

Letter of Intent for Detector R&D Towards an EIC Detector

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1 Description of Project

On January 28 2011, a call for detector R&D proposals addressing relevant issues for an Electron-Ion Collider was put forth from Brookhaven National Laboratory. The requested proposals were to be "site-neutral" in that they would be motivated by the physics program and not the geographical location of the detector or accelerator. Clearly, the EIC facility and physics program will require developments in many areas at or beyond the present state-of-the-art in detector technology. Key among these will be the tracking systems and particle ID. Tracking technology spans a rather large phase space of technology, each branch of which has various advantages (position resolution, small radiation length, etc...). The physics program requirements will drive the community both to the best existing technology choices as well as to the key areas wherein the state of the art must be advanced. Often tracking technology serves intrinsic particle identification functions or is most naturally paired with particular PID technologies. For this reason tracking and PID technologies are often closely linked and should be considered as a package rather than separately.

In the time since the announcement of this R&D program an ever-growing group of experienced and capable scientists has been forming with the central goal of addressing the EIC tracking and PID issues completely and thoroughly. It is neither possible nor wise for a specific technology choice to have been made in time for the first funding round. We have thus chosen to submit a letter of intent rather than a full proposal to the first round of R&D funding. This letter of intent has the following over-arching goals:

- Establish a broad community of scientists with experience spanning RHIC, Jefferson Lab, and other relevant facilities.
- Widely advertise our fledgling efforts to attract an even larger community.
- Formulate a well reasoned program for the **second round** of R&D.

Contained within this document is a description of how the physics program drives detector choices, various options that we intend to consider as candidates for later research, a description of the facilities and capabilities of our collaboration, and a small request for funds applied to projects whose merit is self-evident and independent of the larger technology considerations.

The end product of this research program will be one or more well-formulated and coherent proposals to the next round of EIC Detector R&D. As indicated below, each of our participating institutions has significant in-house capabilities and experience. However, the effective utilization of these resources for simple yet critical tests during the present funding cycle is **only** possible after the small scale operating costs associated with these facilities have been covered. Thus we propose a series of "Seed Grant" funds, institution by institution, to cover these operating costs.

2 Kinematics and Detector Designs for the different EIC Machine Designs

2.1 Kinematics and Requirements for an EIC Detector

The physics program at an EIC imposes several challenges on a detector design as it spans a wide range in center-of-mass energies, different combinations of beam energies, beam particle species and several different physics processes. It covers inclusive measurements ($ep/A \rightarrow e' + X$), which require detecting the scattered lepton with high precision, semi-inclusive processes ($ep/A \rightarrow e' + h + X$), which require detecting in coincidence to the scattered lepton at least one hadron and exclusive processes (i.e., $ep/A \rightarrow e' + p'/A' + \gamma$), which require detecting all particles in the reaction. In the following kinematic plots will be shown characterizing the differences in particle kinematics due to the different process types as well as the various beam energy combinations. The directions of the beams are defined as for HERA at DESY with the hadron beam in the positive z direction (0°) and the lepton beam going in the negative z-direction (180°). The upper panel of Figure 1 shows clearly that for lower Q^2 the momentum of the scattered lepton is closer to the original lepton beam energy. For all lepton-hadron beam energy combinations the scattered lepton goes in the original lepton beam direction for low Q^2 and into the barrel detector acceptance for higher Q^2 . For the same hadron beam energies the lepton scattering angle becomes smaller for a fixed Q^2 with increasing lepton energy.

Even though the correlation between x and Q^2 for a collider detector is less strong than for fixed target experiments it is still there and becomes stronger if the momentum and scattering angle resolution deteriorate for small scattering angles corresponding to small inelasticity y . Figure 2 shows the x - Q^2 plane for two different center-of-mass energies. HERA has reached a lower y of 0.005 by reconstructing the lepton kinematics from the hadronic final state [1, 2]. The main reason, why the hadronic methods at low y has better resolution is seen from the following equations $y_{JB} = E - P_z^{had}/2E_e$, where $E - P_z^{had}$ is the sum over the energy minus the longitudinal momentum for all hadronic final state particles and E_e is the beam energy. This quantity has no degradation of the resolution for $y < 0.1$ compared to the electron method, with $y_e = 1 - (1 - \cos\theta_e)E'_e/2E_e$. This becomes clear if we consider the relative resolutions for both quantities $\Delta y_{JB}/y_{JB} \sim \text{const.}$ and $\Delta y_e/y_e \sim 1/y_e$.

Figure 3 shows the distributions of pions for semi-inclusive reactions for momentum vs. scattering angle in the laboratory frame for different beam energy combinations. For low lepton beam energies the pions are very forward (hadron beam direction), with increasing lepton beam energy hadrons are populating more the central region of the detector and at highest lepton energies more and more hadrons are going backward (in the lepton beam direction). The kinematics for kaons and protons applying the same cuts as to the pions in Figure 3 is basically identical. The distributions for semi-inclusive events in electron nucleus collisions might be slightly modified due to nuclear modification effects, but the global features shown in Figure 3 remain. To be able to identify the different hadron types over a wide momentum and angular range an EIC detector needs to have PID-detectors in the forward, central and backward direction. As the hadron momenta in forward and backward direction are higher than in the central one, the best detector technology are RICH detectors with dual-radiators. In the central detector high resolution ToF detectors ($t \sim 10$ ps) or a DIRC or a proximity focusing Aerogel RICH are adequate detector technologies.

The fact that for certain kinematics the hadrons (charged and neutral) go into the scattered lepton direction (see Figure 4) puts an other requirement on the detector, good electron identification. At $-3 < \text{rapidity} < -1$, over a wide momentum range suppression factors of 10 - 100 are needed for both hadrons and photons. Measuring E'_e/p'_e gives a reduction of ~ 100 of hadrons, but this requires to have the same rapidity coverage of tracking detectors and electromagnetic calorimetry. This would of course also immediately suppress the misidentification of photons in the lepton sample by requiring a track has to point to the electromagnetic cluster. This would also help the y resolution at low y as the angular as well as the momentum resolution for trackers are much better than for electromagnetic calorimeters. The hadron suppression can be further improved by combining the electromagnetic calorimeter response and the response of the Cerenkov detectors for low momentum scattered leptons. There are other detector technologies like transition radiation detectors, which would provide an other factor 100 hadron suppression for lepton momenta bigger than 4 GeV.

Of special interest in semi-inclusive DIS are events having charmed or bottom mesons. To measure the structure functions F_2^c , F_L^c , and F_2^B it is sufficient to tag the charm and the bottom via an additional lepton (electron, positron, muons) to the scattered lepton. The leptons from charmed mesons can be identified via a displaced vertex of the second lepton ($\langle \tau \rangle \sim 150 \mu\text{m}$). This can be achieved by integrating a high resolution vertex detector into the detector design. For measurements of the charmed (bottom) fragmentation functions or to study medium modifications of heavy quarks in the nuclear environment it is needed to reconstruct

at least one of the charmed (bottom) meson completely to have access to the kinematics of the parton kinematics. This requires in addition to measuring the displaced vertex to have good particle identification to reconstruct the meson via its hadronic decay products, i.e. $D_0 \rightarrow K^\pm + \pi^\mp$.

Figure 5 shows the distributions for hadrons from vector mesons in exclusive reactions for momentum vs. scattering angle in the laboratory frame for different beam energy combinations. For increasing lepton beam energy the hadron distribution goes from being only a forward peaked distribution to a distribution with a forward and backward peak. The distributions from hadrons from exclusive reactions do not impose any additional constraints on the detector design, which are also not required by semi-inclusive reactions.

Figure 6 shows clearly that with increasing lepton beam energy the photon and scattered lepton will be in the same detector hemisphere. Overall electromagnetic calorimetry is required from forward to backward angular acceptance of the detector. To have tracking and electromagnetic calorimeter covering the same rapidity range will greatly enhance to separate the photon and lepton and such a problem ZEUS had with their DVCS events.

To ensure exclusivity for the events it is extremely important to detect that the proton or nucleus stayed intact during the scattering. Because of the extremely small scattering angle the detection of these protons is extremely dependent on the interaction region design.

Combining all the requirements described in Section 2.1 a schematic view of the emerging dedicated EIC detector is shown in Figure 7. It was already discussed that it is important to have equal rapidity coverage for tracking and electromagnetic calorimetry. This will provide good electron ID and give good momentum and angular resolutions at low inelasticity y .

The projected rates for a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ are depending on the center-of-mass energy between 300 - 600 kHz with an average of 6 - 8 charged tracks per event.

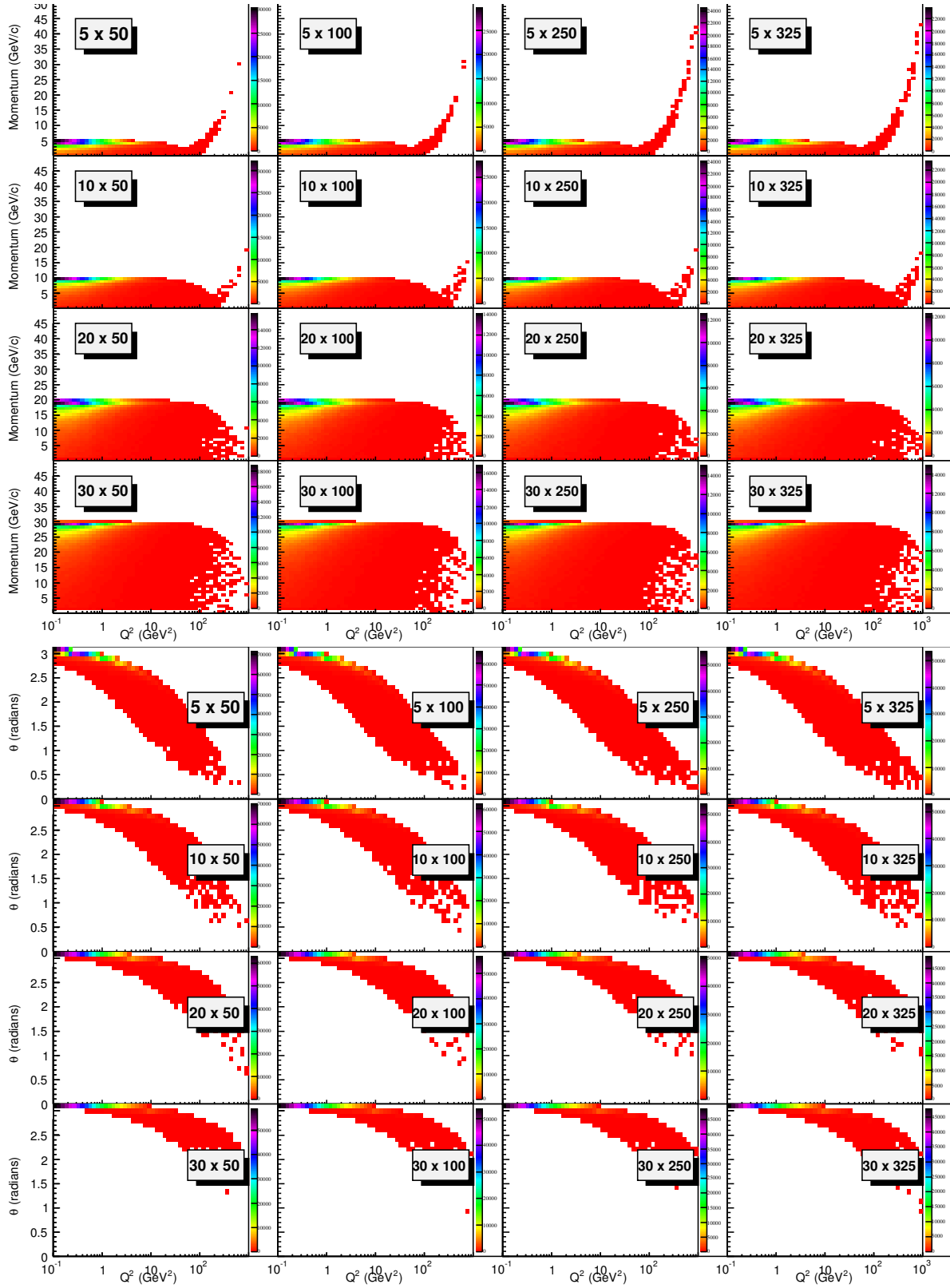


Figure 1: Q^2 vs. momentum (upper panel) and Q^2 vs. scattering angle (lower panel) in the laboratory frame for the scattered lepton. The following cuts have been applied $Q^2 > 0.1 \text{ GeV}^2$, $0.01 < y < 0.95$ to both plots.

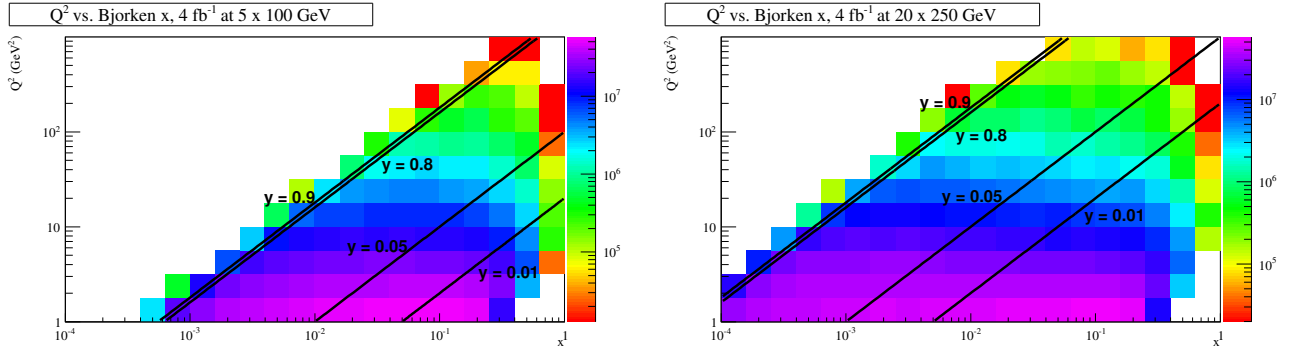


Figure 2: The x - Q^2 plane for two different center-of-mass energies (45 GeV and 140 GeV). The black lines indicate different y -cuts placed on the scattered lepton kinematics.

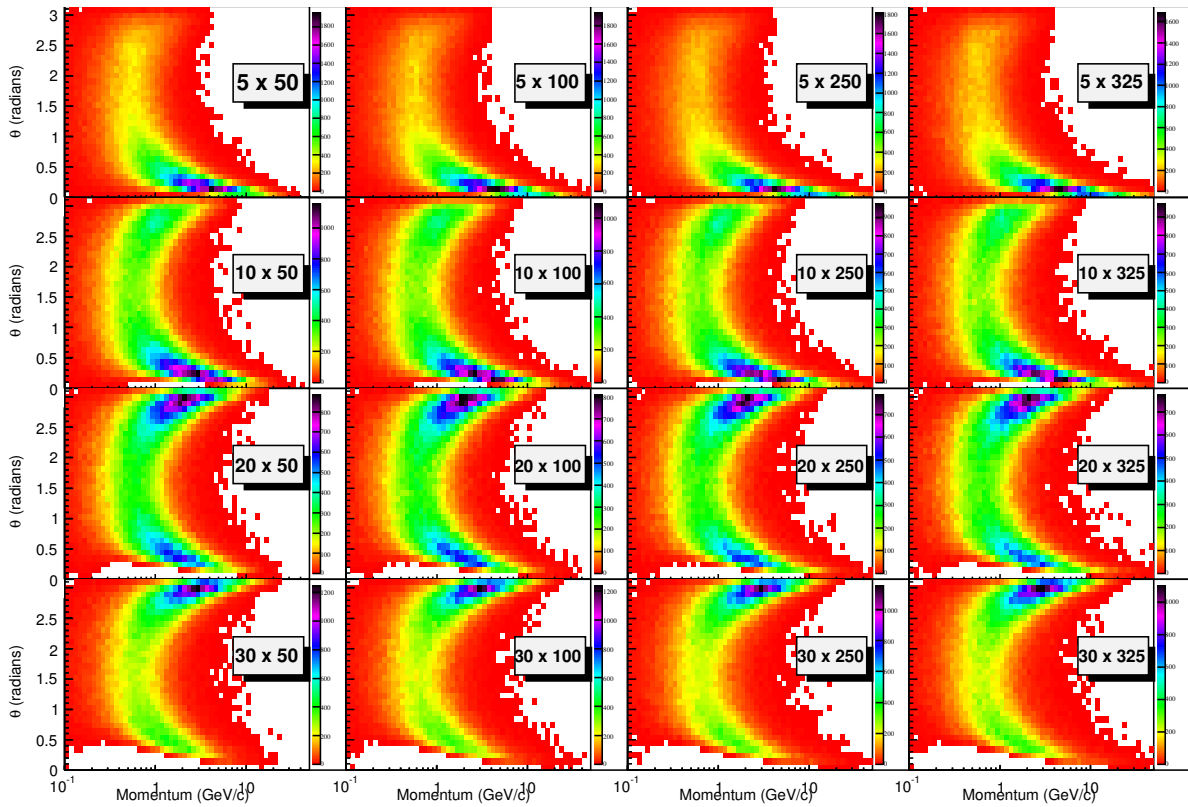


Figure 3: Momentum vs. scattering angle in the laboratory frames for pions from non-exclusive reactions. The following cuts have been applied $Q^2 > 1 \text{ GeV}^2$, $0.01 < y < 0.95$ and $0.1 < z < 0.9$

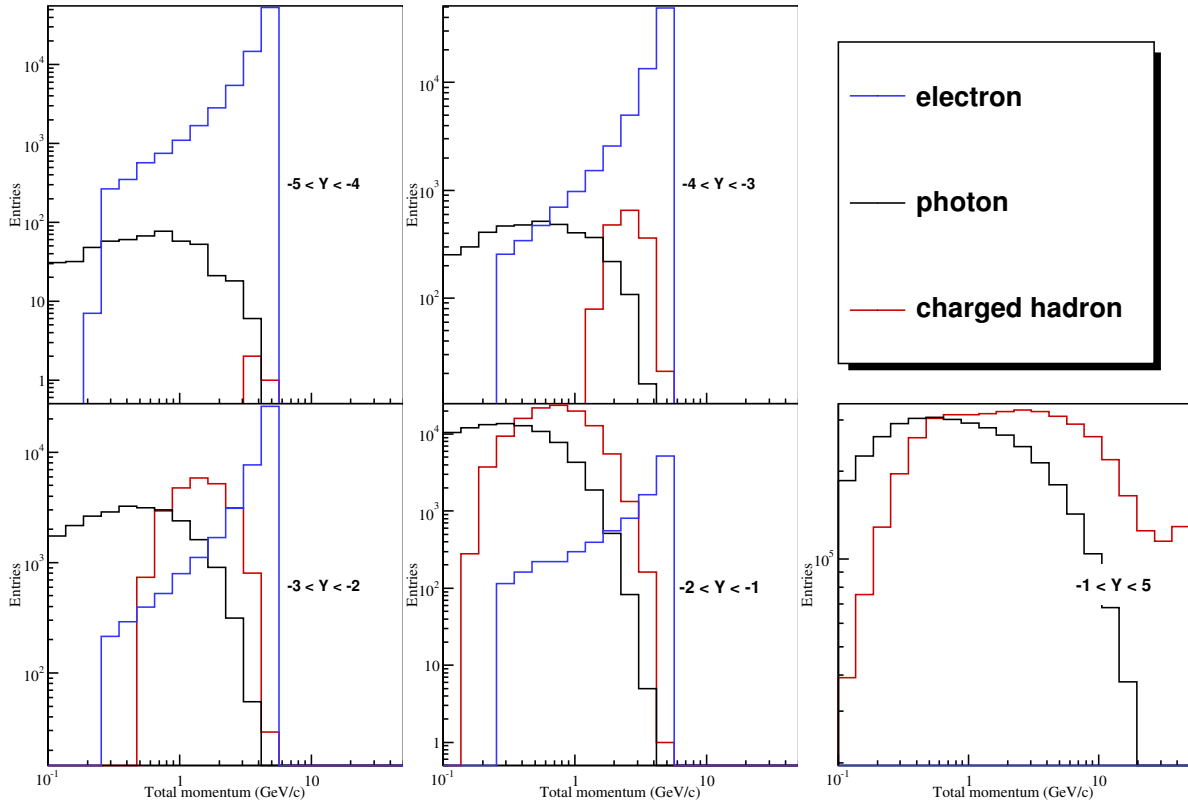


Figure 4: The number of photons and hadrons as well as the number of scattered leptons in a rapidity bin vs momentum having 5 GeV leptons colliding with 100 GeV protons. No kinematic cuts are applied.

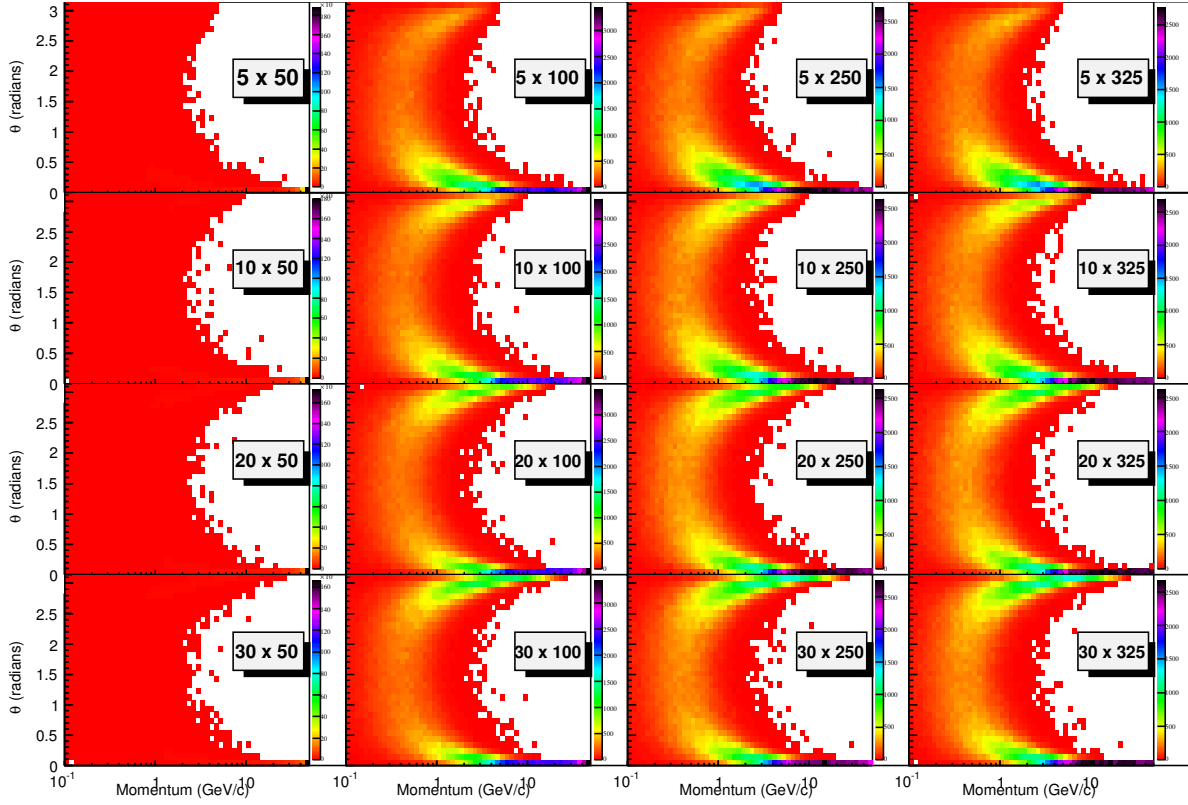


Figure 5: Momentum vs. scattering angle in the laboratory frames for hadrons from exclusive reactions. The following cuts have been applied $Q^2 > 0.1 \text{ GeV}^2$, $0.01 < y < 0.95$

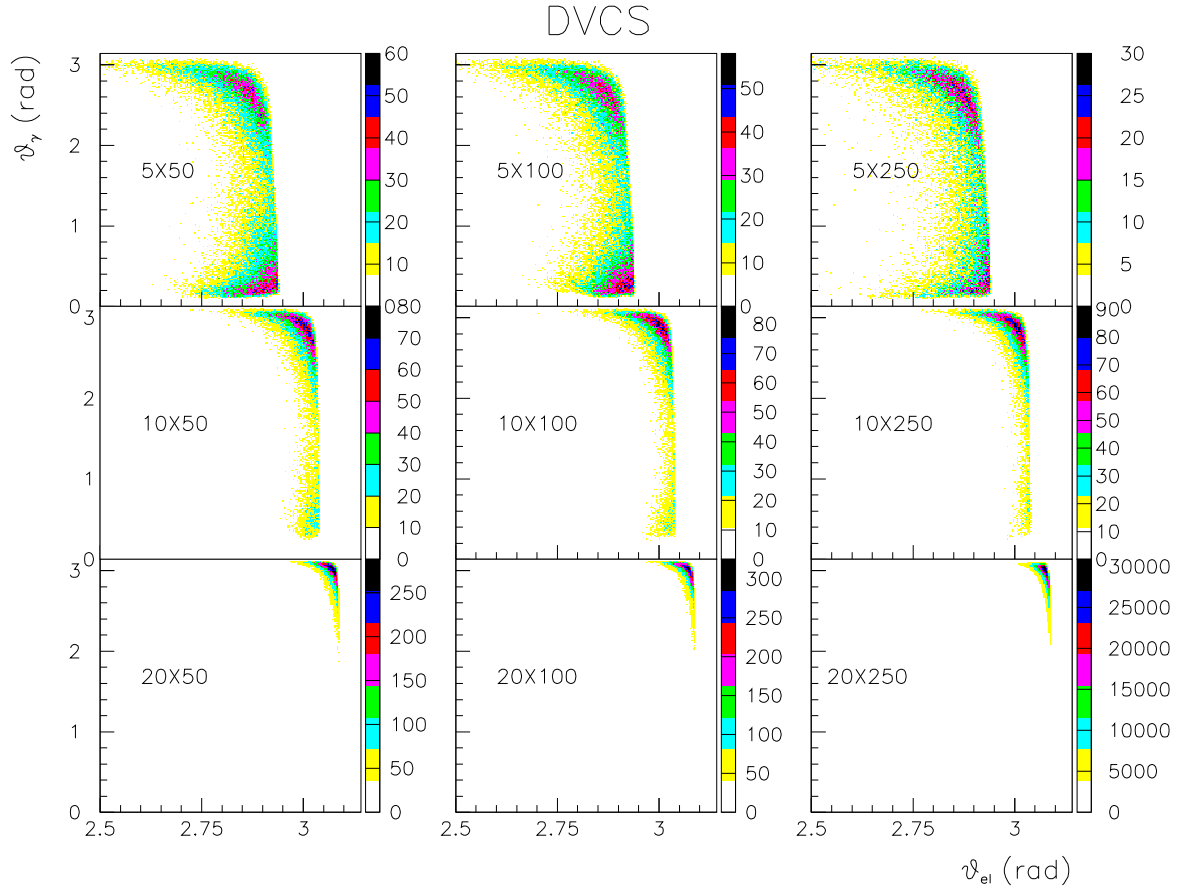


Figure 6: The scattering angle in the laboratory frame for photons vs. the one of the scattered lepton for DVCS events. The following cuts have been applied $Q^2 > 1.0 \text{ GeV}^2$, $0.01 < y < 0.95$ and $E_\gamma > 1. \text{ GeV}$

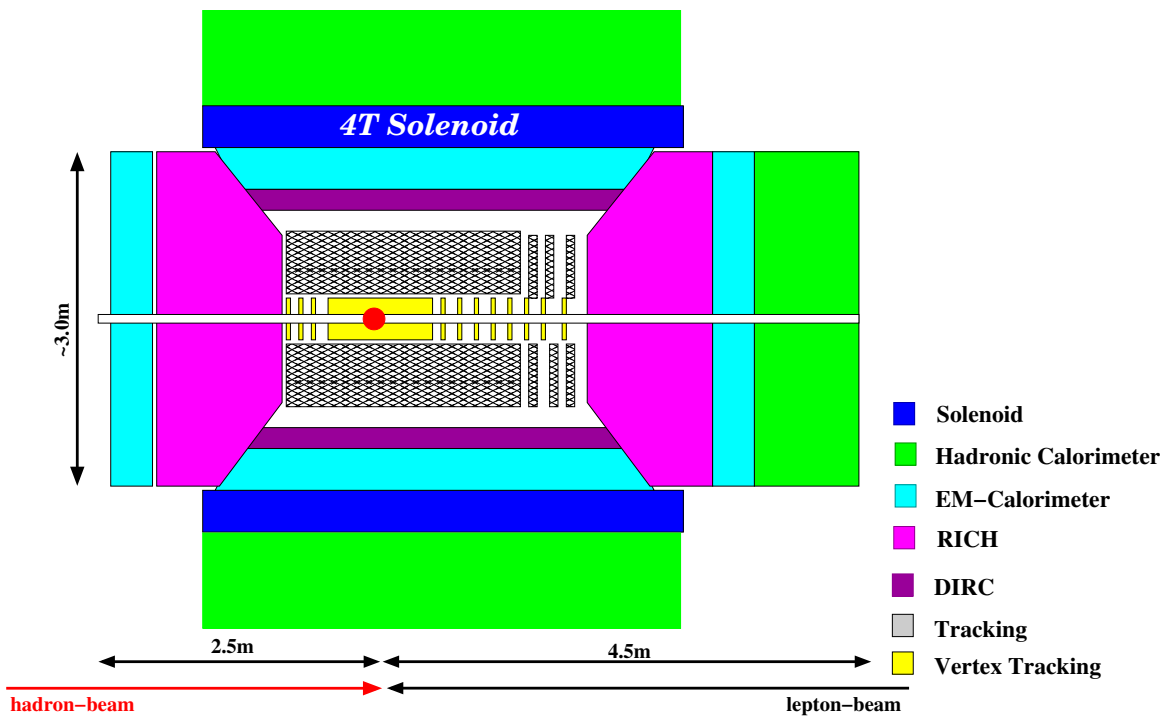


Figure 7: A schematic view of a dedicated EIC detector. Details of the GEANT-3 model can be found at https://wiki.bnl.gov/eic/index.php/Detector_Design.

2.2 Technology Choices for Particle Tracking

It is clear that in order to address the broad range of physics topics at EIC that are described above, it will be necessary to have excellent particle tracking that will provide good momentum and angular resolution over a very wide kinematic range. This will place stringent demands on the tracking system for an EIC detector that will certainly push the limits of the technologies that are currently available. One particular requirement is the need to have very low mass in the tracking system, including the vertex detector, in order to reduce the energy loss of low momentum particles, in particular the scattered electron, which needs to be measured over a wide range of angles. In addition, while the multiplicity in typical ep and eA events is rather low, the total event rate is expected to be quite high ($\sim 300 - 600$ kHz), which imposes additional requirements on the tracking system in terms of rate capabilities.

There has been significant progress in the last decade in the development of Monolithic Active Pixel Sensors (MAPS) in which the active detector, analog signal shaping, and digital conversion take place in a single silicon chip (i.e. on a single substrate) (see [3] and references therein), which provides a unique opportunity for a μ -vertex detector for EIC. These devices are built using CMOS technology with an epitaxial layer as the active sensing element. Ionization deposited in the epitaxial layer is collected by N+ wells embedded in the epitaxial layer. The “pixel” pitch is determined by the location of the N wells, so there is no need for actual segmentation of the detector as is done with traditional hybrid pixel detectors. As a result, CMOS pixel detectors can be built with very high segmentation, limited primarily by the space required for additional shaping and digital conversion elements. The key advantage of CMOS MAPS detectors is the reduced material required for the detector and the (on substrate) on-detector electronics. Such detectors have been fabricated and extensively tested (see e.g. [4]) with thicknesses of about $50 \mu\text{m}$ corresponding to 0.05% of a radiation length. A vertex tracker based on such technology is under construction at STAR. Continued R&D is certainly relevant to a future EIC detector.

Here, we focus on tracking at larger radii and are considering several possible options. One would be several layers of GEM tracking detectors that would surround the intersection region just beyond the vertex detector. For central rapidity, one could consider a cylindrical GEM tracker consisting of 4-6 layers of individual GEM detectors, each with its own readout. While cylindrical GEM detectors have already been constructed [5], these have so far been rather small with readouts only on the ends. For a larger detector as we envision here, with a radius of 1 m or more and a total length of perhaps 2 m or more, and requiring good spatial resolution ($\leq 100 \mu\text{m}$), the number of readout channels becomes very large. This would imply having a highly segmented readout plane for the GEM detectors in order to provide high precision space points at least in the bending (r - ϕ) plane, and placing at least some portion of the readout electronics on the back of the detector, which would add to the mass.

We plan to address these issues in two ways in an R&D program. One would be to explore various options for the readout plane of the GEM detector. One possibility would be to use a so-called strip-pad readout, such as what has been developed for the STAR Forward GEM Tracker [6]. This provides a two dimensional readout on a single layer readout plane, thus reducing the mass, but concentrates the readout on the edges of the plane. While the STAR FGT provides only two coordinates, it may also be possible to provide a third coordinate using this technique, which would help resolve ambiguities within a given readout plane. However, this idea needs further study as to what is possible in terms of fabrication and what level of position resolution can be achieved. Another possibility would be to use a charge sharing readout, such as chevron strips or pads, to reduce the number of readout channels while preserving the position resolution in one direction. Both of these options would have to be addressed using Monte Carlo simulations to study the resolution and occupancy questions, and by building various prototype devices and measuring their performance in the lab and in a test beam.

In addition to studying the different types of readout planes, we would also investigate what options are available for high density, low power readout electronics.

One natural choice would be to use the 128-channel APV25 chip that has been extensively used for many micro-pattern detector applications. A number of groups in this collaboration have experience with this chip and some could make a limited number of these chips available for initial readout systems for the R&D proposed here. The RD51 MPGD collaboration at CERN picked this chip as its first implementation of a front-end chip for the development of a Scalable Readout System (SRS) with modular front-ends. Currently 300 APV25 hybrid boards are in production at CERN with 160 slated for Florida Tech (Figures 8 - 11).

However, it appears that at this point no further chips are available from the original APV25 producer at Imperial College, UK. Other chips that could be used for MPGD readout for this R&D project are the digital VFAT chip from the TOTEM experiment, which is also in short supply, and the analog BEETLE

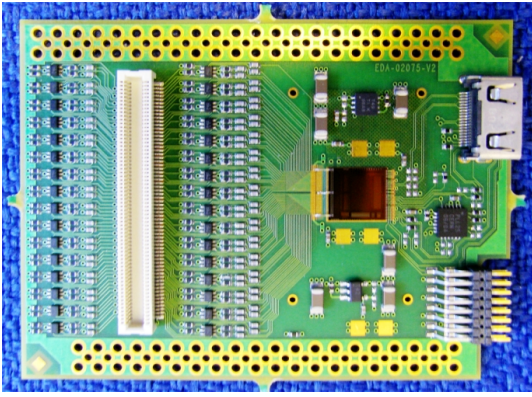


Figure 8: Photo of RD51 SRS frontend hybrid card with diode protection, Panasonic connector (white), and bonded APV25 chip (black).

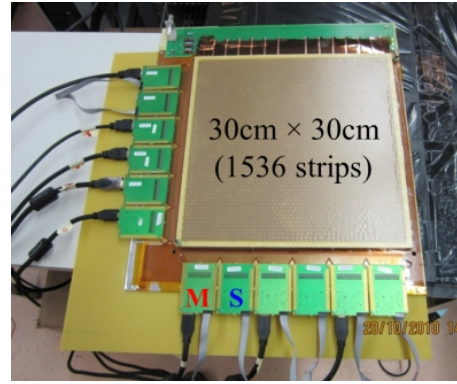


Figure 9: 30 cm \times 30 cm Triple-GEM detector read out by 12 APV25 hybrids. A master (M) and a slave (S) APV hybrid card are indicated.

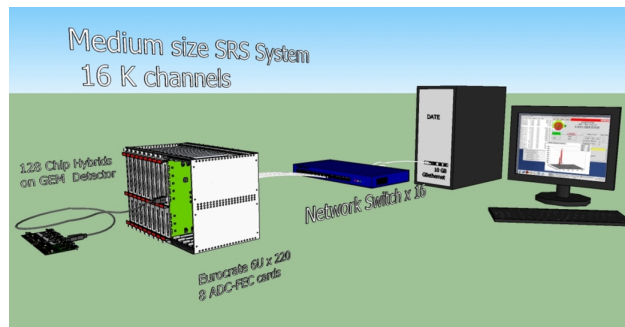


Figure 10: Components of MPGD Scalable Readout System for 16k channels currently under development by CERN and Florida Tech.

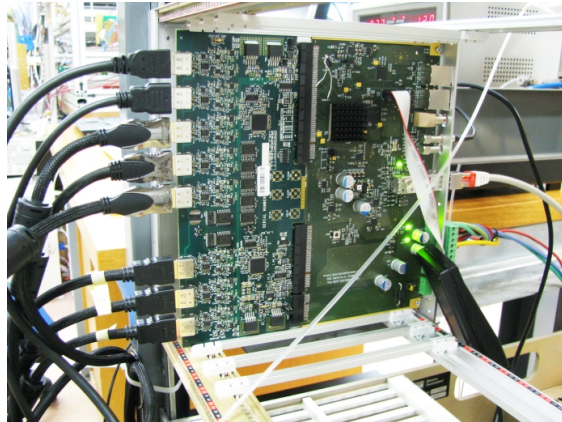


Figure 11: Photo of SRS ADC adapter card (left) with input cables from 12 APV hybrids and Frontend Concentrator card (right) connected via PCIe interface. This combination as shown provides up to 2048 readout channels.

chip, which can provide a fast-OR trigger output. New front-end hybrid boards employing these chips could be developed for the SRS or for other DAQ systems. We will investigate these possibilities as part of this project to identify the best choice of existing readout electronics. On the time scale of EIC, one should certainly also look at the possibility of developing a new ASIC specifically for an EIC detector, which could offer much reduced mass and power consumption. For example, the CMS collaboration at CERN is currently

considering the development of a VFAT 2 chip specifically designed for MPGD readouts to be used at the Super-LHC, which has a similar time scale.

Another option for tracking in the central region would be to have a low mass, fast, and compact TPC. This would give the lowest possible mass for a tracking detector by providing multiple tracking layers in a single gas volume with the readout located only on the ends. In fact, it might be possible to place all of the readout on one end of the detector (e.g., the hadron side), thus reducing the mass on the electron side. It would be a cylindrical device with an inner radius of $\sim 20 - 30$ cm, starting just outside the vertex detector, and could extend radially to perhaps ~ 1 m, and have a length of ~ 2 m. It could employ a fast drift gas such as CF_4 which would allow achieving a drift time ~ 10 cm/ μsec . This would give a total drift time $20 \mu\text{sec}$ for a single ended readout, or $10 \mu\text{sec}$ for a double ended readout. The readout would utilize a micro-pattern detector, such as a GEM or MicroMegas, which would reduce the ion feedback considerably below that of a conventional wire chamber readout TPC. With the rates and multiplicities expected at EIC, it would not appear that this would be a problem in terms of space charge or pileup, but this would have to be investigated by more extensive Monte Carlo simulations. Also, a great deal of R&D on TPCs with micro-pattern detector readouts have been studied by the ILC Collaboration, and we would plan to thoroughly investigate all that they have done and try and collaborate on their efforts wherever possible.

In the forward direction, we would plan to investigate large area GEM tracking detectors, such as those currently being developed at CERN, and with the company Tech Etch that is supplying GEM foils for the FGT. New developments in this area include single sided etched foils at CERN, which have areas approaching 1 m^2 , and large foils produced using glass masks at Tech Etch, with areas $\sim 0.5 \times 0.5 \text{ m}^2$. The investigation of various types of readout planes and new readout electronics being carried out for the central tracker would also be included in this study.

2.3 Triple-GEM R&D Development

Profiting from the expertise by various groups at RHIC in novel tracking detectors based on silicon and triple-GEM technology, a dedicated R&D program of the inner tracking system for a future EIC detector is proposed. The main specifications of such a tracking system are as follows:

- High rate, low dead material, full acceptance and compact tracking system (Radius < 1 m) based on silicon and triple-GEM (cost effective) type tracking detectors
- High multiplicity in forward direction (eA)
- Acceptance at mid-rapidity and very forward / rear rapidity
- High precision inner silicon vertex tracking (heavy flavor production) and planar (forward/rear) and barrel (mid-rapidity) triple-GEM-type tracking system

It is in particular the barrel tracking system at larger radii where further R&D work is needed beyond the development of the technology for the STAR forward tracking upgrade, which uses the triple-GEM technology in a planar arrangement. A prototype barrel layer is planned to be designed employing a larger area-coverage of triple-GEM detectors using light-weight materials and GEM foils in a triple-GEM configuration that are mounted in a curved configuration on a cylinder barrel layer. Engineering work is required on how to mount and assemble such a configuration. If successful this would provide a cost-effective tracking solution at high rate compared to a layout based on silicon detectors only, while maintaining a hit resolution at the level of $80 \mu\text{m}$. Such a layout is also the focus by experiments at the future JPARC facility (Japan) and the DAPHNE facility (Italy). In addition to mechanical design aspects, the design of a 2D readout board and the coupling and choice of a front-end readout chip is a critical design aspect.

The forward and rear rapidity regions require larger areas to be covered. It would therefore be advantages to go beyond the current standard of industrial GEM foil production of $30 \times 30 \text{ cm}^2$ by Tech-Etch. This will likely require a single-mask production procedure. A dedicated effort is essential to develop large GEM foils on an industrial basis.

2.4 Large Area Gas Electron Multiplier Detector Research and Development

GEM trackers are expected to play a central role in EIC tracking systems. However, one limitation of the GEM chambers has been the limited active area; the largest GEM chambers built have been about $1.0 \times 0.45 \text{ m}^2$. This can be a serious issue in the case of EIC, where tracking chambers may have to cover circular

areas up to 4 m in diameter. We are planning to develop, prototype and test a large GEM chamber with an active area of $1 \times 1 \text{ m}^2$.

A cost effective solution for large-area tracking in a high-rate environment is provided by the GEM technology invented by F. Sauli [7] in 1997. The GEM is based on gas avalanche multiplication within small holes (on a scale of $100 \mu\text{m}$), etched in a Kapton foil with a thin layer of copper on both sides. The avalanche is confined in the hole resulting in very fast (about 10-20 ns rise time) signals. Several GEM foils (amplification stages) can be cascaded to achieve high gain and stability in operation. The relatively small transparency of GEM foils reduces the occurrence of secondary avalanches in cascaded GEM chambers. All these properties result in very high rate capabilities of up to 100 MHz per cm^2 and an excellent position resolution of $70 \mu\text{m}$. Figure 13 illustrates the principle of operation of a triple (three foil) GEM chamber. Triple GEM chambers have been successfully used in the COMPASS experiment at CERN for many years now [8].

Preliminary EIC designs call for trackers with outer radii up to 2 m. This area is significantly large compared to the $32 \times 32 \text{ cm}^2$ area of COMPASS GEM chambers. The STAR Front GEM Tracker chamber under construction now will use four chamber quadrants to cover an area with a diameter of about 0.45 m [9]. The main obstacle to larger GEM chambers has been the limitation on the GEM foils sizes; in the past the maximum GEM foil area had been limited to $45 \times 50 \text{ cm}^2$. However, over the last few years the Micro Pattern Gas Detector (MPGD) group at CERN has perfected two techniques to produce large area GEM foils: single mask GEM etching and GEM splicing [10, 11]. The single mask technique allows for the fabrication of foils as large as $45 \times 100 \text{ cm}^2$. The splicing technique allows for two such foils to be combined with only a 3 mm wide dead zone between the two foils. The MPGD group has already succeeded in producing GEM foils as long as 95 cm and as wide as 66 cm. They are confident that they can fabricate GEM foils as large as $100 \times 200 \text{ cm}^2$ within two years using the two new techniques. The large area foils were recently used to construct a prototype GEM detector with an active area of $\sim 0.66 \times 0.66 \text{ m}^2$ at CERN.

We are proposing to construct and test two large prototype GEM chamber with an active areas of $1 \times 0.9 \text{ m}^2$, with new large area GEM foils from CERN. The first chamber will be constructed by combining two $1 \times 0.45 \text{ m}^2$ “chamber modules” with narrow edges, while the second chamber will be constructed using spliced $1 \times 0.9 \text{ m}^2$ GEM foils.

Another challenge with large area tracking chambers is the cost of electronics. The GEM chambers have had readout planes with strips as long as 50 cm with strip pitches of few hundred microns. While such narrow readout pitch allows for high position resolution, it can translate into hundreds of thousands of readout channels for large area detectors. For the detector positions that do not require high position resolutions, like the locations further away from the interaction point, the number of readout channels can be reduced by having longer readout strips, and combining a few adjacent readout strips together. However, the area covered by a combined group of readout strips is limited by the load capacitance that group presents to the readout electronics and the resulting degradation of the signal to noise ratio.

We plan to develop readout planes with increasing strip areas for our prototype detectors to optimize the position resolution, signal to noise ratio and the cost of electronics for large area detectors. Our estimates of capacitance and electronic noise have indicated that GEM chambers will operate well with readout strips as long as 1 m with a strip pitch of 2 mm.

2.5 TPC

A small TPC scenario: A small TPC with an inner/outer diameter of about 30/60 cm and pad readout of about 40 rows based on GEM amplification [7] techniques would provide an internal momentum resolution (with $\sigma_{r\phi} \approx 150 \mu\text{m}$, $L \approx 30 \text{ cm}$, $N \approx 40$) of $\Delta p/p^2 \approx 1\% / 0.7\%$ for $B = 2 \text{ T} / 3 \text{ T}$: It has been shown

Table 1: Momentum resolution for various p_t .

p_t in GeV/c	$\Delta p_t/p_t$ in %	
	B = 2 T	B = 3 T
1	1.0	0.7
10	10.0	6.6
25	25.0	16.6

that a resolution of $\sigma_{r\phi} \approx 150 \mu\text{m}$ or better is realistic with standard pad readout [12]. The momentum

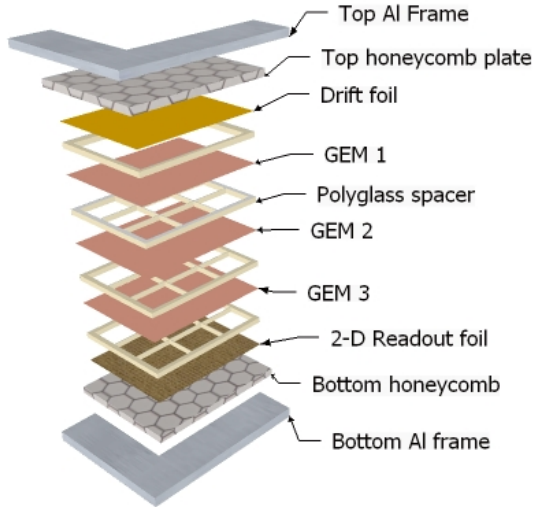


Figure 12: Schematic assembly view of one GEM chamber unit.

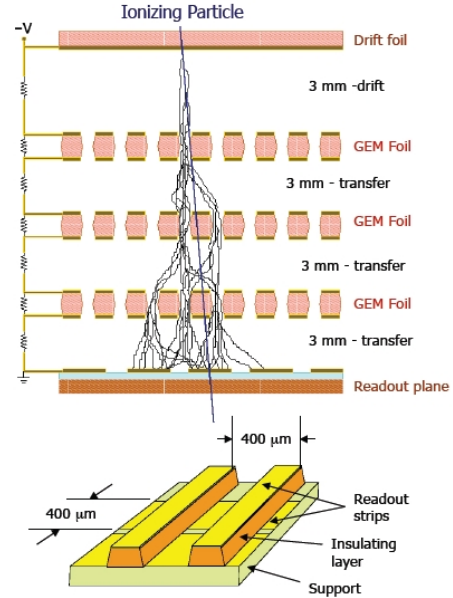


Figure 13: Top: Principle of triple GEM operation; bottom: 3D view of the readout board.

resolution with a TPC can be further improved with higher magnetic fields, better space point resolution, or a larger number of readout pads. A combination of all these features of course will improve the momentum resolution even more. E.g., if the TPC would be having dimensions as described in Section 2.2 the momentum resolution would be $\Delta p/p^2 \approx 2 \times 10^{-3}$.

One could accomplish the improvement of $\sigma_{r\phi}$ and the number of space points by means of smaller pad sizes. One could envisage the usage of the TimePix [13] (Figure 14) readout in order to reduce the pad size to even microscopic dimensions, though keeping the readout electronics at a reasonable level. The TimePix would allow to have a digital readout of the tracks. A hybrid structure, mixed with standard readout pads and equivalent readout electronics at larger radii and TimePix at smaller radii could be a reasonable solution for tackling the problem of measuring tracks with rather low transverse momentum and providing an acceptable number of readout channels. A TPC with MPGD readout will also support the particle identification features of an EIC detector due to its ability of measuring the specific energy loss dE/dx of specific particles traversing the TPC which is used routinely for particle identification in other experiments. Several of us are interested in investigating the possibility to simultaneously read out the Cerenkov radiation of 0-5 GeV electrons traversing the TPC gas as a means to aid the essential separation of (scattered) electrons and hadrons at a phased EIC.

A generic detector R&D program should be followed in order to make use of already existing efforts, facilities, collaborations, etc. A strong effort towards a TPC for an ILC detector is already advanced and the usage of the achievements, modified to the needs for an EIC detector should be undertaken. The results of such an effort would be a generic TPC for an EIC detector based on the outcome of the goals that one need to pursue which are described above. We are expecting to pursue the development of a small scale TPC after a study based on Monte Carlo simulation regarding the feasibility of a TPC as a tracker for an EIC detector. The development of such a TPC would go along with one or more modules which will be serving as readout structures in the end plate of a TPC. The module(s) will be equipped with the different readout electronics options and tested. A fast TPC means that the time to completely read out the track information of an event should be as fast as possible. Dependent on the drift gas to be used in a TPC, drift velocities of up to $10 \text{ cm}/\mu\text{s}$ have been achieved. Typically readout cycles for a proposed EIC-TPC can be as low as $5 \mu\text{s}$. A TPC is an integrating device, however, time stamp information would provide an aid to disentangle events due to the $\sim 75 \text{ ns}$ bunch interaction rate.

2.5.1 TimePix and MIP Sensor

The TimePix serves as the readout for different sensors which are delivering the charge to be processed by the readout. By developing the readout electronics using standard CMOS technology the increase in component density can be fully exploited and advanced signal processing such as energy discrimination and

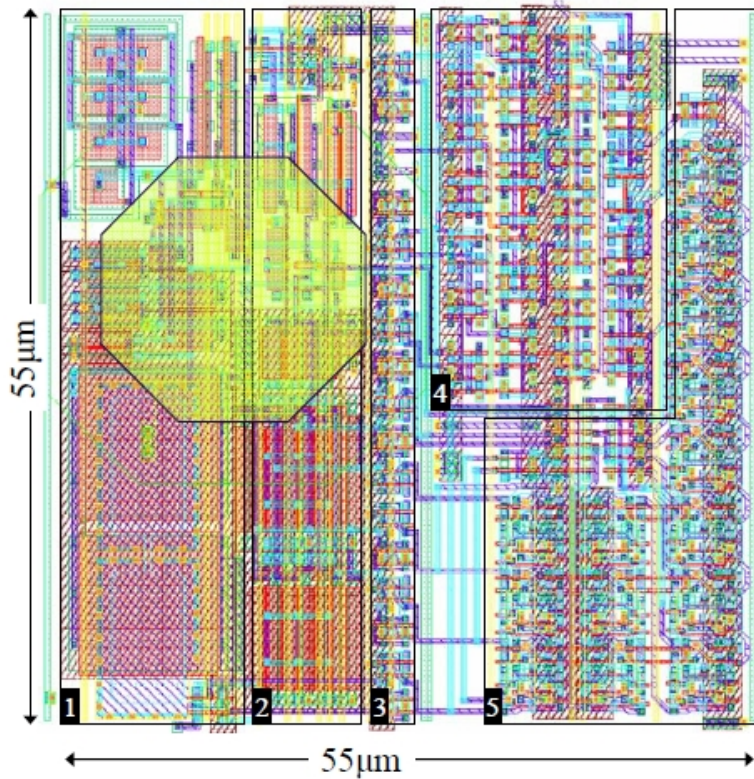


Figure 14: TimePix pixel cell layout: 1) CSA, 2) Discriminator with 4-bit threshold equalization, 3) 8-bit PCR, 4) Ref_Clk buffer and TSL and 5) 14-bit shift register and overflow control.

digitalization can be performed on the pixel level. The pixel itself serves then as a direct anode in a gas amplification structure, having a full chain of readout electronics. Successful tests have shown promising results where it was shown that single electrons could be detected.

An interesting feature might be to investigate the possibility to match the TimePix readout with a gaseous sensor element and a solid state sensor element at one time. One way how to implement this is to place a silicon sensor on top of the the TimePix readout as it is common for a Si-pixel detector. The silicon layer would act as a medium that will be traversed by the minimum ionizing particle (MIP) and delivering a fast and very precise signal to the readout, but spatially restricted to the Si-layer. If one could place on top of the Si-layer a pixelized pad-like structure which would collect the charge from an MPGD device and transferring it to the TimePix readout, thus providing three-dimensional space point information of a TPC track one would make use of one readout system for two independent detectors.

The technical producibility and a possible implementation have to be shown with a feasibility study.

Monte Carlo studies will be performed on the basis of a fast detector simulation. This would ensure the feasibility of a TPC to be used in an EIC detector. Following detector simulation in particular for MPGD readout will show the parameters to be used for a TPC readout module.

Subsequently, a module will be developed that has the basic features as it is expected to have in the EIC detector. GEMs will be the MPGD readout and electronics have to be either developed or acquired from other institutes that are pursuing TPC development.

Several items for a TPC-MPGD readout have to be studied: dimensions, mechanical and electrical stability for low mass approach, gain stability, ion feedback, efficiency, resolution, etc. These studies can be performed within a TPC prototype and under laboratory conditions. Several of these studies have to be performed as new studies compared to studies which have been already performed for TPCs of other experiments. Studies for the TPC have be performed regarding its mechanical, electrical, and thermal properties. The housing of a TPC needs to be having the least mass though the maximum stability. The same applies to an end plate which will be accommodating the readout modules. FEM calculations will be performed and sample pieces have to be built in order to verify the calculations. One option is a single readout-plane TPC which has to be investigated. A common problem for a TPC readout module is the dead area due to supporting

structures for the MPGD planes. The dead areas introduce inefficiencies along the readout-plane and need to be diminished or even vanished. One way to achieve this is to investigate so called bulk-techniques which try to produce the MPGD patterns in one or a few combined production steps. Such techniques have to be developed with electronics-workshops. Another problem of a TPC could be the ion feedback. Ion feedback would create space charge drifting into the main tracking volume where it can disturb the needed electric drift field configuration. The investigation of such phenomena is necessary and in case of severe disturbances one has to find solutions. One solution to ion feedback is to eliminate the charge that is responsible for the build up of the space charge. MPGDs are based on charge amplification, so one would need devices to hold the ions back from drifting into the tracking volume. Here, gating grids have been successful in previous TPCs used as ion traps. However, gating grids have to operated in prohibitively long duration switching mode. Furthermore, wires introduce $\mathbf{E} \times \mathbf{B}$ effects and need quite stiff supporting material which increases the material budget. One option to reduce the ion feedback is to get rid of the charge amplification and make use of electroluminescence [14]. However, this effect has to be studied in detail. One could perform such study with the construction of a GEM based readout module, however, using a VUV readout plane like Multi Pixel Photon Counters (MPPC) [15] or GEM based multiplication modules as have been used for the Hadron Blind Detector (HBD) [16]. The proof of principle of such a device could then initiate the construction and test of a module for a TPC and be tested under lab conditions.

2.6 Particle Identification

As described above, particle identification will be a critical element of the EIC program and perhaps more so than in prior research. The reason for this emphasis is that some of the envisioned reaction kinematics will result in hadron production into the so-called electron direction. As such, the best vision for an EIC detector will have particle identification in all directions. Likely this PID will be of different technology in the forward/backward vs. central regions.

2.6.1 Dual Radiator RICH

The “straw” picture of the EIC detector indicates that forward & backward directions could possible use a dual radiator RICH technology to measure ring radius and hence particle ID. The difficulty in the proposed setup is that one might require large area photon detection in a strong magnetic field.

Experience with the PHENIX HBD, has shown that it is indeed viable to use CsI-coated GEM detectors as a large area and cost effective photon detector. The difficulty is that CsI only has sensitivity in the deep UV ($\lambda < 200 \text{ nm}$) and would thereby be incompatible with all presently known aerogel materials. A possible alternative is to pursue a liquid & gas (rather than an aerogel & gas) combination. Possible candidates would be C_6F_{14} liquid along with C_4F_8O gas. These gases have indices of refraction 1.27 and 1.001389 in the deep UV and would produce Cerenkov angles as indicated in Figure 15. Although the index of refraction of the liquid is higher than typically desired, photo-detection via a gas detector could conceivably provide sufficient position resolution to compensate. Present facilities at Stony Brook have nearly all the necessary equipment to not only evaporate CsI photo cathodes (SBU did all the production of photo cathodes for the PHENIX HBD), but also a prototype box used for the PHENIX RICH detector measurements complete with front-surfaced mirror.

Our deliverable for this project is one or several full, coherent, and well thought out proposals for targeted R&D to be submitted to the second round of EIC R&D efforts.

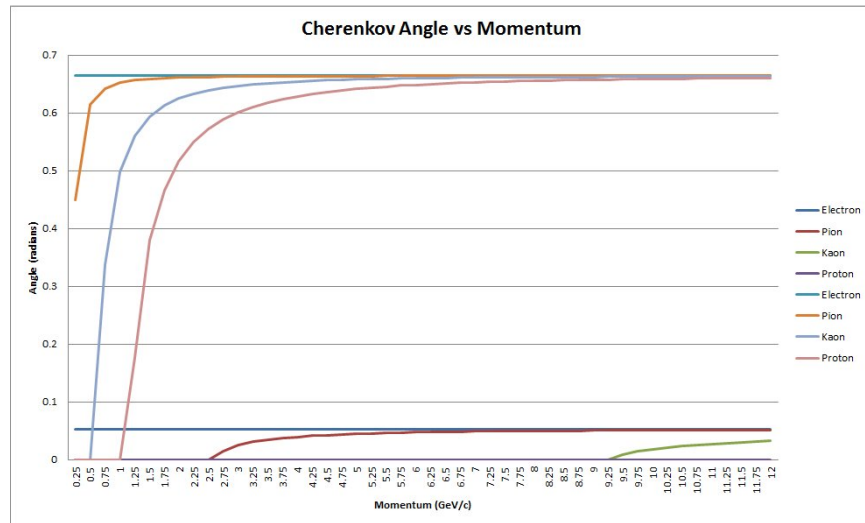


Figure 15: The Cerenkov angle as a function of momentum is calculated for light hadrons. The upper curves result from the liquid radiator and the lower curves result from the gaseous radiator.

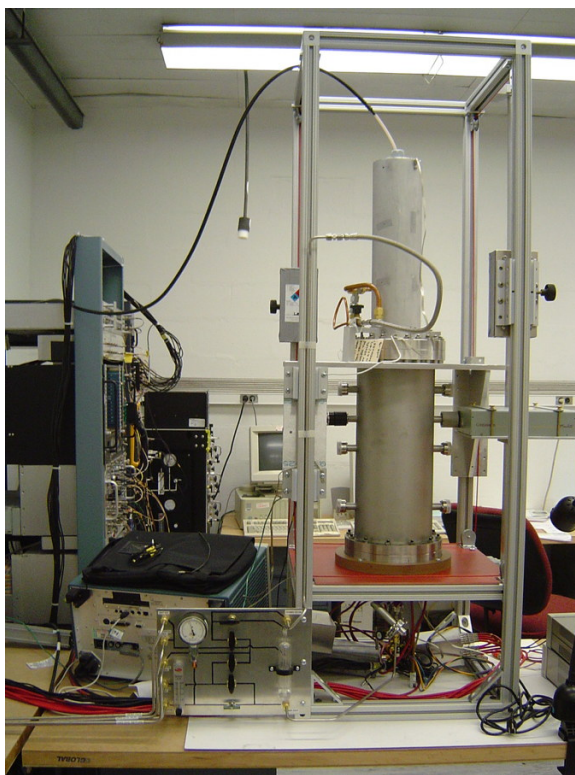


Figure 16: Drift vessel with GEM readout to measure parameters of various gas mixtures at BNL.

3 Description of Resources

The various group expressing interest on this letter are offering a number of resources that can be made use of for pursuing the goals and deliverables as described above.

3.1 Laboratory and Equipment

Brookhaven National Laboratory:

Brookhaven National Lab has considerable experience, expertise and facilities for the development of micro-pattern gas detectors for particle tracking applications, including their associated readout electronics and data acquisition systems. The BNL PHENIX Group was one of the principal groups responsible for the design, construction and operation of the PHENIX Hadron Blind Detector (HBD), which just completed two successful runs at RHIC, collecting data with polarized proton collisions during Run 9 and heavy ion collisions during Run 10. This group constructed the elaborate gas system required for the HBD, along with a gas transmission monitor used to monitor the gas purity to very precise levels, and instrumentation to monitor the quantum efficiency of the detector over several years of running. It also developed, in co-operation with BNL's Instrumentation Division, the preamps and readout boards for the HBD. The BNL PHENIX Group also installed the HBD detector into PHENIX and supported its operation throughout all of its engineering and data taking runs.

The BNL PHENIX group also has a well equipped gas detector lab which was used for making numerous measurements on GEMs related to the HBD, as well as being used to carry out other research on GEM detectors. It was deeply involved with the development of commercially produced GEM foils at the company Tech Etch through its participation in a two phase SBIR in collaboration with Yale and MIT. It also carried out measurements on a fast, compact TPC with a GEM readout in the early stages of R&D for the HBD detector. The lab is equipped with extensive instrumentation for testing GEMs and other micro-pattern detectors, including several complete test setups, gas systems, readout electronics and DAQ systems, a laminar flow hood, and two scanning vacuum ultraviolet spectrometers (Figures 16, 17). BNL's Instrumentation Division also has extensive experience and facilities for micro-pattern detector development, and is a world

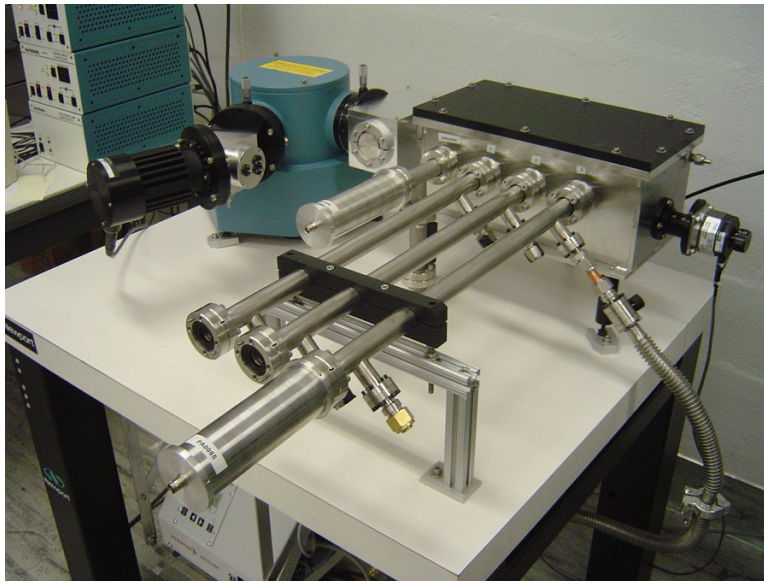


Figure 17: Ultraviolet spectrometer to test and monitor gas purity at BNL.

renowned leader in the development of readout electronics for particle detectors. The Instrumentation Group designed and built the compact TPC for the LEGS Experiment at the NSLS, which utilized a single ended GEM readout with charge sharing readout pads and a custom designed ASIC that was designed by BNL as part of the readout system. They are also currently developing a new ASIC for reading out MicroMegas detectors for the ATLAS Collaboration, and have been involved with numerous other projects to develop micro-pattern detectors and readout electronics for other experiments.

Florida Tech:

The group of Florida Tech can provide the following laboratory and equipment:
Facilities in the Department of Physics and Space Sciences housed in the F.W. Olin Physical Sciences Building (constructed in 2005) on the Florida Tech Campus available for this project:

A. Laboratory

Gaseous-Detector Development Laboratory (600 ft²) with gas system infrastructure, ppm-level gas quality monitoring (O₂ & H₂O), electronic leak hunter, laminar flow hood (12 ft², ~ class 10 clean area), portable dust particle for monitoring clean room air, basic electronic detector readout system with amplifiers and NIM modules, one 10GSample 4-ch LeCroy storage scope (purchased in 2009) with integrated data acquisition and analysis software, four Tektronix 100 MHz 2-ch scopes, two 10cm×10cm modular GEM test detectors (CERN standard GEMs) with 256-ch. 1D and 512-ch 2D readout strips for R&D purposes, prototype of muon tomography station with ten 30cm×30cm Triple-GEM detectors and associated electronics (15,000 ch.), picoammeters for leakage current measurements, variety of scintillation detectors (NaI and plastic scintillators with PMTs) with associated digital DAQ cards for providing cosmic triggers, several computer work stations for data analysis (see below), online data monitoring and offline data analysis software suite AMORE for GEM data taking with Scalable Readout System (CERN).

High-Bay Experimental Hall (3,000 ft², two-storey) with 200 ft² movable tent clean room (~ class 100), infrared heating device for stretching large GEM foils mounted on flat optical table.

Clean Room (80 ft², ~ class 1,000) with gas-tight box for HV testing of medium-size GEMs under nitrogen flow.

B. Computers

High-Performance Linux Cluster serving dual function as Tier-3 site FLTECH on Open Science Grid for CMS experiment and as general data analysis cluster, 180 CPU cores on 23 nodes, at least 2 GB RAM per each core, currently 12 TB of data storage being increased to 84 TB in RAID array (using received ARRA stimulus funding), GEANT4 installation for Monte Carlo simulations. Six medium to high-end PC



Figure 18: Florida Tech high-bay experimental area with 200 ft² clean room (class 100).

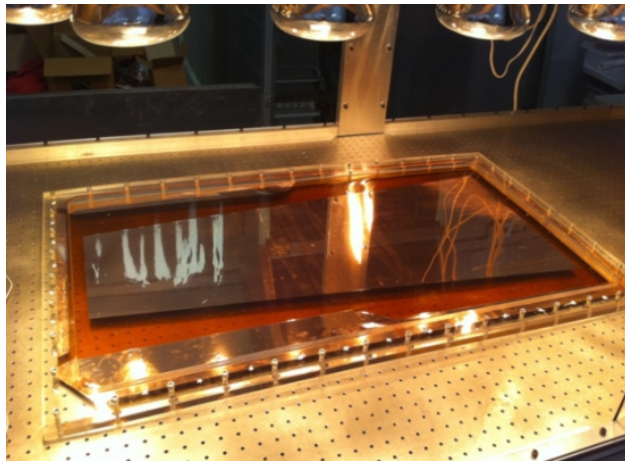


Figure 19: Trapezoidal drift foil of large-area (1 m × 0.45 m) GEM chamber stretched using the infrared heating array installed in the Florida Tech clean room.

Workstations in Gaseous-Detector Development Laboratory with a variety of operating systems (Ubuntu Linux, Scientific Linux CERN, Windows). Three high-end stations feature quad-core CPU (> 3 GHz), 8 GB RAM, 1 TB disk in RAID.

Other Resources on the Florida Tech campus:

University Machine Shop near the Physics and Space Sciences Department (100 yards distance) operated by two full-time professional machinists; standard set of machines and tools including large NC machine. Jobs can be done for reasonable hourly fees (~\$35) or for free if a student project. Students get trained by machinists on use of standard machines in dedicated 3-week training course before beginning work. Many students in the Florida Tech group have completed this course and are certified to machine parts there.

LBL:

In year-1 LBL will take part in simulations, in particular those aimed at a low-mass compact TPC with particle identification capabilities. Adequate compute resources will be made available to do so. The year-1 outcome and other factors will drive out-year participation, availability of other resources and future funding requests. No seed-funds are requested for year-1 through this letter of intent.

MIT:

The following resources have been successfully used for the STAR Forward GEM Tracker project at MIT:

- CCD camera scan set up for optical uniformity scans
- Source scan set up
- Leakage current characterization in nitrogen gas volume
- Two dedicated clean rooms (Class 1000) for test and assembly work

Stony Brook:

The Stony Brook group has a large and well-equipped facility for the production not only of GEM-based detectors, but also of CsI-coated GEM detectors for photosensitive applications. The facility is housed inside a large class 100 clean room 20' tall, 24' wide and 40' long. An end view of this facility is shown in Figure 20. Originally build for the production of the PHENIX drift chambers, this facility was retrofitted and upgraded for PHENIX HBD work. In addition to a very large volume clean room, the facility houses a high vacuum evaporator facility on loan from Franco Garibaldi from INFN. This device is featured in Figures 21. The PHENIX HBD housed 20 active CsI-coated GEMstacks and was operated over a two-year period with no



Figure 20: The Stony Brook University clean room featuring a class 100 tent, class 1 laminar flow table, high vacuum evaporator, and large volume glove box.

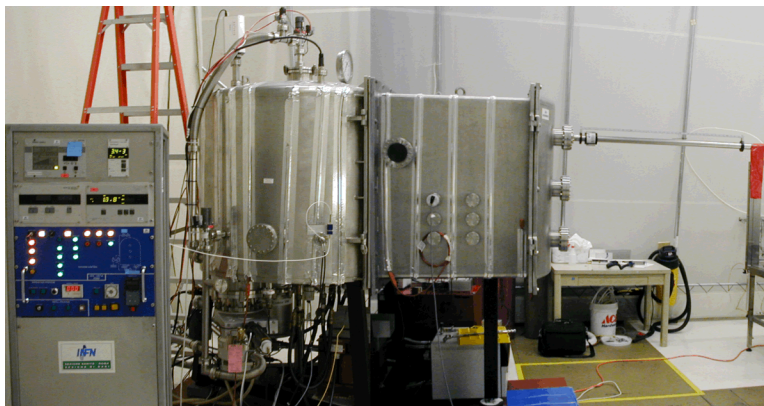


Figure 21: A side view of the evaporator used to make CsI depositions at Stony Brook.

measured loss in quantum-efficiency. CsI GEM technology is a candidate for the EIC RICH detector and could be readily developed in these facilities.

SBU also owns a recirculating gas system capable of 5 lpm recycling flow and a gas chromatograph capable of measuring gas impurities at the ppb level. Finally, the custom-made glove box maintains water and oxygen contamination levels below 10 ppm during detector construction, a vital aspect for GEM handling after their CsI coatings are applied.

The SBU facility is fully capable for both uncoated and coated GEM measurements as well as construction of large scale detectors.

Univ. of Virginia:

- UVA physics Detector development lab: This 10 x 10 m², well equipped nuclear physics detector lab, has been used for the development, construction and testing of many large detector systems. The detector lab consists of a 4 × 4 m², level 10,000 clean room. The Bigbite spectrometer Multi-Wire Drift chambers as well as prototype GEM chambers were constructed in this clean-room.
- GEM readout system based on APV25-S1 electronics: We are currently assembling a state of the art, 2000 channel GEM readout system based on APV25-S1 electronics at UVA. APV25-S1 is a fast pipeline readout chip used for COMPASS GEM trackers, CMS silicon stripe detectors and STAR FGT GEM chambers [17]. We expect to have our readout system fully operational by this June. The capacity of this system is sufficient to readout the the prototype chambers we are proposing here.
- Wiener-Iseg multi-channel High Voltage system The UVA detector group owns a brand new Wiener-Iseg multi-channel High Voltage system that is especially suited to provide high voltage to sensitive tracking chambers. This system currently has 16 channels and can be expanded to 160 channels.
- CODA based Data Acquisition system The detector group owns and operates a complete CODA (Jefferson lab DAQ software) based data acquisition system for prototype GEM chamber readout.
- GEM chamber test stand in Jefferson lab hall A A GEM chamber test-stand, complete with a lead-glass calorimeter trigger, is currently assembled in Jefferson hall A for testing prototype GEM chambers in beam.

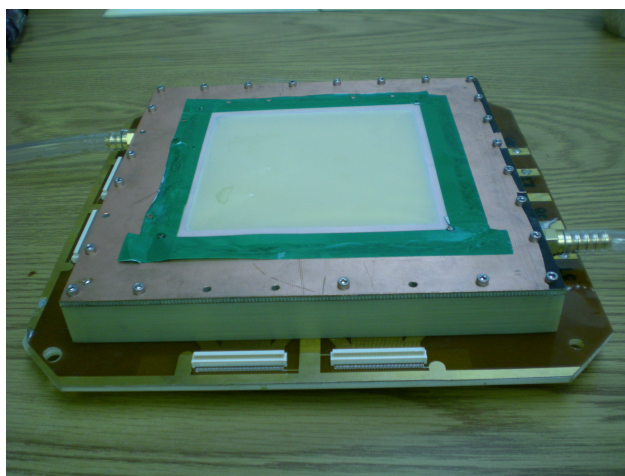


Figure 22: One of the UVA prototype GEM chambers; five such chambers were constructed to build a tracking telescope.

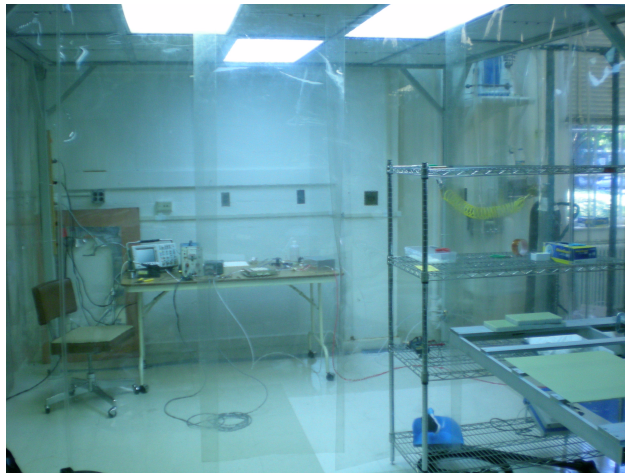


Figure 23: The clean room at the UVa detector development

Yale Univ.:

The group from Yale Univ. can provide the following facilities:

- Laboratory set up specifically for testing and evaluating GEM foils, GEM chambers and GEM readout boards.
- Laminar flow bench for clean work
- Laminar flow hood (2 m x 3 m) for clean assembly area
- General purpose stainless steel test vessel 50 cm deep x 50 cm diameter, with several large ports, two remote manipulators, HV, LV, gas, BNC and multi-pin feed throughs. Can be pumped to vacuum (Figure 24).
- Gas system for supply of multiple gases with pressure, temperature, water and oxygen monitoring.
- Stereo inspection microscope with 60 cm reach
- 3-D coordinate measuring machine with 60 cm x 70 cm scan area, better than $1 \mu\text{m} \times 1 \mu\text{m} \times 5 \mu\text{m}$ resolution (Figure 25).
- Vacuum oven
- Ultrasonic cleaner
- CAMAC based DA system
- Cosmic ray telescope and trigger logic
- Wiener-Iseg High Voltage system.



Figure 24: Yale GEM R&D laboratory showing the general purpose test vessel, gas system and (in the background) clean area with laminar flow bench.

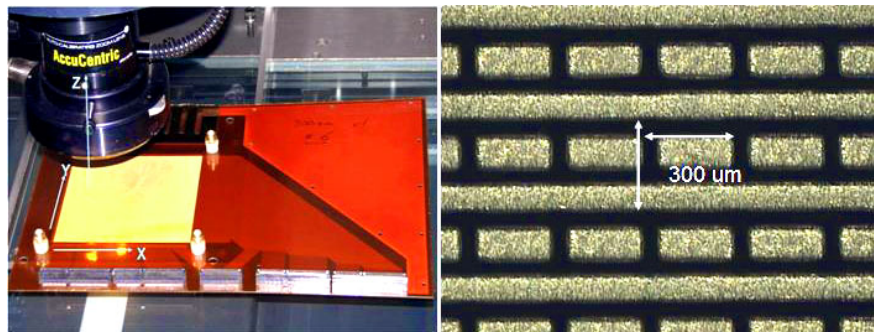


Figure 25: Single layer 2-coordinate GEM readout board with $300\ \mu\text{m}$ pitch manufactured at Tech-Etch. Left panel: Board mounted on optical coordinate measuring machine at Yale. Right panel: image from measuring machine showing pattern. The rectangular pads are connected in columns by vias and routing traces on the opposite side of the board.

4 Funding Request and Budget

As noted above, a variety of simple tests (*e.g.* what are the gas gain limits in for GEM amplification in C_4F_8O , can we devise a 3-coordinate readout scheme on thin 2-layer substrate, etc.) are well within the capabilities of our in-house facilities so long as these facilities are operated using “Seed Grant” funds during the present round of R&D. The budget tables below indicate, institution-by-institution, the costs for our facilities.

4.1 BNL Group Budget Request

Studies for a fast drift TPC

The BNL group would like to carry out some preliminary studies on the use of GEM detectors as a readout for a fast drift TPC. The BNL PHENIX Group and Instrumentation Division already have experience in this area, with the PHENIX Group having studied a fast, compact TPC in the early stages of designing the HBD, and Instrumentation Division having built both the detector and the electronics for the LEGS TPC. In the study proposed here, we would investigate the use of a fast drift gas in such a TPC, such as CF_4 or various mixtures containing CF_4 , and measure some of their basic properties such as drift time, diffusion, etc. In addition, we would investigate various structures for the readout plane, such as charge sharing chevron pads or strips, strip-pad readouts, etc. There is currently equipment in both the Physics Department and Instrumentation Division which could be used for this study, but some modifications and new components would be required, as well as the need to purchase certain expendables such as gas. The budget for this preliminary study is listed below. The BNL group also plans to investigate the design of a cylindrical GEM tracker as a possible upgrade for the PHENIX detector. A separate R&D proposal for this study has been submitted to the PHENIX Collaboration, and this effort would also be relevant as part of a general investigation of possible tracking detectors for EIC as well.

Table 2: BNL Group Budget Request

Item	Cost (\$k)
Materials (GEMs, readout boards, etc)	8
Gas system components	8
Electronic components	5
Expendables (gas)	5
Total	26
Overhead (1.52)	14
Total budget request	40

4.2 Florida Institute of Technology Budget Request

Development of large-area GEM detectors with high spatial resolution but low channel count

To address the trade-off between desired high performance and cost for GEM readouts, the Florida Tech group proposes to develop a medium-size GEM detector that can achieve $\sim 100 \mu\text{m}$ resolution with a readout that features strip pitches of 2 mm or slightly larger. Such an improvement could be achieved by replacing the standard straight parallel strips by zigzag readout strips that provide much stronger correlation between the charge-sharing of adjacent strips and the hit position perpendicular to the main strip direction. This structure allows high-precision position measurement via position interpolation based on the ratio of charges induced on adjacent strips as was shown previously by the BNL group. For a large detector system where high-precision measurement of mainly one readout coordinate is desired, *e.g.* the ϕ -coordinate critical for momentum measurement and track triggering in collider experiments with axial magnetic fields, this would be an attractive option for the readout employed in a GEM detector.

We plan to develop prototypes of printed circuit boards (pcbs) with zigzag and regular parallel readout strips, integrate them into triple-GEM detectors, and compare the resulting detector performances. Initially, we will design small 10 cm \times 10 cm pcbs featuring both zigzag and parallel strip structures similar to the pcbs developed at BNL (Figure 26).

We will integrate a 130-pin Panasonic connector into the design of this pcb so that the strip readout structure

can be readily interfaced to our existing analog APV25 hybrids and to the Scalable Readout System described above. These pcbs will be integrated into standard 10 cm \times 10 cm triple-GEM detectors that we obtained previously from CERN (Figure 27).

An important issue to be addressed for zigzag strip readouts is the increased strip area compared to regular parallel strips and consequently the increased input capacitance that the zigzag strips present to the readout electronics. This has the potential for causing increased electronic noise and cross talk in the readout. We will constructing a medium-size (30 cm \times 30 cm) triple-GEM similar to the Florida Tech detectors described above (Figure 9) but featuring zigzag strips of different lengths up to 30 cm long to investigate this noise issue in detail.

Table 3: Florida Tech Group Budget Request.

Item	Cost (\$k)
10 cm \times 10 cm PCBs with zigzag readout for use in CERN standard GEMs	5
Small Amptek Mini-X X-ray generator for testing under medium rates	7
30 cm \times 30 cm 4 GEM foils and 1 drift foil	5
30 cm \times 30 cm GEM spacer frames with ribs	2
30 cm \times 30 cm PCB with zigzag readout strips	4
Gas (Ar/CO ₂ 80:20)	1
Miscellaneous materials (cables, pipes, etc.)	1
Overhead (1.48 on gas and materials only)	1
Total budget request	26

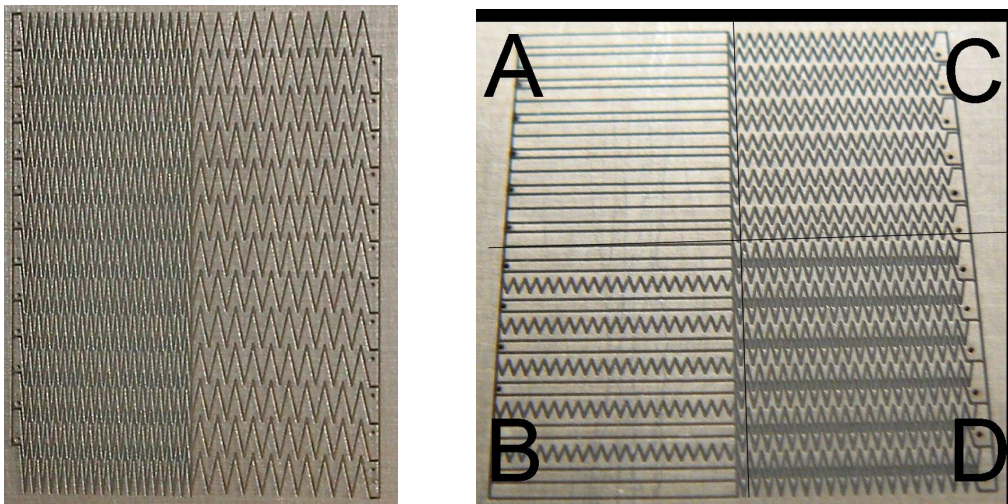


Figure 26: Small printed circuit boards previously developed at BNL for prototyping different zigzag GEM readout structures in section A-D.

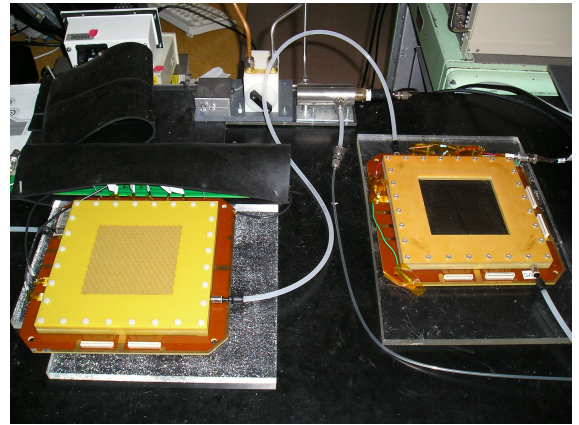
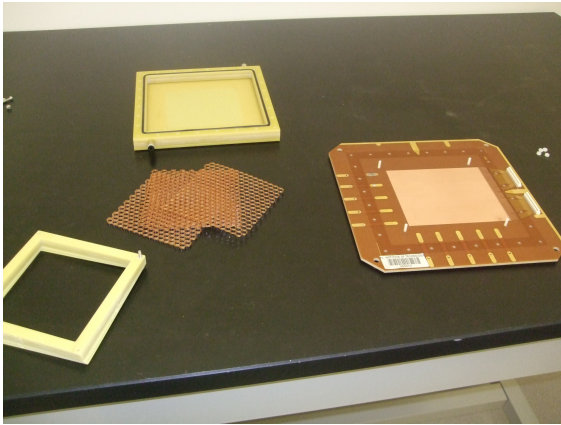


Figure 27: Components of $10\text{ cm} \times 10\text{ cm}$ standard CERN modular triple-GEM detectors with $400\text{ }\mu\text{m}$ -pitch strip readout pcb (left) and two such detectors assembled at Florida Tech (right).

4.3 Stony Brook University Budget Request

Development of CsI Readout for a Double-Index RICH

The facilities at SBU are uniquely suitable for investigating the feasibility and performance of a RICH made from dual indices of refraction using UV-transparent materials coupled to a CsI-coated GEM detector. We have demonstrated and tested capabilities for the production of high quality CsI photo-cathodes, beam test equipment from the R&D studies of the PHENIX RICH, as well as a sophisticated recirculating gas system, and gas chromatograph for monitoring gas purity at trace levels. Candidate RICH liquids include C_6F_{14} and candidate RICH gasses include C_4F_8O . As shown in Figure 15, these would provide adequate particle separation if a sufficiently high ring radius resolution is achieved.

The existing beam test apparatus mimics the full PHENIX RICH mirror (4 meter radius, 2 meter focal length) and focal plane, each consisting of a $\sim 20 \times 20 \text{ cm}^2$ area. The mirror section and focal plane are located on articulating mechanical feedthroughs that allow the system to be adapted to be similar to an EIC forward(backward) arm. The area of this focal plane is well-matched to the foil sizes from the PHENIX HBD.

Research and development topics include:

- Obtaining stable gain sufficient for single photo-electron measurements from the gaseous radiator choice.
- Optimization of photo-electron yield from liquid radiator vs. the material budget.
- Readout segmentation sufficient to provide adequate ring-radius resolution.
- Optimization of the readout plane segmentation (ring patterns are NOT random and could be troublesome with strip-pad readouts as described below).
- Materials investigation for all elements to maintain gas transparency in the deep UV.

Below is a budget necessary to carry out these studies:

Table 4: Stony Brook University Budget Request

Item	Cost (\$k)
Custom made GEM foils matching focal plane area	10
Readout PCB	4
Electronics & DAQ	10
Liquid radiator	6
Sum	30
Overhead (1.52)	15.6
Overall request	45.6

4.4 Univ. of Virginia Budget Request

Construction and test of large prototype GEM chambers

The UVa group would like to construct and test two large prototype GEM chamber with active areas of $1 \times 0.9 \text{ m}^2$, with new large area GEM foils from CERN. The first chamber will be constructed by combining two $1 \times 0.45 \text{ m}^2$ “chamber modules” with narrow edges, while the second chamber will be constructed using spliced $1 \times 0.9 \text{ m}^2$ GEM foils.

Several large readout planes with increasing strip areas will be tested with these prototype detectors to optimize the position resolution, signal to noise ratio and the cost of electronics for large area detectors.

Table 5: UVa Group Budget Request.

Item	Cost (\$k)
GEM foils	20
Readout planes	10
Chamber planes and mechanics	10
GEM chamber supplies	5
Undergraduate student	5
Total	50

4.5 Yale Univ. Budget Request

Development of 3-coordinate single plane readout for GEM chambers

Low mass high resolution tracking detectors are a key element of an EIC detector. As discussed above, GEM technology can be used to provide low mass detectors with measurement precision below $100 \mu\text{m}$. The GEM readout board will be in the active area so it is desirable to minimize the mass of this structure. Previous R&D at Yale in collaboration with Tech-Etch [19] has shown that a single plane 2-coordinate readout structure with a pitch as small as $\sim 300 \mu\text{m}$ can be fabricated by Tech-Etch. This technology allows the readout plane to be as thin as a GEM foil. In a multi-particle environment, 2-coordinate readout suffers from ambiguities in matching the hits between the two coordinates. Ambiguities can be avoided by reducing the chamber size to the point where multiple hits are unlikely and using many chambers to tile the required area. This will result in having to put some readout electronics in the active area and possibly structural elements as well, thereby increasing the mass in the acceptance of the detector. For 2-coordinate GEM readout the electron cloud impinging on the readout structure is shared between the two coordinates so pulse height matching can be used to aid in resolving the ambiguities to some extent. The traditional way to eliminate ambiguities in hit matching is to add one or more additional coordinates so hit matching is required in at least 3 coordinates. Having a third coordinate plus pulse height matching for single plane GEM readout structures will make possible a thin readout structure with readout electronics at the edges and overall size limited only by manufacturing capability and ultimately by the capacitance of a single readout channel. Based on the development of single plane 2-coordinate readout with Tech-Etch we know that 2-coordinate structures with pitches down to $300 \mu\text{m}$ can be produced (approximately 3mil trace/space). This small pitch is currently at the limit of capability and would require some further development to have a good yield. With 3mil trace/space one can have a 3-coordinate single plane structure with $\sim 600 \mu\text{m}$ pitch. We know from beam tests [20] that a 2-coordinate chamber with $600 \mu\text{m}$ pitch gives $\sim 70 \mu\text{m}$ resolution for normal incidence. We propose a program to build and test at least two versions of a 3-coordinate readout board. One version will have $800 \mu\text{m}$ pitch which should fit easily into the current fabrication capabilities and have high yield. A second version would have $600 \mu\text{m}$ pitch which with current technology will be challenging and may have low yield and require further development. We propose to carry out the following program to evaluate and optimize these readout boards that will include the following tasks:

1. Design small ($10 \text{ cm} \times 10 \text{ cm}$) read out boards with two pitches as listed above 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.

We expect the first 4 tasks can be carried out in the first year of the program. Scheduling and operating in a test beam will likely occur in the second year. The budget shown in Table 6 is the expected first year incremental costs to support this activity.

Table 6: Yale Univ. Budget Request.

Item	Cost (\$k)
1. GEM Chamber	
1.1 GEM foils	5
1.2 Mechanical (frames, gas enclosure, HV distribution board)	3
2. Readout Board	
2.1 NRE for 2 versions	2.5
2.2 Boards (6 of ea. Version)	5.4
3. Readout Electronics	
3.1 APV Readout system	17
3.2 Interface and DAQ	6
4. Operating	
4.1 Gas	1
Total budget request	39.9

4.6 Budget Request Summary

We propose to request seed grant funds for the participating groups as described in Sections 4.1-4.5 with a total of \$ 201,500. This will allow the groups to start with their programs in order to establish the above described proposed tasks and coming up with well defined proposals for the second round of R&D.

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