eRD22 GEM-TRD/T R&D Progress Report

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Project Name GEM based Transition radiation detector and tracker
Period Reported: from 07/2020 to 07/2020
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Abstract

Transition radiation detectors are widely used for electron identification in various particle physics experiments. For a high luminosity electron-ion collider a high granularity tracker combined with a transition radiation option for particle identification could provide additional electron identification/hadron suppression. Due to the low material budget and cost of GEM detector technologies, a GEM based transition radiation detector/tracker (GEM/TRD/T) is an ideal candidate for large area hadron endcap where a high flux of hadrons is expected at the EIC.

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1 Introduction

Identification of secondary electrons plays a very important role for physics at the Electron-Ion Collider (EIC). J/ψ has a significant branching ratio for decays into leptons (the branching ratio to electrons (e^+e^- pair) is similar to muons ($\mu^+\mu^-$ pair) and is at the order of 6%). The branching ratio of D-mesons is Br($D^+ \to e + X$) $\sim$ 16% and the branching ratio of B-mesons is Br($B^\pm \to e + \nu + X_c$) $\sim$ 10%. By using more sophisticated electron identification the overall J/ψ and open charm or beauty mesons efficiency could be increased and therefore statistical uncertainties could be improved. Electron identification is also important for many other physics topics, such as spectroscopy, beyond the standard model physics, etc. A high granularity tracker combined with a transition radiation option for particle identification could provide additional information necessary for electron identification or hadron suppression.

The scope of this project is to develop a transition radiation detector/tracker capable of providing additional pion rejection (>10-100).

2 PAST

- *What was planned for this period?*

  During the FY20 period we planned to perform a test of different radiator materials, perform a scan of HV to find an optimal operation point, and to test different gas mixtures, which would also allow us to verify our gas mixing system using the newly purchased gas chromatography. During all tests we planned to use a setup with 3-6 GeV electrons at the pair-spectrometer in Hall-D.
  It is critical for our project to get estimates with a pion beam (to estimate real e/π rejection). We planed to test our prototype with pions coming from decays of ρ-mesons using the Glue-X detector. In the fall, the Glue-X experiment planned to perform a commissioning run of the DIRC detector (2 weeks in December). We were planning to install our prototype together with other tracking detectors in front of the DIRC detector and integrate our GEM-TRD readout into the Glue-X data-acquisition system. In addition to the pion beam setup we are planning to install a few modules of an EMCAL (in collaboration with eRD1) and mRICH (in collaboration witheRD14) to perform a joint test run. The main goal of this test would be to evaluate the impact of the tracker resolution on the performance of EMCAL and mRICH detectors, as well as to estimate a global PID performance.

- *How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?*
  Due to the lab and facilities closures we were not able to finish a test with different radiators and gas mixtures, or to perform the planned joint beam test with the EMCAL and mRICH to get global PID estimates. At the moment all hardware related activities are postponed and we are focusing on the analysis of our test beam data.

- *How much of your FY20 funding could not be spent due to pandemic related closing of facilities?*
  We received our FY20 funding in May 2020. We were able to purchase a Xe-gas. Purchases for the electronics are still in the pending state.

- *Do you have running costs that are needed even if RD efforts have paused?*
  No.

- *What was achieved?*

As was proposed in July, we were planning to continue a test of different radiators, perform an optimization of HV settings, and test different gas mixtures.

Additionally, we have been working on measuring the response of the GEM-TRD module with pions. To achieve this, a joint setup with GlueX during the commissioning run of the DIRC detector (scheduled to take place around mid December 2020) has been proposed. We will study the detector response with pions coming from particle decays, such as the ρ. Preparation for this setup, as well as a noise measurements will be discussed.

- **Noise measurements**

  We adapted the available readout from GlueX (preamp cards, cables, fADC125 modules) to readout the GEM-TRD and characterize the signal characteristics of the GEM with flash ADCs. We developed interposer boards that route traces from the detector strips to the preamps. Each preamp card has 3 ASIC chips for a total of 24 channels per card. Some of the routing traces can be very long due to the card form factor (size) and are shielded to minimize pickup. However, this is problematic due to the higher capacitance presented to the preamps.

  After the tests at UVA, the GEM-TRD prototype was installed in Hall-D, for noise and pedestals measurements. On the left plot of Fig. 1 the baseline noise of the electronics alone with two carrier PCBs, each with 10 preamps, all powered (480 channels) are shown. The noise is nominally 9 mVpp and is the same as previously measured in the lab. Fig 1 shows the noise with one of the carrier boards attached to the detector X coordinate connector. The noise is similar at 11 mVpp. Figure 2 (left) shows the noise with with the two carrier boards attached to the detector X and Y coordinates. The noise increased considerably to 61 mVpp. These show that there is coupling on the detector between the X and Y strips. The long strips on the carrier boards, though shielded, may act as antennae. Although this needs further researched to determine if the issue can be resolved via a new, more compact readout design or via a detector re-design. The readout of the Y coordinate was disconnected for the test until further investigation (see plans for FY2021).

  To estimate an amplification we performed measurements with an Fe55 source. Those measurements were important for FlashADC calibration and pre-amplification chain gain measurements. Fig. 2 (right) shows the Fe55 spectrum on the oscilloscope.

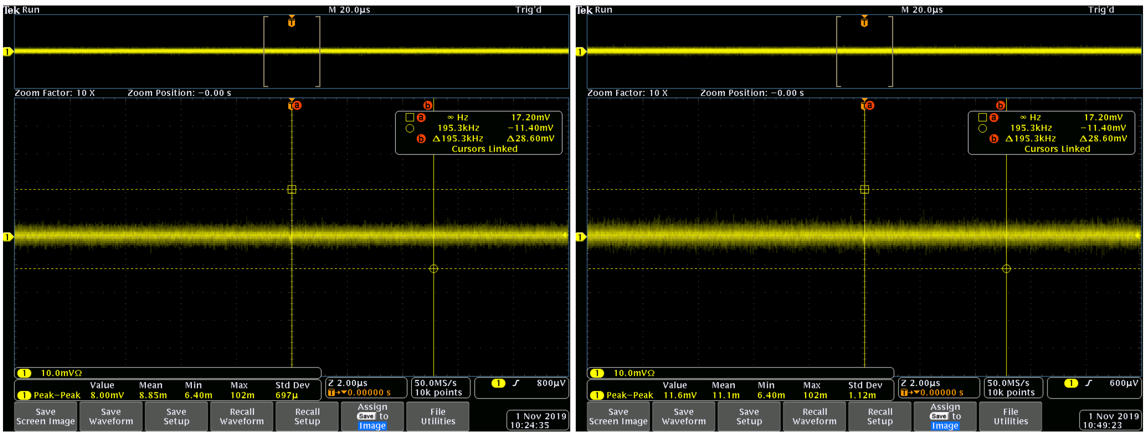

Figure 1: (a)- left- the baseline noise of the electronics alone with two carrier PCBs, each with 10 preamps, all powered (480 channels). (b)-right- one of the carrier boards attached to the detector X coordinate connector.

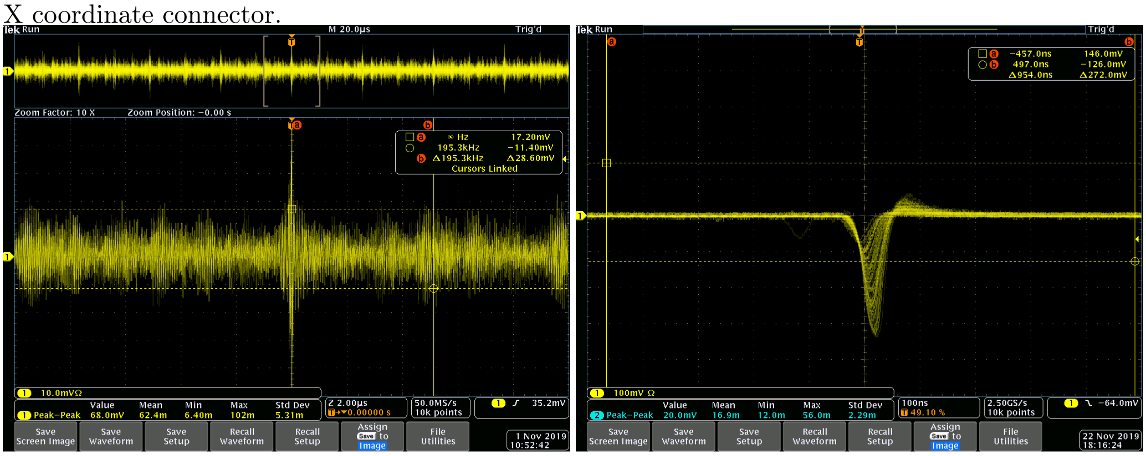

Figure 2: (c)-left- noise with with the two carrier boards attached to the detector X and Y coordinates. (d)-right- Fe55 measurements).

- **Test beam setup for Feb-March**

  During the February-March beam test we performed a number of measurements:

  – High Voltage optimization
  – Test with several radiators
  – Different Gas mixtures

- **High voltage optimization:**

  The test was performed with the standard fleece radiator. We increased an overall thickness of the radiator to ca 15cm (Fig. 3. During the test we varied the gain voltages in the range between 3200V to 3600V to improve the efficiency of the TR photons. It is important to keep the gain at the optimal settings, which allowed it to pickup low energy clusters and not overshoot the electronics for the high energy clusters.

  Several runs were taken, here are best points:
  a) Run 1350. HV 3450V, Rejection 3.4.
  b) Run 1346. HV 3500V, Rejection 3.0
  c) Run 1345. HV 3400V, Rejection 2.97

  During these gain scan measurements we kept the drift field at 1500V/cm. This drift field corresponds to a drift time ca. 720 ns or to a drift velocity ca, 3 cm/μs.

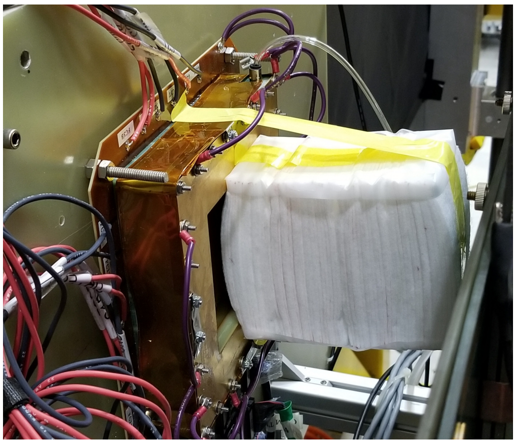

Figure 3: GEMTRD setup with fleece radiator

  Fig. 4 Shows the performance of the detector at the optimal settings (HV 3450V).

- **Test of new radiators**

  We performed a test with two different radiator thicknesses (Fleece radiator, 9cm and 15 cm) and compared the results with Monte Carlo predictions. Tests were done with electron-only beam, by comparing the responses for the areas with and without the radiator. The data points are in the good agreement with the MC predictions.

  We continue to search for a proper transition-radiation radiator. In the previous runs we tried foils which also showed very good response (see previous reports). For this setup we prepared 4 types of radiator: aerogel, two types of a foam material, and a different type of a fleece. Unfortunately due to the COVID19 lab closure we were able to test only the first two.

  Fig 6 shows the aerogel radiator in the box. The exit window is covered with a thin (50μm) kapton foil (left photo) and its installation at the test beam setup (right photo).

  As one could see on Fig 7 we do not observe any transition radiation yield from the aerogel radiator. The red and blue curves, which correspond to the area with and without radiator, correspondingly, are identical and could not be separated (see, neural network output on the upper right plot of the Fig 7).

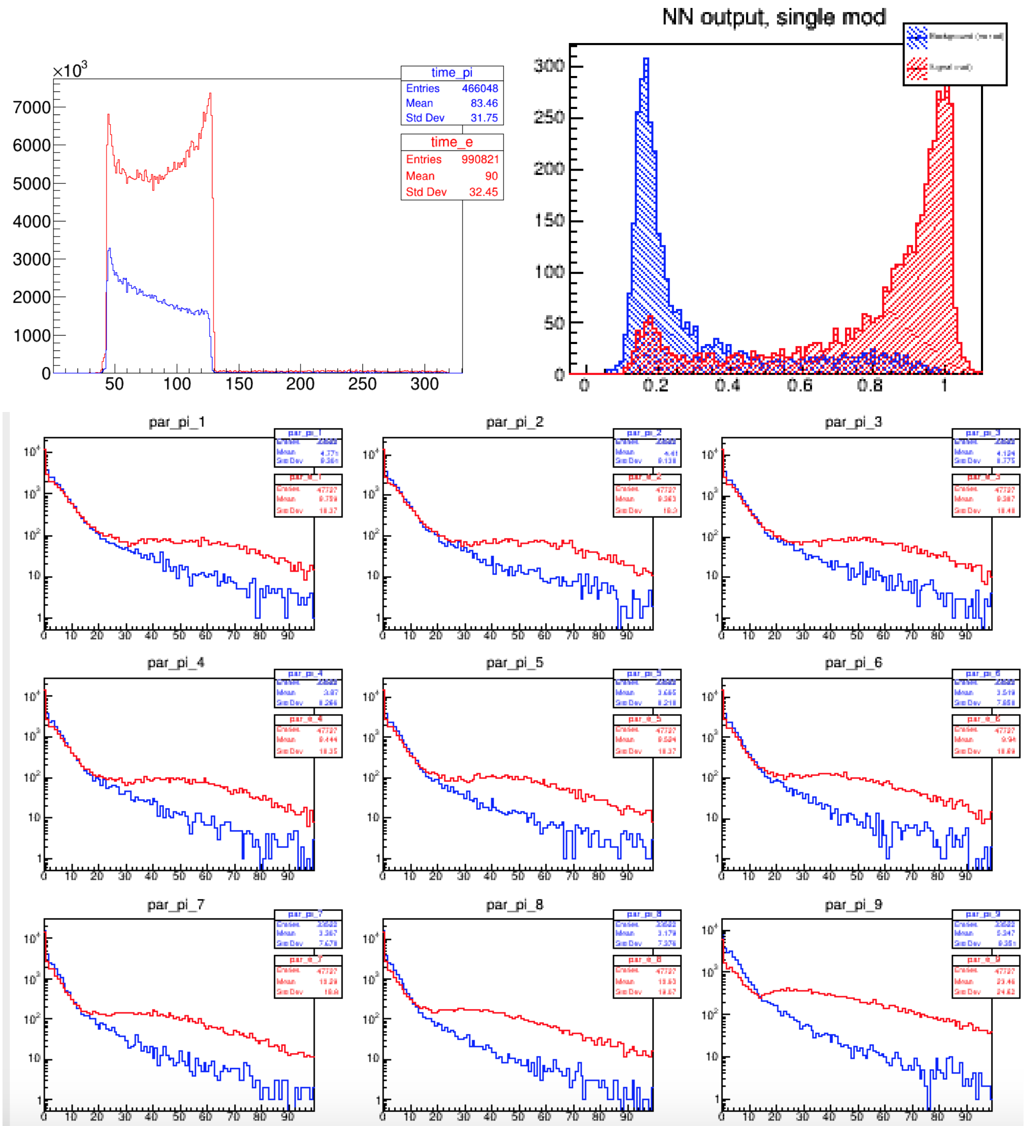

Figure 4: Run 1350. Upper left plot shows average energy deposition along the drift time (x-axis in fADC time-bins). Upper right plot is output from Neural Network, showing the separation between electrons and pions. Lower plots shows ADC spectrum in time-bin slices (slice 9 is the closest to the entrance window)

We also tested a foam radiator, shown on fig. 8. This type of radiator showed some yield of transition radiation photons (Fig 9, upper left plot). But, as one could see in the lower plot of the fig. 9, it produces a very soft spectrum which absorbs TR photons in the first window (closest to the entrance) and therefore could not be used for rejection purposes in this setup.

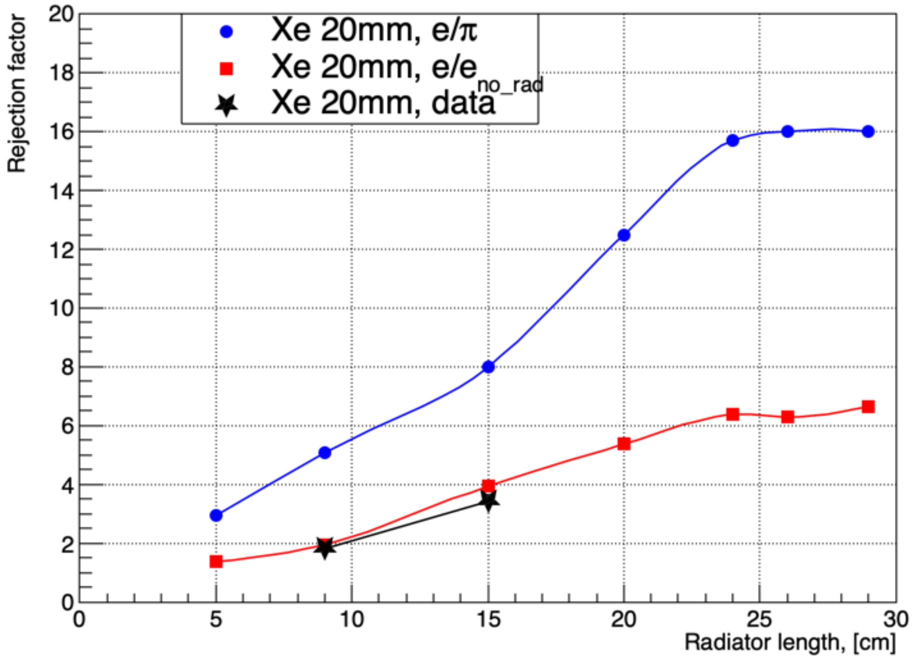

Figure 5: Rejection as a function of a radiator thickness for data (star-points) and Monte Carlo (curves)

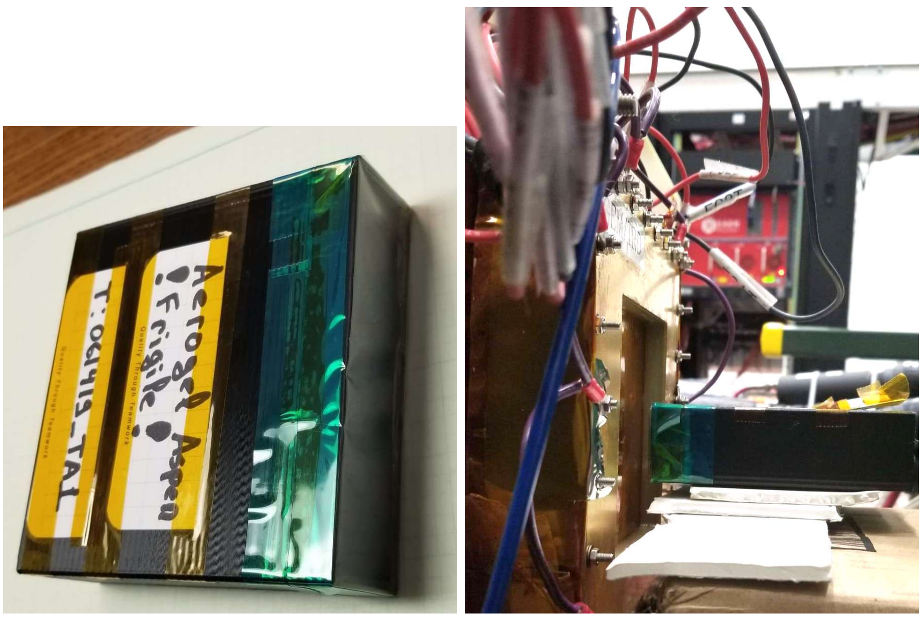

Figure 6: Aerogel radiator

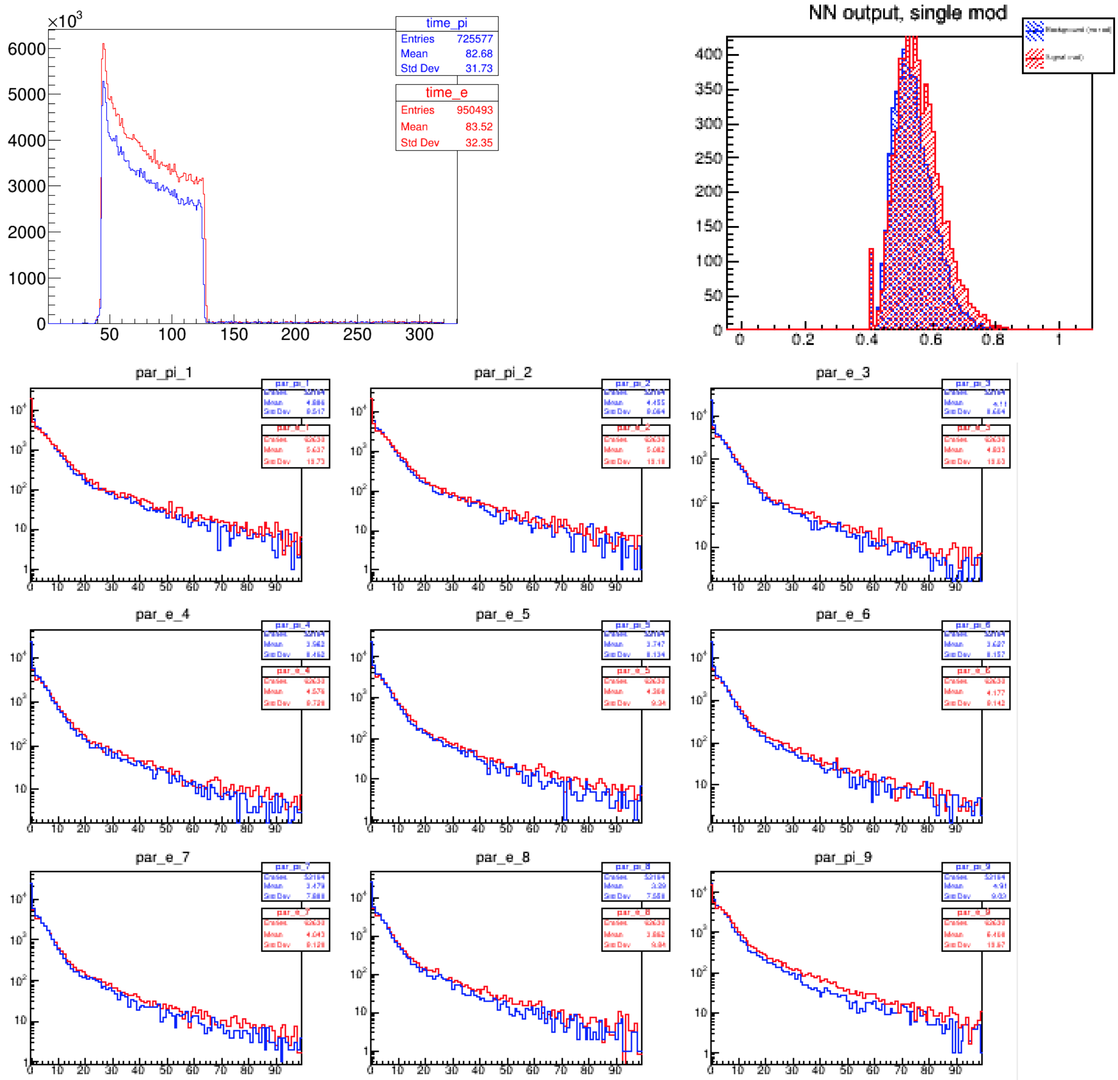

Figure 7: Run 1355 with aerogel radiator. Upper left plot shows the average energy deposition with and without radiator (different normalization in the plot). Upper right plot shows result of the neural network output (no separation). Lower plots shows ADC spectrum in the different time-bin slices (slice 9 is the closest to the entrance window

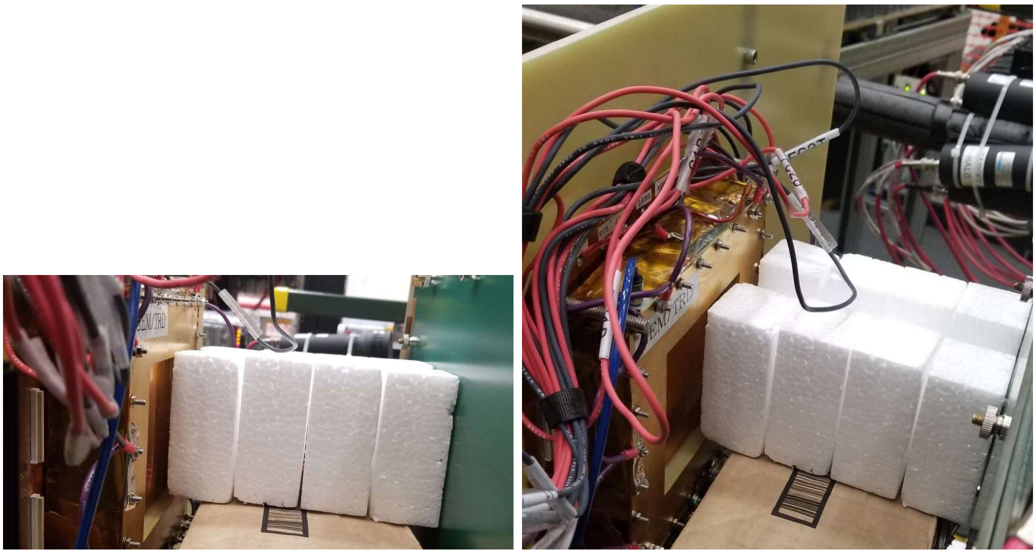

Figure 8: Foam radiator.

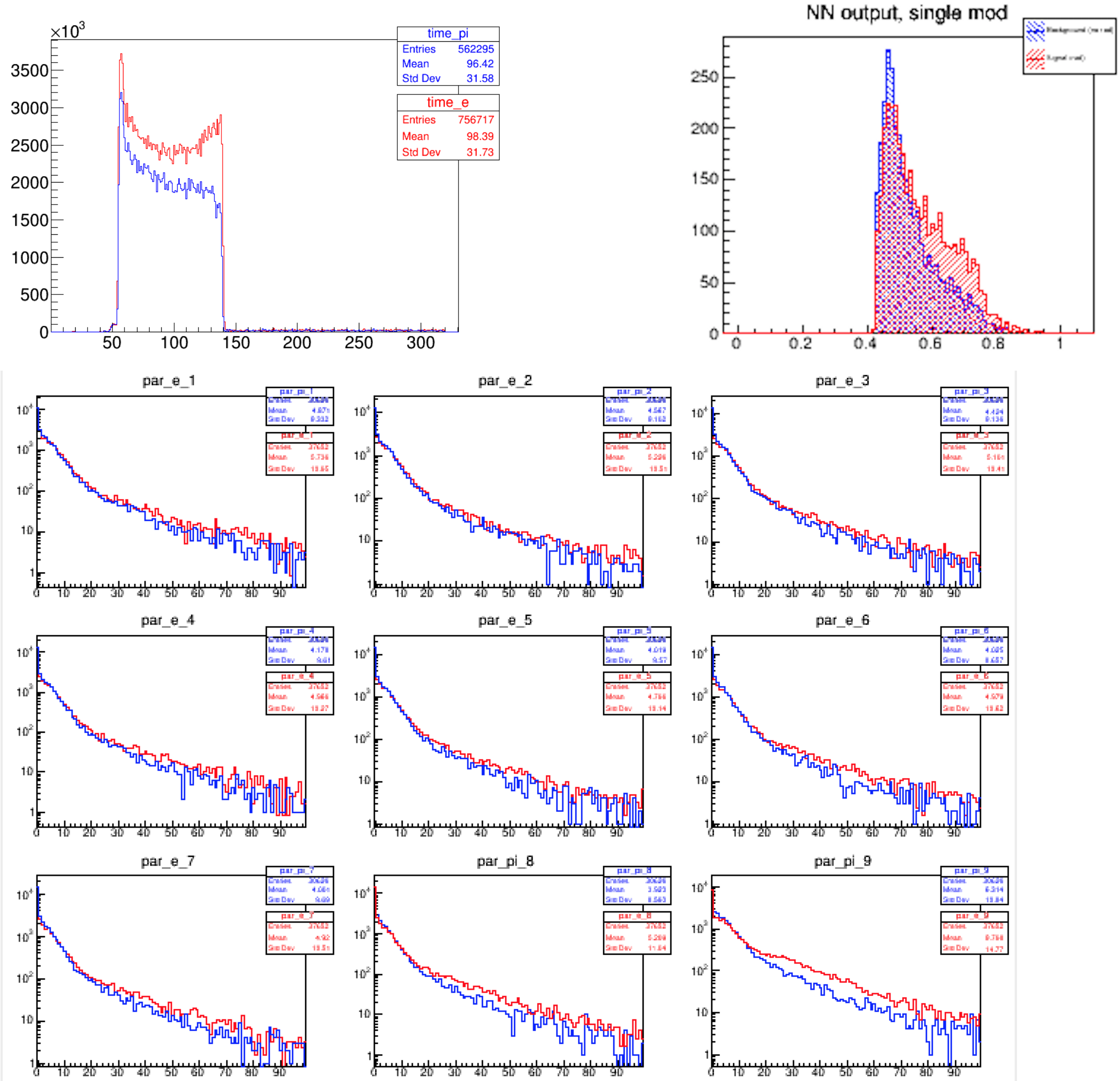

Figure 9: Run 1368 with a foam radiator.

- **Gas system**
The Gas system, which has been developed in Temple Uni. has been successfully installed in the Gas Room of the Hall-D (JLAB). All gas lines (50m) have been installed and connected to the system. All elements of the gas system that operate above 1 bar are kept in a separate gas room, elevated approximately 7 m above the detector.
Many thanks to Scott Spiegel for his help with gas system installation and commissioning. The control and operation can be done via computer interface (Fig. 10 left). Figure 10 shows the installation of the gas mixing system in the Hall-D setup. The large bottles on the left are pure Argon and CO_2 gases, respectively. The small bottle in front of the gas rack is pure Xenon gas. During the operation we mixed Ar and CO_2 gasses in the proportion of 75:25, respectively. Due to a high price of the Xe gas, we used it only during the dedicated TRD runs. The gas was mixed in the proportion of 80:20 (Xe/CO_2).

Figure 10: Gas mixing system in Hall-D experimental setup).

Before and after the operation, the quality of the gas mixture was analyzed by the SRI 8610C gas chromatograph with a column 6' MS5a Helium 15 PSI carrier (Fig. 11(b).

Figure 11(a,c) shows an actual gas properties, such as percentage of Xe-CO2 gas ratio as well as the contamination. We could resolve/measure the contamination down to 50ppm. We can not resolve Argon and Oxygen, but the total contamination is below 74ppm. The actual measured ratio of Xenon and $C0_2$ was 80.85 and 19.15 percent.

- **Test with pions**
As was proposed in July, we were planning to have a joint setup with GlueX during the commissioning run of the DIRC detector (2 weeks before Christmas break). The idea was to measure the response of the GEM-TRD module with pions, coming from particle decays, for example that of the ρ.

The setup for this test had 5 modules (with 4 different tracking detectors technologies), counting from the target: Standard GEM plane, μRWELL, TRD Multi wire chamber (TRD-MW), GEM-TRD, and a standard GEM plane. All 5 modules were mounted on a single aluminium stand. The alignment of all modules with respect to the reference frame (GlueX global system coordinate) has been performed. This tracking setup has been installed in front of the DIRC detector right after the exit from the GlueX solenoid.

The upper left picture of the Fig. 12 shows sub-detectors mounted together. Middle and lower pictures of the Fig. 12 show how this setup was lifted up and also shows its location in

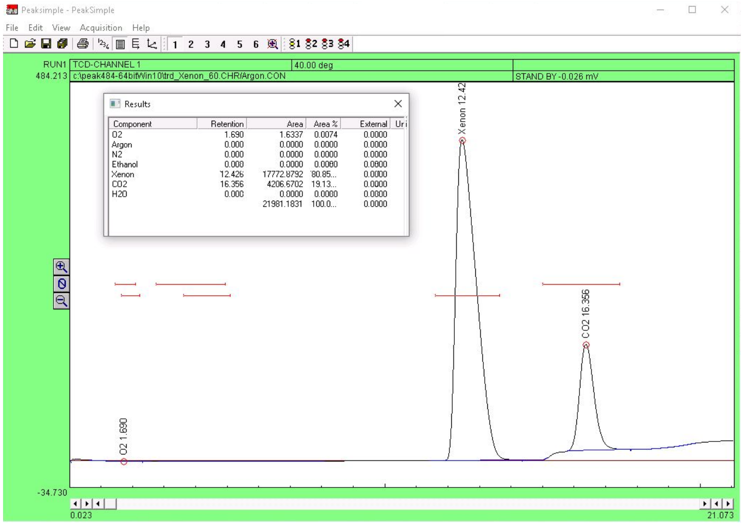

Figure 11: Gas quality measurements using a gas chromatograph).

front of the DIRC detector after the solenoid exit. Readout electronics were kept closer to setup at the ground level, as shown on the upper right photo of the Fig 12.

We would like to thank the GlueX team for their help with providing the mounting stand for the tracking modules, their alignment and installation. Especially, we would like to thank Tim Whitlatch for his help with installation.

We have had a set of issues with the prototype during the joint GlueX test beam in December 2019. The prototype was tested thoroughly with cosmic at UVa and was performing perfectly before installation in Hall D at JLab. After installation and before the beam start, we perform an additional test with Fe^{55} source to setup the optimized operating voltage to minimize the signal-to-noise ratio. However when exposed to the first beam, the prototype quickly develop a discharge-like behavior which remained for a long period time even after the beam was off. The discharge-like state propagated over all of the FE readout channels and effectively rendered the active area of the detector inactive. We initially suspected a short in one of the 3 GEM foils of the amplification stages and when we had the opportunity, we brought the prototype back to UVa to replace the GEM foils. However, before the replacement, the prototype was tested again with cosmic and start working perfectly once again. So we decide not to open the chamber to replace the foils and brought it back to the test beam setup in Hall D at JLab. We tested it again with Fe^{55} source to ensure it was working correctly before the beam start. But again, after the first beam from the Hall, the sustained discharge situation came back and made it impossible again to collect any meaningful data.
We now understand that the instabilities with the prototype was related to its operation in a high particle rate environment, so we brought the prototype back to UVa once again and this time tested it both with cosmics as well as our high intensity x-Ray setup at UVa. With the x-ray setup, we were able to emulate JLab Hall D test beam environment and reproduce the problem with the prototype even though when going back to cosmics the prototype respond perfectly. Now that we can reproduce the problem, we understand that it was not coming from short the GEM foils or readout strip PCB board, but from somewhere else in the detector. We strongly suspect that one of the G10 frames used for the field cage in the drift volume became prone to charging up in a high particle rate enviorment and altered the electric field as well as the resulting electric signal of the detector. We proceed to replace this part in the detector and now the prototype is operating perfectly in beam, tested in a subsequent run in early 2020. We are still investigating the cause of failure of this G10 frame which is a rather standard and ubiquitous material for GEM detectors. We suspect that the specific frame was probably severely damaged during an earlier operation where we had a lot of issues with our newly installed HV power supply system. However, though the problem prevented us from successfully collecting data during the December test beam, it is expect to be a very rare occurrence of a faulty material used in the assembly of the detector and is not viewed as a significant issue for the overall GEM-TRD R&D activities.

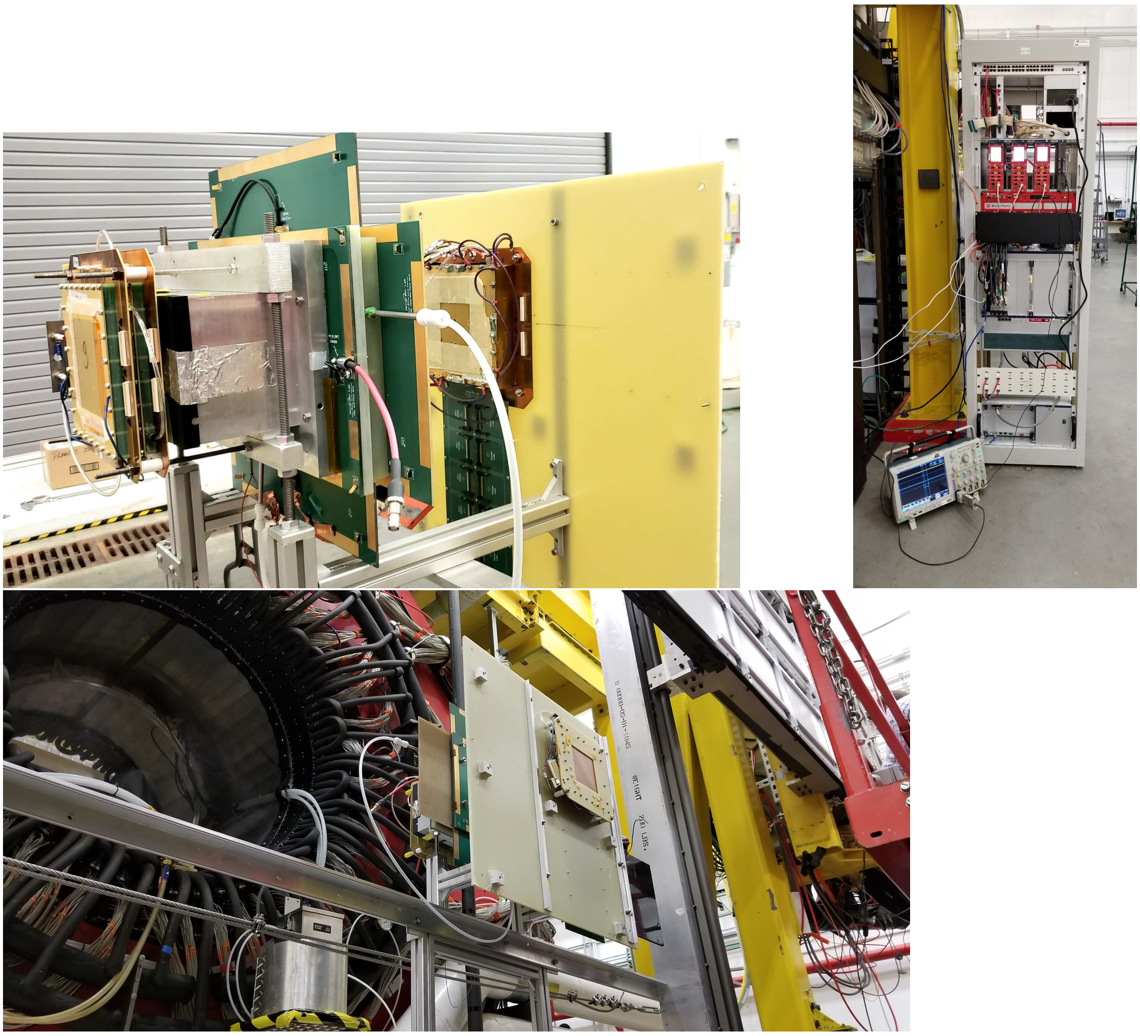

Figure 12: Test beam setup at Hall-D (CEBAF).

We are waiting to see if in the near future we will have another opportunity to perform the same experiment. In addition we are looking into the possibility to use Fermilab test beam in a collaboration with eRD6 group.

3 PLANS

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

Preparation and proposed program for the Test-beam measurements in FY2021 (Fall-Spring:

- **Development of GEM-TRD with new High-Performance & Large-Pad Readout** The anode readout PCB layer of the current GEM-TRD prototype is based on the so-called COMPASS readout made of X and Y strips of pitch size of 400 μm. Though with the standard APV25-base readout electronics used for GEM trackers, the noise level with these strip layer is very low, we observed very high noise when we connect both, X and Y strip layers, to the customised fADC125 electronics that we used to read out the GEM-TRD and the high noise seems directly linked to the strip capacitance from the two X and Y layers. This strongly deteriorates the detection efficiency of the GEM-TRD prototype. We have been working on a new concept of pad readout PCB as anode readout for MPGD technologies more suited to the GEM-TRD application. This novel large-pad readout PCB, by design, combines three crucial advantages that will greatly benefit GEM-TRD: large readout pad which means a small number of electronic channel to be readout, excellent spatial resolution despite the large pad size and we expect a better noise performance despite the the large size. The basic

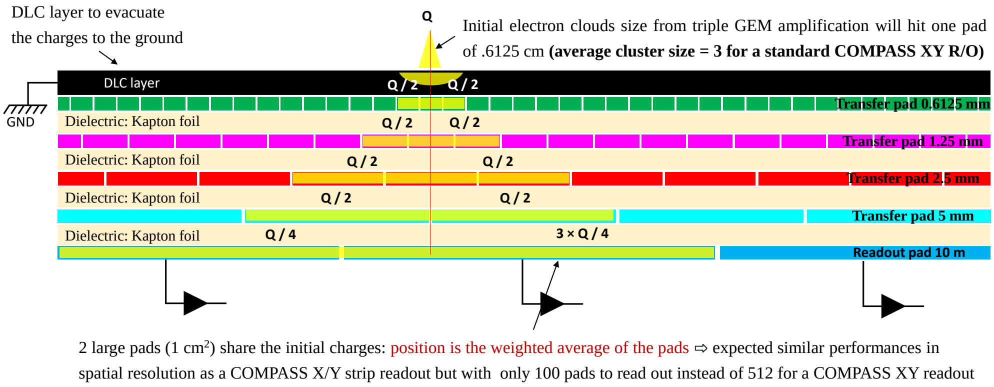

Figure 13: Principle of capacitive-coupling large-pads anode readout for MPGDs.

principle is illustrated on the sketch of Fig. 13 and consists of vertical stack of square Cu-pad layers, separated by 50 μm thick kapton foils as dielectric to form a capacitor. The pad size doubles (and subsequently the area is multiplied by 4) from a one layer (layer[i]) to the one underneath it (layer[i+1]) and each pad of layer[i] are arranged in space so that its center is either always perfectly aligned with the larger pad of layer[i+1] or with the center of two adjacent pads of layer[i+1]. This space arrangement of the pads from one layer to the other ensures that two adjacent pads collecting charges on layer[i] will always transfer the total charges to two adjacent pads of layer[i+1] no matter the size of the pads of layer[i+1]. The charge is transferred between layers via capacitive coupling as two Cu-pad layers separated by the kapton foil act effectively as a perfect capacitor. The pads of the bottom layer[n], that we name here *charge-collection layer* are connected to the front end (FE) electronics readout, while all the other pad layers above, that we name here *charge transfer layers* just serve to transfer and spread the original charges through capacitive coupling. With such a scheme the area a[n] of the pad of the *charge-collection layer* (layer[n]) in a n-layer-stack readout board is equal to a[1]$\times 2^n$ with a[1] being the area of the pad of the top *charge transfer layer* (layer[1]) and the total number of pads of layer[n] is $1/2^n$ of the total number of pads of layer[1]. By design, the top layer pad size of this readout board basically defines the spatial resolution performances of the pad readout scheme and in effect which is transferred via capacitive coupling the bottom layer which pad size define the total number of channel count to be read out.

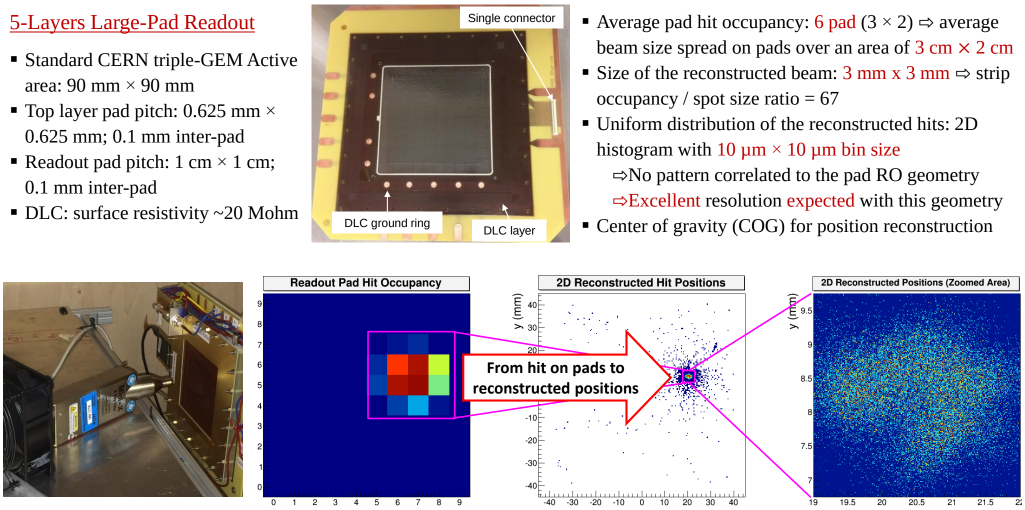

Figure 14: ***(Top):*** Picture of large-pad anode readout PCB. ***(Bottom - from left to right):*** GEM with large-pad anode readout installed in x-ray setup at UVa; Readout pad hit occupancy; Reconstructed hit positions; Zoomed area of the reconstructed positions

We tested the idea on a small Triple-GEM equipped with 1 cm × 1 cm pad size large-pad readout PCB to establish the proof of the concept. The specifications of this prototype are shown on the top Fig. 14. The prototype was tested in x-ray setup at UVa with a 1 mm^2 collimated x-ray source as shown on bottom left of Fig. 14. The 2D plot of middle left of the figure shows the incoming x-ray beam spot spread over a few readout pads covering an area of 3 cm × 2 cm. The reconstructed positions of the x-ray hits are shown in the 2D plot of middle right of Fig. 14 and the plot on the right shows a zoomed area of high granularity reconstructed hit positions with 10 μm × 10 μm histogram bins. We see, as expected a uniformed distribution of the reconstructed positions with no pattern associated to the pad readout geometry which is a strong indication that excellent space point resolution can indeed be expected with this new readout technology. These very preliminary results are very encouraging for us to further develop this new idea and test the performances with the GEM-TRD prototype to provide excellent spatial resolution performance together with a high signal-to-noise ratio performance and minimal readout channels. The channel count with the large-pad readout on a 10 cm × 10 cm GEM-TRD prototype is a factor 5 smaller than with the same detector equipped with X-Y COMPASS strip readout. We plan to assembled a second GEM-TRD prototype with this large-pad readout concept and test it with beam at JLab and FNAL. We will compare the performances with the current prototype with COMPASS readout. We will request limited additional funding only for the large pad anode readout layer for this second prototype as we already received some funding for the GEM foils and other parts for a second prototype in the FY20 funding request.

- **Noise and readout** We would like to characterize the detector noise performance to establish a baseline for the noise performance with the aim of minimizing the trace length. It is important to minimize the trace capacitance by developing a dedicated readout setup with ASICs mounted directly on PCBs and connected as close as possible to the strips (240 X by 240 Y). This may require a stack of PCBs per readout plane given the low ASIC channel density. Also with newly developed GEM design (see above about Large-Pad Readout) by shielding strip planes or using a strip-stitch technique it might be possible to minimize inter-strip capacitance between planes (i.e. strip and pixel design). We would like to characterize the noise performance of such design.

- **Joint test beam mRICH and EMCAL**
we were planning to install few modules of EMCAL (in collaboration with eRD1) and mRICH (in collaboration with eRD14) to perform a joint test run at the end of April, which didn't happened due to COVID-19 quarantine. We will try to perform this test during the fall run. The main goal of this test would be to evaluate the impact of the tracker resolution

on the performance of EMCAL and mRICH detectors, as well as to estimate the global PID performance.

- **Test of different radiators**
  We are planning to continue a test of new materials, that are currently available for purchasing. We would like to test them for a transition-radiation yield.

- **Test of different gas mixtures**
  Our gas mixing system is ready (see above). The first commissioning showed very good performance. Gas chromatograph would allow us to cross-check a quality and the actual percentage of the gas mix. We would like to perform a test with different Xe percentages.

- Possible test run using the pion beam at Fermilab In collaboration with eRD6 we would like to use the pion beam at the Fermilab test facility to estimate real response of the GEM-TRD detector to the pions. This test is very preliminary, and will depend on beam availability and restrictions due to COVID19, progress with paper work needed to run the setup at the testbeam, as well as a gas or gas-system restrictions.

- **Begin design of Xe re-circulation system:**
  Over the past few years, the price of Xe has gone up significantly, as of this writing a small portable bottle of Xe costs about $8,500. It is no longer practical or an efficient use of funding to continue semi-frequent purchases. We plan to begin designing a small Xe gas cleaning and re-circulation system for our GEM TRD prototypes. We would like to design a recirculation system such that it could also be easily applicable to multiple GEM TRD prototypes and ones which move beyond 10 cm $\times$ 10 cm to ensure its use with future prototypes and tests.

  To do this we can compliment our current gas mixer and analyzer modules with additional modules needed to purify, distribute, circulate, and recover the gas. A cartoon block diagram of this is shown in Fig. 15. For the implementation of these modules we plan to build off the knowledge and expertise of the ATLAS experiment at CERN, who also installed a Xe recirculation gas system for their TRT detector. We plan to visit CERN to see and learn about the ATLAS TRT gas system, which would be greatly beneficial and directly applicable to our GEM TRD detector.

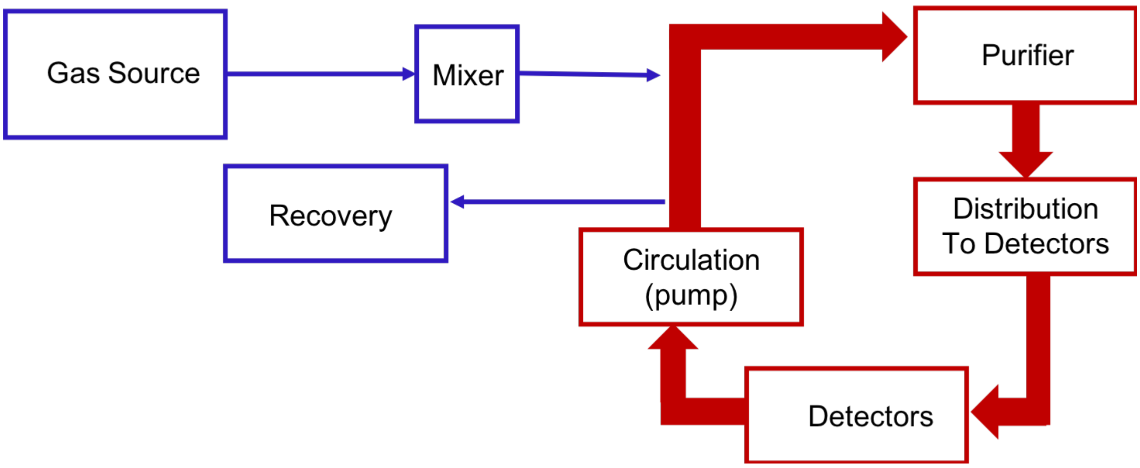

Figure 15: Cartoon block diagram for proposed GEM TRD gas recirculation system.

3.2 *What are critical issues?*

4 Additional information

Manpower *Include a list of the existing manpower and what approximate fraction each has spent on the project. If students or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.*

None of JLAB, Temple or UVA members are funded by EIC R&D.

Jefferson Lab (JLAB):
F. Barbosa Electrical Engineers 10%
S. Furletov Research Scientist 5 %
Y. Furletova Research Scientist 20 %
L. Pentchev Research Scientist 5 %
C. Stanislav Technical Staff 10%
B. Zihlmann Research Scientist 5 %

Temple University :
M. Posik Research Scientist 15 %
B. Surrow Professor 10 %

University of Virginia (UVa):
K. Gnanvo Research Scientist 10 %
N. Liyanage Professor 5 %

Table 1 below summarizes the Temple University budget request for FY21. Funding below $5k will the trip to CERN to transfer knowledge of the ATLAS TRT gas system not possible.

Table 1: **Temple University-Gas System** FY21 request.

	Request	**-20%**	**-40%**
Travel to CERN	$5,000	–	–
Overhead (58.5%)	$2,925	–	–
Total	**$7,925**	–	–

Table 2 below summarizes the Jefferson Lab budget request for FY21.

Table 2: **JLAB: Xe-gas, readout and mechanics** FY21 request. Travel to the Fermilab test beam is included.

	Request	**-20%**	**-40%**
Readout,Gas,etc	$10,000	$10,000	$8,000
Travel	$5,000	-	-
Overhead (ca 12%)	$2,233	$789	$ 631
Total	**$17,233**	**$10,789**	**$8,631**

Table 4 below summarizes the University of Virginia budget request for FY21.

Table 3: **UVA prototyping** FY21 request.

	Request	**-20%**	**-40%**
Large-pad readout PCB	$5,000	$4,000	$3,000
Travel	$5,000	$4,000	$3,000
Overhead (61.5%)	$3,075	$2,460	$1,855
Total	**$13,075**	**$ 10,460**	**$7,845**

The table 4 below summarizes a total budget request for FY21.

Table 4: **A total eRD22** FY21 request.

	Request	**-20%**	**-40%**
JLAB	$17,233	$10,789	$8,631
UVA	$13,075	$ 10,460	$ 7,845
Temple U	$7,925	$ 0	$ 0
Total	**$38,233**	**$ 21,249**	**$16,476**

4.1 Publications

Please provide a list of publications coming out of the R&D effort. We are very proud to announce our first NIM paper: "A new Transition Radiation detector based on GEM technology" Nucl.Instrum.Meth. A942 (2019) 162356 (2019-10-21) DOI: 10.1016/j.nima.2019.162356

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