# eRD22 GEM-TRD/T R&D Progress Report

F. Barbosa[1], L. Belfore[4], C. Dickover[1], S. Furletov[1], Y. Furletova*[1], K. Gnanvo[2], N. Liyanage[2], L. Pentchev[1], M. Posik[3], C. Stanislav[1], B. Surrow[1], and B. Zihlmann[1]

[1]Jefferson Lab
[2]University of Virginia
[3]Temple University
[4]Old Dominion University

March 5, 2021

**Project ID:** eRD22
**Project Name** GEM based Transition radiation detector and tracker
**Period Reported:** from 07/2020 to 07/2021
**Project Leader:** Yulia Furletova
**Contact Person:** Yulia Furletova (yulia@jlab.org)

**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.

*yulia@jlab.org

Identification of secondary electrons plays a very important role for physics at the Electron-Ion Collider (EIC). A high granularity tracker combined with a transition radiation (TR) option for particle identification could provide additional information necessary for electron identification or hadron suppression. The scope of the project is to develop a transition radiation detector/tracker capable of providing additional pion rejection ($> 10 - 100$).

# 1 Past

===========================

What was planned for this period? What was achieved? What was not achieved, why not, and what will be done to correct? How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project? How much of your FY20 funding could not be spent due to pandemic related closing of facilities? Do you have running costs that are needed even if R&D efforts have paused?

===========================

## 1.1 GEM-TRD concept

The transition radiation detector (TRD) readout is based on well established GEM technology. The basic concept of GEM-based TRD is shown on the Fig. 1. A standard GEM tracker with high granularity (400 $\mu$m strip pitch) capable of providing high resolution tracking was converted into a transition radiation detector and tracker (GEM-TRD/T). This was achieved by making several modifications to the standard GEM tracker. First, since heavy gases are required for efficient absorption of X-rays, the operational gas mixture has been changed from an Argon based mixture to a Xenon based mixture. Secondly, the drift region also needed to be increased from $\sim$3 mm to 20-30 mm in order to detect more energetic TR photons. Then to produce the TR photons, a TR radiator was installed in front of the GEM entrance window. Finally, the standard GEM readout (originally based on the APV25) was replaced with one based on the relatively faster, JLAB developed, flash ADC (FADC125).

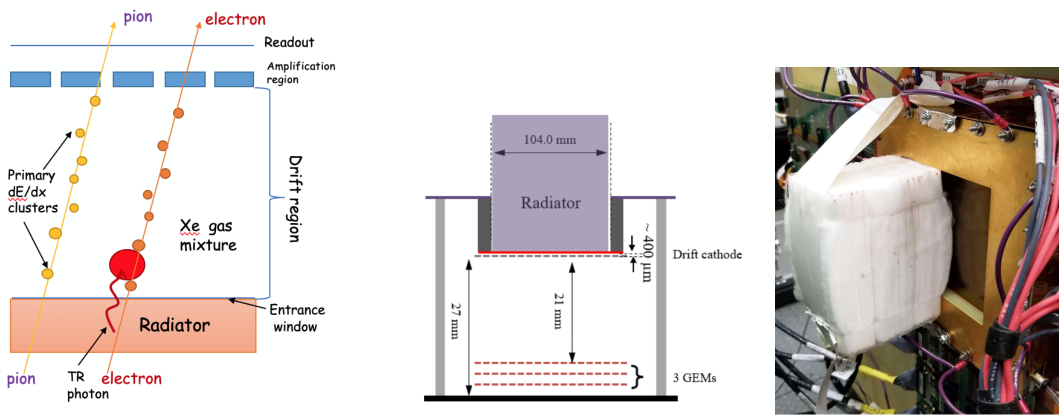


Figure 1: The basic concept of GEM-based TRD ( left), the prototype scheme (middle), and prototype at the testbeam setup (right)

A small 10 cm $\times$ 10 cm prototype, as shown in Fig. 1 has been built and tested at UVA.

The first beam test measurements using the GEM-TRD/T prototype have been performed at Jefferson Lab (CEBAF, Hall-D) using 3-6 GeV electrons, produced in a photon converter of a pair spectrometer. The TR-radiator (made of $\sim$10 cm thick fleece) was mounted in front of the GEM-TRD/T module and covered about half of the sensitive area (Fig.1 right) . Since there was no hadron beam in this setup, the effect of electron/hadron separation was evaluated by comparing data from electrons with and without the TR-radiator present, assuming that hadrons only start to emit TR-photons above a momenta of $\sim$100 GeV/c.

To determine the electron identification efficiency and pion rejection power we tested several methods: total energy deposition, cluster counting, and a comparison of the ionization distribution along a path using maximum likelihood and neural network (NN) algorithms. The maximum likelihood and NN algorithms demonstrated similar performances. However, the NN algorithm has an advantage in practical application as it allows for the optimization of various test parameters and was used as the main analysis method. The ionization along the track was used as input to a neural network program (JETNET, ROOT-based TMVA).

The FADC readout setup was able to provide about 60-200 energy measurements along each particle trajectory (Fig. 4), depending on drift velocity. However, most of the soft TR photons were absorbed in the part of the GEM-TRD/T close to the entrance window (see Fig.2) . The presence of additional ionization from TR photons along the particle trajectory was used for TR-identification and is clearly visible in the data with the TR-radiator (Fig. 3). The measured dE/dx profile shown in Fig. 3 is in good agreement with the Monte Carlo simulation. A typical waveform signal, analyzed with the FADC system is shown in Fig. 4.

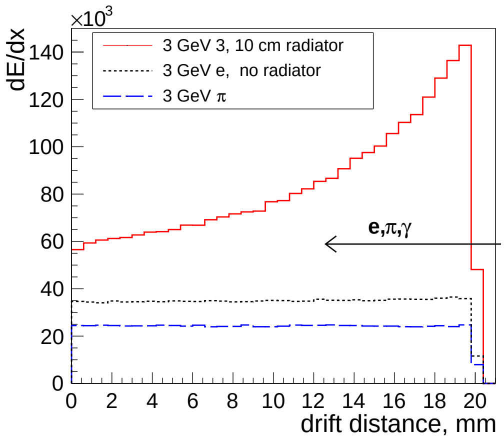


Figure 2: Geant4 simulation of dE/dx vs. drift distance for 3 GeV electrons with and without radiator compared to 3 GeV pions.

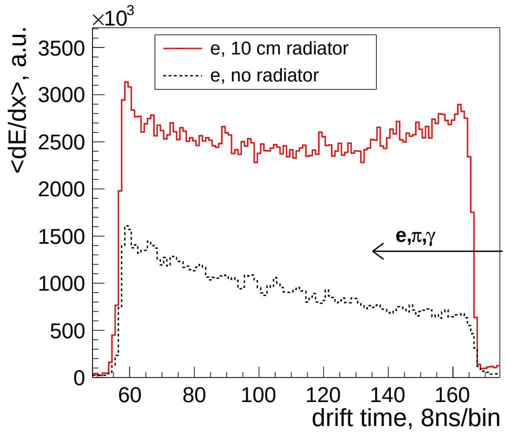


Figure 3: The measured dE/dx vs. drift time for 3 GeV electrons with (red) and without (black) radiator, drift distance is 21 mm.

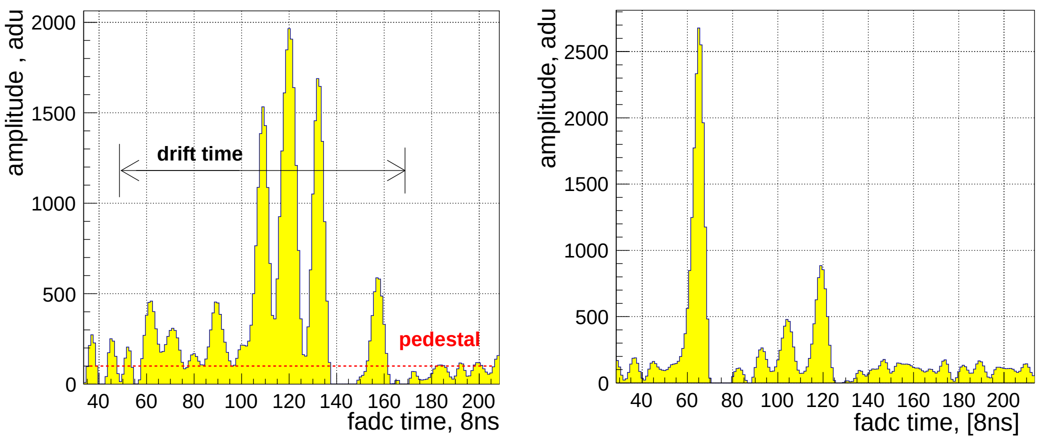


Figure 4: Typical flash ADC waveform

## 1.2 Prototyping and anode readout PCB layers

The anode readout PCB layer of the current GEM-TRD prototype is based on a a readout developed for the COMPASS experiment that is made of X and Y strips with a pitch size of 400 $\mu$m. While this is optimal for a high occupancy environment, the large number of channels does increase the price of the readout electronics. Work is under way to develop a new type of low channel count readout board based on the capacitive-sharing concept more suited for GEM-TRD applications. This novel capacitive-sharing readout PCB combines three crucial advantages: large readout pads or strips to reduce the number of readout channels, excellent spatial resolution (despite the large pad size) and improved noise reduction. The principle of capacitive-sharing readout with large pad pitch is illustrated on the Fig. 5 with a picture of the protoype on the top right of the picture. A

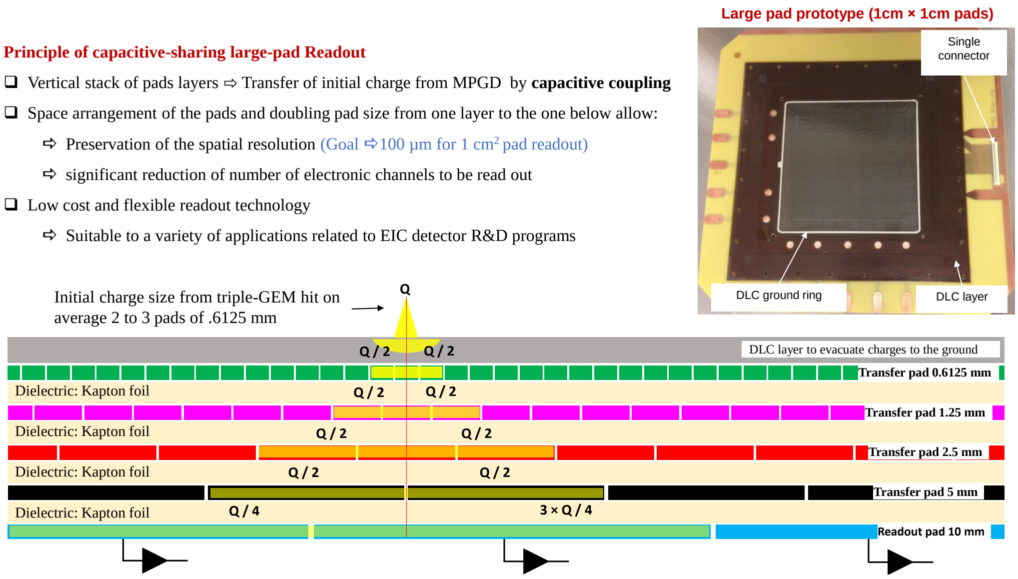


Figure 5: Principe of capacitive sharing large pad readout

large-pad capacitive-sharing readout board prototype was assembled with a triple GEM detector at UVa and tested in Hall D at JLab during CEBAF Fall run 2020. The test beam setup is shown in Fig. 6. Preliminary results of the test beam data of the large pad capacitive-sharing readout indicate that a spatial resolution of 200 $\mu$m could be achieve with a readout PCB with 1 cm × 1 cm pad size. This represents a very encouraging achievement for a first prototype large pad readout. Lessons learnt from this first prototype have been implemented in the next generation of boards we just recently received from CERN to improve performances of this new type of readout structure.

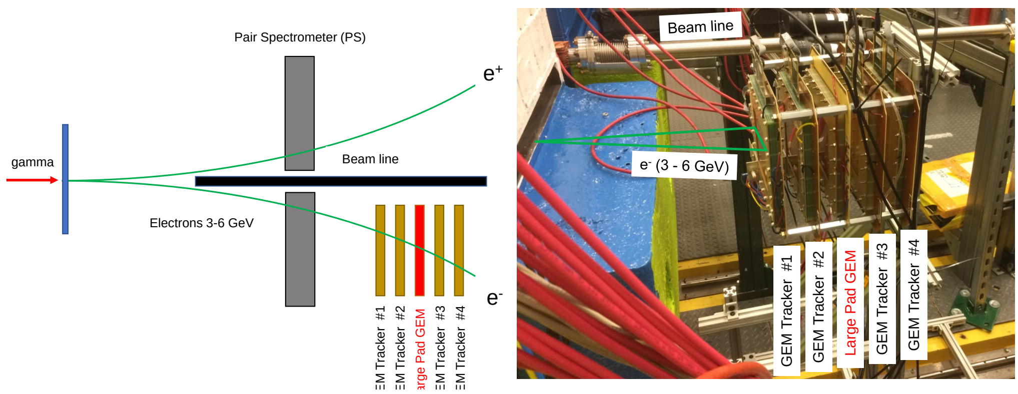


Figure 6: Setup of the capacitive-sharing pad readout prototype with 4-GEM trackers in the electron arm of Hall D Pair Spectrometer at JLab

## 1.3 Summer 2020 beam test at JLAB

The main purpose of the summer 2020 beam test was to estimate a performance of TRD with pions. Pions, comming from the decays of $\rho$-mesons could be identified by the other GlueX detectors. The readout of all tracking modules was integrated into the GlueX Data-Acquisition system. A special trigger setup was created which allowed to perform a joint run with GlueX, DIRC and TRD/tracking detectors.

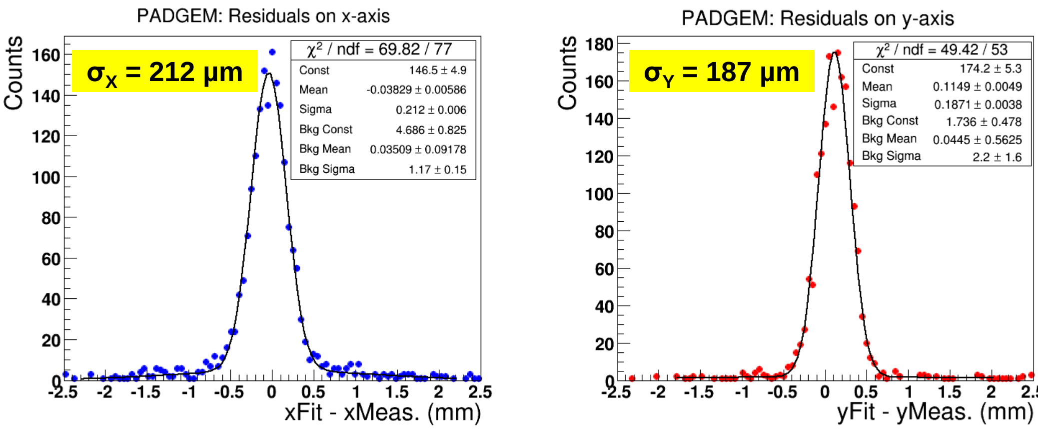


Figure 7: Spatial resolution in x (left) and y (right) for 1 cm × 1 cm pad readout prototype.

Our originally planned beam test (in Glue-X setup in front of DIRC) in March 2020 has been cancelled due to the COVID-19 quarantine, and we had to postpone our program until summer 2020. The summer 2020 test beam occured under COVID-19 restrictions. Special procedures in terms of personal protection and distancing were put in place during the installation and operations period (Fig. 8). The number of people allowed to access the facility was limited and all data-taking shifts were done remotely.

We performed a test with a 15cm thick fleece radiator and compared the results with Monte Carlo predictions. Tests were done by comparing the responses for the areas with and without the radiator, as well as with a data, taken with an electron only beam. The data points are in the good agreement with the MC predictions. As one could see from the Fig. 9 the preliminary e/pi rejection 9 has been achived. Since tests with electron and pion particles has been performed in the different locations, an additional scan of the gain uniformity needs to be performed.

Figure 8: Installation of GEMTRD modules during the COVID period

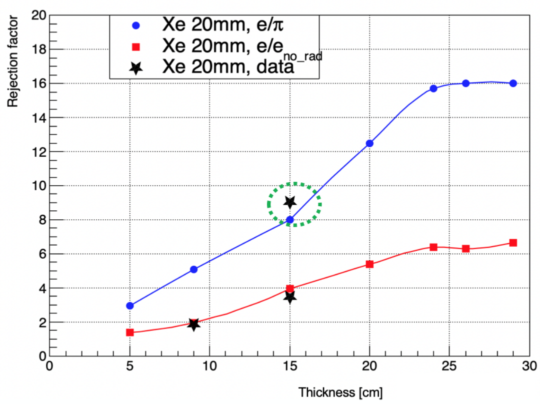


Figure 9: Rejection as a function of a radiator thickness for data (star-points) and Monte Carlo (curves)

Unfortunatelly, due to the limited beam-time and limited amount of detector accesses allowed, we were not able to perform our full pre-planned program. We have prepared a set of diffrent material types for TR radiators, and we are planning to test them during the next test beam oppertunity. Examples of such TR radiators are shown on Figs. 10, 11. Foil radiators are made out of 300-500 layers of thin (25$\mu$m) mylar foils with spacers in between layers. Other types of materials, such as fleece or foams, which are available for purchasing, needs to be tested to estimate the TR yield.

Figure 10: Foil radiators. Ca 300-500 layers of thin mylar foils with spacers

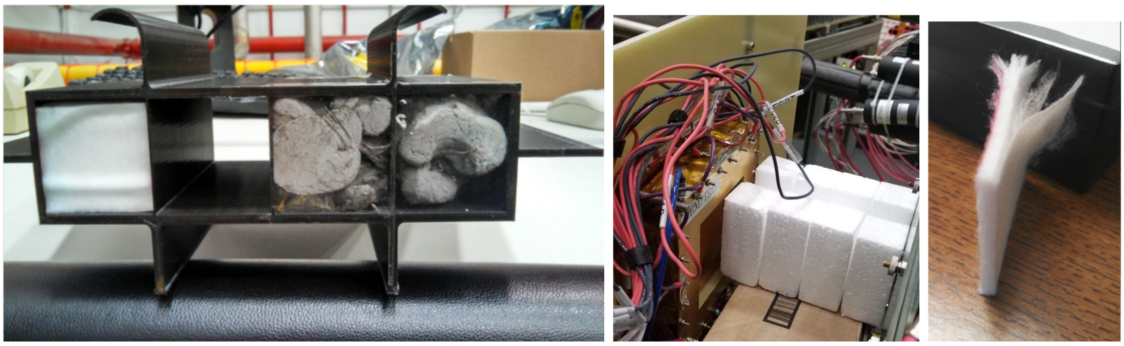

Figure 11: Other types of TR radiators prepared for tests: fleece, foam

## 1.4 Preparation of a joint test beam with mRICH and EMCAL and preparation for Fermilab test beam

We were planning to peform a beam test with a few modules of EMCAL (in collaboration with eRD1) and mRICH (in collaboration with eRD14) during the JLAB summer 2020 run, which didn't happened due to COVID-19 quarantine. We will try to perform this test during the next JLAB summer 2021 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.
We started preparation for a Fermilab test beam, to measure the TRD pion rejection factor, which originally was planned for March 2021 with the eRD6 tacking consortia. We purchased LV module and a small crate, which could be used during the test beam runs (currently using free/unused LV channels of FDC/GlueX detector). Unfortunatelly, the Fermilab beam test during this period has been cancelled due to the COVID-19 travel restrictions, but we are planning to reserve time to preform our test during the next year.

## 1.5 FADC streaming readout development

The present readout system in use employs ASIC preamps with relatively fast shaping times of 10ns to 12 ns and 12-bit flash ACDs developed for their readout and with 125 MHz sampling (fADC125). This setup is very useful to study the properties of the detector as it allows for waveform sampling and benefitting from offline characterization and optimization of readout parameters for future applications. The DAQ system for these fADC125s requires a VXS crate with clock synchronization and distribution, trigger distribution and a VME controller.

The SRO125 (streaming readout at 125 MHz sampling) development of a compact readout improves on the fADC125 performance while allowing connectivity via ethernet and without the use of the VXS infrastructure. The SRO125 will maintain the fast sampling characteristics and resolution of the present system. This stand-alone system has numerous adavantages over the present system: improved processing performance with a streaming readout architecture; allows for ML algorithm development; portability for beam tests in remote locations due to its compactness; and allows for full detector characterization and DAQ development as a guide to EIC finalization.

### 1.6 ML-FPGA optimization

Modern concepts of trigger-less readout and data streaming will produce a very large data volume to be read from the detectors. Most of this will be uninteresting and ultimately discarded. Handling this large volume using traditional means would require either a huge farm for real time processing, or a very large volume of data stored on tapes. From a resource standpoint, it makes much more sense to perform both the pre-processing of data and data reduction at earlier stages of acquisition. The growing computational power of modern FPGA boards allows us to add more sophisticated algorithms for real-time data processing. Some tasks, such as clustering and particle identification, could be solved using modern Machine Learning (ML) algorithms which are naturally suited for FPGA architectures.

The anticipated hardware platform will use high performance Xilinx devices. The candidate products include the new Xilinx VersalTM series adaptive compute acceleration platform (ACAP) platform along with the XCVU9P. In addition to providing FPGA programmability, the Versal platform includes "intelligent engines" that are very long instruction word (VLIW) single instruction multiple data (SIMD) processors that can be programmed to accelerate ML/AI computations. Figure. 12 gives an overview of the detector data processing architecture. The architecture reflects a waterfall architecture for data processing where at the top, high volume/high speed data is streamed from the ADC readout. The system will be able to receive data from any front-end board with a fiber interface. But, for the GEM/TRD use case we will be using the prototype SRO125 (currently being manufactured). The VME version of this board, the fADC125, currently provides processed data for the offline ML system described previously. The streaming version (SRO125) will allow for an apt comparison of online and offline results. The SRO125 runs a 16 bit bus at 125 MHz with a 2.5 GB/s transceiver.

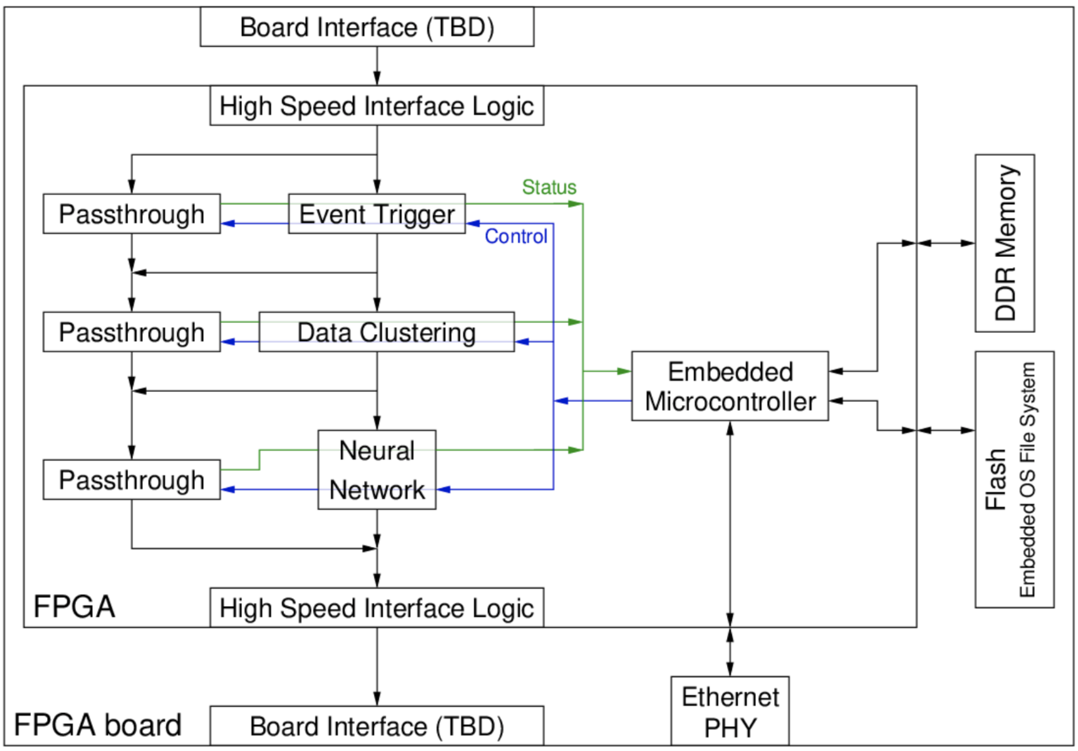


Figure 12: ML FPGA data processing architecture.

### 1.7 Collaboration formation

Our group actively participate in promoting GEM-TRD/T concept. We submitted an EOI for the SnowMass21 proccess for EIC detectors [1]. Memebers of our group are collaborating with a number of institutions such as Vanderbilt University, Weizmann Institute of Science, BNL, etc., and submitted a joint NSF-BSF proposal. Another important collaboration relates to the LHC Far-Forward instrumenteation, there a GEMTRD-based concept was proposed for very-high (from 100GeV to few TeV) energy $\pi$/K/p separation [2]. This resulted in the submission of another NSF proposal in collaboration with Louisiana State University and Fermilab.

## 2 Future

=========================

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

=========================

- **Large scale prototype**
  For the generic R&D activity our group used a small-size ($10\times10\ cm^2$) to validate a property of GEM-based TRD concept. Once the EIC project moves forward (to a large-scale production stage) we need to perform tests on the large-size modules in order be able to workout possible issues: like noise, gain-uniformity, drift-time issues, HV stability, etc.
  Fig. 13 shows a proposed design of a full-size GEM-TRD/T sector for EIC. In order to check the performance of large-scale modules, we propose to build and test one LRD and one SRD modules. This would allow us to work-out the design of gas/field cages which will be suitable for TR applications.

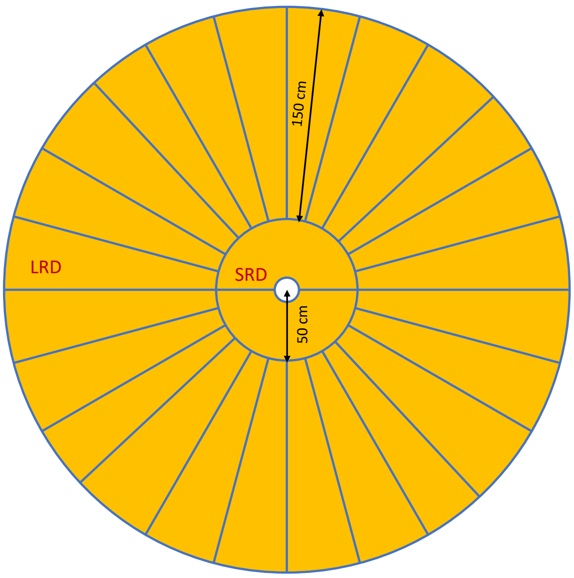


Figure 13: A proposed design for a large-scale GEMTRD sector.

- **Field/gas-cage and HV optimization**
  In order to keep the electric field uniform a special field cage needs to be developed. This includes the mechanical design and construction of the field-/gas-cage to minimize a Xe-filled gas gap between the radiator and the drift cathode.

  The GEM TRD will need 2 HV lines, one for the GEM amplification stage and the second to set a uniform drift field. To work in a high occupancy environment, the drift time needs to be minimized, requiring fields of ∼2-3 kV/cm. For a 2 cm drift distance the HV should be at the level of 4-5 kV. Depending on the chosen grounding scheme, the total voltage including

GEM stage, could be up to 8-9 kV. Optimization of HV for large drift distances for a large scale prototypes needs to be performed.

- **Anode readout PCB layers**
  We plan to built a new GEM-TRD (10 cm $\times$ 10 cm) prototype with capacitive-sharing pad readout to demonstrate that the concept works equally well with TRD application. The next step will be to expand the R&D program beyond pad readout to large 2D strip readout as well as the development of large size readout that will equip the large scale GEM-TRD prototype for EIC.

  In this context we also plan to test a zigzag readout option.

- **Readout electronics**
  In the current tests the GEM TRD uses the readout electronics originally developed for the GlueX wire chambers. It consist of a preamplifier (GAS2 ASIC chip) with shaping times of $\sim$10-12ns. The flash ADC has a sampling rate of 125 MHz and 12 bit resolution but provides only pipe-lined triggered readout. The total price is about \$ 50 per channel. The collected high resolution data recorded in test beams allow us to estimate the minimum needed shaping times of preamplifier, the FADC sampling rate and corresponding resolution. Development of the new FADC125 (i.e. SRO125) will be needed to enable the streaming of zero-suppressed data over fiber links. Other possibilities would be to adopt other existing readout chip, such as SAMPA or VMM3, or consider alternative solutions with a new ASIC for the GEMTRD application. Considering the SAMPA ASIC, significant improvements of the shaping time would be needed: the latest SAMPA v5 version has a peaking time of 80ns, which is so much slower and less flexible for studying GEMTRD performance, as well as a return-to-baseline time for a single cluster, to allow multi-clusters measurements from a single GEM strip/pad (see Fig. 14). Additionally, a final implementation to the GEM readout based on improvements to the SAMPA or the VMM chips will require their compliance to the EIC streaming readout architecture. These will include off-chip drive enhancements, which will provide for better thermal management at the detector while enabling data collection, processing and transport via high speed optical fibers. The currently employed readout electronics will be used to formulate a final set of specifications in driving the design of an ASIC and readout in conformance with the EIC streaming readout architecture.

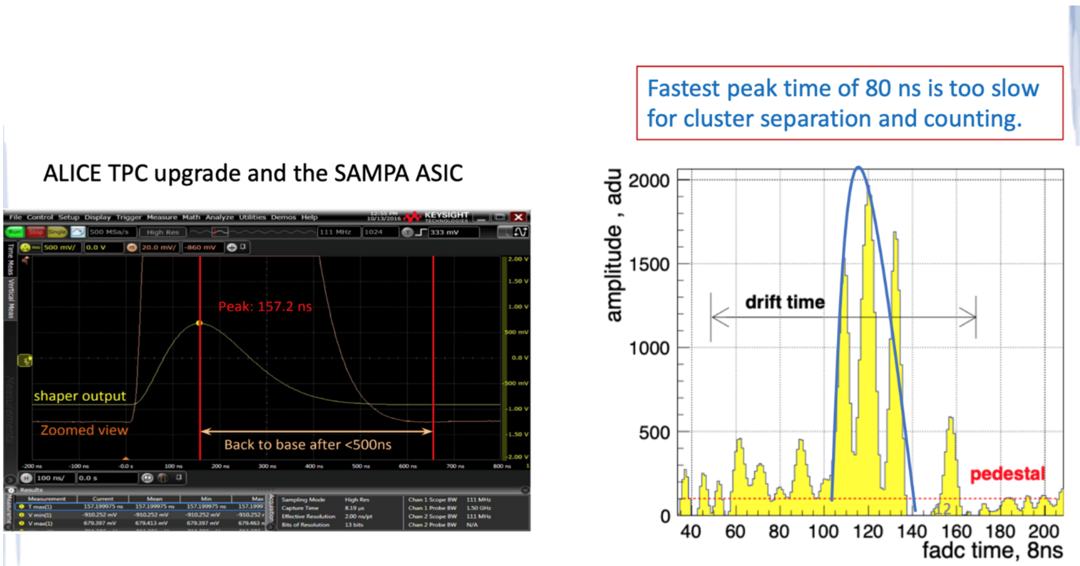


Figure 14: SAMPA vs FADC comparisons

- **TR-radiator**
  A low mass radiator available for mass production is critical and various materials still need

to be tested and optimized. This includes the optimization of a pseudo-regular radiator using thin ($\sim 12 - 15\,\mu$m) Kapton foils and thin net spacers and a detailed test of available fleece/foam materials for TR-yield.

- **Gas-system**
  Over the past few years, the price of Xe has gone up significantly. Design and development of a recirculation system to purify, distribute, circulate, and recover the gas, possibly based on a design of ATLAS TRD gas system at CERN will be necessary, but will require only moderate R&D.

## 3 Manpower

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

Jefferson Lab (JLAB):
F. Barbosa Electronics Engineer 10%
C. Dickover Electronics Engineer 15%
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 15 %
N. Liyanage Professor 5 %

Old Dominion University (ODU):
L.Belfore Professor 5 %

## 4 External Funding

## 5 Publications

NIM paper [3], participation in the EIC Yellow report actrivity[4] and SnowMass2021 EOI [1]:

## 6 Acknowledgments

We would like to thank whole JLAB Hall-D collaboration, in particular Eugene Chudakov and Tim Whitlatch for their continues support and help during the test beam period.

## References

[1] Snowmass 2021 expression of interest: Mpgd-based transition radiation detector.https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF5_IF0-193.pdf.

[2] Identification of tev hadrons: Transition radiation detectors (expression of interest: Snowmass if02, if09).

[3] A new transition radiation detector based on gem technology, Nucl. Instrum. Meth. (2019). doi:DOI:10.1016/j.nima.2019.162356.

[4] Eic yellow report.http://www.eicug.org/web/content/yellow-report-initiative.