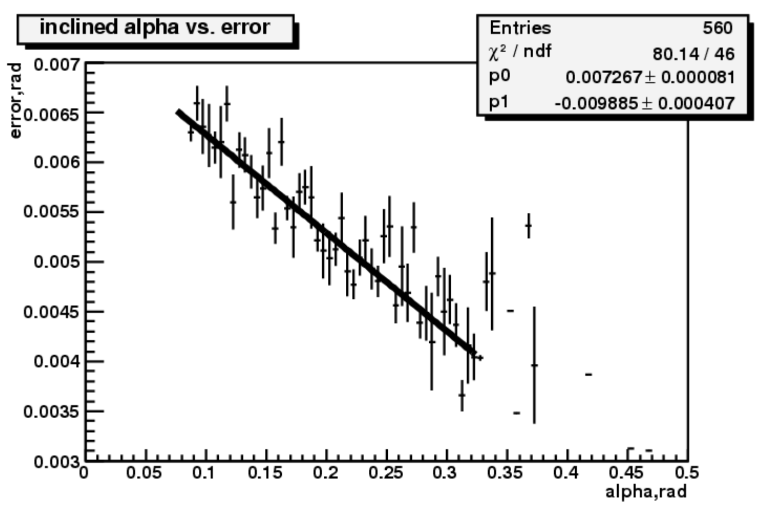


Figure 16: Data measured by the ATLAS Muon Trigger Group for a micro-drift micromegas detector with a 1.3 cm drift gap for particles passing through the detector at incident angles between 0.1 and 0.3 radians.

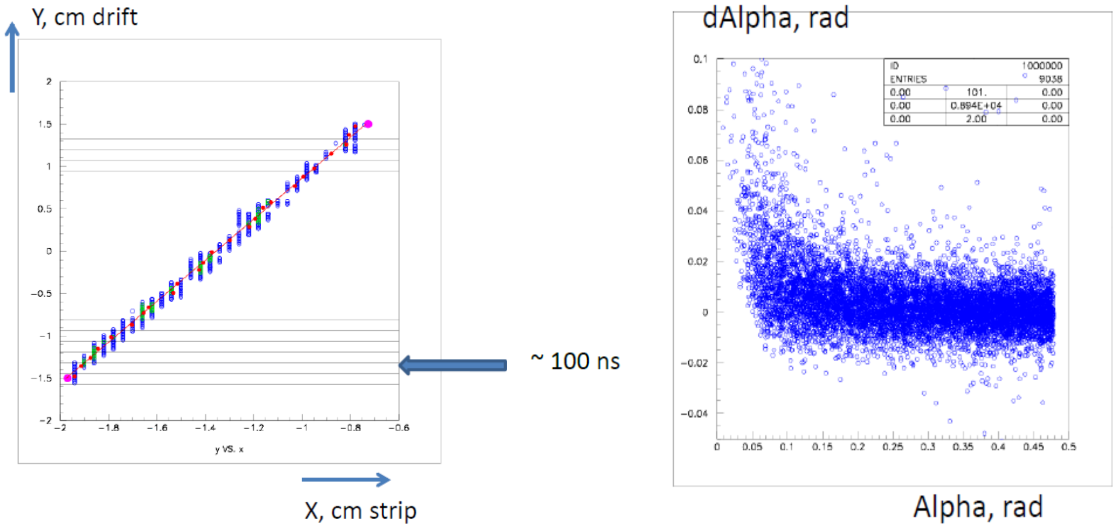


Figure 17: Simulation of a micro-drift GEM detector with 400 μm pitch strip/pad readout; 3 cm drift, 1.3 cm/μsec drift velocity, and 1.5 x 103 gas gain. Left panel shows ionization along a single track; right panel shows track angle error vs. angle.

Work Plan.

We plan to build several small prototypes for the micro-drift chambers based on 10 x 10 cm^2 GEM detectors and various readout structures developed in the previous and ongoing R&D effort. These prototypes will be used to measure the position and time resolution of these micro-drift detectors, and in particular, to study how these resolutions are affected by the fluctuations in the primary charge deposited along the track. We will determine the optimal size of the drift gap and investigate various sizes and shapes for the readout structures, and study the tradeoff between the total amount of charged produced in the gas and how much is collected on each of the readout electrodes. This will also include a study of various detector gases. Some of the structures we plan to study include simple XY strips (similar to the COMPASS readout), the strip-pad structures being developed by the Yale group, and chevron pads (with and without floating strips), including those being studied by the FIT/UVA groups for large area GEM detectors. It should be noted that many of these same structures can be used for the larger scale TPC described earlier.

Many of the initial tests with the micro-drift detectors can be carried out in the lab using a Sr-90 beta source to study the signal characteristics, timing properties and readout electronics. However, a cosmic ray test stand will be required to measure the actual spatial and timing resolution of the various detectors. This will require building at least three detectors such that two can be used to characterize the third. The test stand will also require a fast scintillation trigger in order to accurately measure drift times.

We will also continue to develop the simulation tools needed to better understand the expected characteristics of these detectors we measure in the lab. This will provide feedback for improving their performance, both in terms of their detector design as well as from the readout electronics.

After measuring the various detectors using a beta source and cosmic rays, we plan to take a set of detectors with an optimized design and readout scheme to a test beam for a complete characterization of their properties. We expect to combine this with measurements of other detectors by our group in order to make most efficient use of our resources, manpower and available beam time.

The following is an itemized list of the various tasks included in our work plan on micro-drift GEM detectors:

- Build and characterize short drift GEM detectors with various readout electrodes (strips, strip-pads, chevrons) using a beta source. Study various detector gases, determine optimized drift gap, readout electrodes, and shaping time for readout electronics.
- Develop simulation programs to compare with data measured in lab.
- Build 3 micro-drift detectors and set up a cosmic ray test stand to measure spatial and angular resolution of previously optimized detectors. Implement further improvements and changes to detector design and electronics as needed.
- Carry out complete characterization of optimized detectors in a test beam.

Readout Electronics

Initially we will use the SRS readout electronics to read out the TPC, and the Cherenkov detector, and the micro-drift GEM detectors. This electronics is not optimized for multihit TPC operation, but it should be adequate to obtain useful information about the performance of the TPC under test conditions. The TPC prototype would initially be tested in the lab with sources and cosmic rays and then undergo a complete study in a test beam.

There is, however, a separate independent development of new readout electronics for micropattern gas detectors by the ATLAS group for an upgrade of the ATLAS muon trigger system. The upgrade uses microdrift micromegas detectors, similar to the microdrift GEMs proposed here, that will be read out with a new readout chip, the VMM1, that is being developed by the Instrumentation Division at BNL . This chip is based on the design of another chip (also designed at BNL) for the LEGS TPC detector that was used at the National Synchrotron Light Source [G.De Geronimo, IEEE Trans. Nucl. Sci. 51-4 (2004) 1312-1317]]. The VMM1, shown in block diagram form in Figure 18, is a 64 channel ASIC that contains a preamp, shaper and discriminator for each channel, that can accommodate a large range of input signals and detector capacitances, and has a wide range of peaking times that can be set by software. It will provide energy and timing information for each channel, along with trigger information that can be used externally. We have been in close contact with BNL's Instrumentation Division during the development of this chip, and they have already made important modifications to its design to accommodate the use of this chip for reading out our microdrift GEM detectors (it should be noted that this development is currently proceeding at no cost to this R&D effort, although it may require some dedicated funding in the future). It could also be used for reading out the Cherenkov part of the combined TPC/RICH detector, and could be used for reading out the TPC section as well. The current design of the VMM1 does not provide multihit capabilities, but it could be used for initial testing of the TPC prototype detector, including beam tests. We will also investigate what types of modifications would have to be made to the VMM1 to make it suitable for use with a full size TPC at the EIC. However, this design will involve many factors, such as event rates, occupancies, double hit resolution, spatial and time resolution, power consumption, cost, etc. We consider the development of the appropriate final readout electronics for a full size TPC at the EIC to be outside the scope of this current proposal, and defer that to a time when a more complete design of the TPC and its requirements are known. One should also investigate at that time what other types of TPC readout electronics are available or could be developed for this purpose.

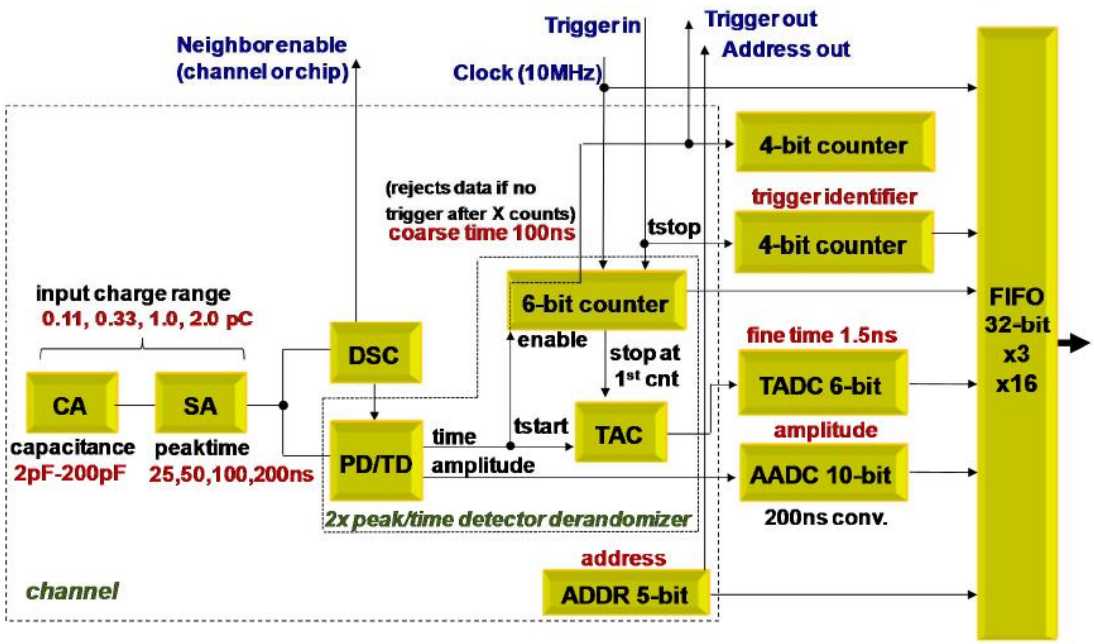


Figure 18: Block diagram of the VMM1 readout chip being developed for an upgrade of the ATLAS muon trigger system. The chip is being designed to read out microdrift micromegas detectors, but its operational parameters are sufficiently flexible for it to be used with the microdrift GEM detectors being studied in this proposal. It can also be used for other types of GEM readout, such as for the RICH part of the TPC/RICH detector, and for initial testing of the TPC.

R&D for a large-area forward GEM detector system

In our current design for an EIC detector, two to three ring-shaped detector stations would be positioned at various forward distances from the interaction point. These distances would range from about a meter up to a few meters to cover tracks at higher η (see Figure 8). The final R&D goal for years 2 and 3 of this project as proposed here would be to perform a slice test of a configuration that uses one trapezoidal GEM detector module from each of these forward detector stations and study the tracking performance. Due to the geometry, the radial dimensions of these detector modules would have to increase with the distance from the interaction point. The GEM detectors grow in size proportional to their distance from the collision point reaching a maximum radius equal to that of the magnet, currently estimated at 1.5 m. A natural progression of the proposed R&D would be to first design, construct, and test a prototype for the smallest, innermost station and then to scale this up for prototypes of the outer stations.

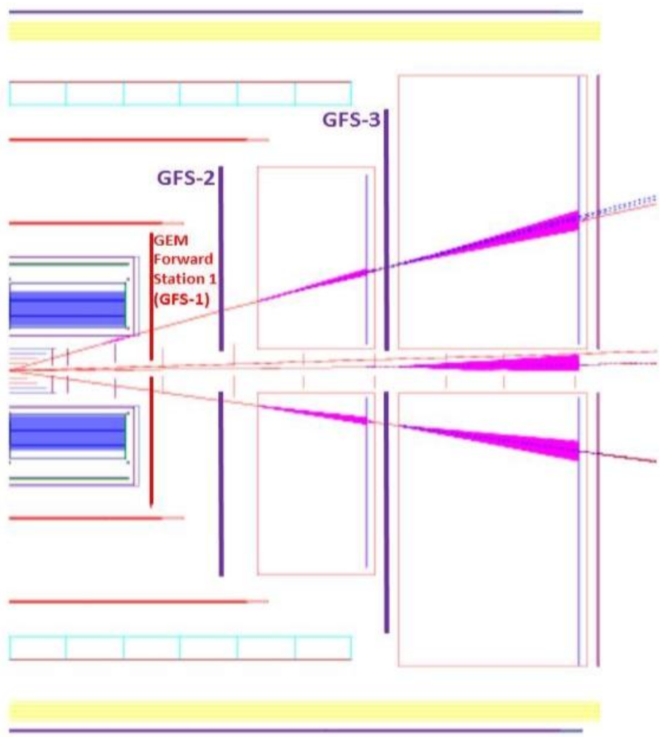


Figure 19: Approximate locations and geometries of three GEM Forward Stations (GFS) are highlighted in the conceptual EIC detector geometry.

The magnitude and direction of the magnetic field permeating these detectors is expected to vary appreciably from station to station. The innermost stations will be inside a mostly axial field produced by the solenoid whereas the outer station would be exposed to the fringe field at the end of the solenoid. This makes it desirable to simulate this situation by performing the slice test in an appropriate magnetic field and to study the GEM tracking performance in such a configuration. In this context, we will investigate the possibility of getting access to a large magnet at CERN that was used for beam tests of GEM detectors by CMS.

Florida Tech and U. Virginia will leverage their involvements with the RD51 collaboration and the proposed CMS forward-muon GEM upgrade for the development of large-area GEM detectors for EIC. Florida Tech and U. Virginia team member K. Gnanvo were involved in the testing of the first 1m-size GEM detectors ever built in 2010 and 2011. In 2012, CERN is designing trapezoidal 1m-size GEM prototypes that employ a new mechanical "self-stretching" technique for the stretching of GEM foils during detector assembly. There are certain potential advantages to this new construction technique. It might be possible to leave out the spacer ribs inside the active volume of the GEM detector, which would remove all dead zones within the active detector area and thus increase overall acceptance of a detector module. The technique would also remove the need for permanently gluing GEM foils to frames. This in turn would allow a re-opening of a detector after assembly, e.g. for swapping out a problematic GEM foil or for testing a different readout strip board.

We would like to capitalize on this last characteristic and develop a 1m-size zigzag strip readout board for an EIC version of the 1m-size GEM detector under this proposal. This is in direct line with the ongoing development of zigzag readout boards in year 1 of the project to reduce the number of electronic channels and thus cost needed for the readout. The Florida Tech group is currently testing a 10cm × 10cm Triple-GEM with zigzag readout strips (Figure 20 left), which have larger area and capacitance than comparable straight strips. First results for these 10cm long zigzag strips are encouraging as they show a rather small increase in noise (Figure 20 right). An increase in the pedestal width of less than 1 ADC count (corresponding to <0.1% of the used ADC range) compared with the pedestal width for straight strips is measured. A 30cm × 30cm Triple-GEM with self-stretch assembly technique is currently on order from CERN. An undergraduate student has started the design of a zigzag strip readout board for this detector. The next logical step is to scale this up for large-area GEM detectors with zigzag strip readouts.

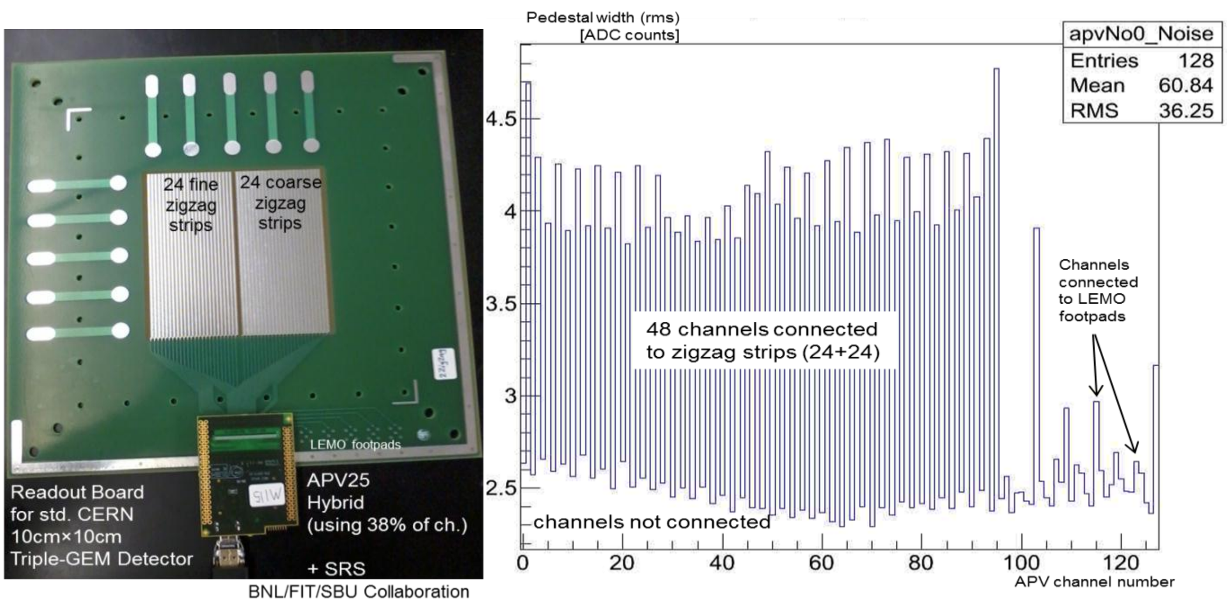


Figure 20: Left: Zigzag readout board for 10cm × 10cm Triple-GEM Detectors designed and built by the EIC R&D collaboration with APV25 hybrid card plugged in for readout. Right: RMS widths of pedestals vs. channel number. Note that the used full ADC range is about 1,500 ADC counts.

We propose to develop, construct, and test two to three large-area GEM detectors over the course of two years. The first prototype would be about 1m long and 50cm wide with a trapezoidal shape and follow the new ``self-stretch'' design from CERN. It would be initially equipped with a standard 1D readout board with straight radial strips segmented into sectors of 10 cm length that is available from CERN and would serve as a first reference detector readout.

In parallel, more advanced readout boards will be developed at the two institutions. At Florida Tech, a large 1D zigzag strip readout board will be designed and constructed, which could then be swapped in for the regular readout board in the first large-area GEM prototype. U. Virginia will design and build a 2D straight-strip readout and is planning to work with Tech-Etch or other available companies to develop this 2D readout on a single flexible layer similar to the STAR FGT x/y strip readout design. Alternatively, a pad-strip readout structure similar to the Yale/SBU readout board design with u/v strips would be considered (Figure 21.). A challenge will be to produce these types of readout structures over a large area of ≈ $0.5m^2$ at relatively low cost and with a pitch that allows a position resolution of less than 100 micron in both x and y and a hit multiplicity resolution up to 10 by exploiting information from equal charge sharing among the two coordinates.

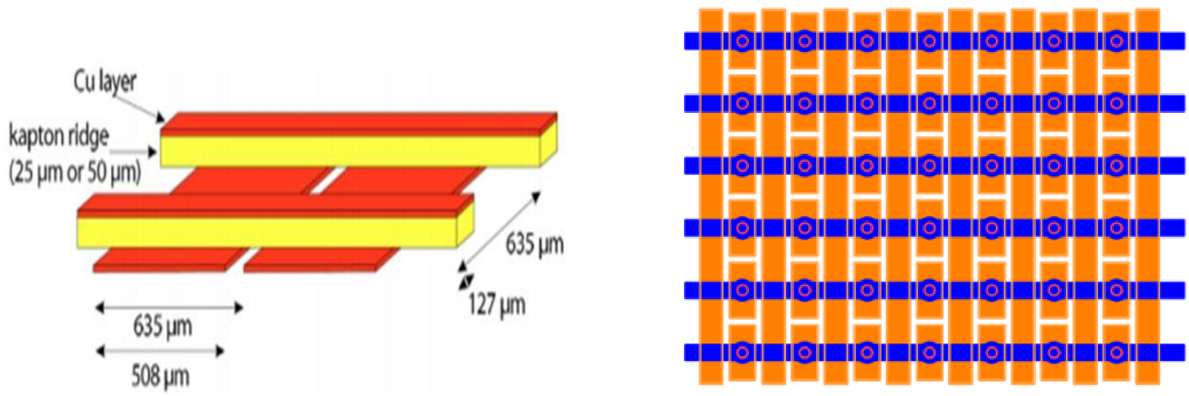


Figure 21: Two-dimensional GEM readout structures using two-layer crossed strips a la COMPASS (left) or strip-pads with pads connected with vias a la Yale/SBU (right).

Based on the experience with this first detector prototype, one or two ≈ 1.5m long trapezoidal GEM detectors would be developed subsequently as prototypes for the most forward GEM tracking stations in the EIC detector. Initial standard bench tests at the home institutions would be carried out with cosmics, x-rays, and radioactive sources. We plan to set up gain uniformity measurements of large GEM foil based on the system put in place at Yale for 10cm × 10cm GEM foils. U. Virginia will develop such a setup initially for 50cm × 40cm SBS GEM foils and then expand it for use with the larger foils for the EIC GEM tracker. All detectors would ultimately be tested together as a unit in a tracking-slice in a beam as described above. This test would be planned for the end of project year 3.

As a backup, in case the CERN self-stretch method turns out not to be viable for our purposes, U. Virginia will be developing a mechanical stretching station for large GEM foils based on their existing experience with intermediate-size foils. The group has built an easy to operate stretcher (Figure 22) for the 40cm × 50 cm GEM foils that they use for the SBS GEM tracker. This mechanical stretcher is an upgraded design of the one developed by Benciveni et al. (Frascati, Italy) and later by Cisbani et al. (Roma, Italy). Some simplifications on the design now allow more flexible handling during the stretching process, and it is also possible to monitor the tension applied at different locations of the foils during the stretching using seven load cells and a display.

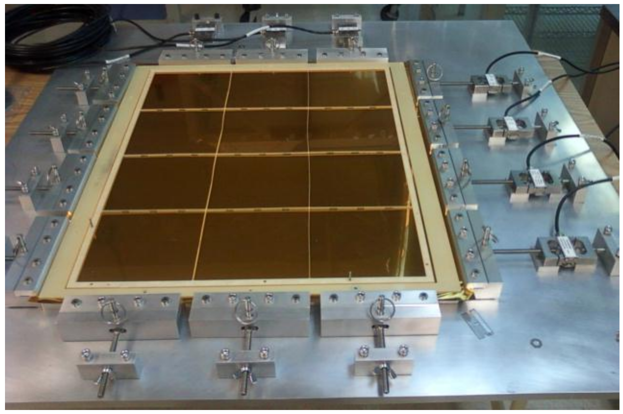


Figure 22: Mechanical GEM foil stretcher at U. Virginia.

The forward tracking working group plans to continue using the RD51 Scalable Readout System (SRS) for reading out the proposed detector prototypes during the planned tests. Such readout systems for R&D purposes are currently in place at both institutions. Initially, existing APV25 hybrid front-end cards will be used. For a full slice test, additional hybrid, ADC, and FEC modules will need to be procured from CERN. As the APV25 chips need to be triggered externally, we are also interested in testing the chambers with SRS-compatible electronics that is either self-triggered or that provides a trigger signal, e.g. the VMM chip currently being developed at BNL or the Beetle chip (RD51).

Development of 3-coordinate single plane readout for GEM chambers.

The R&D program outlined in our previous proposal listed the following steps:

1. *Design small (10cm x 10 cm) read-out boards with two pitches as listed above* [800 μm and 600 μm] *and have them fabricated.*
2. *Basic physical and electrical inspection of the boards to assess quality and yield (measurement of feature sizes and pitch, probe for electrical shorts)*
3. *Test the boards with triple GEM chambers and radioactive source for charge sharing ratio and uniformity of the ratio.*
4. *Test boards with cosmic rays and a multiple chamber stack to get a first measurement of resolution (multiple scattering and statistics will limit the precision to which resolution can be measured with CR) and a first pass at optimizing spatial precision vs. chamber parameters (drift and transfer fields and operating gas).*
5. *Operate chambers in a test beam to fully characterize and optimize performance.*

As indicated in that proposal, the budget request covered the first four items which are expected to be carried out in the first phase. To complete the characterization of the 3-coordinate readout structures we would operate prototype chambers in a test beam.

The design for the 800 μm pitch board was completed and submitted for manufacture at Tech-Etch. Six boards have been delivered and are undergoing initial inspection and testing. Figures 23 & 24 show composite image of the design and readout surface for that board. The various mechanical parts for the chambers are in hand with final fabrication underway in the Yale Instrumentation Shops. Once the basic tests are completed on the 800 μm pitch boards (steps 1-3 above) a 600 μm pitch design will be submitted to Tech-Etch for fabrication. Tests with sources and cosmic rays should be completed by the end of this year.

As indicated in the initial proposal additional funding (mostly travel) is required to support a test beam effort. The budget for this test beam effort is based on requirements for a two week run in MTest at Fermilab. Fermilab will be off for 11 months starting ~May 1, 2012, so the earliest this could occur is ~April, 2013. Although this is perhaps later than when the chambers and readout could be ready, the flexibility of Mtest and lower travel costs compared to more remote facilities makes Fermilab's Mtest the location of choice.

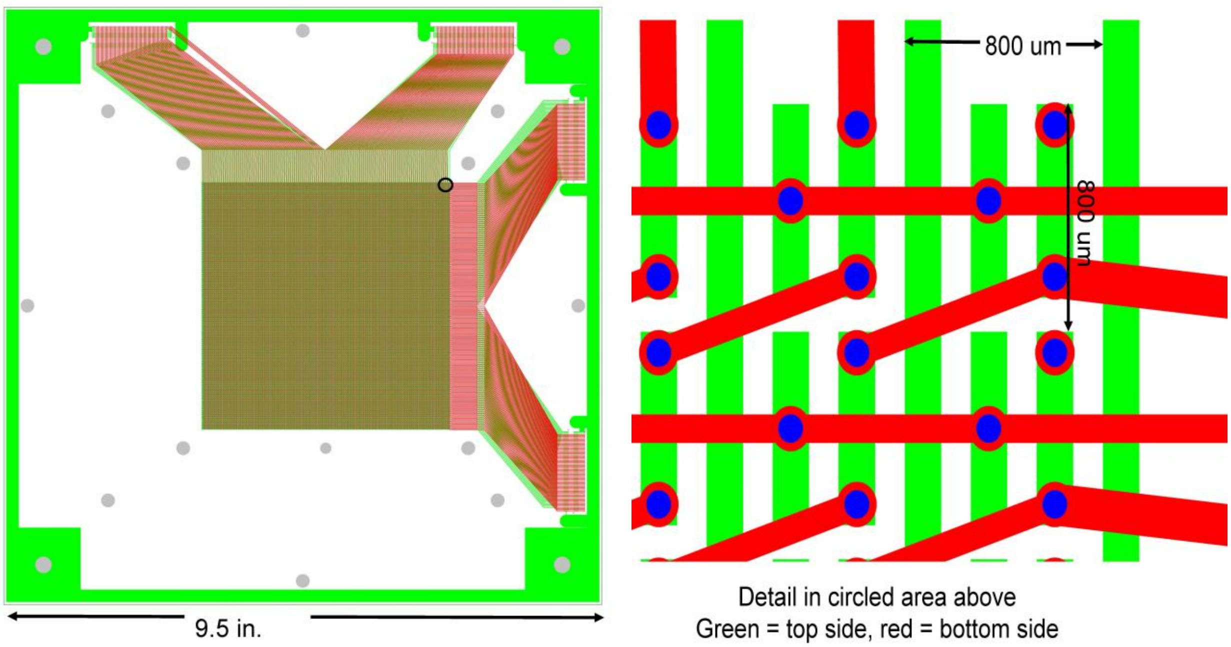


Figure 23: Layout of prototype 800 μm pitch 3 coordinate readout board. Detail for circled area at upper right is shown at right and below.

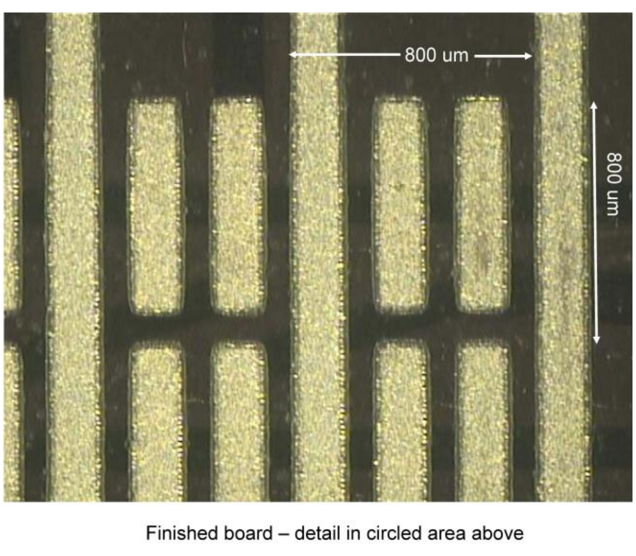


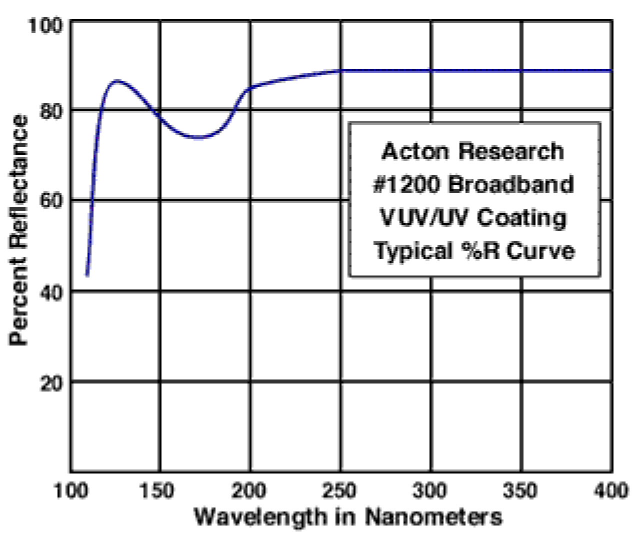
Figure 24: Finished 800 μm pitch 3 coordinate readout board.

Cherenkov Particle ID

The EIC physics program requires “positive” particle ID of pions and kaons, however for the proton so-called “negative” particle ID (a particle that is neither electron, pion, nor kaon shall be labeled as a proton) will be sufficient. Although applications of Cherenkov technology are interesting over the full phase space of the EIC detector, they are most challenging in the forward direction where the particle ID should extend to lab momenta of ~80 GeV/c. In this region Cherenkov Ring-Imaging is among the most viable solutions and will provide high momentum particle ID if the following conditions are met:

- Low index of refraction of the radiator medium.
- High count of measured photoelectrons.
- Precise position determination of each photoelectron.

The design of our test beam device has been made to take each of these criteria close to an extreme. We have selected a design with CsI photocathodes applied to a GEM detector operating in pure CF_4 with the aid of a mirror with reflectivity deep in the VUV range. The index of CF_4 is only 1.00062 in the wavelength range of interest. Experience with the PHENIX HBD showed an impressive N_0 of 322 in a windowless configuration. Although an HBD-like configuration coupled to the central arm TPC is a viable choice for additional electron ID in the central arm, unfocussed blobs will not provide sufficient particle ID in the forward direction. Thus we have actively pursued development of a mirror technology with sufficient reflectivity deep in the VUV. For our test beam run (ongoing at the time of this writing), we have used a commercial mirror purchased from Acton Optics, the characteristics of which are shown in the figure below.



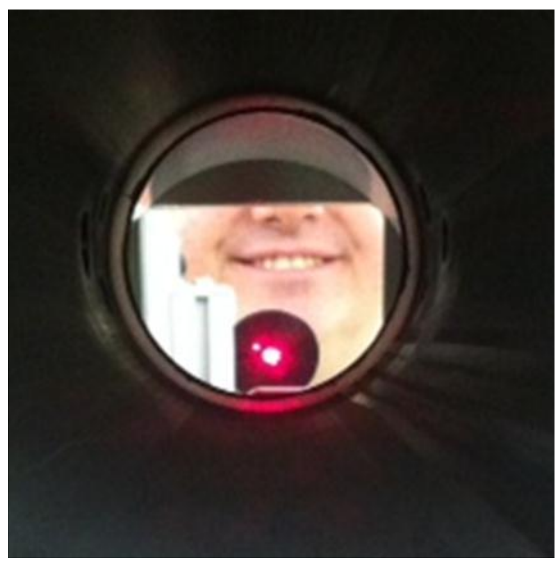


Figure 25 Reflectivity of our mirror and the mirror installed into the test beam apparatus.

This technology of the mirror was developed in the 1960s and uses a carefully tuned thickness of MgF_2 (250 Angstrom) overcoating a pure Al surface. At this thickness the overcoating not only protects the Al from oxidation, but also serves as a thin-film reflector with a peak reflectivity at λ=120 nm, leading to the peculiar shape of the reflectivity curve shown in the figure. The custom R=2 meter spherical mirror used for the test beam was expensive ($5500 for an 18 cm diameter), and so our future plans involve developing in-house capability of producing cost effective large area mirrors.

An additional challenge faced in moving from the blob-imaging HBD of PHENIX to a true RICH involves detection of single photoelectrons. The principle challenge lies in achieving sufficient gain to not only detect single photoelectrons with high efficiency, but to have enough total avalanche charge to implement a charge division readout scheme to provide high position resolution for each photoelectron. We have addressed the gain using a GEMstack of 5 GEMs. When run in reverse bias, the stability criteria are effectively driven by typical performance of a 4-GEM stack. To good approximation, only single photoelectrons experience an avalanche in the first GEM layer and thereby produce a charge similar to that of a MIP. Thus, we have found that it is not difficult to achieve gains of ~100,000 or higher in this configuration.

Charge division has been addressed by using a cathode plane with segmentation similar to the STAR FGT detector as shown in the figure below.

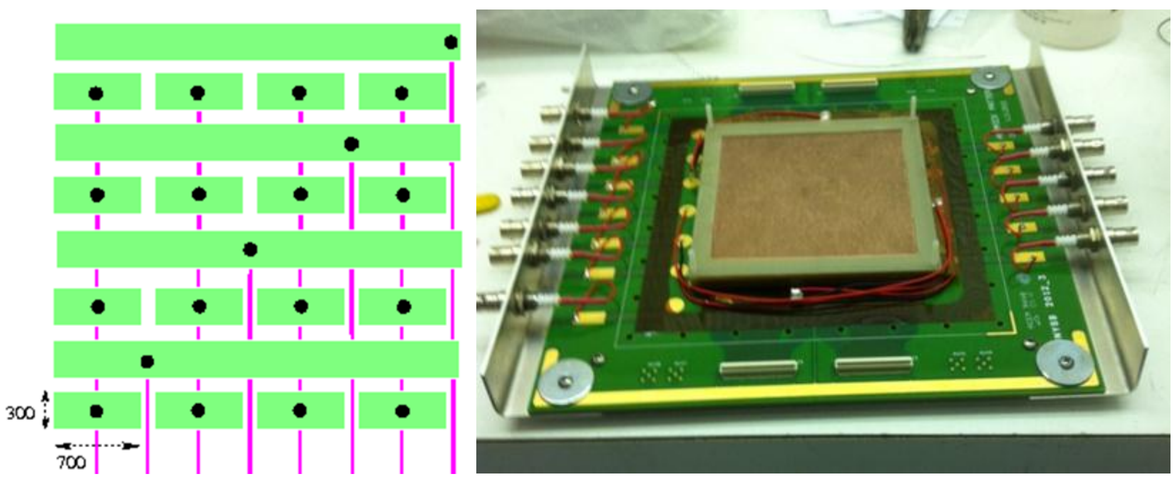


Figure 26 The FGT-style readout pattern is shown schematically in the left panel wherein all dimensions are in microns. The final assembly is shown in the right panel.

Although a Cartesian pattern for the readout plane is not optimal for a ring, we have circumvented this problem by dividing the readout plane into four separate readouts, each of which views ¼ ring. In this way X-Y ambiguities are reduced.

One drawback of using CF_4 as an avalanche gas for single photoelectrons is the very small diffusion in the gas as shown in the figure below.

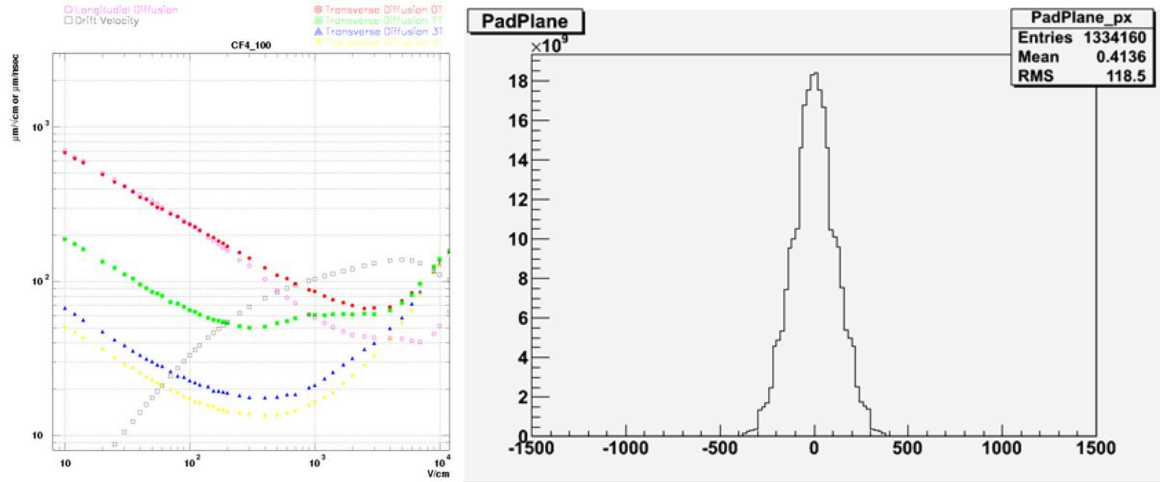


Figure 27 The left panel shows diffusion in CF_4, which can be converted to a mere 27 μm per layer. The right panel shows a Monte Carlo calculation including "hole sharing" (mis-alignment of GEM holes) leading to only 120 micron sigma of the deposited charge cloud.

Because of the small diffusion, the major contributor to charge spread on the pad plane is the hole-misalignment wherein the avalanche from a hole on one layer uses multiple holes on the next layer. These measurements have been verified in the HBD prototype currently receiving beam using an ^{55}Fe source via the charge asymmetry distribution between X and Y readouts. The result of these calculations is used to determine that we expect 80% efficiency for single photoelectrons to fire both and X and Y readout for all gains above 70,000.

Test Beam at Jefferson Laboratory

At the time of this writing, our apparatus is installed at Jefferson Lab Hall A and is taking data. The figure below shows the setup.

Figure 28 The left panel shows the HBD Cherenkov detector positioned for measurements at Jefferson Lab. The right panel shows the two Pb Glass blocks arranged as "PreShower & Shower" that are used to identify electrons.

The stainless steel tube is the Cherenkov detector. Since the "beam" consists of particles scattered from the target the spectrometer is attached to a rotating table so as to be pointed at the target. The tilt can be remotely controlled to compensate for a strong horizontal field applied to the target. Electrons are identified by a pair of calorimeters arranged as a "Tee" so that the first counter is a "PreShower" and the second one is a "Shower" detector. Shown in the figure below are two results for these counters:

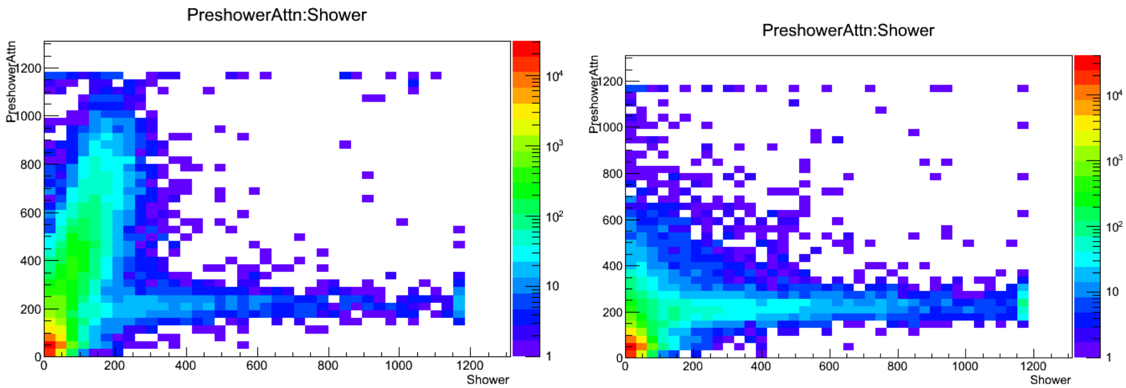


Figure 29 The left panel shows the calorimeter response while beam is being tuned. Many scattered electrons enter the device. The right panel shows "stable running" for which the particles are dominantly pions.

All aspects of the device seem to be working, however collecting ample data is proving to be a challenge. The current running in Hall A has a beam energy of only 1.2 GeV and when the beam only hits the target, particles scattered in our direction are dominantly pions. During beam tuning conditions, upstream beam scraping shows copious electrons impinging on our device and demonstrates the ability to separate out an electron spectrum.

Year 1 Plans

We are gaining valuable experience operating our Cherenkov detector at JLab and expect that we will learn the number of photoelectrons per ring accurately. Unfortunately, because of the low beam energy not all aspects of the device will have been characterized during this first run. Statistics will be poor and the electrons (including rare elastic scatters to our angle) will be low enough energy that multiple scattering will overwhelm the detector's intrinsic ring radius resolution. Thus we will require further running of this device at other facilities in the coming year.

Although our mirrors for the test beam are of excellent quality, they are far too costly for the EIC and have inappropriate substrate material (fused silica) to be used at the EIC. We will thus embark on an R&D effort to develop less expensive large area mirrors. Within our immediately available resources we have multiple options for producing high quality mirrors:

- Target Maker's Lab:
  - Vacuum ~ 4 x 10^{-7} torr.
  - Ohmic heating for evaporation.
- Thin Film Lab
  - Vacuum ~1 x 10^{-8} torr.
  - Electron Gun
- Spectra Thin Films Company (Hauppague, NY)

- Vacuum ~1 x 10^{-6} torr.
- Electron Gun

Using these facilities, along with BNL equipment for measuring reflectivity, we will investigate the techniques for making high quality mirrors in house. Many of the techniques used by Acton Optics are their intellectual property. Our goal is to produce mirror coatings of equal quality on commercial substrates to equal the performance achieved by Acton.

We will also pursue along with faculty from the SBU material science department thin substrate candidate materials and the ability to polish these to ~20 Angstrom surface roughness.

Year 2 Plans

During year 2, we plan to scale up our activities in the direction of a so-called sector of the eventual EIC detector. This device would be nicely matched to the sector test planned for the trackers. In doing so, we would not only use the large area GEM techniques developed for the trackers, but also use mirrors produced in house. Available to us is the so-called "Big Mac" scattering chamber as shown in the figure below:

Figure 30 The Big Mac is a large chamber that provides an 8 foot diameter cylinder of vacuum at ~5 x 10^{-7} torr. This device, or the large scattering chamber at Spectra Films (1 meter diameter mirrors) are candidates for "in house" production.

Smaller, but perhaps sufficient is the large chamber at the Spectra Films Company. The latter one has been used in the past to make mirrors of 1 meter diameter, but not reflective in the deep VUV. This facility would be able to significantly reduce costs at the EIC for producing high quality large area mirrors.

BUDGET

Included in our budget is a single postdoc salary. Our varied projects all require postdoctoral assistance; however, hiring more than one postdoc would be an inefficient use of funds. Since all facets of the research involve GEM detectors we feel that an effective solution would be to have a so-called travelling postdoc. This person would work on all aspects of this R&D program and necessarily travel among the institutions. Florida Tech has the most cost effective overhead & fringe rates and thus the postdoc would be hired by them and expected to travel (using additional funds) to three focal points of effort in Florida, Virginia, and New York throughout the year. We have already identified one qualified applicant who would accept (and even prefer) this unusual arrangement and have contact with two additional competitors for the position.

Budget by Task

Item	Year 1	Year 2
Combined TPC/RICH, and Micro-Drift		
Short drift planar prototype detectors	$10,000.00	
Compact TPC prototype	$15,000.00	$10,000.00
CsI Cherenkov detector		$15,000.00
Cosmic ray test stand	$15,000.00	
Gas, supplies, etc	$10,000.00	$10,000.00
Test beam activities		$15,000.00
Technical support, designer	$10,000.00	$15,000.00
Subtotal (incl. 50% overhead)	**$90,000.00**	**$97,500.00**
Forward Tracking		
3 large-area prototype GEM detectors	$10,000.00	$20,000.00
Zigzag and strip-pad r/o boards (design & construction)	$10,000.00	$10,000.00
mechanical stretcher for large foils	$12,000.00	$0.00
GEM frames w/ various spacers for stretcher tests	$3,000.00	$0.00
SRS electronics	$0.00	$20,000.00
Materials & Supplies (gas, cables, …)	$3,000.00	$3,000.00
Equipment & Material Subtotal (incl overhead)	**$38,750.00**	**$53,750.00**
Cherenkov		
Test Beam Expenses	$12,500.00	$10,000.00
CF4 and ArCO2 gas	$2,800.00	$5,000.00
Clean Room Supplies	$2,500.00	$2,500.00
Small mirror substrates	$2,000.00	$0.00
Refurbish transparency mon. for reflectivity measurement	$3,000.00	$0.00
Small evaporator materials & supplies	$3,000.00	$0.00
Large evaporator refurbishing	$5,000.00	$32,000.00
Thin substrate development	$4,000.00	$18,000.00

Subtotal (incl 48% on-campus overhead)	**$51,504.00**	**$99,900.00**
Equipment Subtotal	**$180,254.00**	**$251,150.00**
Domestic: Joint work at FIT, UVA	$10,000.00	$4,000.00
Foreign: Beam tests, QA at CERN	$10,000.00	$10,000.00
Travel Subtotal (incl overhead)	**$30,800.00**	**$21,560.00**
3 Coordinate Test Beam Effort		
Travel & Housing	$2,000.00	$4,000.00
Supplies, mounts and fixturing		$5,000.00
Subtotal (incl. 26% Yale off campus rate)	**$2,520.00**	**$11,340.00**
Costs Spanning Multiple Tasks		
12 mos. Postdoc (fully loaded)	$85,635.55	$88,204.62
Engineering support	$15,000.00	$15,000.00
Undergraduate student support	$5,000.00	$5,000.00
Postdoc support while on travel	$10,000.00	$15,000.00
Electronics Development	$10,000.00	$10,000.00
Other Common Costs	$5,000.00	$5,000.00
Personnel Subtotal	**$143,335.55**	**$153,404.62**
TOTAL	**$356,910**	**$437,455**

Budget by Institution (Year 1)

Equipment & Material		BNL	FIT	UVa	SBU	Yale
Short drift planar prototype detectors		$10,000.00				
Compact TPC prototype		$15,000.00				
Cosmic ray test stand		$15,000.00				
Large-area prototype GEM detectors			$10,000.00			
Zigzag and strip-pad r/o boards (design & construction)			$5,000.00	$5,000.00		
Mechanical stretcher for large foils				$12,000.00		
GEM frames w/ various spacers for stretcher tests				$3,000.00		
Electronics development		$10,000.00				
Small Mirror Development					$12,000.00	
Large Mirror Development					$5,000.00	
Materials & Supplies (gas, cables, mounts, fixturing)		$10,000.00	$1,500.00	$1,500.00	$5,300.00	
Overheads		$30,000.00	$750.00		$10,704.00	
	Sum	**$90,000.00**	**$17,250.00**	**$21,500.00**	**$33,004.00**	
Personnel						
12 mos. Postdoc salary			$45,500.00			
Postdoc support while on travel		$10,000.00				
Engineering & Technical support		$10,000.00	$7,500.00	$7,500.00		
Undergraduate student support				$5,000.00		
Overheads & Fringe		$10,000.00	$40,135.55	$2,700.00		
	Sum	**$30,000.00**	**$93,135.55**	**$15,200.00**		
Travel						
Domestic: Joint work at FIT, UVA, Nat'l Labs			$5,000.00	$5,000.00		
Foreign: Beam tests (at CERN in Year 2)			$5,000.00	$5,000.00		
3-coordinate test beam effort (FNAL)						$2,000.00
RICH prototype test beam					$12,500.00	
Overheads			$5,400.00	$5,400.00	$6,000.00	$520.00
	Sum	**$0.00**	**$15,400.00**	**$15,400.00**	**$18,500.00**	**$2,520.00**
Other Common Costs						
Shipping, etc.		**$1,000.00**	**$1,500.00**	**$1,500.00**	**$1,000.00**	
TOTALS		**$121,000.00**	**$127,285.55**	**$53,600.00**	**$52,504.00**	**$2,520.00**

Budget by Institution (Year 2)

Equipment & Material		BNL	FIT	UVa	SBU	Yale
Compact TPC prototype		$10,000.00				
CsI Cherenkov detector		$15,000.00				
Large-area prototype GEM detectors			$10,000.00	$10,000.00		
Zigzag and strip-pad r/o boards (design & construction)			$5,000.00	$5,000.00		
Electronics development		$10,000.00	$10,000.00	$10,000.00		
Large Mirror Development					$50,000.00	
Materials & Supplies (gas, cables, mounts, fixturing)		$10,000.00	$1,500.00	$1,500.00	$7,500.00	$5,000.00
Overheads		$22,500.00	$750.00		$27,600.00	$1,300.00
	Sum	**$67,500.00**	**$27,250.00**	**$26,500.00**	**$85,100.00**	**$6,300.00**
Personnel						
12 mos. Postdoc salary (3% raise)			$46,865.00			
Postdoc support while on travel		$15,000.00				
Engineering & Technical support		$15,000.00	$7,500.00	$7,500.00		
Undergraduate student support				$5,000.00		
Overheads & Fringe		$15,000.00	$41,339.62	$2,700.00		
	Sum	**$45,000.00**	**$95,704.62**	**$15,200.00**		
Travel						
Domestic: Joint work at FIT, UVA, Nat'l Labs			$2,000.00	$2,000.00		
Foreign: Beam tests (at CERN in Year 2)			$5,000.00	$5,000.00		
3-coordinate test beam effort (FNAL)		$15,000.00				$4,000.00
Cherenkov Detector Test Beam					$10,000.00	
Overheads		$7,500.00	$3,780.00	$3,780.00	$4,800.00	$1,040.00
	Sum	**$22,500.00**	**$10,780.00**	**$10,780.00**	**$14,800.00**	**$5,040.00**
Other Common Costs						
Shipping, etc.		**$1,000.00**	**$1,500.00**	**$1,500.00**	**$1,000.00**	
TOTALS		**$136,000.00**	**$135,234.62**	**$53,980.00**	**$100,900.00**	**$11,340.00**