EIC Detector R&D Progress Report

The EIC Tracking and PID Consortium
(eRD6 Consortium)

June 29, 2018

The Consortium

Project ID: eRD6

Project Name: Tracking & PID detector R&D towards an EIC detector

Period Reported: from January 2018 to June 2018

Project Leader:

Brookhaven National Lab (BNL): Craig Woody

Florida Institute of Technology (FIT): Marcus Hohlmann

INFN Trieste: Silvia Dalla Torre

Stony Brook University (SBU): Klaus Dehmelt, Thomas Hemmick

University of Virginia (UVa): Kondo Gnanvo, Nilanga Liyanage

Yale University: Richard Majka, Nikolai Smirnov

Project Members:

BNL: B. Azmoun, A. Kiselev, M. L. Purschke, C. Woody

BNL - Medium Energy Group: E. C. Aschenauer

FIT: M. Bomberger, M. Hohlmann

INFN Trieste: S. Dalla Torre, S. Levorato, F. Tessarotto

SBU: K. Dehmelt, A. Deshpande. N. Feege, P. Garg, T. K. Hemmick

UVa: K. Gnanvo, M. Dao, H. Nguyen, N. Liyanage, J. Matter, A. Rathnayake

Yale University: R. Majka, N. Smirnov

Contact Person: Kondo Gnanvo; kgnanvo@virginia.edu

Contents

1 Past

1.1 Brief overview of project histories

1.1.1 Brookhaven National Lab

The group at BNL is mainly engaged in optimizing micro-pattern gaseous detectors (MPGD's) for reading out a time projection chamber (TPC) for use at the EIC.

Over the last few years we have built and tested numerous planar GEM detectors with long (~16mm) and short (~3mm) drift regions and have equipped them with both zigzag pad and strip readout geometries in an effort to study the spatial and angular resolution of a host of detector configurations. Following detailed studies of these detectors in the lab, beam tests were also carried out in 2012 and 2104 at Fermilab to fully characterize the performance of GEM detectors with extended drift gaps under beam conditions. The results of these efforts were published in a peer reviewed journal in 2014[1].

In addition, in collaboration with Stony Brook U. and Yale U., we have built a prototype combination TPC-Cherenkov (TPCC) detector to study the feasibility of performing tracking and pID measurements in a common detector volume. The detector was filled with a specially chosen gas to be used as both the Cherenkov radiator and the TPC working gas. After investigating important characteristics such as the drift velocity and the charge spread in various candidate gases, a beam test was conducted to demonstrate a proof of principle of the viability of this detector concept. The results from these tests were positive and are detailed in a recently completed manuscript that will be submitted very shortly to a peer review journal (IEEE TNS) for publication. (Preliminary results from the TPCC have also already been presented at several conferences and have appeared in various conference proceedings[2].)

More recently we have focused on optimizing the design of the readout plane for a GEM detector made of zigzag shaped charge collecting anodes. We initially performed simulations to study the zigzag geometry, followed by a systematic set of measurements in the lab to reveal which geometrical parameters drive the performance of the readout. The results of these investigations were recently published in a peer review journal [3], with collaborators from Florida Tech and Stony Brook U. We have continued to refine the design of the zigzag readout by pushing the design parameters beyond what could be produced using standard chemical etching processes. A novel laser etching technique was used to generate PCB's with zigzag pad geometries with significantly finer features that more closely resemble idealized patterns determined by simulation. These new PCB's were also tested in the lab and very recently at a beam test at FNAL. A summary of these investigations was recently submitted to the 2018 IEEE NSS conference for consideration.

Now that our work with optimizing the zigzag pads is complete, our focus is primarily aimed at investigating various avalanche technologies for a TPC readout including GEM's, Micromegas, a combinations of the two, and μRWELL.

1.1.2 Florida Tech

The Florida Tech group has been focusing on the development of large low-mass GEM detectors with low channel count for the forward tracker (FT) of the EIC detector. In the next funding cycle the group will begin shifting focus towards R&D on cylindrical μRWELL detectors for a fast central tracker at an EIC detector.

We designed and implemented radial zigzag strips on large readout PCBs to achieve low-channel count while maintaining good spatial resolution. We constructed a first one-meter-long prototype with such a readout at Florida Tech using a purely mechanical construction technique without any gluing and tested it in beams at Fermilab in 2013. This study showed a non-linearity in the position measurement of hits[4]. The reason was an over-etching of tips and under-etching of troughs in the zigzag strips, which caused insufficient interleaving of adjacent strips and consequently insufficient charge sharing among strips. We adjusted the zigzag strip design to improve the strip interleaving. Small PCBs and a flex-foil with the improved zigzag strip design were produced by industry and by CERN, respectively. We subsequently tested these with highly collimated X-rays at BNL. A substantial reduction in the non-linearity and an improvement in spatial resolution were observed[5].

Next, we designed a second large Triple-GEM detector that implements the drift electrode and a readout electrode with improved radial zigzag strips on polyimide foils rather than on PCBs to reduce the material in the active detector area[6]. These foils were then produced by CERN. To provide sufficient rigidity to this new detector while maintaining low mass, we produced the main support frames from carbon fiber material. We designed the GEM foils for this second detector in such a way that they can also be used for the second UVa FT prototype and for the eRD3 FT prototype being designed by Temple University ("common GEM foil design"). A number of these GEM foil were produced for Florida Tech and UVa by the CERN workshop using the single-mask foil etching technique. We recently successfully assembled this second prototype. A beam test at Fermilab is currently ongoing to measure its performance.

1.1.3 INFN Trieste

The task of the INFN participants to the eRD6 Consortium is "Further development of hybrid MPGDs for single photon detection synergistic to TPC read-out sensors".

Particle identification of electrons and hadrons over a wide momentum range is a key ingredient for the physics programme at EIC. One of the most challenging aspects is hadron identification at high momenta, namely above 6-8 GeV/c, where the only possibility is the use of Cherenkov imaging techniques with gaseous radiator. The overall constrains of the experimental set-ups at a collider impose a limited RICH detector length and to operate in magnetic fringing field. The use, for this RICH, of gaseous photon detectors is one of the most likely choice. The goal of our project is an R&D to further develop MPGD-based single photon detectors in order to establish one of the key components of the RICH for high momentum hadrons. This R&D has also some aspects synergistic to the development of TPC sensors: the miniaturization of the read-out elements and the reduction of the Ions Back-Flow (IBF).

The starting point are the hybrid MPGD detectors of single photons developed for the upgrade of the gaseous RICH counter [7, 8, 9, 10] of the COMPASS experiment [11, 12] at CERN SPS. These detectors are the result of several years of dedicated R&D [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31]. They consists in three multiplication stages: two THick GEMs (THGEM) layers, the first one coated with a CsI film and acting as photocathode, followed by a resistive MicroMegas (MM) multiplication stage. The COMPASS photon detectors can operate at gains of at least 3×10^4 and exhibit an IBF rate lower than 5% [30, 32, 33, 34]. An original element of the hybrid MPGD photon detector is the approach to a resistive MM by discrete elements: the anode pads facing the micromesh are individually equipped with large-value resistors and the HV is provided, via these resistors, to the anode electrodes, while the micromesh is grounded. A second set of electrodes (pads parallel to the first ones) are embedded in the anode PCB: the signal is transferred by capacitive coupling to these electrodes, which are connected to the front-end read-out electronics.

The whole R&D project develops over several years and it includes further improvements of the hybrid MPGD-based photon detectors in order to match the requirements of high momenta hadron identification at EIC and initial tests relative to the application in gaseous detectors of a novel photocathode concept, based on NanoDiamond (ND) particles [35].

1.1.4 Stony Brook University

SBU is concentrating on the study of Ion Backflow (IBF) for a TPC, a possible candidate for the central tracker in at least one of the EIC detectors for an EIC. Furthermore, the TPC for sPHENIX has the same physical size when used in, e.g., the BeAST EIC detector.

It has been shown that IBF will pose a problem in an EIC detector and that the ultimate EIC TPC device must do more than sPHENIX to achieve the same level of position distortion. Our approach is to investigate new structures in and around the multiplication stage that promise significant better performance when considering IBF.

SBU also is working on the final installation of a unit that allows to produce high quality large size mirrors for RICH applications. The project is ongoing and expected to be finalized in about two months.

1.1.5 University of Virginia

The focus of the group at UVa is the development of high performance, large and low mass GEM detector for the forward region of an EIC detector.

Our R&D at UVa shares some similarities with the development by the Florida Tech group and by Temple U. group within the eRD3 program but we are specifically focused on the development of high performance, large area two dimensional U-V strip readout with fine pitch to provide excellent spatial resolution in both radial and azimuthal direction. A first prototype of such detector was built and successfully tested at the Fermilab Test Beam Facility (FTBF) in 2013. The analysis of the test beam data fully validated the expected performances of the U-V strip readout and the results were published in [36].

We are going through the second phase of the R&D with a design improvement of the U-V strip readout to push even further the spatial resolution capabilities in both dimensions. The new prototype is conceived around the "Common EIC GEM foil design" jointly developed by UVa, Florida Tech groups of the eRD6 consortium and in collaboration with Temple University eRD3 group. We have also been testing new ideas such as the ultra low mass Chromium GEM foil to reduce even further the material budget of EIC-FT GEM detectors and the development of the double-sided zebra connection scheme to provide an elegant solution for the fine pitch U-V strip readout layer. These innovative ideas will ultimately be integrated in the final design of the large area EIC forward GEM trackers.

We have successfully completed the assembly of the second prototype based on the common GEM foil and are currently testing at the FTBF for performance studies.

1.2 What was planned for this period?

1.2.1 Brookhaven National Lab

1. ***Zigzag pad development***: We planned to continue the development and optimization of zigzag pad geometries of readout planes for GEM detectors. In particular, we planned to design zigzag pads with greater pad overlap and smaller pad-to-pad gaps, which according to our simulation results should exhibit improved performance over our older designs. We then intended to use these designs to fabricate new zigzag PCB's by employing a laser ablation process capable of generating very high precision electrode structures on the PCB substrate. Following the production of the PCB's we planned to measure the position resolution of several variants of the optimized zigzag geometry in the lab using our x-ray scanner.

2. ***Beam Test with multi-zigzag PCB***: We planned to test a planar GEM detector equipped with the same new readout PCB's comprising an array of different zigzag patterns at the Fermilab test beam facility (FTBF). As each set of pads with a unique zigzag geometry is exposed to the primary 120GeV proton beam at the FTBF, we hoped to gauge the performance of each pattern with the goal of ultimately identifying the optimum zigzag parameters for a particular GEM detector configuration.

3. ***Measurements with GEM-based cosmic ray telescope***: We planned to complete the assembly and commissioning of a GEM based cosmic ray telescope. The telescope consists of four triple GEM detector layers, each outfitted with a COMPASS style readout board consisting of XY strips. The

telescope should be capable of reconstructing reference particle tracks to relatively high precision such that it may be used to obtain a realistic measure of the position resolution for most of the detectors we plan to study within a lab setting. This is in contrast to the position resolution measured with our x-ray scanner, which only allows a measure of the resolution using discrete clusters of charge produced by x-ray conversions within the detector gas.

4. ***GEM Studies using TPC gas mixtures in a compact TPC prototype***: We planned to complete the assembly of a new compact TPC enclosure to house a pre-existing 10cm x 10cm x 10cm field cage used for the TPCC studies mentioned above. The new TPC will be read out with either one of our optimized zigzag PCB's or another suitable readout plane, and will utilize a quadruple GEM stack, or Micromegas detector, or some combination of the two. Each detector variant will be tested to find an optimal readout configuration for maximizing detector performance. In addition, the TPC may be used in conjunction with the cosmic ray telescope to study the reconstruction of particle tracks using different gases and operating parameters, including studying charge spread due to diffusion, space charge effects, attachment in the gas, among other gas characteristics.

1.2.2 Florida Tech

Forward Tracker Prototype: Our main goal for the past six months was to assemble the new large, low-mass FT GEM detector with zigzag readout and to put it through a battery of quality control tests. We planned to work closely with the BNL and UVa groups to prepare for a joint forward tracker beam test at the Fermilab test beam facility in June/July 2018. We also hoped to procure a small (10×10 cm^2) resistive micro-well detector from CERN during the next period to begin some basic R&D on this detector technology for fast tracking in the barrel region of the EIC detector.

EIC Simulations: An undergraduate student, Matt Bomberger, was to begin work on EIC simulations for investigating the impact that material budgets in the forward and backward regions will have on the overall EIC detector performance. In the reporting period he was to familiarize himself with the EICroot simulation framework. We planned to send Matt to BNL in May or June to spend some time working directly with EICRoot expert Alexander Kiselev.

1.2.3 INFN Trieste

Activity planned in period January 2018 - June 2018

Two R&D items were foreseen in this period:

1. The laboratory studies of the novel prototype of **single photon detector by MPGD technologies with miniaturized pad-size** and the realization of a set-up adequate for test beam studies, to be performed in Autumn 2018;
2. The initial studies to understand the compatibility of an **innovative photocathode based on NanoDiamond (ND) particles** with the operation in gaseous detectors and, in particular, in MPGD-based photon detectors.

2018 milestones:

- September 2018: The completion of the laboratory characterization of the photon detector with miniaturized pad-size.
- September 2018: The performance of the tests to establish the compatibility of the ND photocathodes with the operation of MPGD-based photon detectors.

1.2.4 Stony Brook University

It was planned to continue installation of an electron-ion beam system into the evaporator at SBU.

We were also planning to start up the IBF measurements and test the performance of a TPC prototype in a test-beam campaign.

1.2.5 University of Virginia

The main goals for the current cycle are:

1. **Assembly of the large area low mass EIC-FT-GEM:** Complete the assembly of EIC-FT-GEM prototype with the new U-V strips readout pattern and double-sided zebra connection scheme and to characterize its performance in our detector lab with cosmics, x-ray and Sr^{90} sources. We then planned to test the chamber in the in high energy proton beam (120 GeV) at the Fermilab Test Beam Facility (FTBF) jointly with the parallel effort by Florida Tech and Temple U in summer 2018.
2. **Chromium GEM (Cr-GEM) studies:** Continue the performance study of Cr-GEM with our existing prototype and draft a paper of the results for peer-reviewed publication in NIMA or TNS journal.
3. **Basics R&D on μRWELL detector technology:** Acquire a small μRWELL detector with 2D COMPASS-like readout from CERN and perform some basic R&D on this new technology that we view as a strong candidate for the fast tracking device in the barrel region of the EIC detector.
4. **Monte Carlo simulations:** Study the impact of low mass triple GEM material budget on the performance of the EIC detector, specially in far forward region where the ultra light Cr-GEM detector could be used to complement the MAPS technology and to provide fast tracking information. We identified one graduate student, committed to participate to the EIC R&D effort and work on simulations, with the assistance of Alexander Kiselev from the BNL group.

Below was the milestone regarding the construction and characterization in test beam of UVa large forward tracker GEM prototype.

2018 milestones:

- March - April 2018: Assembly of EIC-FT GEM prototype
- May - June 2018: Performance tests with Cosmic, X-rays, Sr^{90} sources
- July 2018: Beam test at Fermilab

1.3 What was achieved?

1.3.1 Brookhaven National Lab

1. ***Zigzag pad development***: Over the past several months we have procured several readout PCB's, each containing multiple versions of an optimized zigzag pattern for testing in the lab and in a beam test. The zigzag patterns were generated using a laser ablation process which has made it possible to carve out zigzag shaped electrodes with fine design parameters never tested before. In this process, a pulsed laser beam with a carefully tuned power setting is precisely translated across the PCB substrate to cut a gap between adjoining electrodes to define the zigzag shape. A gap width of about 20μm was achieved on average, well below the standard ~75μm gap width of standard chemical etching. This in

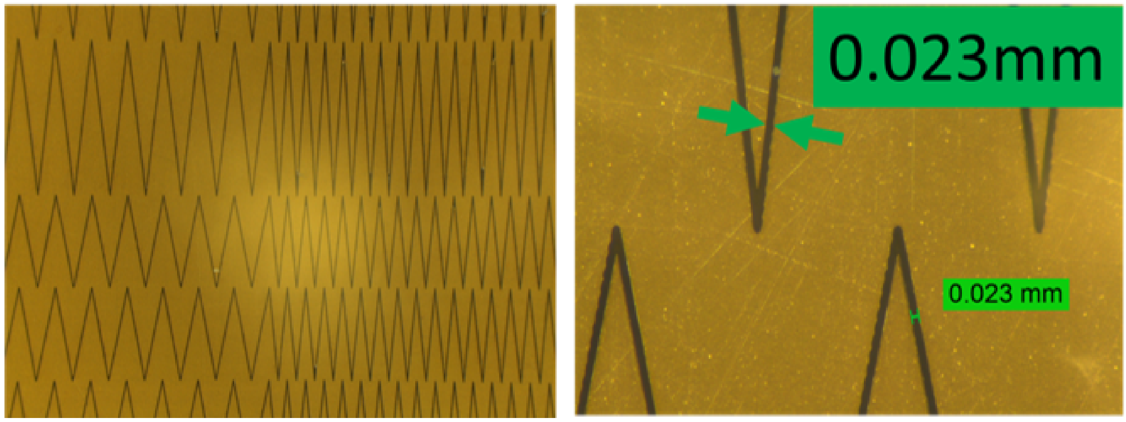

Figure 1: Microscope photos of the multi-zigzag patterns of the tested readout PCB. The right photo shows the measured gap spacing between neighboring electrodes to be 23μm.

turn has allowed the interleaving (i.e., the amount by which neighboring zigzags overlap) to increase from roughly 80% in previously tested boards to more than 90% while maintaining the percent coverage of copper on the PCB surface at the level of 90% or more, both of which are critical parameters in terms of the quality of charge sharing on the readout.

Fig. 1 shows zoomed in microscope photos of the zigzags on one of the PCB's. The different zigzag geometries are arranged in an array of 100 1cm x 1cm regions each filled with 2 to15 zigzag strips of a unique zigzag geometry. The gap width between adjacent strips is fixed at the minimum attainable width mentioned above for the entire board and the strip pitch ranges from 0.4 to 3.33mm, with a zigzag periodicity ranging from 330 to 1000μm.

The PCB's were generated by two different PCB manufacturers, TTM (USA), and Elvia (France) with similar fabrication results, although the Elvia boards tended to have consistently narrower gaps (˜18μm), compared to TTM (˜23μm). Though these boards showed a significant improvement in design reproducibility over previously manufactured boards using chemical etching, on average about 20-30% of all strips were shorted to neighboring ones, which is something we have not experienced with chemical etching. At the moment it is not immediately obvious how the majority of these shorts develop, however in some cases the tips of the zigzag have been seen to delaminate and fold over, bridging two electrodes to one another. We are currently working to further understand how these shorts develop and devise strategies for avoiding them. Thankfully, a substantial portion of the readout for some of the boards was unharmed and allowed a useful range of zigzag patterns to be tested.

Each readout board tested was coupled to a quadruple GEM detector operated in ArCO2 (70/30) at a gain of several thousand, with 1kV/cm and 3kV/cm applied to the drift and transfer gaps respectively. Some very preliminary results from a partial x-ray scan performed in the lab are shown in Fig. 2 for a PCB manufactured at Elvia and are compared to earlier results from PCB's produced using chemical etching. In addition, the table in Fig. 3 tabulates the design and actual PCB specifications of the various PCB's that are compared.

As the overlapping region of the pattern is increased from one PCB to the next, there is a clear shift in the cluster size distribution away from single pad hits, as expected. In addition, as seen in the fit results of the residual distributions for the different PCB's, the position resolution also improves incrementally from 93μm for the older PCB to about 63μm for the recently manufactured PCB. The background component of the newer board is believed to be due to events where the majority of the charge is collected by a single pad, which in turn deteriorates the signal to noise ratio of the peripheral pads that play a big role in regulating the centroid. Since the detector gain was particularly low for the measurement of this board, we speculate that this background component will be suppressed by increasing the gain.

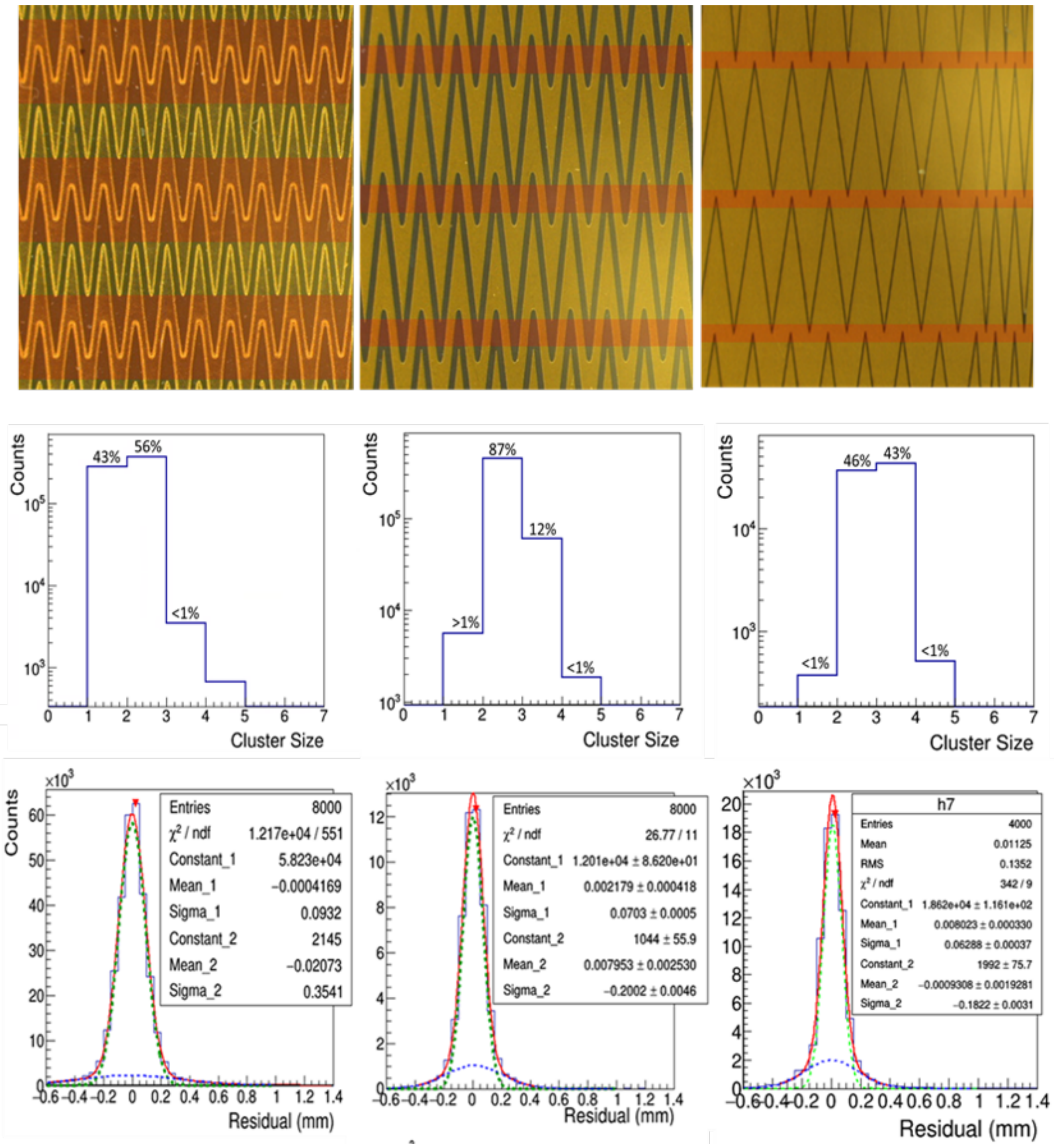

Figure 2: Top: Microscope pictures of three different zigzag PCB's, including a non-optimized zigzag patterned PCB manufactured using chemical etching, an optimized pattern developed using chemical etching and a recent PCB generated by Elvia using laser etching, respectively. The red band corresponds to the region on each pattern where there are no overlapping pads. Middle: corresponding cluster size distributions for the three PCB's. Bottom: corresponding residual distributions after the small systematic global shifts in the reconstructed position (i.e., the differential nonlinearity) is removed from the data. Each distribution is fit to a double Gaussian function to reveal a dominant and background component for the residuals.

2. ***Beam Test with multi-zigzag PCB***: We have conducted a beam test of the multi-zigzag PCB's described above at the FTBF in March 2018. The detector was placed in the primary 120GeV proton beam at FTBF and positioned just downstream of a high precision silicon tracking telescope for the purpose of measuring the position resolution. The detector was mounted to a XY-movable stand such that the beam axis is normally incident with respect to the readout plane, as shown in Fig. 4. As the XY-table translates the detector in a plane orthogonal to the beam axis, this allows the beam to scan across each zigzag pattern, thereby allowing a multitude of zigzag geometries to be studied in a

	Older PCB (ACE)		Newer PCB (Somacis)		Laser Etched PCB (TTM/Elvia)	
Zigzag parameter	Design	PCB	Design	PCB	Design	PCB
pad pitch (mm)	2.000	2.000	2.000	2.000	2.000	2.000
zigzag period (mm)	0.500	0.500	0.587	0.587	0.500	0.500
gap width (mm)	0.075	0.082	0.075	0.084	~0.025	~0.020
strip width (mm)	0.175	0.159	0.155	0.141	>0.350	>0.350
strip overlap %	69	40	94	83	~96	87
conductor coverage %	70	66	67	63	~94	~90

Figure 3: Table of design and actual PCB specifications for the three PCB's compared above.

Figure 4: The quadruple GEM detector (zoomed in on right picture) with multi-zigzag board readout positioned in beamline at FTBF. To the left the long silicon telescope is visible.

single board. The zigzag parameters for this board span an interesting range of the parameter space and were chosen for the goal of revealing important behavioral trends.

Some results from the beam test are shown below in Fig. 5 for a particular set of zigzag parameters and indicate a substantial improvement over earlier zigzag boards. The beam position in the detector is reconstructed using a simple charge weighted mean of the fired strips (or centroid) using only 2,3, and 4 strip clusters. A position residual is formed with the position as determined from the high resolution silicon telescope. The scatter plot of the residuals vs the actual hit position exhibits systematic up and down displacements, which may be interpreted as deviations from linearity. This so-called differential non-linearity (DNL) is characteristic of zigzag shaped strips, however the magnitude of these deviations appears to be significantly suppressed compared to earlier zigzag PCB's. For example, the maximum mean deviation from linearity in this case is below 50μm, whereas the maximum deviation for earlier boards was at best more than 70μm. In addition, the position resolution, given as the width of the 1D residual distribution in Fig. 5 is 53μm, compared to 100μm for earlier zigzag boards and 50-60μm for boards with straight strips and a pitch of 400μm.

It should be noted that this resolution was achieved with no effort to remove the DNL from the residual distributions along the zigzag coordinate. Additionally, the 1D residual distribution plot shows a negligible background with respect to the Gaussian fit. This is in contrast to earlier PCB's tested and to the tests performed in the lab with a similar PCB, which has a noticeable background.

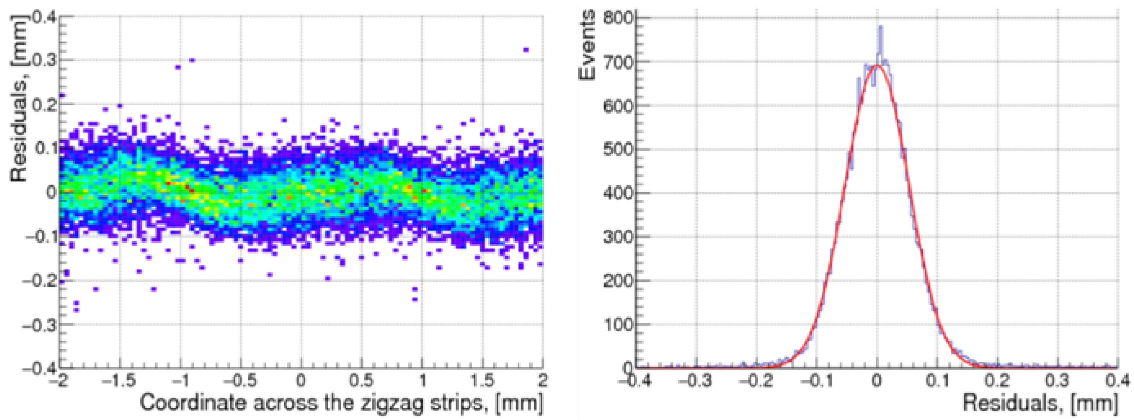

Figure 5: The scatter plot on the left shows the behaviour of the position residuals across a particular zigzag pattern with the following parameters: 2mm pitch, 0.4mm zigzag period, >90% interleaving, and 1mil gap spacing. The plot on the right is the corresponding position residual distribution with a sigma equal to 53m. No attempt was made so far to subtract silicon telescope track resolution to this number. The latter contribution must be of an order of 15-20μm (in quadrature).

The suppression of this background for the beam test data may be due to the operation of the GEM at higher gain at the beam test. It may also be that the discrete clusters of charge generated by x-rays in the lab have a smaller footprint on the readout, resulting in worse charge sharing. Finally, the beam test results exhibited no single strip hits, which can be a serious issue for non-optimized zigzag designs.

A systematic study was also performed to explore the dependence of the spatial resolution on the zigzag stretching parameter. This parameter basically describes how much the zigzag interleaving stretches beyond its neighbor, in terms of a percent of the pitch. A minimum is found at 5% over-stretching (as shown in Fig. 6) and the resolution degrades quickly away from this point. This rather unexpected result requires further investigation and will be addressed in more detail in the future.

3. ***Measurements with GEM-based cosmic ray telescope***: We have successfully completed the final assembly of the cosmic ray telescope. A photo of the cosmic ray stand showing the arrangement of the four detector layers is shown in Fig. 7. A zoomed in photo of a single layer is also shown, which consists of a triple GEM stack coupled to a COMPASS readout plane consisting of 10cm XY strips with a 400μm pitch. So far, each detector layer was commissioned by stress testing each GEM foil (by applying 500V across the two electrodes in air) and acquiring signals from Fe55 from each detector, as indicated by the scope screen-shot of an Fe55 spectrum in Fig. 7. Additionally, a gas system panel was built specifically for this setup and is also shown in Fig. 7.

4. ***GEM Studies using TPC gas mixtures in a compact TPC prototype***: The engineering design of the compact TPC prototype has been completed and the assembly of the enclosure is nearing completion (Fig. 8). The fabrication of the base plate is complete and will shortly be mounted to the enclosure once it is finished.

Publications:

1. A manuscript entitled, "Beam Test Results from a GEM-based Combination TPC-Cherenkov Detector" has been completed and will very shortly be submitted to the peer reviewed journal, IEEE Transaction on Nuclear Science. Consortium members from Stony Brook University and BNL are co-authors for this paper.

2. A manuscript entitled, "Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multi-stage GEM detectors" has recently been published in the peer reviewed journal, IEEE Transactions

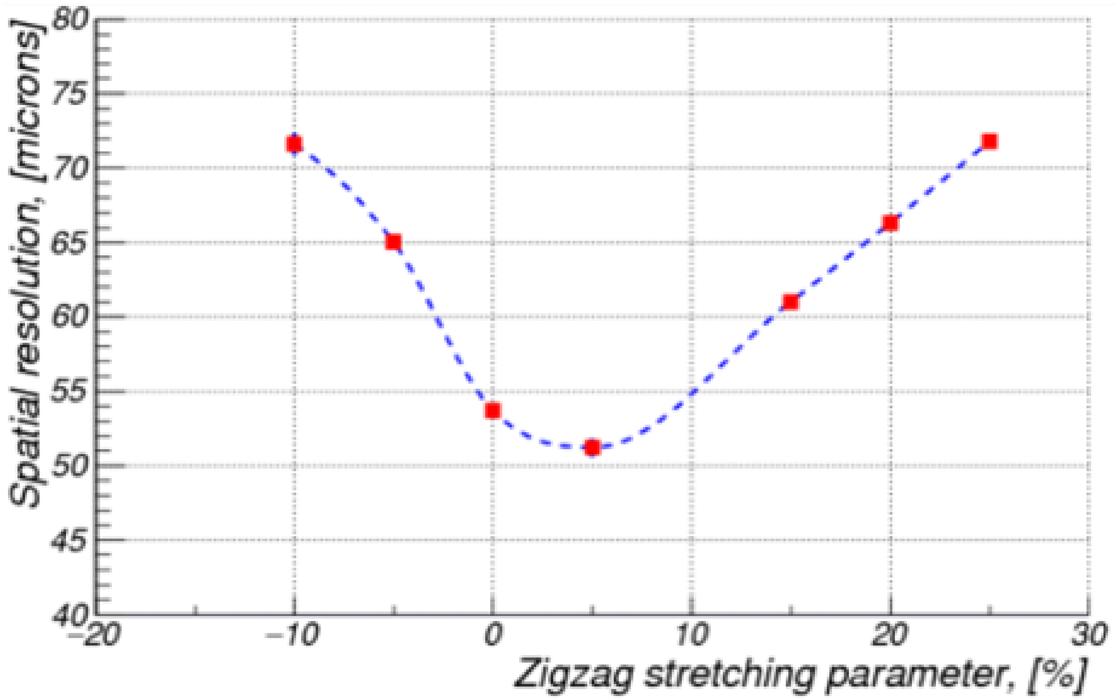

Figure 6: Plot showing the dependence of the spatial resolution on the degree of zigzag stretching. The zigzag parameters include a 2mm pitch, 0.4mm zigzag period, and 1mil gap spacing. No DNL correction applied to either of the data sets.

on Nuclear Science [3]. Consortium members from both Stony Brook University, FIT and BNL are co-authors for this paper.

3. A summary/abstract entitled, "Design Studies of High Resolution Readout Planes using Zigzags with GEM Detectors" presenting the results of new PCB's produced using laser ablation was submitted for consideration at the 2018 IEEE NSS/MIC conference.

1.3.2 Florida Tech

Construction and commissioning of low-mass EIC Forward Tracker GEM detector prototype: We assembled the new low-mass FT GEM detector with zigzag readout strips. Fig. 9 shows a couple of steps from the stack assembly process. Fig. 10 shows the stack of five foils before and after stretching. A new flex-circuit foil that we designed was produced by the CERN workshop and is used in this assembly. Spring-loaded pins are soldered to this HV foil and make contact with the drift foil and GEM foils to provide the appropriate electric potentials. A standard ceramic HV divider circuit from CERN provides the potentials from a single HV input voltage and is also soldered onto the HV foil (Fig. 11). After assembly, each GEM foil showed an impedance across its two faces in excess of 2 GΩ in air with 50% humidity. After stretching the foil stack and closing the chamber with the Al-Kapton window, no deformation of the carbon fiber structure is observed, which proves its ability to take up the tension of the five stretched foils as designed. The assembled detector has a mass of about 3 kg including an on-board HV filter and cable, but not including readout electronics. This is to be compared with, e.g. the GE1/1 Triple-GEM detector for the CMS forward muon upgrade that has a mass of about 20 kg.

The HV stability and linearity of the HV divider was successfully tested in pure CO_2 up to a drift voltage of -4600V. Commissioning in Ar/CO_2 70:30 is ongoing. At the time of the writing of this report, the detector

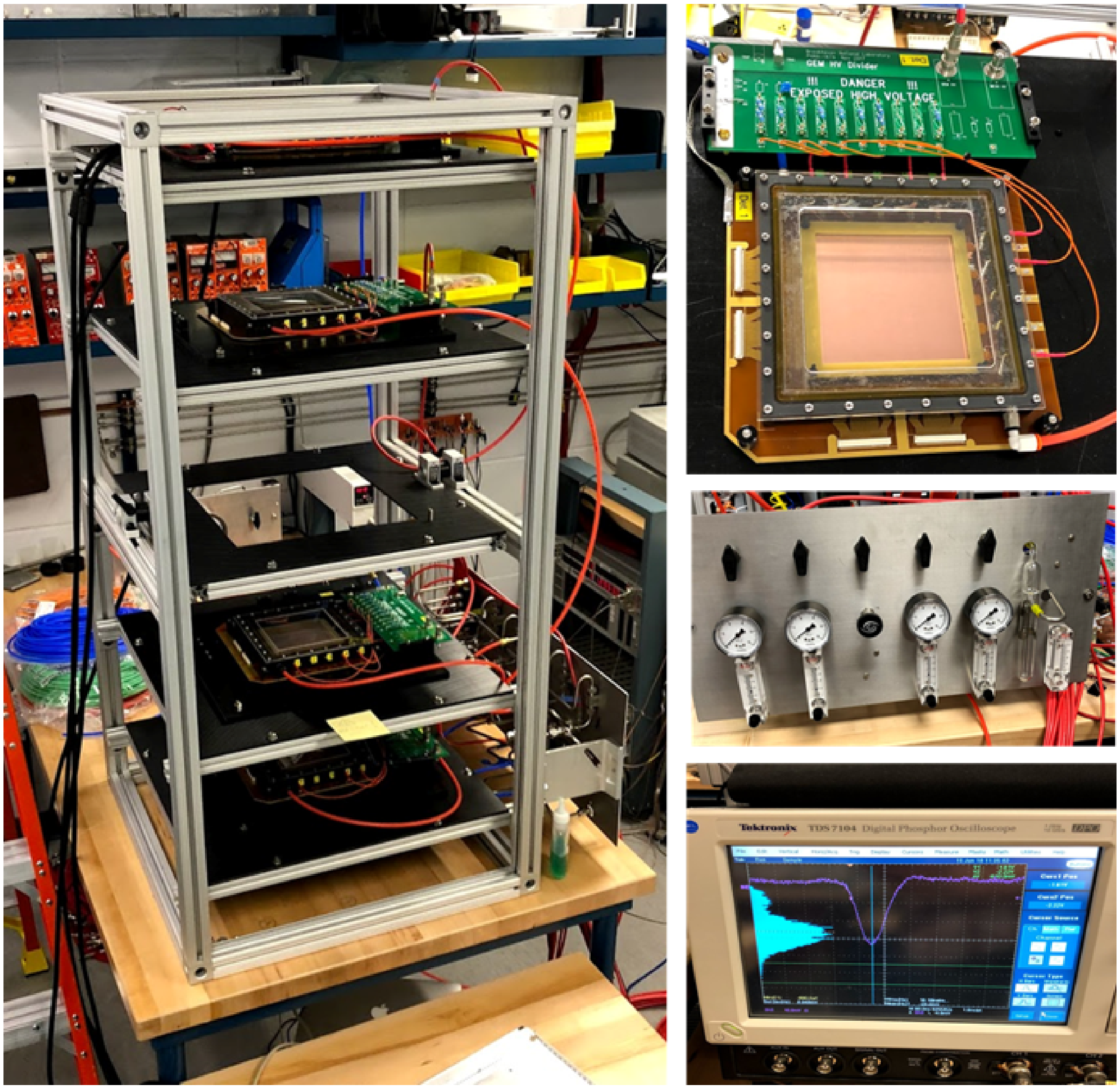

Figure 7: Cosmic ray stand outfitted with four GEM detector layers. The GEM's from each detector layer are powered using an independent voltage divider (seen as the green PCB in the upper right photo), which also provides a trigger output by providing a capacitively coupled output to the bottom GEM HV. In addition, a measurement of an Fe55 spectrum is shown from one of the layers.

is being tested at the Fermilab test beam facility. This test was prepared in close coordination with the UVa and BNL groups as planned. UVa and Florida Tech are sharing one setup; BNL is providing a reference tracker composed of four small GEMs for this setup.

R&D on μRWELL detector: We have ordered a 10×10 cm^2 resistive micro-well detector from CERN to begin some basic R&D on this detector technology for fast tracking in the barrel region of the EIC detector. To complement the 2D readout with Cartesian strips chosen by the UVa group for their μRWELL detector prototype, we opted for a 1D zigzag strip readout foil based on the foil design that we had used for the 10×10 cm^2 prototype[5] of the low-mass FT detector. We expect to receive this small detector in August or September 2018.

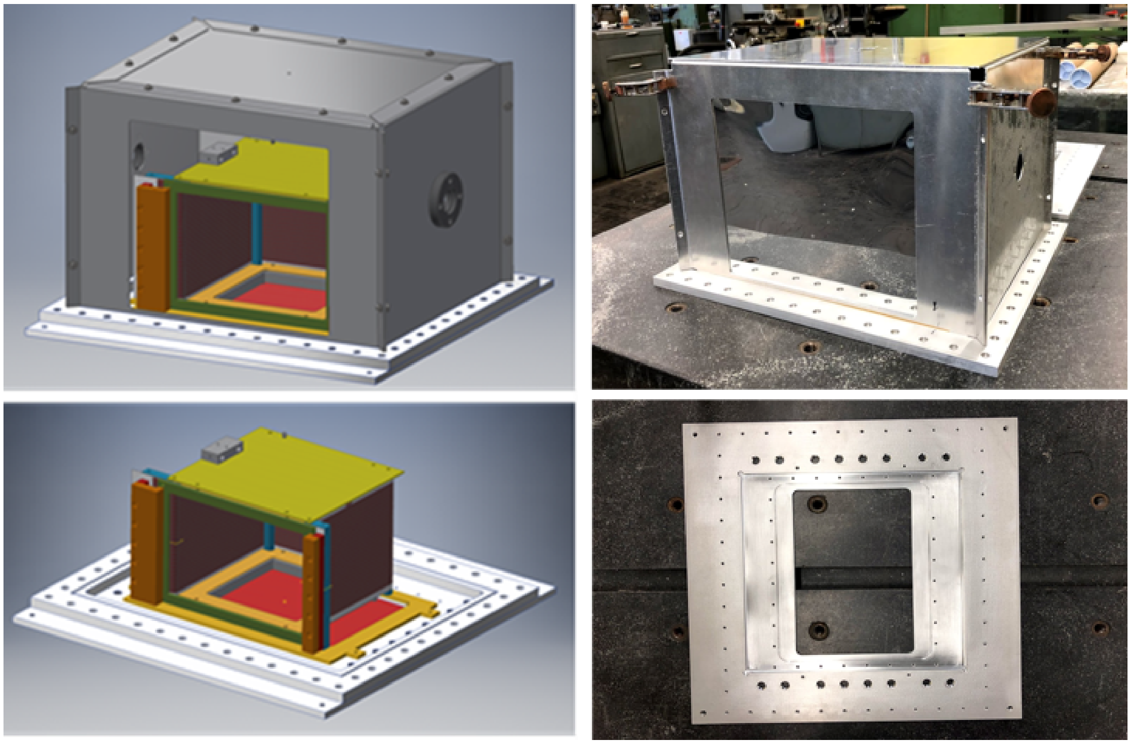

Figure 8: Compact TPC engineering model and photos of the actual detector enclosure and base plate.

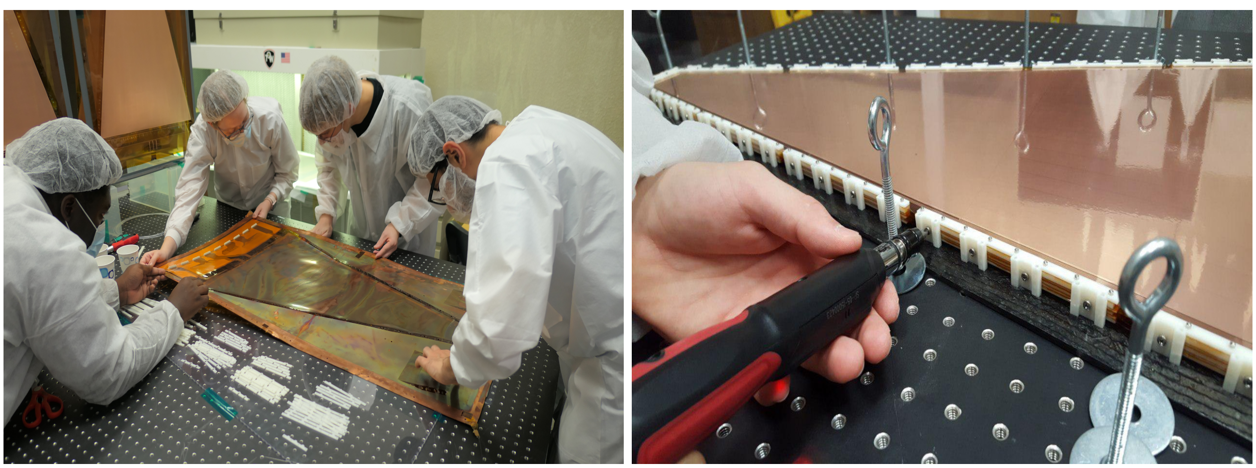

Figure 9: Assembly of low-mass forward tracker prototype at Florida Tech. Left: Placement of readout foil at bottom of foil stack. Right: Stretching of completed foil stack with electronic torque screwdriver.

EIC Simulations: Undergraduate student Matt Bomberger began work on EIC simulations for investigating the impact that material budgets in the forward and backward regions will have on the overall EIC detector performance. He installed the EICroot simulation framework on our computers. Using a basic example, he learned how to run the simulation, change detector parameters and plot their impact on the momentum resolution of forward particles. Matt will go to BNL in early August for a week to work directly with EICRoot expert Alexander Kiselev on the implementation of a forward tracker based on Triple-GEMs.

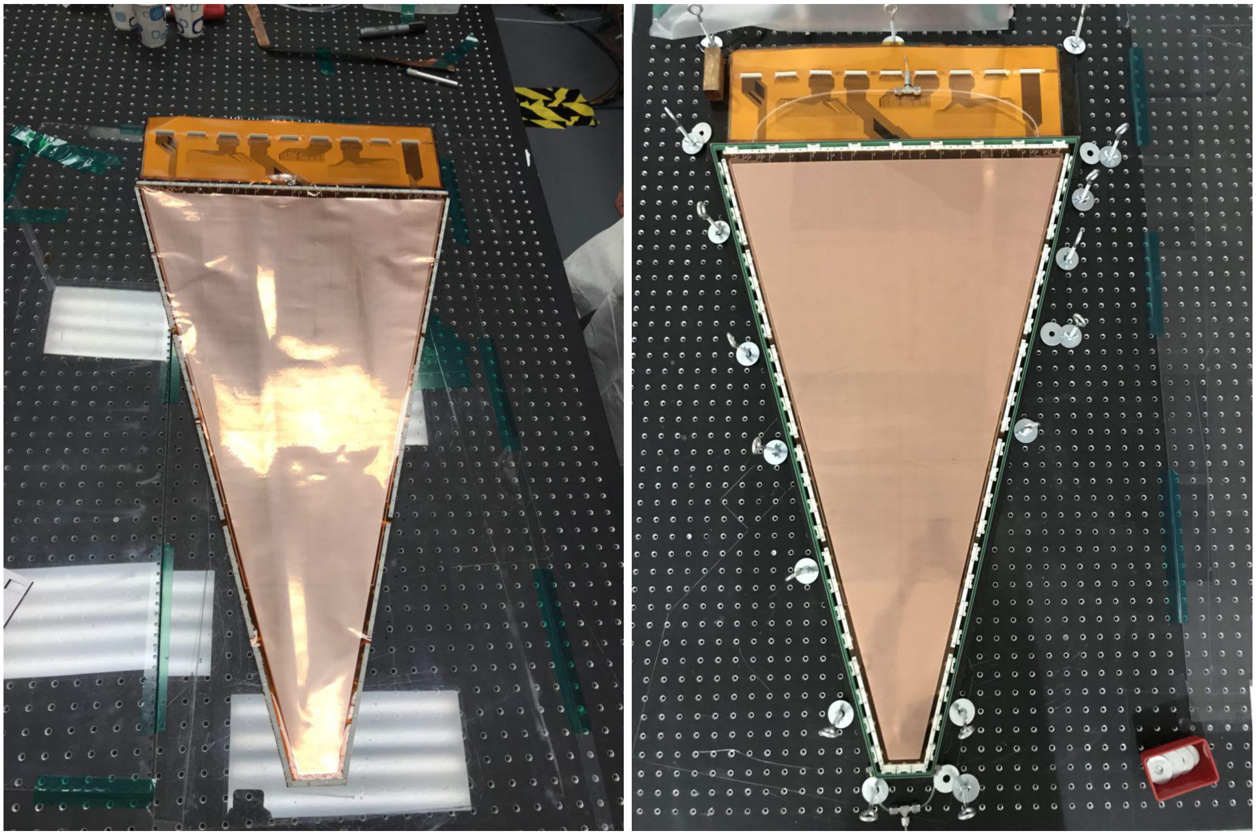

Figure 10: Stack of readout foil, three GEM foils, and drift foil before (left) and after (right) stretching against 3D-printed pull-out posts mounted on carbon fiber frame. Note the absence of spacers in the active area.

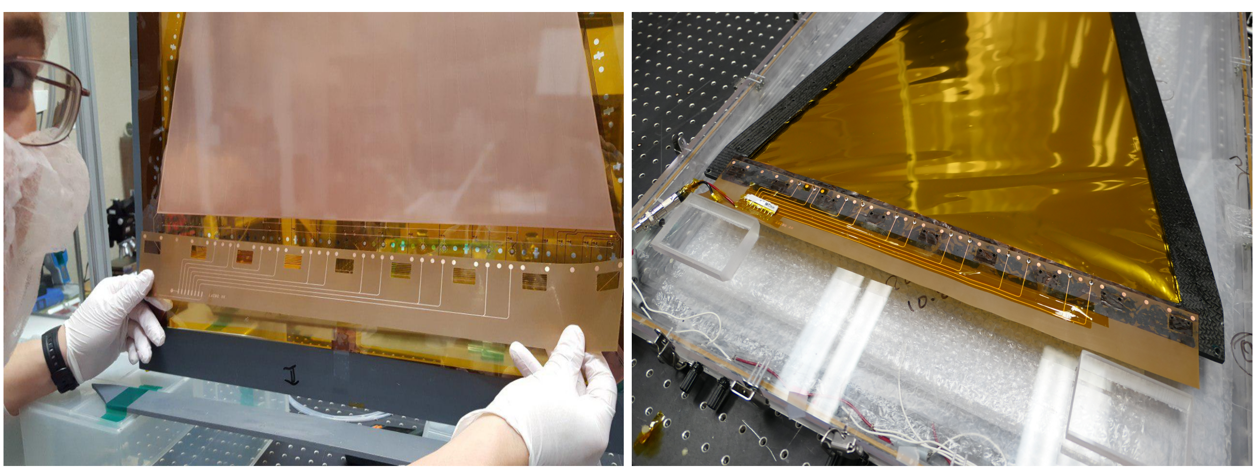

Figure 11: High-voltage foil for spring-loaded pins that make contact with the drift foil and GEM foils to provide the appropriate electric potentials. Left: Alignment check against GEM foil. Right: HV foil glued to carbon fiber frame with HV pins and ceramic HV divider soldered onto HV foil.

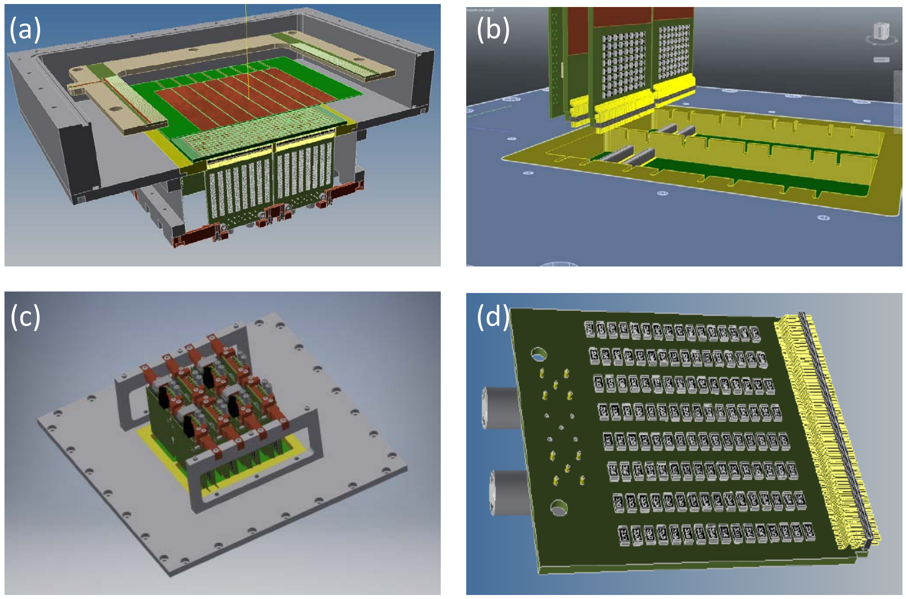

Figure 12: Prototype design. (a) Cross-section of the detector: the elements visible from top to bottom are the THGEM layers, the MM stage and the resistor cards. (b) Detector rear side: detail of the connectors and the read-out and resistor cards. (c) The rear side of the detector fully equipped. (d) The design of the resistor card.

1.3.3 INFN Trieste

Activity in period January 2018 - June 2018

1. **Laboratory tests of the single photon detector by MPGD technologies with miniaturized pad-size in period January 2018 - June 2018**
   The prototype architecture consists in two staggered THGEM layers, the first one also acting as photocathode substrate, followed by a resistive MM by discrete elements. The detector active surface is 100×100 mm^2. The THGEM geometrical parameters are: 400 μm hole diameter, 800 μm pitch, 400 μm thickness and hole without a rim. The MM has 128 μm gap; the pad-size is 3×3 mm^2 with 3.5 mm pitch, for a total number of 32×32 pads. The pads are grouped in 32×4 modular units; each unit is equipped with a connector interfacing the signal pads to the front-end electronics and a second, identical connector, providing the biasing voltage to the anode pads via protection resistors, one per pad, housed in a dedicated resistor board. Figure 12 illustrates the detector design, while the construction activity is documented in Fig. 13. The tests have been performed both using a single-channel read-out including a CREMAT CR110 preamplifier, an ORTEC 672 amplifier and an AMPTEK 8000A Multichannel Analyzer and a multichannel SRS system with the original DAQ system RAVEN developed last year for this application and having high rate capabilities.

   The various multiplier of the detector exhibit good electrical stability and gain performance (Fig.s 14). Figure 15 presents examples of amplitude spectra obtained illuminating with ^{55}Fe source and single photons from an UV LED the complete detector including the three multiplication layers. The amplitude spectra confirm the overall high gain of the detector.

   A single problematic aspect appeared during the laboratory tests of the prototype: the non uniform gain observed reading the signal from the different pads with variations up to a factor 2 even between

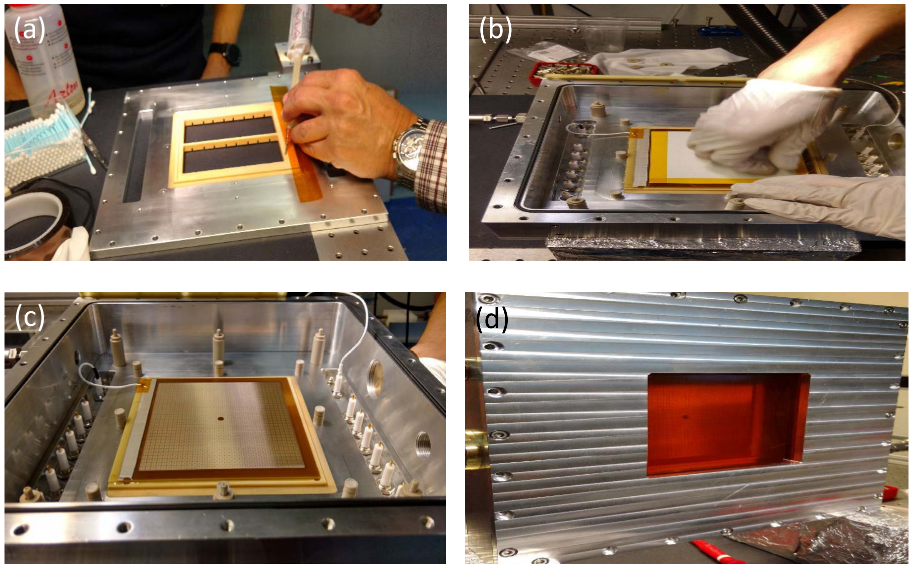

Figure 13: Prototype construction. (a) The fiberglass frame supporting the MM is glued onto the Al chamber structure. (b) The MM is glued onto the fiberglass frame. (c) The MM installed in the chamber and its power lines are visible. (d) The chamber is closed with a mylar window.

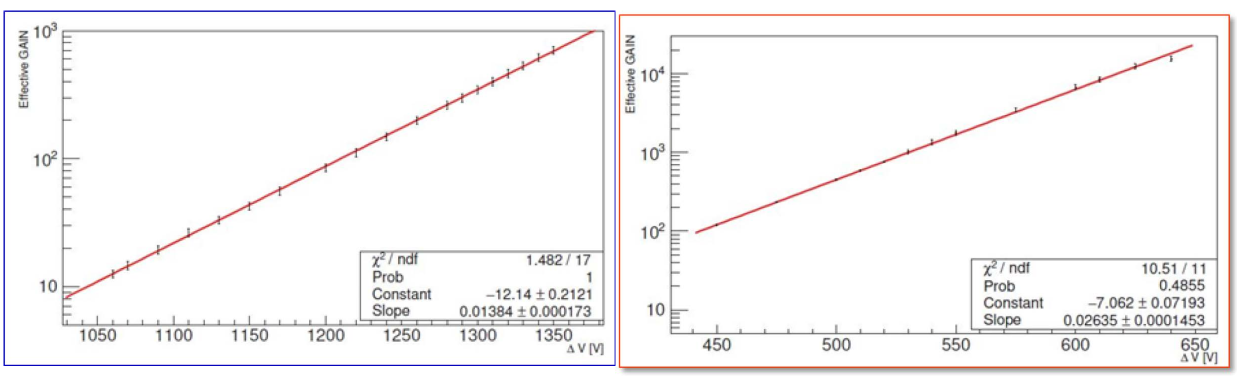

Figure 14: Gain versus applied bias voltage of a THGEM of the miniaturized-pad prototype (left) and of the MICROMEGAS of the miniaturized-pad prototype. The gain is extracted from ^{55}Fe amplitude spectra.

adjacent pads (Fig. 16, left). The source of the non-uniformity could be identified in the parasitic capacitance, different pad by pad, which is present in the first version of the anode PCB. This is confirmed correcting the amplitude spectra by the measured effect of the parasitic capacitance (Fig. 16, right). A new version of the anode PCB has been designed equalizing the parasitic capacitance of the pads. It will be realized making use of the 2019 resources.

The activity to prepare the setup for the prototype test on a test beam line is ongoing. A compact setup is being built. It consists in the mechanical support for the trigger detectors (scintillating counters, finger-shaped), for the prototype and for all the required services (gas lines, LV and HV power supplies), the scintillator counters for the trigger and the step-motors, remotely controlled, used to optimize the

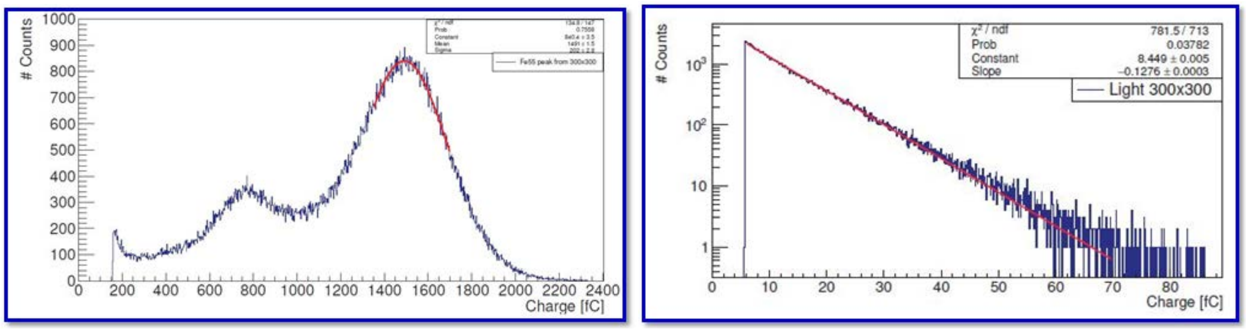

Figure 15: Spectra collected with the complete detector including two THGEMs and a MICROMEGAS layer; left) illuminating with X-ray source (^{55}Fe); right) illuminating with single photons.

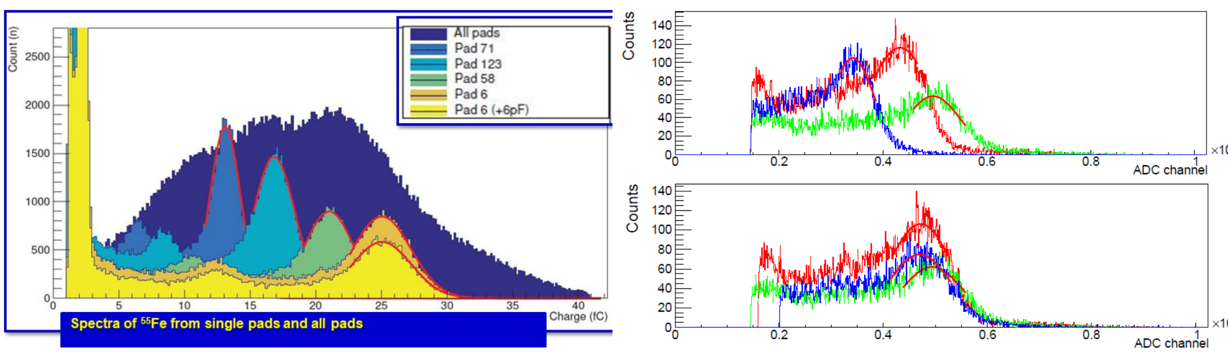

Figure 16: left) ^{55}Fe amplitude spectra collected by different pads using the MICROMEGAS multiplication stage only. right) Excited Cu amplitude spectra collected with three different pads; right top) raw spectra; right bottom) applying the correction accounting for the different capacitance of the pads.

counter position. The setup is now almost complete (Fig. 17).

2. Initial studies to understand the compatibility of an **innovative photocathode based on NanoDiamond (ND) particles** with the operation in gaseous detectors and, in particular, in MPGD-based photon detectors

   Six small-size (3×3 cm^2) THGEMS have been fully characterized before any coating in order to have a precise reference of their performance. Then, the samples have been coated in Bari either with CsI or with non-hydrogenated ND powder or with hydrogenated ND powder. A complete characterization of the coated pieces has been performed.

   The THGEMs with non-hydrogenated ND powder coating exhibit higher gain for a given biasing voltage (Fig. 18). At the moment there is no explanation for the increased gain, that will be further studied.

   The two THGEMs with hydrogenated ND powder coating cannot stand voltage large enough to make the gain measurement possible. Microscope images indicate the presence of large grains in the THGEM with hydrogenated ND powder coating, not visible in the THGEM with non-hydrogenated ND powder coating (Fig. 19). The images suggest a different morphology of the ND grains in hydrogenated and non-hydrogenated surfaces and further investigation is needed.

The preliminary results concerning the performance of the photon detector prototype with miniaturized pads have been present at **the 14th Pisa Meeting on Advanced Detectors**, La Biodola, Isola d'Elba (Italy),

Figure 17: Picture of the setup for the test beam, present status.

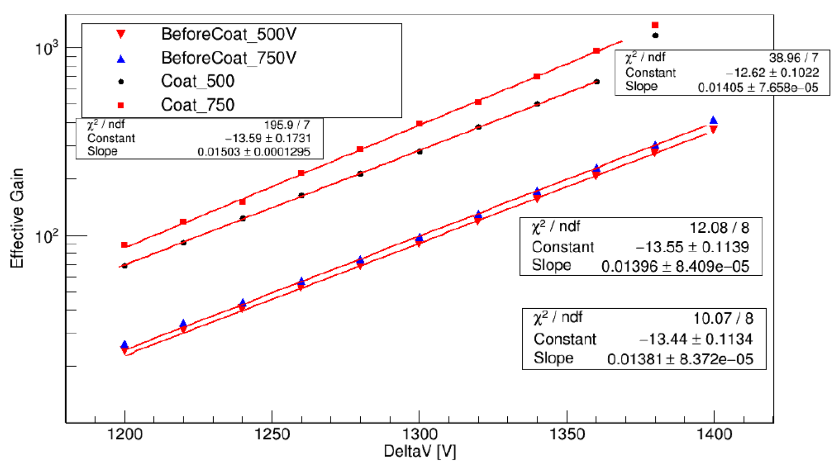

Figure 18: Effective gain versus biasing voltage for a THGEM piece before coating and after coating with non-hydrogenated ND powder. The gain has been measured for two different values of the drift field applied above the top THGEM face.

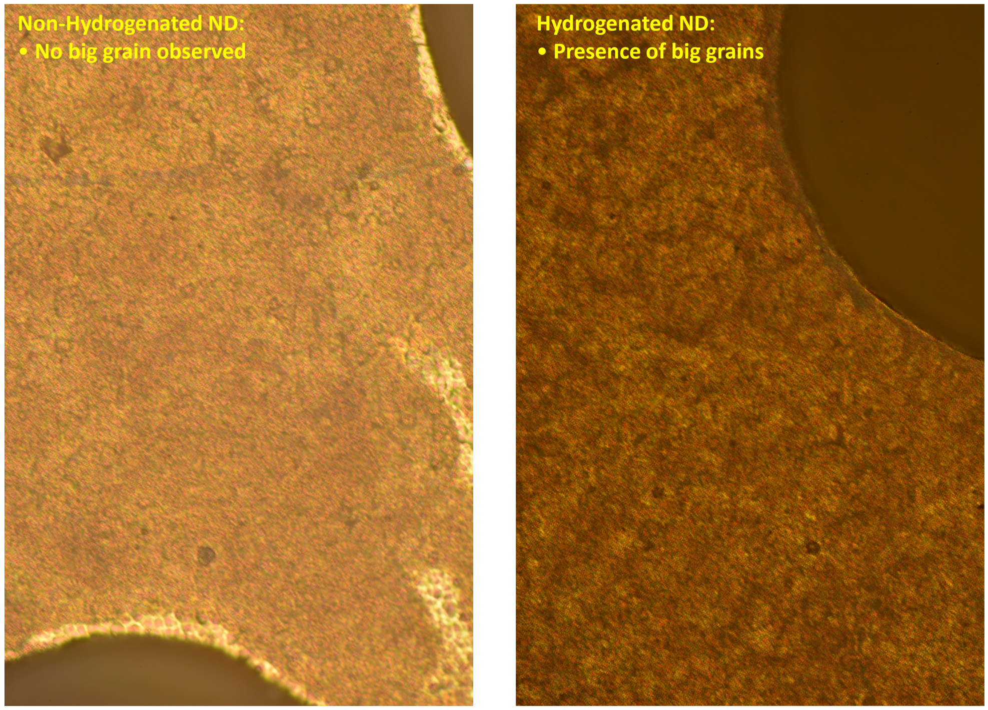

Figure 19: Microscope images (× 20) of the coated surface of two THGEMs: non-hydrogenated ND powder coating (left) and hydrogenated ND powder coating (right). Large grains are present at the surface in the THGEM with hydrogenated ND powder coating.

27 May - 02 June 2018, and will be presented at **the 10th International Workshop on Ring Imaging Cherenkov Detectors**, Moscow (Russia) 29 July – 4 August 2018.

Concerning the **milestones for 2018**:

- **September 2018: The completion of the laboratory characterization of the photon detector with miniaturized pad-size.**
  The exercise is almost complete already now and the milestone will be successfully matched.
- **September 2018: The performance of the tests to establish the compatibility of the ND photocathodes with the operation of MPGD-based photon detectors.**
  The tests have been performed and, therefore, the milestone has been matched. Nevertheless, the totally unexpected results demand for further investigation in 2019.

1.3.4 Stony Brook University

A TPC prototype has been constructed and a sophisticated test-beam setup (20) established. We purchased picoammeter from PicoLogic in Zagreb/Croatia which is a unique device that allows to measure very small currents at high potential. The floating current measurements can be performed at potentials much larger than 5 kV, ideally suited for IBF measurements in a TPC.

The TPC prototype has been equipped with a real size readout module, based on a quadruple-GEM stack similar to the ALICE-TPC readout and zig-zag pad readout structure. At the time of this write-up the prototype is exposed to the 120 GeV protons at the Fermilab Testbeam Facility (FTBF) to establish the working parameters of the TPC based on a fast Ar-based gas mixture. This is the first time the a quadruple-GEM stack with a special configuration to minimize IBF will be operated with an Ar-based gas. In parallel,

Figure 20: TPC-prototype setup at FTBF with the SBU/FTBF crew.

the installation of first parts of the electron-gun for the evaporation of thin layer structures on mirror surfaces has begun.

1.3.5 University of Virginia

Construction and commissioning of low-mass UVa EIC-FT-GEM prototype
We have completed the assembly of the meter-long low-mass Triple-GEM detector with 30° stereo-angle U-V readout strip foil. The standard stretch-and-glue assembly technique was used for this prototype. Fig. 21 shows a couple of steps from this assembly process. The key points for the prototype relevant for EIC are:

1. **Development of low mass & large area Triple-GEM detector:** For this Triple-GEM prototype, we use only foils including for the drift cathode and the U-V strips readout board, with no rigid PCB or support structure in the active area. The 2D U-V strips readout layer and the drift cahtode were all produced at CERN from the same copper cladded Kapton base material used for the production of GEM foils.The elimination of rigid support structure in the active area of the detector is motivated by for low material requirement to minimize multiple scattering as well as photon induced background. Entrance and exit gas volume with 25 μm thick Kapton foil have been added to the stack of active foils for pressure balance inside the chamber in order to maintain uniform gap between different layers needed for an uniform gain accross the active area. Top left picture of Fig. 21 shows a cross section of the all foils EIC-FT-GEM prototype with the entrance and exit gas windows.

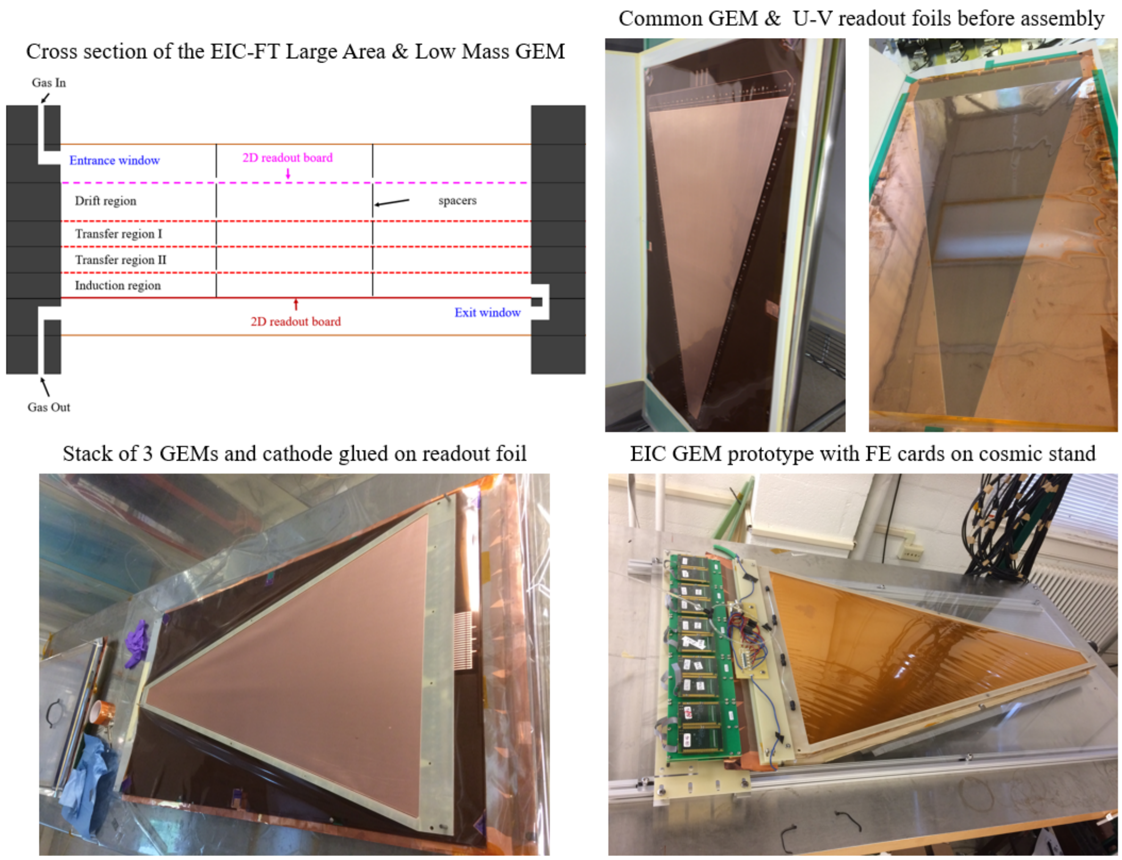

Figure 21: Large area & low-mass EIC-FT-GEM: Cross section of the chamber (*top left*); GEM and readout foil before the assembly (*top right*); Stack of the 3 GEMs and cathode foil glued to the readout (*bottom left*), assembled prptptype on cosmic stand (*bottom right*)

2. **Development of low cost support frames:** We have developped a new approach for a cost effective production of the support frames needed for the stretched foils of a Triple-GEM detector. We are testing this new idea on the EIC-FT GEM prototype, replacing the high cost Permaglass frames produced by RESARM company (Belgium) used for the entrance and exit gas window foils of the chamber (half of the total number of frames) by the low cost frames. Each of these low cost frames are made of three G10 parts glued together as shown on bottom left of Fig. 22. The design of the parts was made by UVa student and the production done at the UVa Physics Department machine shop. The parts were later glued together into frames in the clean room at the UVa detector lab. The parts needed for all four frames of this prototype (see Ppicture at top right of Fig. 22) were cut out from a single 915 mm $\times$ 1220 mm G10 plate. The picture on the bottom right of Fig. 22 shows the exit window foils stretched and sandwiched between two of the low cost frames. The total cost of these low cost frames is about half of the cost of the standard RESARM frames that we used for the inner layers (GEMs, readout foil and drift cathode), which constittue of reduction of about 30% of the total cost of the frames for this prototype.

3. **Implementation of the double sided zebra strip concept:** Another new concept that we are testing with the EIC-FT GEM prototype is the use of double sided zebra strip connection scheme to read out the signal at the outer radius side of the U-V strip readout board. This approach allow to read out a high density on electronic channels from the wider side of the detector and avoid having front end (FE) electronic at the back (active area) or on the side of the detector. This is critical for EIC to not only reduce multiple scattering but also limit the exposure of he FE electronics to radiation damage. The proof of principle of the double side zebra contact was previously demonstrated on a small (10

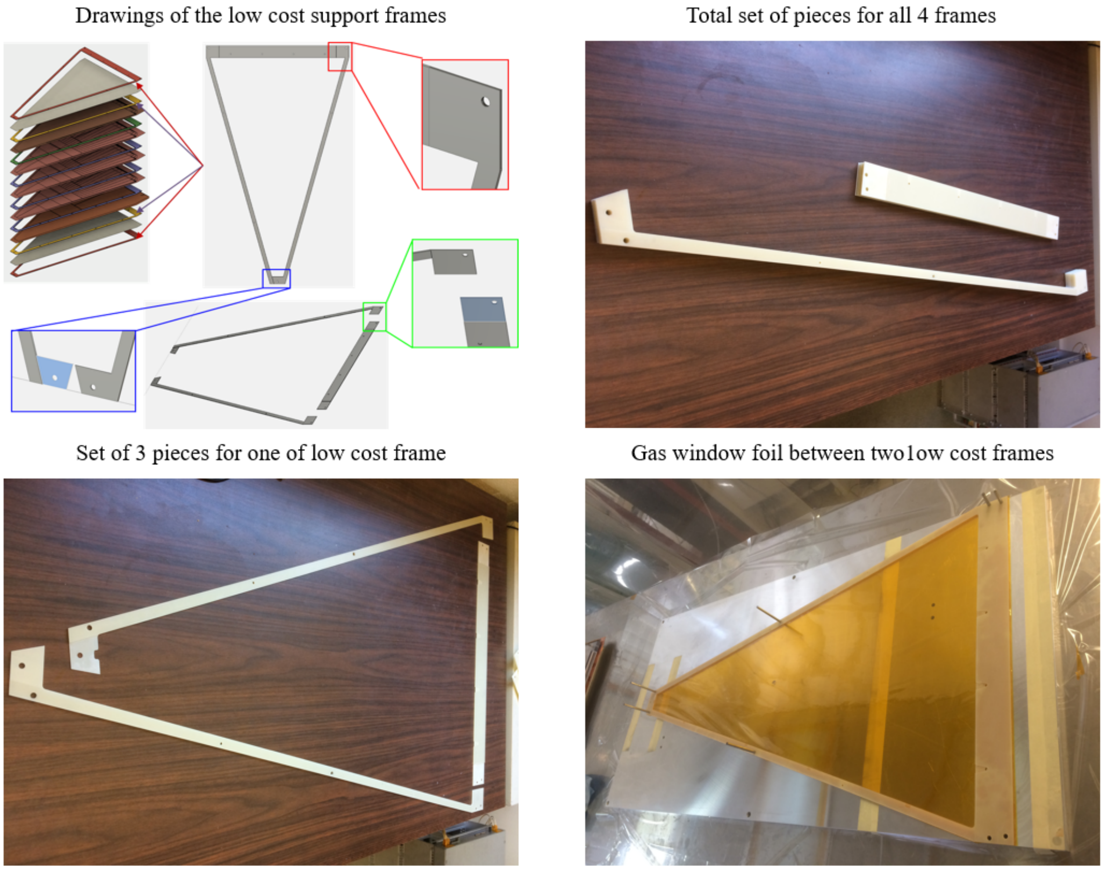

Figure 22: Production of low cost support frames for top and bottom gas window foils the EIC-FT-GEM prototype at UVa.

cm × 10 cm) triple-GEM prototype and now been implemented at a larger scale on the EIC-FT-GEM prototype. Fig. 22 shows a couple of steps for the connection of the zebra strips on both sides (U and V strips) of the readout foil.

EIC-FT-GEM prototype has been successfully tested under HV as well as with cosmic. Picture on the bottom right of Fig. 21 shows the prototype o the cosmic stand in the detector lab at UVa. At the time of writing this report, the prototype is under tested at the summer 2018 test beam effort conducted jointly with Florida Tech and Stony Brook University at the Fermilab test Beam Facility (FTBF). A picture of the detector on the MT6.2b area at the FTBF can be seen on Fig. 24, together with the BNL GEM Telescope that we are using for the tracking.

Assembly and test of a small μRWELL detector prototype with 2D Cartesian strip readout
We have received from CERN, the kit for a small (10 cm ×10 cm) resistive micro-well detector (μRWELL) with 2D X-Y strip readout a la COMPASS. We assembled the chamber and performed preliminary test in the detector lab at UVa in order to familiarize ourself with this new technology. The prototype is also currently under test beam at the FTBF for the study of its basic performances such as efficiency vs. gain, the gain uniformity and the spatial position resolution. Fig. 25 shows a picture of the μRWELL prototype with the 2D Cartesian strip readout (top left), the cross section of the detector (bottom left)and on the right as the prototype on its stand, currently being tested on the MT6.2b moving table at the FTBF test beam.

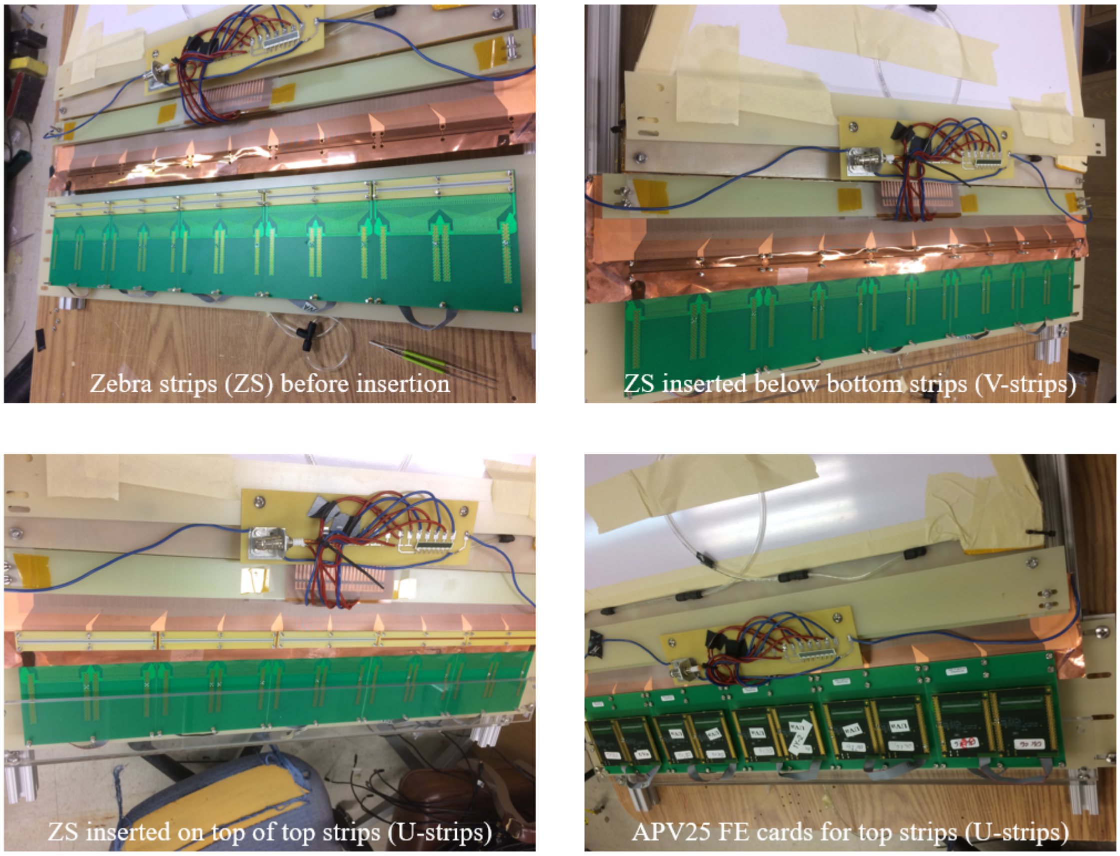

Figure 23: Steps of the assembly of the 2D zebra strip connection scheme to the EIC-FT-GEM U-V strip readout foil.

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

1.4.1 Brookhaven National Lab

We were not able to complete the assembly of the cosmic ray telescope in time to make any useful measurements with it since we were preoccupied with preparing for and carrying out the beam test of the multi-zigzag PCB described earlier. We also were not able to complete the assembly of the compact TPC enclosure for the same reasons. However, we did in fact make good progress on both fronts and expect to have the assembly of the prototype TPC detector completed within the next few months and will also start using the telescope in earnest for the various tests mentioned earlier.

1.4.2 Florida Tech

We have mostly achieved the goals that we had set for ourselves for the reporting period. There is some delay in the quality control tests for the low-mass prototype since the preparation for the assembly took a bit longer than expected.

1.4.3 INFN Trieste

The activity is progressing according to planning.

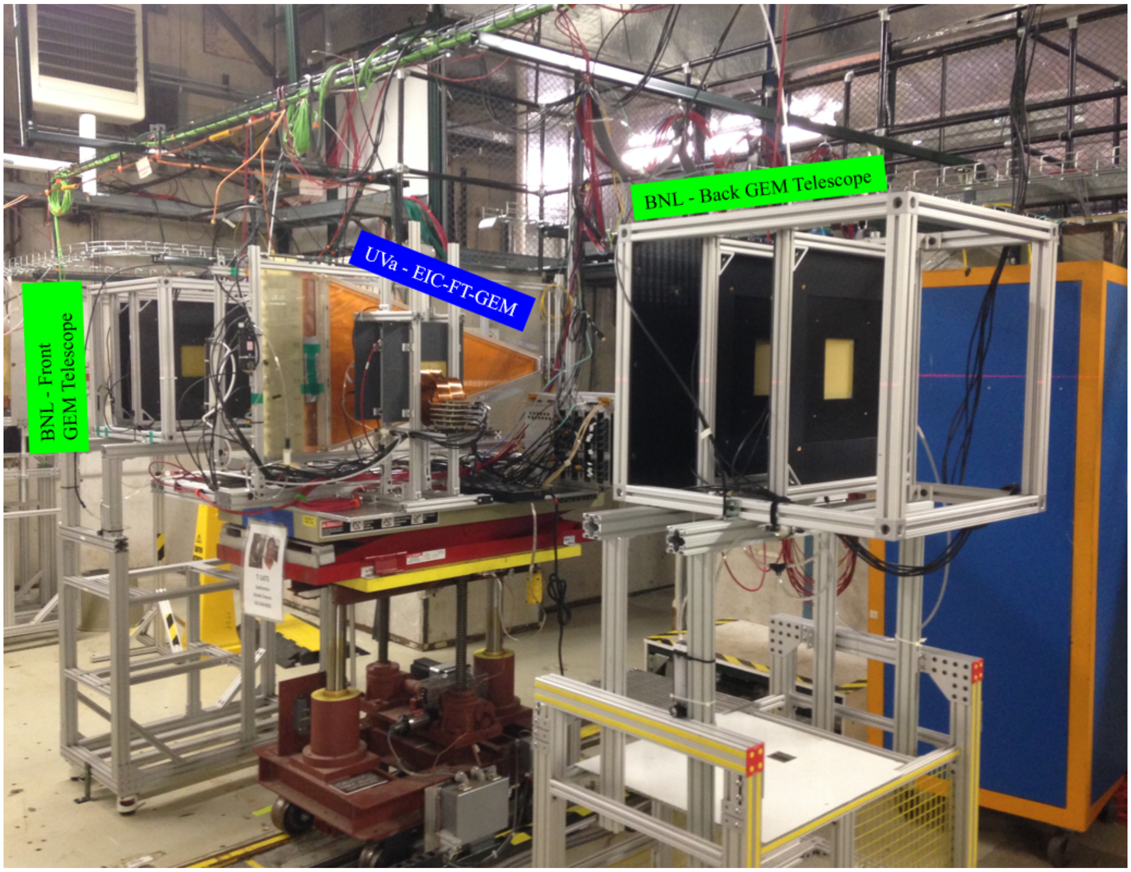

Figure 24: UVa EIC-FT-GEM prototype on the moving table stand at the MT6.2b area of the FTBF during the June 2018 joint test beam effort with FIT and SBU.

1.4.4 Stony Brook University

The completion of the evaporator setup is yet to be completed as the construction of the TPC-prototype took away significant time.

1.4.5 University of Virginia

We have not been able to make any progress on the simulation studies of the impact of light low mass GEM foil like Cr-GEM in the EIC detector. The student that we initially anticipated to participate to this activity was no longer available for the work due to other commitments that were of higher priority.
There were also little progress regarding the draft paper that we started on the recent results on the Chromium Cr-GEM. We are going to focus on this part in the next couple of months.

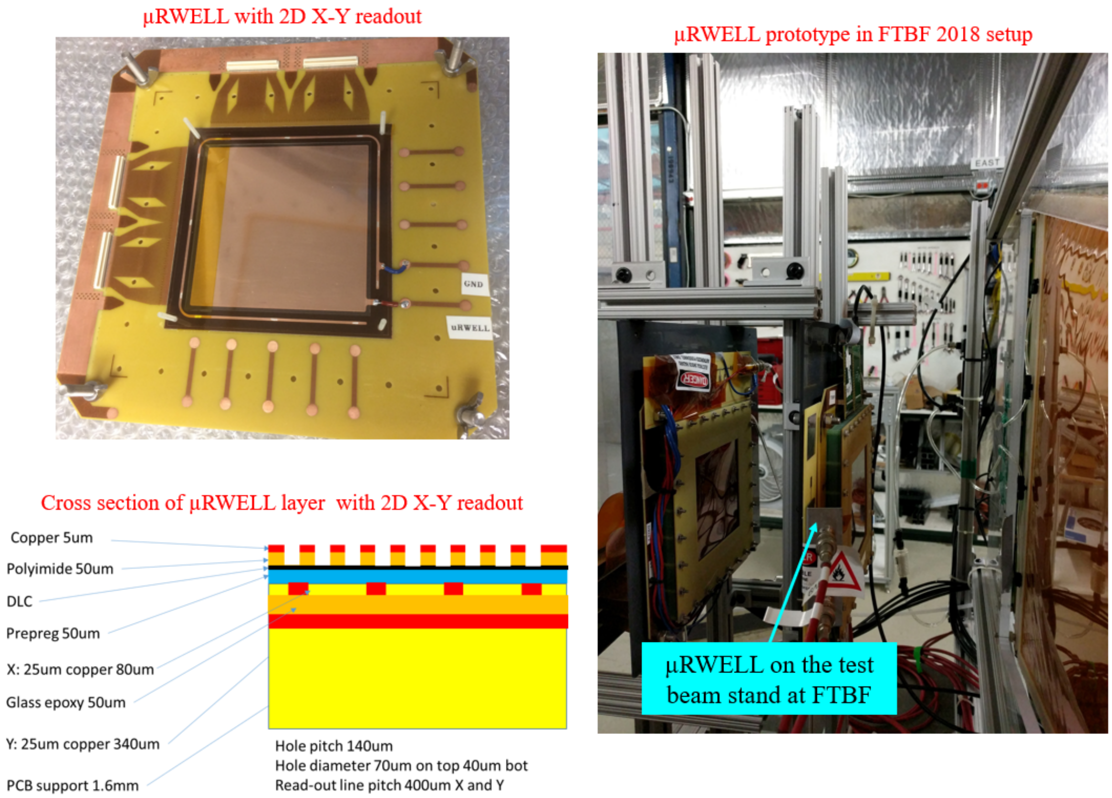

Figure 25: μRWELL amplification device (*top left*); cross section of the detector (*bottom left*); UVa prototype on test beam at the Fermilab FTBF (*right*).

2 Future

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

2.1.1 Brookhaven National Lab

Our proposed R&D activity for FY19 is as follows:

- Utilize our small TPC prototype that was redesigned and rebuilt from our TPC/Cherenkov prototype (uses same field cage & drift volume with a new, smaller and more compact enclosure that allows easy exchange of readout detector).
- Test with Multistage GEM, μMegas, Hybrid GEM+μMegas and μRWELL readout.
- Investigate various types of readout boards (including zigzags and other patterns) and different gases to optimize readout with each type of gain structure.
- Carry out simulation studies for various readout patterns and gas combinations.
- Read out using SAMPA readout electronics currently being developed for sPHENIX and/or DREAM electronics. Can also read out up to 128 ch over limited drift range using our high resolution V1742 DRS system.

- Measure spatial resolution and track resolution in a TPC operating mode using cosmic ray telescope in the lab and then in the test beam.
- Can also study laser calibration of TPC drift region using our UV laser.

These plans are well aligned with our initial goals for this time period.

2.1.2 Florida Tech

Forward Tracker Prototype: Our main goal for the next funding period is to extract the performance characteristics of the low-mass prototype from the data that we are hopefully about to collect at the Fermilab beam test and to present the results at conferences and in a publication. In addition, we will perform additional measurements on the detector with X-rays at Florida Tech, e.g. gain curves.

EIC Simulations: Undergraduate Matt Bomberger will continue his EIC simulations to investigate the impact that material budgets in the forward and backward regions will have on the overall EIC detector performance. Our goal is to have results from a realistic simulation of the forward tracker region by May 2019.

μRWELL detector: We plan to work closely with UVa on the design of a first prototype for a small cylindrical μRWELL detector. More details on this can be found in the proposal section below that describes the overall μRWELL detector R&D that is proposed by the eRD6 consortium. Finally, we will assemble and commission the 10×10 cm^2 μRWELL prototype with zigzag-strip readout and characterise its performance using X-rays.

2.1.3 INFN Trieste

The whole R&D project develops over several years and the overall time-lines are presented in Fig. 26. According to the planning, two activities will be pursued in 2019.

1. The realization and characterization by laboratory tests of a **second version of single photon detector by MPGD technologies with miniaturized pad-size**. The construction of a second version of the prototype is related to the observed non-uniformity of the gain. As explained in Sec, 1.3.3 the source of the effect has been understood: it is related to the design of the anode PCB of the MM multiplication stage. A modified version has already been designed. The construction and characterization of the modified prototype will take place in 2019.
2. The initial studies to understand the compatibility of an **innovative photocathode based on NanoDiamond (ND) particles** with the operation in gaseous detectors and, in particular, in MPGD-based photon detectors, have been performed in 2018. The characterization of THGEMs with ND coating, both in the case of hydrogenated and non-hydrogenated powder has presented unexpected features, even if very different in the two cases. The 2019 activity will be dedicated to further explore these performance in order to understand the origin of the modified THGEM behavior by producing under controlled parameters a new set of small-size THGEMs, that then will be fully characterized.

Following the activity planning, the **milestones for 2019** are:

- September 2019: The completion of the laboratory characterization of the second version of the photon detector with miniaturized pad-size.
- September 2019: The completion of the studies to understand the performance of THGEMs with ND coating, both in the hydrogenized and non-hydrogenized versions.

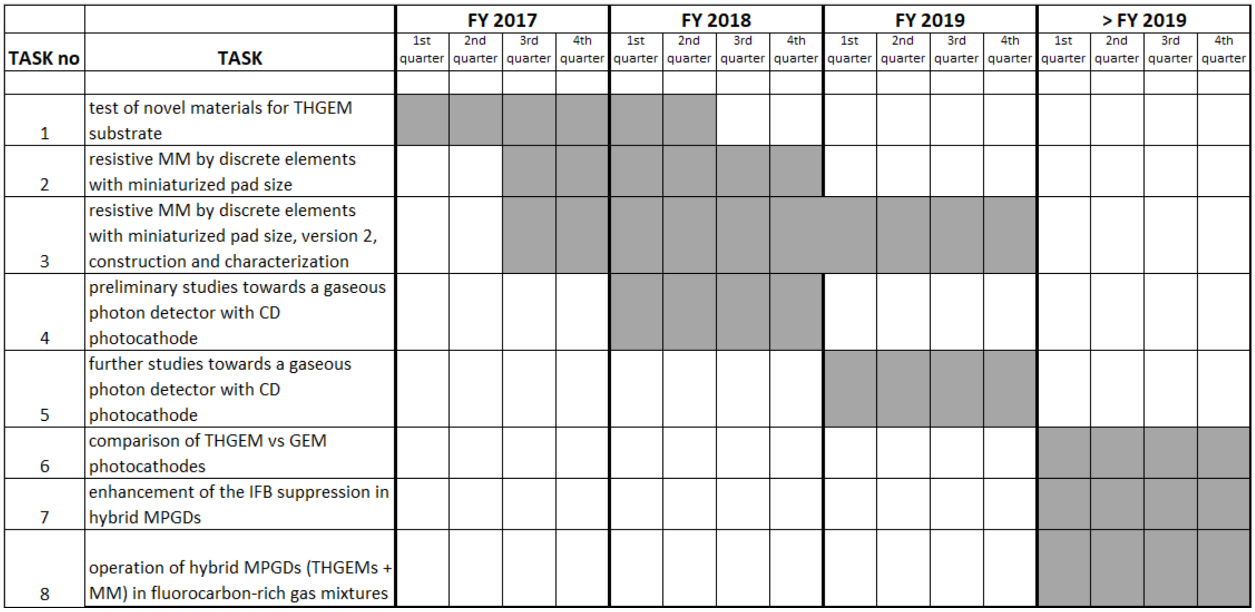

Figure 26: Time-lines of the R&D activity "Further development of hybrid MPGDs for single photon detection synergistic to TPC read-out sensors.

2.1.4 Stony Brook University

The test-beam campaign at FTBF will be completed in the first week of July. Followed by the analysis of the obtained data we are subsequently planning to prepare for the first IBF-measurement with the picoammeter. We are in possession of a rather strongly active Fe^{55}-source that will allow us to obtain the amount of charge to be significant for IBF measurements.

The installation of the evaporator equipment will be continued and first operation is expected in early fall.

- July-Aug 2018 Analysis of test-beam data
- Sept-Oct 2018 IBF measurements
- Sept-Oct 2018 Evaporation setup complete

2.1.5 University of Virginia

Our plans and R&D goals for FY19 are:

1. **Large EIC-FT-GEM prototype:** The main goal for the coming cycle is to start the analysis of the test beam data that we are curreny collecting at Fermilab (June - July 2018 campaign with FIT and SBU). We plan to present the results on the measured spatial resolution and overall performances of the prototype at conferences and start preparing for publication of these results in peer-reviewed journal. In the meantime, we will continue the chaacterisation of the prototype with cosmic and x-ray at UVa and at the BNL x-ray scan setup if required.
2. **R&D on μRWELL detector technology:** As already stated in the Florida Tech section, we will work closely with FIT on the design of a small cylindrical μRWELL detector. We will also continue the study and characterisation of our current small prototype and we are requesting additional fund to acquire additional small 10 cm $\times$ 10 cm prototypes with the R&D focus on low mass and high resolution 2D readout strips patterns.

3. **VMM readout Electronics:** We plan to acquire a small size VMM-based Scalable Readout System (SRS) and test this new promising electronics with the our large EIC-FT-GEM and μRWELL prototypes. VMM chip has been developped at BNL for the ATLAS Micromegas Muon Chamber Upgrade and is an excellent candidate for Micro Pattern Gaseous Detectors such as GEM and μRWELL detectors for the EIC tracking system. We will compare the performances of VMM-SRS readout system with the APV25 electronics.
4. **Draft paper on Chromium GEM (Cr-GEM) studies:** We plan to continue the performance study of Cr-GEMs with our existing prototype and continue drafting a paper on the results of these studies for publication in NIMA or TNS journal.

2.2 What are the critical issues?

2.2.1 Brookhaven National Lab

The most critical issue we wish to study is the performance of the various forms of readout in a TPC in an operating mode that is optimized for EIC. This is significantly different than what has been studied with these types of MPGDs and readout boards in eRD3/eRD6 in the past since the spatial resolution is affected by the diffusion of the primary ionization across the drift volume. One therefore wants to study the effect of this when used in combination with various forms of gas amplification devices and readout structures. In addition, the time resolution of the detector and the readout plays an important role as well, which is not so important in a simple planar detector. Finally, since the amount of ion feedback for a TPC operating at EIC will mostly likely be much less than for a TPC operating in a heavy ion environment such as sPHENIX and ALICE, the design of those TPCs will not necessarily be optimal for a TPC for EIC, and we would therefore like to determine the optimal design and operating conditions for the electron ion collider environment.

2.2.2 Florida Tech

Technical Issues: The original 3D-printed design of the pull-out posts for the low-mass detector proved to be not robust enough. Under tension force in the open detector, they tend to bend more than we expected and some show cracks. The original pull-out design is a copy of the pull-out used in the CMS forward muon GEM upgrade, but there the pull-outs are made from stainless steel whereas we attempted to use very light ABS material in the EIC prototype. We have changed the pull-out design to a solid block (Fig. 27 left) that appears to be more stable. Some of the original pull-outs could be replaced with redesigned block pull-outs that are more robust before the beam test. At the time of the writing this report, the chamber is being retrofitted with additional pull-outs that are being 3D-printed at Fermilab. After the beam test, we plan to replace all pull-outs with new pull-outs made from aluminum or possibly PEEK.

On the long side of the detector, there are centimeter-wide gaps between the inner frames that cause some foil warping in those gaps (Fig. 27 right). This in turn causes shorts between foils or HV instabilities as the distances between foils are not sufficiently constant. By contrast, the inner frames at the wide end of the trapezoid are very close to each other which keeps the foils smooth in that region. The gaps are the consequence of our original attempt to simplify the frame design by keeping all inner frame pieces at the same length. At the time of writing this report, we are retrofitting the chamber with longer inner frames on the sides that are being 3D-printed at Fermilab to close the gaps. Here we are taking advantage of the purely mechanical chamber construction method that allows a re-opening of the chamber.

Manpower Issues: The departure of our post-doc Aiwu Zhang back in December 2016 has severely slowed down progress. While our undergraduates are doing a great job and are very enthusiastic about building and testing prototype detectors and analyzing beam test data, they have limited availability and experience.

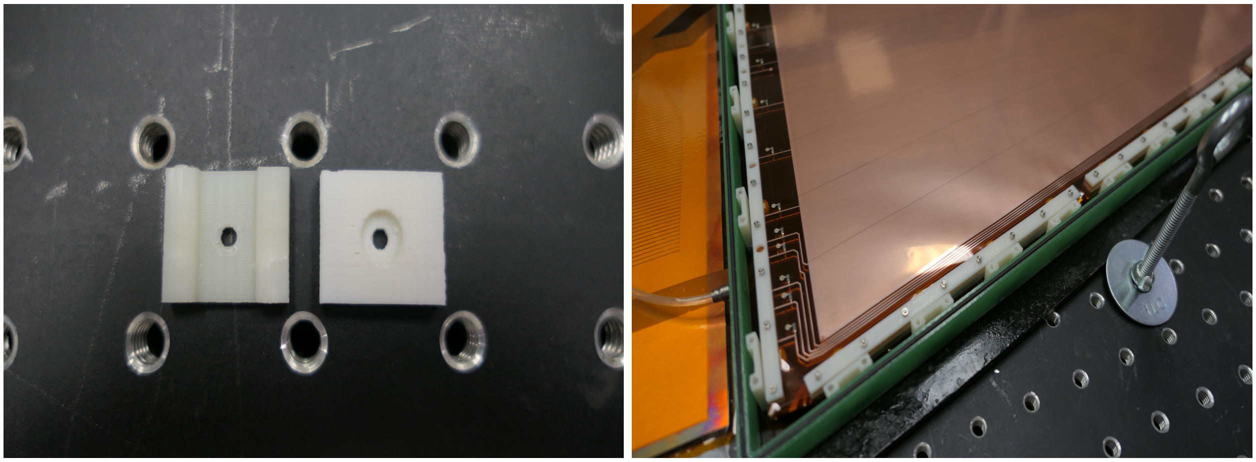

Figure 27: Left: Comparison of original pull-out post (left) and redesigned pull-out post (right) that is more robust. Right: Gaps between inner frames on long sides (on right) cause some foil warping.

2.2.3 INFN Trieste

No technical critical issue is expected for the completion of the planed 2019 activity.

The request support for year 2019 has been kept at the minimum needed to perform the planed activities. Therefore, a reduction of the resources requested would result in the suppression of one or both the foreseen tasks (according to the reduction level).

2.2.4 Stony Brook University

No critical issues have been identified.

2.2.5 University of Virginia

No critical issues.

2.3 Additional information

2.3.1 Brookhaven National Lab

None.

2.3.2 Florida Tech

None.

2.3.3 INFN Trieste

None.

2.3.4 Stony Brook University

None.

2.3.5 University of Virginia

None.

3 Manpower

3.1 Brookhaven National Lab

This work is being carried out by members of the BNL Physics Department. It includes two Senior Scientists (0.2 FTE), two Physics Associates (1.2 FTE), and one Technician (0.3 FTE).

3.2 Florida Tech

- Marcus Hohlmann, Professor, 0.25 FTE, not funded under this R&D program.
- Matthew Bomberger, physics undergraduate student, funded with $1.7k in summer 2018 by this R&D program.
- Samantha Wohlstadter, physics undergraduate student, not funded.

3.3 INFN Trieste

From INFN Trieste:

- J. Agarwala (ICTP and INFN, fellowship)
- C. Chatterjee (Trieste University and INFN, PhD student)
- S. Dalla Torre (INFN, Staff)
- S. Dasgupta (INFN, postdoc)
- S. Levorato (INFN, staff)
- F. Tessarotto (INFN, Staff)
- Y. Zhao (INFN, postdoc)

The contribution of technical personnel from INFN-Trieste is also foreseen according to needs.

From INFN BARI:

- Grazia Cicala (NCR staff and INFN)
- Antonio Valentini (Bari University and INFN, professor)

Globally, the dedicated manpower is equivalent to 3 FTE.

3.4 Stony Brook University

- K. Dehmelt, Research Scientist, 0.3 FTE
- T. K. Hemmick, Professor, 0.1 FTE
- P. Garg, Postdoc, 0.1 FTE

All personnel is not funded under this R&D program.

3.5 University of Virginia

None of the labor at UVa is funded by EIC R&D. The workforce is listed below:

- N. Liyanage; Professor; 0.1 FTE
- K. Gnanvo; Research Scientist; 0.5 FTE
- H. Nguyen; Research Scientist; 0.1 FTE
- J. Matter; Graduate Student; 0.1 FTE
- A. Rathnayake; Graduate Student; 0.1 FTE
- M. Dao; High School Student; 0.1 FTE

4 External Funding

4.1 Brookhaven National Lab

All scientific manpower at BNL would be provided by internal funding. However, technician and designer labor would need to be supported through EIC R&D funds.

Additional work on R&D on Micropattern Detectors for EIC is also being provided by a BNL LDRD in collaboration with Saclay and Stony Brook. This is supporting our continued work on zig-zag readout with GEMs and Micromegas and we do not request any funding for this effort from EID R&D funds. However, our proposed work on TPC R&D for EIC would not be covered under LDRD funds.

4.2 Florida Tech

None.

4.3 INFN Trieste

A support of 18 keuro for the year 2019 is being requested to INFN.

Stony Brook University

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

4.4 University of Virginia

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

eRD6 R&D Funding Request for FY19

The New eRD6 Consortium: Merger of eRD3 and eRD6 Consortia

Project ID: eRD6

Project Name: Tracking & PID detector R&D towards an EIC detector

Period Proposed: FY19

Project Leaders:

Brookhaven National Lab (BNL): Craig Woody

Florida Institute of Technology (FIT): Marcus Hohlmann

INFN Trieste: Silvia Dalla Torre

Stony Brook University (SBU): Klaus Dehmelt, Thomas Hemmick

Temple University (TU): Matt Posik, Bernd Surrow

University of Virginia (UVa): Kondo Gnanvo, Nilanga Liyanage

Yale University: Richard Majka, Nikolai Smirnov

Project Members:

BNL: B. Azmoun, A. Kiselev, M. L. Purschke, C. Woody

BNL - Medium Energy Group: E. C. Aschenauer

FIT: M. Bomberger, M. Hohlmann

INFN Trieste: S. Dalla Torre, S. Levorato, F. Tessarotto

SBU: K. Dehmelt, A. Deshpande. N. Feege, P. Garg, T. K. Hemmick

TU: M. Posik, A. Quintero, B. Surrow

UVa: K. Gnanvo, N. Liyanage

Yale University: R. Majka, N. Smirnov

Contact Person: Kondo Gnanvo; kgnanvo@virginia.edu

5 eRD6 R&D Proposals for FY19

5.1 R&D on MPGD readouts for EIC TPC

5.1.1 Motivation

At Brookhaven, we plan to start a new activity in FY19 to investigate various forms of readout for a TPC that would optimize its operation for EIC. While there have been R&D activities within eRD3/eRD6 that are relevant to the operation of a TPC at EIC, there have so far been no dedicated activities on the actual design or performance of a TPC within the EIC R&D program. We believe the design of a TPC that is optimized for EIC requires such a dedicated and focused effort in order to understand its requirements and to optimize its design parameters. We plan to collaborate with Yale on this project since they have extensive experience in both MPGDs (both GEMs and MicroMegas) as well as with TPCs. They were involved with the operation of the STAR TPC and are currently building a portion of the GEM detectors for the ALICE TPC. We feel that their expertise and participation in this project is essential and that they will make a significant contribution throughout its duration.

5.1.2 R&D Plan

We wish to begin this study with the investigation of various types of MPGD readouts that can be optimized for operating a TPC at EIC. This builds on our previous experience with GEMs and Micromegas, and would also include other types of gas amplification stages, such as hybrid GEM/Micromegas configurations as well as μRWELLs. We will study these devices with different types of readout, including 1D zigzag patterns and various types of 2D readout patterns, that would also build on our past experience with these types of readout boards. Due to the differences in the size of the resulting charge cloud from these different types of devices, the choice of the readout pattern must be studied and optimized for each type of device and combination independently.

Part of the reason for not doing these studies in the past is that they require a significant investment in equipment to carry them out. However, we are now in a position to do so with much of the equipment already in hand. We would utilize the small TPC prototype built to study the TPC/Cherenkov detector that was carried out as part of this R&D program several years ago. As mentioned, we are rebuilding the TPC portion of this detector to include just the TPC part, which has a 10x10x10 cm^3 drift volume, which should be working in our lab in a few months. It utilizes a 10x10 cm^2 readout board that can be easily switched between one type of gas amplification device and another. We have also built a cosmic ray telescope that will accommodate this detector that will allow us to measure tracks in the TPC and use it to study various forms of readout. We also have a complete gas system that can be used to study each detector/readout combination with different gases.

Another major component required to study a TPC is having a readout system that will allow measuring long enough drift times to reconstruct tracks in the detector. Until recently, we had only the SRS readout system, which suffers not only from having a very limited dynamic range but also has a very limited drift time range. However, as a result of the work we are doing on the sPHENIX TPC, we now have a working system using the SAMPA readout chip that provides a full range of 5 - 10 μsec for reading out the drift time with 1024 samples at 10 – 20 MHz sampling rate. This should be more than sufficient to study our small TPC prototype. We also now have a version of the DREAM electronics that can also be used to readout the TPC, as well as a system of CAEN V1742 DRS modules, which can provide excellent time resolution (up to 5 Gs/s) for up to 128 channels, with a more limited drift time range.

We would fabricate two or more versions of readout boards that would be used to study the TPC readout with various combinations of gas amplification stages. These would include zigzag patterns similar to those developed in our previous R&D, including laser etching of the PCB that can in principle significantly improve their performance. We would select what we feel are several of the most optimal combinations of these patterns for each of the gain structures to be tested and have readout boards fabricated with those patterns. They would have a uniform pattern across the entire 10x10 cm^2 readout area in order to provide uniform resolution for finding tracks in the TPC.

5.2 R&D on Meta-Materials for Detection of Cherenkov Radiation

5.2.1 Introduction

We are proposing the extension of the R&D on the short length radiator RICH prototype that has been so far performed until 2015. It has been concluded then that the segmentation of the readout (hexagonal pads with apothem of 5 mm) limits the resolution requirement for the ring of the Cherenkov cone so that the momentum reach of the RICH in an EIC detector would be jeopardized. The reason for this limitation is that the radiator medium (CF_4) provides only little diffusion so that charge sharing over more than one pad on the readout plane is essentially excluded. One possibility to overcome that limit is to decrease the pad size, however, this will significantly increase the channel count. Another possibility is to introduce charge broadening via resistive layers, however, this introduces other complications which makes this approach less desirable.
Another option might be to change the conditions for the radiator material in the way that it acquires properties of high index-of-refraction material in one direction and small index-of-refraction in the other direction. These highly inhomogeneous properties of materials might be possible with specifically tailoring them.
It is conceivable that a material can be constructed whose permittivity and permeability values may be designed to vary independently and arbitrarily throughout a material, taking positive or negative values as desired. This opens a domain of activity which enables to control a variety of electromagnetic applications. The term used is *transformation optics* and its core idea is the correspondence between coordinate transformation and material implementations, in short Transformation Optics Meta-materials (TOM).

5.2.2 Electromagnetic and Physical Space

There is an equivalence between geometries (Electromagnetic Space ***ES***) and media (Physical Space ***PS***). The recipe for transformation optics is to distort the coordinate system, (x, y, z) $\rightarrow$ (u, v, w) and the trajectory of any rays of light as well. A coordinate transformation implies a refractive index change. Using transformation theory to calculate the refractive index that gives the distorted ray trajectories yields: $n' = n \cdot$ g(u, v, w) and g(u, v, w) is obtained from the coordinate transformation. A schematics of this procedure can be seen in Fig. 28.

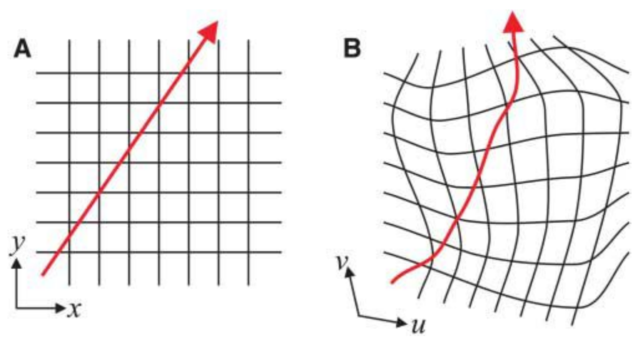

Figure 28: A field line in free space with the background Cartesian coordinate grid shown. (B) The distorted field line with the background coordinates distorted in the same fashion. The field in question may be the electric displacement or magnetic induction fields $\vec{D}$ or $\vec{B}$, or the Poynting vector $\vec{S}$, which is equivalent to a ray of light ([37]).

The geometric techniques of transformation optics can be used to understand the Cherenkov radiation emitted in arbitrary anisotropic media. Using a geometric formalism to obtain an increased understanding

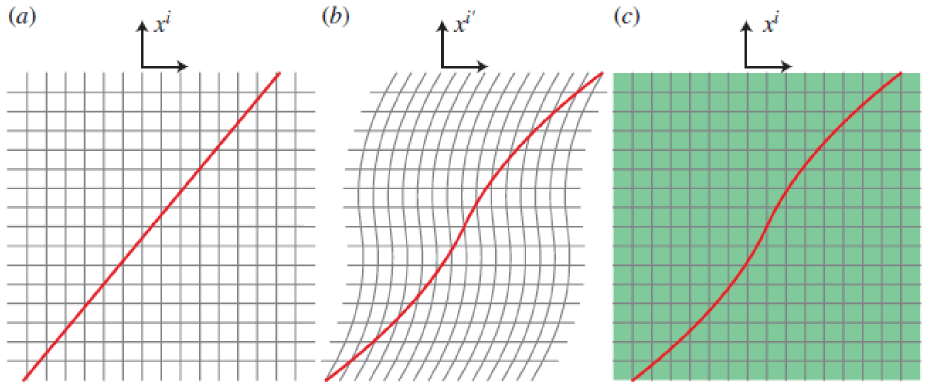

Figure 29: TOM principle ([38]): (a) ES, described with a Cartesian coordinate system. (b) The same ES described in a deformed coordinate system, in which the x′-coordinate is described by a function $f(x, y)$ and the y′-coordinate remains the same. The black lines represent the old coordinate lines viewed from the new coordinate system. (c) PS, in which the meta-material is implemented as of the curved ES (b).

in the propagation of light through complex dielectrics often leads to novel methods for the design of optical components.

Transformation optics allows for local transformations of the coordinate system. It is possible to manipulate light within a certain finite region using a non-trivial coordinate transformation that approaches unity at the boundaries of the region. In this way, it is possible to create a finite component that smoothly manipulates light without reflections at the boundaries. This aspect of transformation optics is closely related to the impedance matching of the equivalence relations: coordinate transformations affect the permittivity and the permeability of electromagnetic space in the same way. The impedance of the optical component in physical space will thus be the same as in the initial system in electromagnetic space.

Material parameters of a medium can be calculated for Cherenkov radiation emitted by a charged particle along the x-axis in a medium with background refractive index $\varepsilon_b = n_b^2$ on top of which a *linear coordinate stretching* along the principle axes has been implemented: $x' = f(x), y' = g(y)$ and $z' = h(z)$. One obtains by applying the equivalence relation of transformation optics the material properties:

$$\frac{\varepsilon_{x,x}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{x,x}}{\mu_0} = \frac{g'(y)h'(z)}{f'(x)}, \; \frac{\varepsilon_{y,y}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{y,y}}{\mu_0} = \frac{f'(x)h'(z)}{g'(y)}, \; \frac{\varepsilon_{z,z}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{z,z}}{\mu_0} = \frac{f'(x)g'(y)}{h'(z)} \tag{1}$$

where the $f',\ g',\ h'$ are BACK-transformations from the system that was arrived via $f,\ g,\ h$. This procedure is depicted in Fig. 29.

By applying transformation optics one can calculate the Cherenkov cone emitted by charged particles traveling through anisotropic media. Cherenkov radiation obeys the geometry of the electromagnetic reality and the Cherenkov cone can be manipulated with material parameters that implement coordinate transformations. One obtains inhomogeneous Maxwell equations and can solve it with a plane monochromatic wave solution. As a result, a dispersion relation can be obtained that allows to calculate the Cherenkov cone's angle in an inhomogeneous medium

$$\tan(\alpha_{PH}) = \frac{k_y}{k_x} = \frac{G}{F}\frac{\sqrt{F^2\epsilon_b\omega^2/c^2 - k_x^2}}{k_x} = \frac{G}{F}\tan\alpha^*$$

with α^* the angle of Cherenkov radiation emitted in a medium with refractive index n_b. Consequently, one obtains

$$\alpha_{PH} = \arctan\left(\frac{G}{F}\tan\left(\arccos\left(\frac{c}{n_b F v}\right)\right)\right).$$

The particle seems to be traveling with a velocity of Fv in ***ES*** in a medium of refractive index n_b

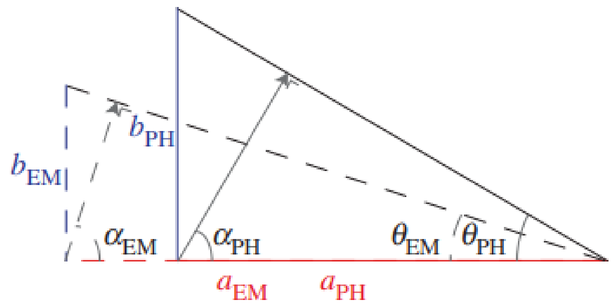

Figure 30: Transformation of the Cherenkov cone from ES (sometimes called EM) to PS (sometimes called PH, from [39]). The solid triangle depicts the anisotropic PS and is a scaled version of the dashed triangle from ES. The scaling factors are F in longitudinal and G in transverse directions..

and emits photons with the Cherenkov cone angle $\theta_{\boldsymbol{ES}} = \arcsin\left(\frac{c}{n_b F v}\right)$. For getting into ***PS*** the coordinates x, y need to be compressed by a factor F, G in ***ES***. In ***PS***, the Cherenkov angle is $\theta_{\rm PS} = \arctan\left(\frac{F}{G}\tan\left(\arcsin\left(\frac{c}{n_b F v}\right)\right)\right)$ [1].
A transformation perpendicular to the trajectory of the charged particle only stretches the Cherenkov cone, whereas a transformation along the path of the particle also alters the velocity of the particle in ***ES***. The velocity cutoff is when the particle's velocity drops below c/n_b. However, for a particle traveling through a dielectric (with refractive index n_b) at a velocity v smaller than the phase velocity of light in that medium $v < v_{phase} = c/n_b$ it is possible to change to a novel coordinate system, in which the particle seems to be traveling faster than the speed of light in the dielectric [2]. This is a consequence of a longitudinal transformation that can scale the particle's velocity above or below the Cherenkov cut-off velocity, see Fig. 31. One needs to change the refractive index of the dielectric ($n = n_b F$, where F is a scaling factor determined by transformation optics, see above), because of which the phase velocity of light also changes in this medium. In this new medium, it is then clear that $v > v_{phase} = c/n$, which explains the existence of Cherenkov radiation in the transformed medium. The aim is now to determine meta-materials that produce small forward stretch factors and large factors perpendicular to the direction of the particle (see Fig. 32).

5.2.3 Meta-Materials for Cherenkov-Radiation Detection

The ACCESSIBLE wavelengths for optical $\rightarrow$ VUV photons are within the 700 $nm \rightarrow 150$ nm-range. ACCESSIBLE means that these photons can be readily measured and do not require newly developed photon-readout devices. It should be possible to fabricate devices that provide materials with inhomogeneous indices of refraction, i.e., providing F, G, and H (see above) and compatible with wavelength in the desired range of $150\ nm \leq \lambda \leq 700\ nm$.
Photonic-crystals and Meta-materials might be such devices. They are formed by building units of a size s intermediate between the molecular scale $m = (1-3)\ nm$ and the optical wavelength λ and cannot be simply synthesized as small organic molecules as is used to form, e.g., liquid crystals. Design, manufacturing, and control of properties of photonic-crystals and meta-materials at the scale $m < s \leq \lambda$ is the major challenge. There are a variety of ways by which the fabrication of liquid crystals can help in the development of photonic-crystals and meta-materials.
A comparison between traditional radiators and meta-material radiators for fixed momentum (40 GeV/c) and wavelength ($\lambda = 700\ nm$) has been performed which is compiled in Fig. 33. There, the black dashed line shows isotropic radiators and their limitations between sensitivity and magnitude of Cherenkov angles. The colored lines depict the properties of several meta-material radiators. Each line corresponds to a different background dielectric, starting from $\epsilon_d = 1.2$ at the lowest curve and increasing with steps of 0.2 for the consecutive curves. The color of the curves encodes the value of the filling factor. The colored circles show that

[1] Analogously, the x-z-plane would need the factor $\frac{F}{G}$ replaced by $\frac{F}{H}$.
[2] In principle, this allows to PRODUCE any turn-on velocity for Cherenkov radiation.

a meta-material with $\epsilon_d = 3$ and $f = 0.076$ (blue circle) supports Cherenkov angles of the same magnitude ($\alpha = 0.310$ rad) as a silica aerogel radiator (red circle), in combination with a more than twofold increased sensitivity ($\Delta\alpha = 0.86$ $mrad \rightarrow \Delta\alpha = 2.27$ $mrad$). In Fig. 33(b) an implementation of a meta-material is shown with parameters corresponding to the blue circle in Fig. 33(a). Several thin silver cylinders are embedded in a dielectric with $f = 0.076$ and provide an example for meta-materials. The central region is unfilled to allow for unobstructed propagation of charged particles. The thickness of the layers equals 20 and 234 nm for the silver and the dielectric, respectively. The material can be treated as an effective, homogeneous medium, so transition radiation can be neglected.
Meta-materials provide an option to significantly improve RICH detector performance, reduction in space by shortening the radiator and extending the momentum coverage. The field of developing meta-materials is a rather new field and allows for exciting future applications and might even change the landscape of detector development.

5.2.4 R&D Plan

We will be performing calculations and simulations for determining the material parameters that constitute particle detectors with enhanced detection sensitivity. We will verify effective Cherenkov radiation and extend to higher dimensions (2-D and 3-D) upon 1-D photonic crystals that have been developed by industry. We will work out with commercial providers a realistic metamaterial implementation of such a detector with transparent dielectrics.
We will upgrade our existing RICH prototype with photo-multipliers and adapt the mirror to new detection conditions We anticipate to perform a proof-of-principle experiment at a test-beam facility like Fermilab's FTBF.

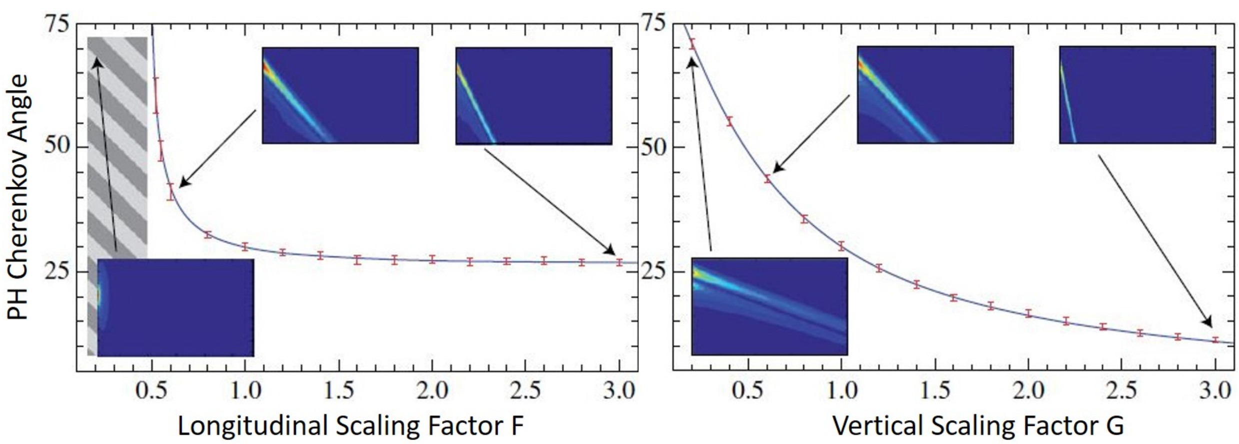

Figure 31: Full-wave numerical simulations of the Cherenkov radiation (red symbols) versus the corresponding analytical expression (from [39]); Left: $F = 1$, Right: $G = 1$ with $c/n_b v$ =0.5. The same results are obtained for impedance-matched and for non-magnetic implementations of the coordinate transformation. The insets show the corresponding density plots of the intensity of the emitted Cherenkov radiation. Left: the shaded area highlights the parameter regime where no Cherenkov radiation is emitted because the velocity of the particles in ES has dropped below the speed of light ($n_b F v < c$).

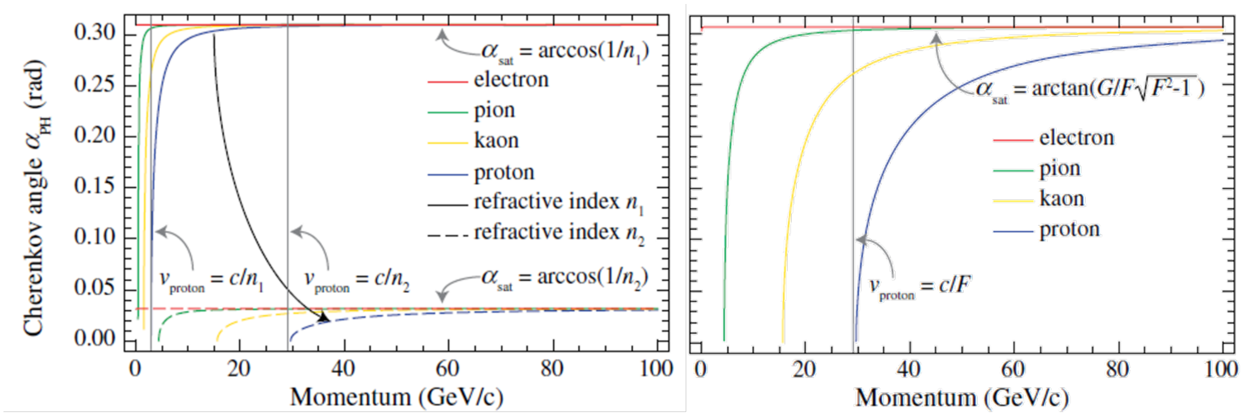

Figure 32: Left: the Cherenkov angle as a function of particles' momentum for several particles for radiators – solid lines: silica aerogel ($n = 1.05$), – dashed lines: CF_4 ($n = 1.0005$). Right: META-CF_4 in a transformation-optical medium in which vacuum is stretched such that $F = 1.0005$ and $G = 10$ (from [39]).

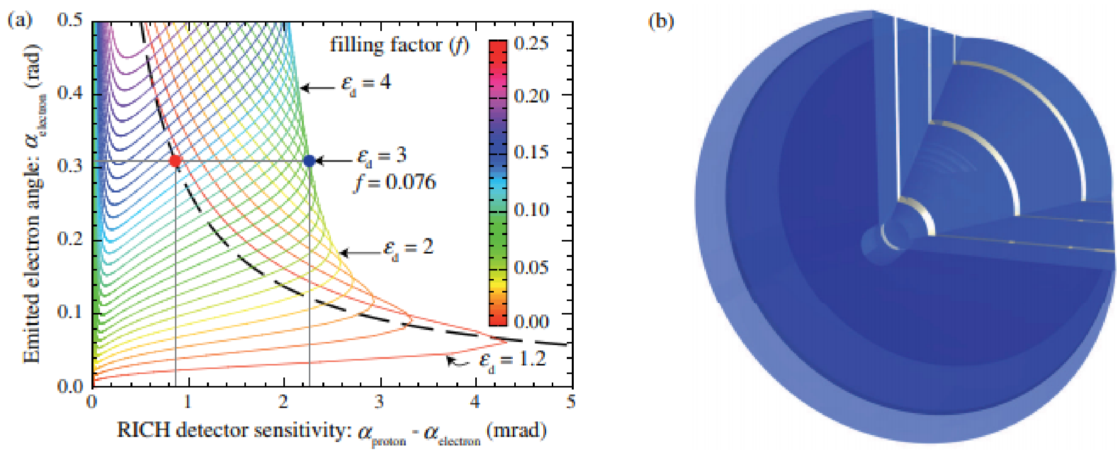

Figure 33: The functionality of several meta-material radiators (from [39]).

5.3 R&D on μRWELL Detectors for EIC Central Tracker

5.3.1 Motivation for Research

During a recent EIC workshop which took place in November 2017 in Philadelphia, PA, a consensus formed within the community that the EIC should ideally have two large detectors - preferably with complementary technologies. One of these detectors would presumably feature a TPC in the central region while the second detector should seek an alternative tracking technology. One such technology that has the specific advantage of providing fast tracking signals could be based on the resistive micro-well detector - aka the μRWELL detector. Conceptually, a μRWELL detector consists of an HV drift cathode, a drift gap, and a micro-well layer (similar to a single GEM foil) which is mounted on a resistive readout board. This detector has seen a lot of development over the past few years and has been tested on small scales (10 cm $\times$ 10 cm) [40, 41] and even on a large scale in an R&D effort for the forward muon upgrade of CMS.

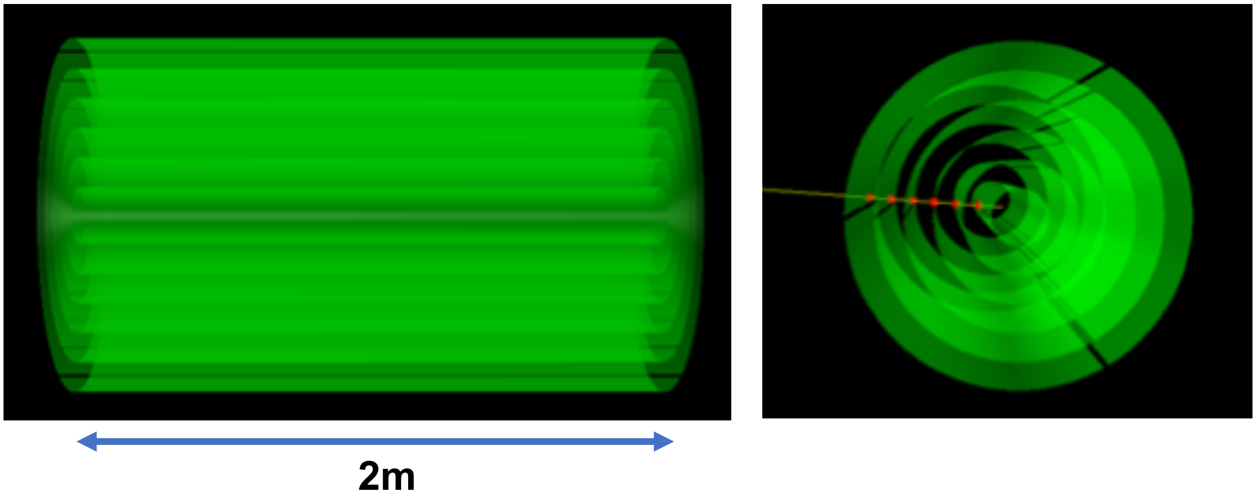

Figure 34: Initial implementation of cylindrical shells based on low-mass μRWELL detector in EICROOT.

5.3.2 R&D Plan

Florida Tech, Temple U., and U. Virginia will be collaborating on this effort. BNL will be in a supporting role, but does not request funding this cycle. Temple plans to focus on simulations to gain a better understanding of the practicality and benefit of implementing such a technology compared with a TPC. Florida Tech and U. Virginia will begin some basic hardware work by studying the characteristics and performance of the small planar 10 cm $\times$ 10 cm μRWELL prototypes that each group procured in the last funding cycle. This includes the test of one such prototype during the 2018 eRD6 test beam effort at FNAL. In addition, Florida Tech and U. Virginia plan to collaborate on designing a first small cylindrical prototype. The BNL group plans to study the performance of several laser etched zigzag pad readout boards joined to a μRWELL structure.

Simulation at Temple U. Our ideal vision sees the TPC replaced with several cylindrical shells of low material μRWELL detectors. We can make these detectors low mass, in principle, by using a HV cathode foil and replacing the readout board with a 2D readout foil. Figure 34 shows an initial implementation of the low mass μRWELL cylindrical shells in EICROOT. There are three initial simulations that we would like to investigate within the EICROOT frame work:

1. Implement these low material μRWELL cylindrical shells and study the reconstructed momentum resolution as a function of the number of cylindrical shells making up the complete detector ensemble.
2. Study the momentum resolution performance of different particle species, i.e. electrons, pions, etc. in the kinematic regime where an EIC central tracker would be needed.
3. Finally, replace the cylindrical μRWELL shells with a TPC and repeat the momentum resolution measurement for different particle species (as in step 2) to provide a direct comparison of the momentum resolution with the μRWELL cylindrical shells.

Hardware and Design at Florida Tech and U. Virginia The main challenge for this R&D project is to make the μRWELL into a cylindrical structure, which has not been done before. We plan to do this by implementing the readout structure on a foil instead of on a PCB to make the entire amplification and readout structure flexible so that it can be mounted on a low-mass cylindrical support structure. Here we will benefit from the experience with the Florida Tech and U. Va forward tracker prototypes that also have their readouts implemented on large foils. If this approach works, there should be no a priori limit to the size of the cylinder for which this can be done since the Kapton base material can be made arbitrarily long in one dimension. This would then allow the manufacturing of a continuous large μRWELL ring that could surround the vertex detector.

As a first step, we will design a low-mass cylindrical μ-RWELL with a diameter of 10-20 cm and a length of about 30 cm. We will address mechanical issues such as ensuring a constant drift gap around the detector and design a readout structure that allows reading out signals from both ends while providing high spatial granularity.

If this is successful, we anticipate a follow-up funding request for the production of such a cylindrical prototype in the FY20 funding cycle.

Studies of a μRWELL coupled to a Zigzag readout at BNL We plan to send several of our laser etched zigzag boards (which we already have in hand) to CERN to have them coupled (through a resistive layer) to a μRWELL structure. Such a device has the potential for exhibiting very good spatial resolution while utilizing only a single gain stage, which may be beneficial in several ways. We plan to determine how suitable the charge spread generated by the μRWELL is for the zigzag patterns, in addition to comparing the overall performance of this device to traditional avalanche schemes like a 4-GEM and to more novel ones including a GEM + Micromegas hybrid structure. We initially plan to study the μRWELL-zigzag detectors in the lab using our x-ray scanner and cosmic ray telescope and will make these facilities available to our colleagues at Florida Tech and U. Virginia and will offer needed assistance in a supportive capacity.

5.4 R&D on MPGDs for EIC RICH Detector

INFN Trieste
The 2019 activity consists in the continuation of the two tasks already pursued in 2018 and detailed in Sec. 2.1.3.

The founding request for this R&D activity, 50 k$ in total, includes three main chapters:

1. the financial support for a postdoc (7 months) fully dedicated to the project: the contribution of a dedicated personnel unit will offer a crucial boost to the R&D program;
2. traveling resources, mainly to have the possibility of closer interaction with the whole eRD6 Consortium and to follow the evolution of the EIC project: two trips to US require about 6000 $; a minor support is requested to allow travelling to and from Bari and Trieste for the common work about the ND photocathodes: this needs is estimated to be 3000 $; another minor support is requested for material procurement, to interact with the producers when non-standard components are needed and for the construction of specific detector elements that must be produced at CERN: this needs is estimated to be 3000 $;
3. Consumables have to cover prototype components and prototype operation costs; the needs for the next year will be partially covered by the delayed availability of the support granted for this year. Consumables for FY2019 include:
    - Material and fabrication of THGEMs to be used as ND photocathode substrates: 2000 $;
    - Mechanics and equipment (connectors, gas connections, mechanical frames) for the last-minute needs at the October 2019 test beam: 2000 $;
    - ND powder samples: 2000 $;
    - production of a new MM for the miniaturized pad prototype according to the new design (Sec. 1.3.3) (high-quality PCB, bulk MM, connectors): 7000 $
    - Miscellanea of laboratory small items: 2000 $.

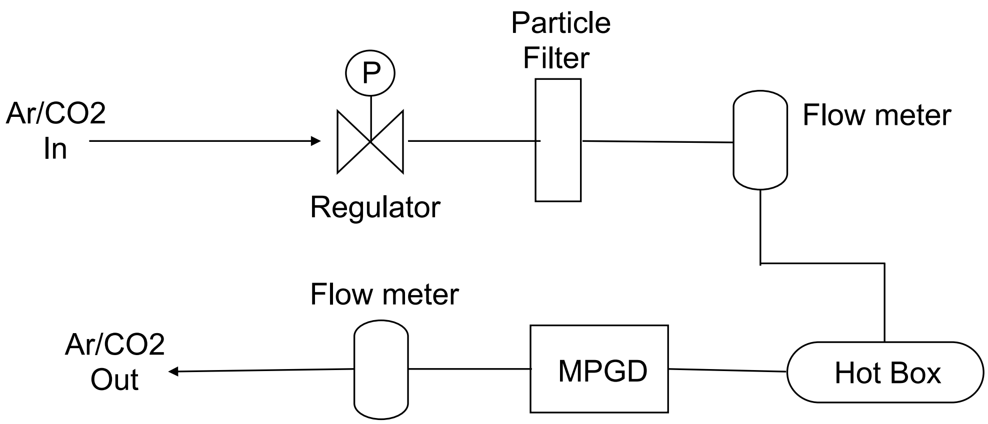

Figure 35: Outgassing test system schematic.

Cost reductions in -20% and -40% scenarios
The requests have been carefully analyzed and kept at a minimal level. Any reduction would severely impact. In the "-20%" hypothesis one of the two foreseen activity has to be stopped. In the "-40%" hypothesis the whole INFN Trieste activity will be stopped.

5.5 Development of Outgas Test System at Temple University

Motivation for Research

With current trends in MPGD assembly moving towards 3D printed structures (sPHENIX, eRD6), many of the printing materials will need to be tested, in particular for their outgassing properties, before they can be used in a detector. As outgassing can hinder the performance of a MPGD detector, it is vital that only printing materials with a low outgas behavior are selected.

We propose the assembly of an outgas testing setup at Temple University. This setup would be based on a similar setup used by the CMS group [42]. The setup consists of a gas system supplying pre-mixed gas to a wire chamber detector, a "hot box", which is a stainless steel cylinder, and an 55Fe source, as can be seen in Fig. 35. The gas is sent through the "hot box", which is a stainless steel cylinder wrapped in resistive tape to allow it to be heated. The test material is inserted into the hot box, and can be heated to increase the outgassing of the material. The gas then leaves the hot box and enters the detector where the gain is monitored using an 55Fe source. The level of outgassing can be inferred from the gain changes in the detector.

Not only will this outgassing setup compliment eRD6's own 3D printing R&D (from FIT and UVa), but can also be used by the broader MPGD community. Temple University has already successfully established a similar relationship with their CCD GEM scanner, which has serviced the larger MPGD community, with foils being scanned for experiments such as BONUS and CMS, as well as EIC related R&D (large CERN EIC foil, Cr-GEM). We envision a similar situation with an outgas testing setup that will serve our specific eRD6 R&D, the broader EIC R&D, as well as the general MPGD community.

Funding Request

This test setup would be built at Temple University and can be split into two phases

1. Setting up the initial test system consisting of the gas system, detector, DAQ, and 55Fe source. This will need to be in place in order to characterize the gain of the detector as a reference.

2. Once the gain behavior of the detector is fully characterized, the hot box can then be installed into

the gas system. This would then complete the testing setup.

There are two detectors that we would like to build the setup around

1. A small wire proportional chamber (similar to the one used in the CMS setup [42]) and accompanying DAQ system.
2. A standard 10 cm x 10 cm triple-GEM detector and accompanying DAQ (CERN SRS).

To complete phase one of the testing setup we would need materials for

1. The gas system: gas, stainless steel tubing, hardware (valves, regulators, flow meter, etc.)
2. Detector(s) (MWPC and triple-GEM)
3. DAQ system
4. Partial manpower (30% postdoc)

The manpower request is needed to build and test the outgassing system. Additionally some of this manpower will go towards completing the data analysis of the commercial triple-GEM detectors, as discussed in the eRD3 progress report.

Phase two of the project, which involves installing the "hot box" can then be carried out the following funding cycle.

5.6 eRD6 Budget Request for FY19

5.6.1 Overall Budget Request and Money Matrix

The budget requests presented in the previous subsections of Sec. 5 are summarized in the following. The money matrix R&D project vs. Institute for eRD6 the fundng requests for FY19 is presented on Table 1

Table 1: Cost matrix per institutes and R&D of eRD6 FY19 budgetary request

k$	**MPGD-RICH**	**μRWELL**	**TPC Readouts**	**Meta-Materials**	**Outgassing**	**Total**
BNL - Yale U.			75			**75**
Florida Tech		75				**75**
INFN Trieste	50					**50**
Stony Brook U.				80		**80**
Temple U.		23			50.421	**73.421**
UVa		25.075				**25.075**
Total	**50**	**123.075**	**75**	**80**	**51**	**378.496**

5.6.2 Budget Request by Institute

BNL: Funds are requested to fabricate two or more versions of readout boards that would be used to study the TPC readout. We also request funds for expendable materials and miscellaneous electronic components in order to interface these readout boards to our various electronic readout systems. Funds are also requested for technician and designer support which would need to be paid for out of EIC R&D funds. We are also requesting travel support for both BNL and Yale for travel back and forth between the two institutions, as well as partial support for testing the detector in the test beam at Fermilab. We envision that this test would be done at the same time as other eRD3/eRD6 or other gas detectors are being tested in the beam in order to minimize the overall cost of the test beam effort.

Table 2 below gives the funding requests for the TPC study for the three funding scenarios of the baseline budget, 20% reduction and 40% reduction. The full budget scenario includes the fabrication of at least two versions of the readout board, while the reduced scenarios include probably only one. In the 40% reduction scenario, we also cut back significantly on technical support and travel.

Table 2: BNL FY19 budgetary request

	Baseline (k$)	**-20% (k$)**	**-40% (k$)**
Readout boards (uniform patterns)	20	10	10
Gas and misc. electronic components	5	5	5
Technical support	10	10	5
Travel (includes support for Yale)	15	15	10
Total w/o overhead	50	40	30
Overhead	25	20	15
Total with overhead	**75**	**60**	**45**

Florida Tech: We request funding to cover 50% of a post-doc salary. We will seek the other half from university matching. The post-doc will analyze forward tracker beam test data, further characterize the forward tracker performance with X-rays, contribute to the design of the cylindrical μRWELL detector prototype, and guide the undergraduate in the EICroot simulations. We also request funds for travel to BNL to conduct X-ray scans of the small μRWELL prototype, for attending one EIC R&D review meeting, and for travel to a conference for presenting results. A small amount is requested for materials and consumables such as gas.

Table 3 breaks down the funding request for the Florida Tech projects, along with the 20% and 40% reduced funding scenarios. In the 20% reduced scenario, we request 12-month funding for a graduate student stipend and tuition and summer support for an undergraduate student instead of half a post-doc salary. In the 40% reduced scenario, the tuition request is dropped. Florida Tech does not charge benefits or overhead on students for the current grant.

Table 3: **Florida Tech** - FY19 budget request including scenarios with 20% and 40% reduction.

	Request	**-20%**	**-40%**
Postdoc salary (50%, fully loaded)	$64,000	$0	$0
Graduate Student Stipend (12 mos.)	$0	$24,000	$24,000
Graduate Student Tuition	$0	$19,500	$0
Undergraduate Summer Stipend	$0	$6,000	$6,000
Travel (fully loaded)	$9,000	$9,000	$9,000
Materials (fully loaded)	$2,000	$2,000	$2,000
Total	**$75,000**	**$60,500**	**$41,000**

INFN Trieste: The founding request have been already detailed in Sec. 5.4; here they are summarized in Table 4, where the bare requests are listed and also the overhead is included assuming the INFN rate of 20%. The requests are related to three main chapters:

1. the financial support for a postdoc (7 months) fully dedicated to the project: the contribution of a dedicated personnel unit will offer a crucial boost to the R&D program;

2. traveling resources, mainly to have the possibility of closer interaction with the whole eRD6 Consortium, to cover expenses related to traveling to and from Bari and Trieste for the common work about the ND photocathodes and visits to supplier of high-tech components;
3. Consumables have to cover prototype components and prototype operation costs.

Cost reductions in -20% and -40% scenarios
The requests have been carefully analyzed and kept at a minimal level. Any reduction would severely impact. In the "-20%" hypothesis one of the two foreseen activity has to be stopped. In the "-40%" hypothesis the whole INFN Trieste activity will be stopped.

Table 4: Funding request INFN

item	cost (k$)	overhead (k$)	total (=cost+overhead) (k$)
manpower	20	4	24
traveling	10	2	12
consumables	14		14

Stony Brook University: We request funding for modifying the existing RICH prototype and purchasing meta-materials. We request also funding for a test-beam campaign at FTBF.
The funding request for meta-materials is based on estimates after consulting colleagues at Stony Brook University and other institutes familiar with the subject. All funding requested is fully loaded.
The funding request is based on a reasonable estimate and a reduction of 20% would delay the performance of the proposed R&D out of FY19. A further reduction by a total of 40% would bring the project to a non-starter situation.

Table 5: Funding request Stony Brook University

	Request	**-20%**	**-40%**
Photon readout	$20,000	$16,000	$14,000
Mirror parts	$5,000	$4,000	$3,000
Travel	$10,000	$8,000	$6,000
Consumables	$5,000	$4,000	$3,000
Developing meta-materials	$40,000	$32,000	$24,000
Total	$80,000	$64,000	$48,000

Temple U.: The barrel μRWELL detector simulation is requesting only partial manpower to carry out the simulations study. The nominal request for the simulation project asks for 20% of a postdoc. For the outgassing test we are requesting funding for purchasing the material and equipment needed to complete phase one of this project, which includes building a gas system, detector, and setting up a detector DAQ system. We are also requesting partial manpower in order to assemble and test the setup. The full breakdown for Temple U.'s funding request is presented in table 6, along with 20% and 40% reduced funding scenarios.

UVa: We are requesting fund to pursue the R&D on μRWELL detector technology mainly in area of the developement of low material hogh spatial resolution 2D readout μRWELL detector structure. The reuquest for this project represent 40 % of our total request. We are also interested in acquiring the SRS implementation of the VMM electronics. The estimated cost of a small VMM-SRS crate is about 20 % of

Table 6: **Temple University** - FY19 budget request scenarios with 20% and 40% reduction.

	Request	**-20%**	**-40%**
Postdoc (%)	$28,184 (50%)	$22,547 (40%)	$14,092 (25%)
Fringe (26.85%)	$7,567	$6,054	$3,784
Total Personal	$35,751	$28,601	$17,876
Material	$3,000	$1,500	$1,500
Equipment	$12,000	$10,000	$10,000
MTDC	$38,751	$30,101	$19,376
Overhead (58.5%)	$22,670	$17,609	$11,335
Total	**$73,421**	**$57,710**	**$40,711**

our budget request. The rest funds are dedicated to travel for conferences, EIC meeting and test beam as well detector lab supplies and technical support and overhead.
Table 7 presents the full breakdown for UVa's funding request along with 20% and 40% reduced funding scenarios.

Table 7: **University of Virginia (UVa)** - FY19 budget request scenarios with 20% and 40% reduction.

	Request	**-20%**	**-40%**
μRWELL	$10,000	$5000	$5000
VMM Electronics	$5,000	$5,000	$3,000
Lab supplies	$2,000	$2,000	$1,000
Travel (fully loaded)	$5,000	$4,000	$3,000
Overhead (61%)	$3075	$2460	$1845
Total	**$25075**	**$18460**	**$13845**

References

[1] B. Azmoun et al. "A Study of a Mini-Drift GEM Tracking Detector". In: *IEEE Transactions on Nuclear Science* 63.3 (June 2016), pp. 1768–1776. ISSN: 0018-9499. DOI: 10.1109/TNS.2016.2550503.

[2] Craig Woody et al. "A Prototype Combination TPC Cherenkov Detector with GEM Readout for Tracking and Particle Identification and its Potential Use at an Electron Ion Collider". In: 2015. arXiv: 1512.05309 [physics.ins-det]. URL: https://inspirehep.net/record/1409973/files/arXiv:1512.05309.pdf.

[3] B. Azmoun et al. "Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multistage GEM Detectors". In: *IEEE Transactions on Nuclear Science* (July 2018), pp. 1–1. ISSN: 0018-9499. DOI: 10.1109/TNS.2018.2846403.

[4] Aiwu Zhang et al. "Performance of a Large-area GEM Detector Read Out with Wide Radial Zigzag Strips". In: *Nucl. Instrum. Meth.* A811 (2016), pp. 30–41. DOI: 10.1016/j.nima.2015.11.157. arXiv: 1508.07046 [physics.ins-det].

[5] Aiwu Zhang et al. "A GEM readout with radial zigzag strips and linear charge-sharing response". In: *Nucl. Instrum. Meth.* A887 (2018), pp. 184–192. arXiv: 1708.07931 [physics.ins-det].

[6] Marcus Hohlmann et al. "Low-mass GEM detector with radial zigzag readout strips for forward tracking at the EIC". In: *2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2017) Atlanta, Georgia, USA, October 21-28, 2017*. 2017. arXiv: 1711.05333 [physics.ins-det]. URL: http://inspirehep.net/record/1636290/files/arXiv:1711.05333.pdf.

[7] E. Albrecht et al. “Status and characterisation of COMPASS RICH-1”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 553.1 (2005). Proceedings of the fifth International Workshop on Ring Imaging Detectors, pp. 215–219. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2005.08.036. URL: http://www.sciencedirect.com/science/article/pii/S0168900205016001.

[8] P. Abbon et al. “Read-out electronics for fast photon detection with COMPASS RICH-1”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 587.2 (2008), pp. 371–387. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2007.12.026. URL: http://www.sciencedirect.com/science/article/pii/S0168900207024576.

[9] P. Abbon et al. “Design and construction of the fast photon detection system for COMPASS RICH-1”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 616.1 (2010), pp. 21–37. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2010.02.069. URL: http://www.sciencedirect.com/science/article/pii/S0168900210002676.

[10] P. Abbon et al. “Particle identification with COMPASS RICH-1”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 631.1 (2011), pp. 26–39. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2010.11.106. URL: http://www.sciencedirect.com/science/article/pii/S0168900210026422.

[11] P. Abbon et al. “The COMPASS experiment at CERN”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 577.3 (2007), pp. 455–518. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2007.03.026. URL: http://www.sciencedirect.com/science/article/pii/S0168900207005001.

[12] P. Abbon et al. “The COMPASS setup for physics with hadron beams”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 779.Supplement C (2015), pp. 69–115. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2015.01.035. URL: http://www.sciencedirect.com/science/article/pii/S0168900215000662.

[13] M. Alexeev et al. “The quest for a third generation of gaseous photon detectors for Cherenkov imaging counters”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 610.1 (2009). New Developments In Photodetection NDIP08, pp. 174–177. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2009.05.069. URL: http://www.sciencedirect.com/science/article/pii/S0168900209010560.

[14] M. Alexeev et al. “THGEM based photon detector for Cherenkov imaging applications”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 617.1 (2010). 11th Pisa Meeting on Advanced Detectors, pp. 396–397. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2009.08.087. URL: http://www.sciencedirect.com/science/article/pii/S0168900209017173.

[15] M. Alexeev et al. “Micropattern gaseous photon detectors for Cherenkov imaging counters”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 623.1 (2010). 1st International Conference on Technology and Instrumentation in Particle Physics, pp. 129–131. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2010.02.171. URL: http://www.sciencedirect.com/science/article/pii/S0168900210004389.

[16] M. Alexeev et al. “Development of THGEM-based Photon Detectors for COMPASS RICH-1”. In: *Phys. Procedia* 37 (2012), pp. 781–788. DOI: 10.1016/j.phpro.2012.02.422.

[17] M Alexeev et al. “Development of THGEM-based photon detectors for Cherenkov Imaging Counters”. In: *Journal of Instrumentation* 5.03 (2010), P03009. URL: http://stacks.iop.org/1748-0221/5/i=03/a=P03009.

[18] M. Alexeev et al. “Progress towards a THGEM-based detector of single photons”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 639.1 (2011). Proceedings of the Seventh International Workshop on Ring Imaging Cherenkov Detectors, pp. 130–133. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2010.10.117. URL: http://www.sciencedirect.com/science/article/pii/S0168900210024022.

[19] M. Alexeev et al. “Detection of single photons with THickGEM-based counters”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 695.Supplement C (2012). New Developments in Photodetection NDIP11, pp. 159–162. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2011.11.079. URL: http://www.sciencedirect.com/science/article/pii/S0168900211021498.

[20] M Alexeev et al. “Detection of single photons with ThickGEM-based counters”. In: *Journal of Instrumentation* 7.02 (2012), p. C02014. URL: http://stacks.iop.org/1748-0221/7/i=02/a=C02014.

[21] M. Alexeev et al. “Detection of single photons with hybrid ThickGEM-based counters”. In: *PoS* PhotoDet2012 (2012), p. 057.

[22] M. Alexeev et al. “THGEM-based photon detectors for the upgrade of COMPASS RICH-1”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 732.Supplement C (2013). Vienna Conference on Instrumentation 2013, pp. 264–268. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2013.08.020. URL: http://www.sciencedirect.com/science/article/pii/S0168900213011467.

[23] M Alexeev et al. “Status and progress of novel photon detectors based on THGEM and hybrid MPGD architectures”. In: *Journal of Instrumentation* 8.12 (2013), p. C12005. URL: http://stacks.iop.org/1748-0221/8/i=12/a=C12005.

[24] M Alexeev et al. “Ion backflow in thick GEM-based detectors of single photons”. In: *Journal of Instrumentation* 8.01 (2013), P01021. URL: http://stacks.iop.org/1748-0221/8/i=01/a=P01021.

[25] M. Alexeev et al. “Status and progress of the novel photon detectors based on THGEM and hybrid MPGD architectures”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 766.Supplement C (2014). RICH2013 Proceedings of the Eighth International Workshop on Ring Imaging Cherenkov Detectors Shonan, Kanagawa, Japan, December 2-6, 2013, pp. 133–137. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2014.07.030. URL: http://www.sciencedirect.com/science/article/pii/S0168900214008730.

[26] M Alexeev et al. “Progresses in the production of large-size THGEM boards”. In: *Journal of Instrumentation* 9.03 (2014), p. C03046. URL: http://stacks.iop.org/1748-0221/9/i=03/a=C03046.

[27] M Alexeev et al. “MPGD-based counters of single photons developed for COMPASS RICH-1”. In: *Journal of Instrumentation* 9.09 (2014), p. C09017. URL: http://stacks.iop.org/1748-0221/9/i=09/a=C09017.

[28] Stefano Levorato et al. “MPGD-based counters of single photons for Cherenkov imaging counters.” In: *PoS* TIPP2014 (2014), p. 075.

[29] M. Alexeev et al. “The gain in Thick GEM multipliers and its time-evolution”. In: *Journal of Instrumentation* 10.03 (2015), P03026. URL: http://stacks.iop.org/1748-0221/10/i=03/a=P03026.

[30] M. Alexeev et al. “Status of the development of large area photon detectors based on THGEMs and hybrid MPGD architectures for Cherenkov imaging applications”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 824.Supplement C (2016). Frontier Detectors for Frontier Physics: Proceedings of the 13th Pisa Meeting on Advanced Detectors, pp. 139–142. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2015.11.034. URL: http://www.sciencedirect.com/science/article/pii/S0168900215013996.

[31] G. Hamar et al. "Investigation of the properties of Thick-GEM photocathodes by microscopic scale measurements with single photo-electrons". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 876.Supplement C (2017). The 9th international workshop on Ring Imaging Cherenkov Detectors (RICH2016), pp. 233–236. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2017.03.016. URL: http://www.sciencedirect.com/science/article/pii/S0168900217303534.

[32] M. Alexeev et al. "The MPGD-based photon detectors for the upgrade of COMPASS RICH-1". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 876.Supplement C (2017). The 9th international workshop on Ring Imaging Cherenkov Detectors (RICH2016), pp. 96–100. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2017.02.013. URL: http://www.sciencedirect.com/science/article/pii/S0168900217301936.

[33] G. Hamar et al. "MPGD-based photon detector upgrade for COMPASS RICH". In: *Journal of Instrumentation* 12.07 (2017), p. C07026. URL: http://stacks.iop.org/1748-0221/12/i=07/a=C07026.

[34] J. Agarwala et al. "Novel MPGD based detectors of single photons in COMPASS RICH-1". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (2017). ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2017.11.011. URL: http://www.sciencedirect.com/science/article/pii/S016890021731197X.

[35] Luciano Velardi, Antonio Valentini, and Grazia Cicala. "UV photocathodes based on nanodiamond particles: Effect of carbon hybridization on the efficiency". In: *Diamond and Related Materials* 76.Supplement C (2017), pp. 1–8. ISSN: 0925-9635. DOI: https://doi.org/10.1016/j.diamond.2017.03.017. URL: http://www.sciencedirect.com/science/article/pii/S0925963516306999.

[36] Kondo Gnanvo et al. "Performance in test beam of a large-area and light-weight GEM detector with 2D stereo-angle (UV) strip readout". In: *Nucl. Instrum. Meth.* A808 (2016), pp. 83–92. DOI: 10.1016/j.nima.2015.11.071. arXiv: 1509.03875 [physics.ins-det].

[37] Pendry J. B. et al. "Controlling Electromagnetic Fields". In: *Science Magazine* 312 (2006), pp. 1780–1782.

[38] Ginis V. et al. "Transformation optics beyond the manipulation of light trajectories". In: *Phil. Trans. R. Soc. A* 373.20140361 (2015). DOI: 10.1098/rsta.2014.0361.

[39] Ginis V. et al. "Controlling Cherenkov Radiation with Transformation-Optical Metamaterials". In: *Physical Review Letters* 113.167402 (2014). DOI: 10.1103/PhysRevLett.113.167402.

[40] Gianfranco Morello et al. "Advances on micro-RWELL gaseous detector". In: *PoS* BORMIO2017 (2017), p. 002. DOI: 10.22323/1.302.0002.

[41] G. Bencivenni et al. "Performance of μ-RWELL detector vs resistivity of the resistive stage". In: *Nucl. Instrum. Meth.* A886 (2018), pp. 36–39. DOI: 10.1016/j.nima.2017.12.037.

[42] Jeremie A. Merlin. "Results of the Longevity Study with Triple-GEM Technology for the Upgrade of the CMS Muon End-Caps". In: *MPGD 2017* (2017).

A List of all EIC publications from the eRD6 Consortium

BNL publications:

[1] B. Azmoun et al. "Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multistage GEM Detectors". In: *IEEE Transactions on Nuclear Science* (July 2018), pp. 1–1. ISSN: 0018-9499. DOI: 10.1109/TNS.2018.2846403.

[2] B. Azmoun et al. "A Study of a Mini-Drift GEM Tracking Detector". In: *IEEE Transactions on Nuclear Science* 63.3 (June 2016), pp. 1768–1776. ISSN: 0018-9499. DOI: 10.1109/TNS.2016.2550503.

[3] Craig Woody et al. “A Prototype Combination TPC Cherenkov Detector with GEM Readout for Tracking and Particle Identification and its Potential Use at an Electron Ion Collider”. In: 2015. arXiv: 1512.05309 [physics.ins-det]. URL: https://inspirehep.net/record/1409973/files/arXiv:1512.05309.pdf.

[4] B. Azmoun et al. “Initial studies of a short drift GEM tracking detector”. In: *2014 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*. Nov. 2014, pp. 1–2. DOI: 10.1109/NSSMIC.2014.7431059.

[5] M. L. Purschke et al. “Test beam study of a short drift GEM tracking detector”. In: *2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC)*. Oct. 2013, pp. 1–4. DOI: 10.1109/NSSMIC.2013.6829463.

Florida Tech publications:

[1] Marcus Hohlmann et al. “Low-mass GEM detector with radial zigzag readout strips for forward tracking at the EIC”. In: *2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2017) Atlanta, Georgia, USA, October 21-28, 2017*. 2017. arXiv: 1711.05333 [physics.ins-det]. URL: http://inspirehep.net/record/1636290/files/arXiv:1711.05333.pdf.

[2] Aiwu Zhang et al. “A GEM readout with radial zigzag strips and linear charge-sharing response”. In: *Nucl. Instrum. Meth.* A887 (2018), pp. 184–192. arXiv: 1708.07931 [physics.ins-det].

[3] Aiwu Zhang and Marcus Hohlmann. “Accuracy of the geometric-mean method for determining spatial resolutions of tracking detectors in the presence of multiple Coulomb scattering”. In: *JINST* 11.06 (2016), P06012. DOI: 10.1088/1748-0221/11/06/P06012. arXiv: 1604.06130 [physics.data-an].

[4] Aiwu Zhang et al. “R&D on GEM detectors for forward tracking at a future Electron-Ion Collider”. In: *Proceedings, 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2015): San Diego, California, United States*. 2016, p. 7581965. DOI: 10.1109/NSSMIC.2015.7581965. arXiv: 1511.07913 [physics.ins-det]. URL: http://inspirehep.net/record/1406551/files/arXiv:1511.07913.pdf.

[5] Aiwu Zhang et al. “Performance of a Large-area GEM Detector Read Out with Wide Radial Zigzag Strips”. In: *Nucl. Instrum. Meth.* A811 (2016), pp. 30–41. DOI: 10.1016/j.nima.2015.11.157. arXiv: 1508.07046 [physics.ins-det].

SBU publications:

[1] M. Blatnik et al. “Performance of a Quintuple-GEM Based RICH Detector Prototype”. In: *IEEE Trans. Nucl. Sci.* 62.6 (2015), pp. 3256–3264. DOI: 10.1109/TNS.2015.2487999. arXiv: 1501.03530 [physics.ins-det].

UVa publications:

[1] Kondo Gnanvo et al. “Large Size GEM for Super Bigbite Spectrometer (SBS) Polarimeter for Hall A 12 GeV program at JLab”. In: *Nucl. Instrum. Meth.* A782 (2015), pp. 77–86. DOI: 10.1016/j.nima.2015.02.017. arXiv: 1409.5393 [physics.ins-det].

[2] Kondo Gnanvo et al. "Performance in test beam of a large-area and light-weight GEM detector with 2D stereo-angle (UV) strip readout". In: *Nucl. Instrum. Meth.* A808 (2016), pp. 83–92. DOI: 10.1016/j.nima.2015.11.071. arXiv: 1509.03875 [physics.ins-det].

Yale publications:

[1] S. Aiola et al. "Combination of two Gas Electron Multipliers and a Micromegas as gain elements for a time projection chamber". In: *Nucl. Instrum. Meth.* A834 (2016), pp. 149–157. DOI: 10.1016/j.nima.2016.08.007. arXiv: 1603.08473 [physics.ins-det].