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A proposal for the GEM based Transition Radiation Tracker R&D for EIC

Project ID:
Project Name: GEM-TRD/T
Period Reported:
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Abstract

Transition radiation detectors are used for electron identification in various particle physics experiments. The high granularity GEM detectors provide precise tracking information for charged particles. Combined with a transition radiation options for improvement of electron identification, because of the low material and cost of GEM detector technologies, a GEM based transition radiation detector/tracker is the ideal candidate for large area end-cap detectors.

A first small test prototype GEM-TRD with an ionization gap of 20 mm was built and tested in an electron beam in Hall D at Jefferson Lab. We propose to perform a detailed GEANT4 simulation, test and optimization of a GEM-TRD prototype as a detector R&D for Electron-Ion Collider.

This proposal is a follow-up to the Letter of Intent sent in January 2017 describing R&D for a GEM-TRD/T detector to improve electron identification for the EIC. At that time, we demonstrated our initial plans and focus of the detector R&D and simulation. The committee encouraged us to work on the physics motivation.

1. Motivation

Identification of secondary electrons plays a very important role for physics at the Electron-Ion Collider. The following processes are regarded as essential for the EIC physics program and could be greatly enhanced with improved electron identification:

- **J/ψ production**

The Electron-Ion collider is a machine to explore the 3-D imaging of nucleons. It would allow access to transverse momentum distributions and generalized parton distributions beyond the longitudinal kinematics studied at HERA. The transverse spatial distribution of gluons, for example, could be obtained from the cross-section of exclusive J/ψ electroproduction [1].
Gluon saturation predicts a suppression of vector meson production in eA relative to ep collisions. The coherent diffractive J/ψ cross section in (eAu)/(ep) collisions normalized by $A^{4/3}$ is shown on Fig. 2 as a function of Q^2 for saturation and non-saturation scenarios.

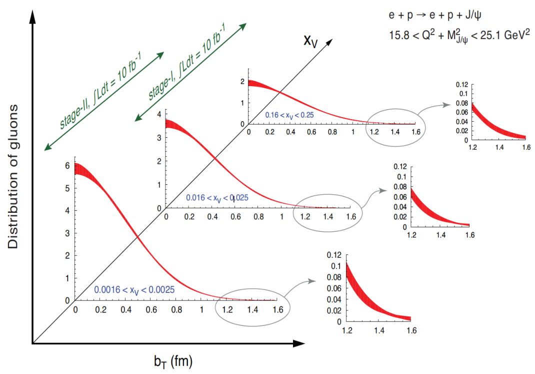

Fig1. The projected precision of the transverse spatial distribution of gluons from the cross-section of exclusive J/ψ production.

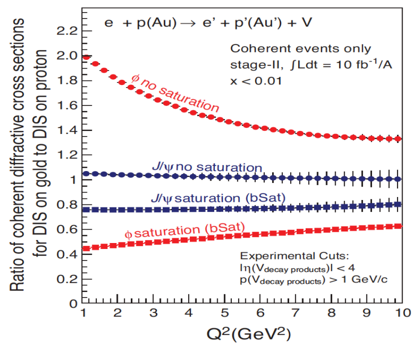

Fig.2 The normalized ration of coherent diffractive vector meson production in eA vs ep collisions.

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 on the order of ~6%. By using more sophisticated electron identification the overall J/ψ efficiency could be increased and therefore statistical uncertainties could be improved.

- **Open heavy-flavor production**

Charm and beauty mesons have significant branching ratios for decays into electrons. For example, the branching ratio of D-mesons is Br(D+→e +X) ~16% and the branching ratio of B-mesons is Br(B± →e + ν +X_c) ~ 10%. Due to the large decay length ($c\tau$~ 500 μm for beauty and $c\tau$~100-300 μm for charm mesons) of heavy-flavor hadrons the *c* and *b* mesons will have a significant decay vertex displacement. Electron identification can be combined with vertex determination for the electron candidate to enhance the reconstruction efficiency of *c* and *b* mesons.

Precise measurements of the nuclear quark and gluon densities are a key objective of nuclear physics and address fundamental questions regarding Quantum Chromodynamics and the origin of nuclear binding [3]. Heavy quark production in DIS (via boson-gluon fusion) provides a direct probe of the gluon density (Fig.3). Open charm and beauty production at the EIC could provide unique measurements of gluon densities and nuclear modifications for very high-x and to very high scales of Q^2. Such measurements could verify gluon-suppression at x>0.3 ("EMC effect") and a hint of enhancement at x~0.1 observed in the earlier experiments.

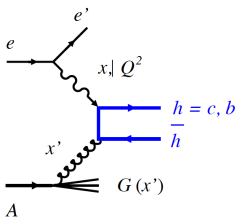

Fig.3 Diagram of boson-gluon fusion

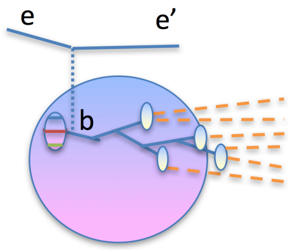

Fig.4 Dense medium propagation of heavy quarks (cold nuclear matter)

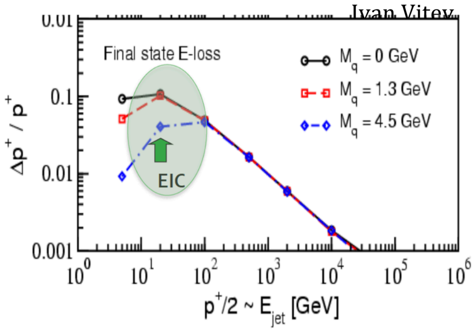

Fig.5 In-medium energy loss of heavy quarks

Parton propagation and hadronization in the strongly coupled plasma of quarks and gluons (sQGP) are the main topic of investigations over the last decade in heavy-ion collision experiments at LHC and RHIC. The Electron-Ion Collider would provide precise measurements of event kinematics (x,Q2), and would allow for the first time to study open charm and open beauty meson production and in-medium propagation in the cold nuclear matter of e+A collisions (see Fig.4). It would allow to perform a fundamental test of QCD predictions for partonic energy losses and study unexpected heavy flavor suppression in the QGP observed at RHIC.

- **Tetraquarks and Pentaquarks (and other XYZ states)**

Exotic hadrons are hadrons having internal structures more complex than the $q\bar{q}$ (mesons) or qqq (baryons) systems in the quark model. Over the last few years many new states have been observed. Since 2003 when the X(3872) state was discovered by the Belle collaboration and its existence has been confirmed by several other experiments, many other new states have been observed whose existence does not fit into our current understanding of hadronic structure. The nature of such states remains unclear and deeper investigations of exotic states is needed .

The resonant production diagram of P^+c states at the Electron-Ion Collider is shown in Fig.6(left). The presence of resonant P^+c states could be observed via decay process $P^+c \to J/\psi p$, where electron identification will play a main role. The resonant production of the new XYZ (Z^+c) state is shown on Fig.6(right). It could be observed via the exclusive decay $Z^+c \to J/\psi \pi^+$.

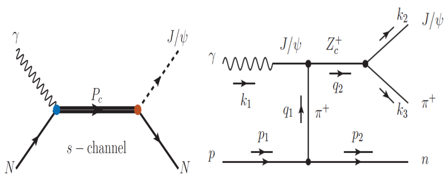

Fig.6 Resonant production of P^+c and Z^+c states at EIC

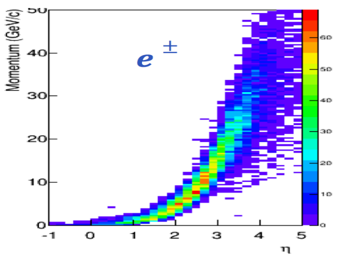

Fig.7 Angular and momentum distributions of e+/e- coming from J/ψ decay, originated from Z^+c states at EIC (ep 10GeV x100GeV)

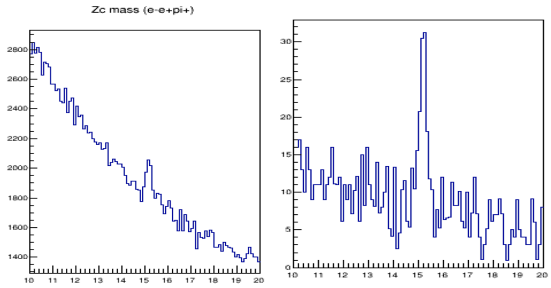

Fig.8 Mass distribution spectrum for $Z^{+}c$ state (m^2 (e+e- π +)) in GeV^2 , using the typical EmCAL e/π rejection factor 100 (left) and with additional rejection 100 (right) for 10GeVx100GeV ep collision.

The electrons emerging from such decays are forward boosted, as one could see from Fig.7. That makes the electron detection much more difficult due to the presence of 4-5 orders of magnitude higher photoproduction hadronic background. As shown on Fig.8, significant combinatorial background suppression is expected by requiring an additional e/π rejection factor 100.

- **Test of Standard Model and physics Beyond the Standard Model.**

Di-lepton and doubly-charged Higgs boson (H$\pm$ $\pm$) production

The high luminosity (more than 10^{34} $cm^{-2}s^{-1}$) expected at the Election Ion Collider would allow to perform high precision tests of the Standard Model. In the Standard Model (SM) the production of a lepton pair is dominated by the two photon process, $\gamma\gamma \rightarrow l^+l^-$. The leading order of multi-lepton production at EIC is shown on Fig.9. The production of multi-leptons at the Electron-Ion Collider plays an important role for the quantitative check of agreement between experiment and theory and may also be sensitive to new physics. The comparison of the yield of ee, eee, eμ, $\mu\mu$, e$\mu\mu$, etc. productions could be used for verification of the Standard Model. The single resonant double-charged Higgs boson production at ep/eA collisions is shown at Fig.10. Double-charged Higgs boson (H$\pm$ $\pm$) could decay into a high mass pair of same charge leptons [7].

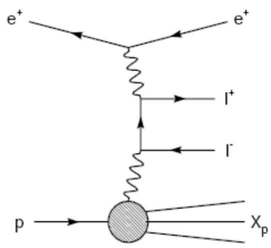

Fig.9 Di-lepton production at EIC

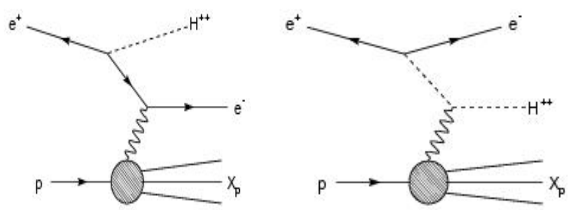

Fig. 10 Double-charged Higgs boson production at ep/eA collisions

Beyond the standard model physics based on electron identification

The Standard Model (SM) describes the fundamental building blocks of nature and their interactions. Nevertheless, there are many questions and observations that do not fit into the SM framework. Over the last decades a large amount of searches for physics beyond the standard model have been performed in different accelerator facilities. The high luminosity and high polarization at the Electron-Ion Collider (ep/eA) offer a unique possibility for searches Beyond the Standard Model (BSM) compared to ee or pp/AA collisions [2]. As an example, single resonance production of Leptoquarks (LQ), Leptogluons (LG) (Fig.11), SUSY or exited fermions(e*,ν*), assuming that they decay into "standard" fermions, could be accessed at EIC, and as one could see from Fig.11 the detection of such processes depends on the electron identification efficiency.

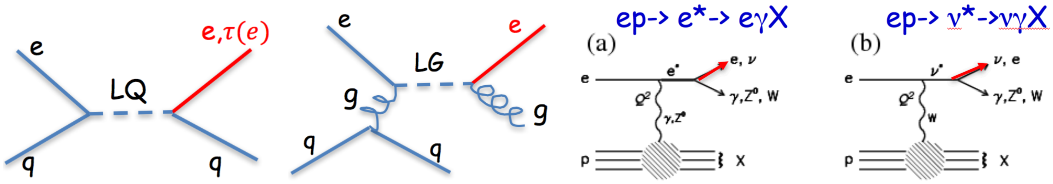

Fig. 11 Leptoquarks, Leptogluons and exited fermions production at EIC.

2. Background and problems of electron identification

To identify electrons mainly electromagnetic calorimeters and tracking detectors are used. For electrons, a track is required to match in position and energy cluster in an electromagnetic calorimeter. Typical pion rejection factors of 100 can be achieved with only an electromagnetic calorimeter [8].

The most crucial part for the identification of secondary electrons at the EIC is instrumentation of the hadron end-cap, since particle occupancy and energy is boosted towards the initial proton/ion direction. PYTHIA simulation, Fig.12, for initial beam energy ep 10x100GeV shows that the angular distribution of hadrons and secondary leptons are boosted towards the hadron endcap. Fig12(left) shows the angular distribution for the photoproduction events (Q^2<1GeV^2, σ~200 μb, sample 50k events) and Fig12(middle) shows the angular distribution of particles in events with Q^2>10GeV (σ~42nb, sample with 1M events). Note, that cross sections differ as several orders of magnitude. Fig12(right) shows that the energy for leptons (red, yellow and black lines) in the hadron endcap (1<η<3.5, Q^2>10GeV^2) is significantly high. From the Fig12a one could see that secondary electrons, coming from a beauty decays, are also boosted towards the hadron-endcap.

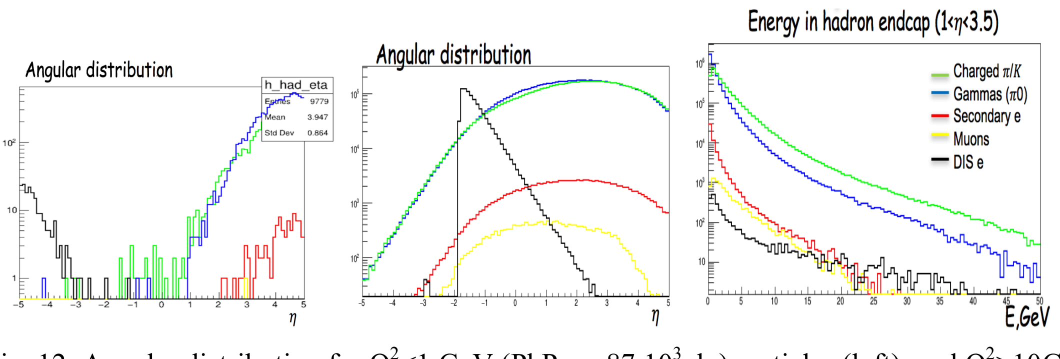

Fig. 12 Angular distribution for Q^2<1 GeV (PhP, σ~87·10^{3}nb) particles (left) and Q^2>10GeV^2 particles for ep (10x100GeV) collisions (middle) and momentum distribution of particles going into the hadron endcap (1<η<3.5) (right).

Note, depending on the process, a several order-of-magnitude difference in the flux of charged hadrons and electrons is expected in this direction.

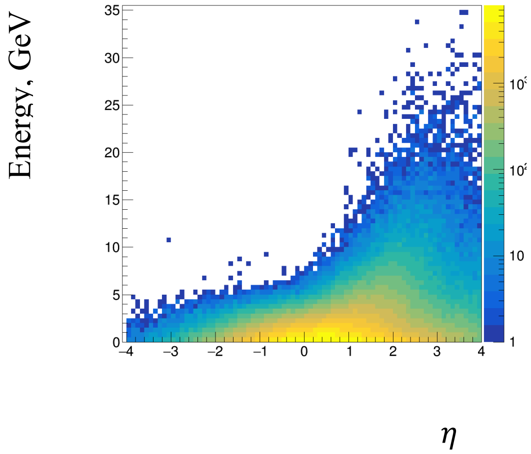

Fig. 12a Energy vs pseudorapidity for electrons coming from beauty decays for Q^2>10GeV and beam energy ep (10x100GeV).

On average one third of the produced pions will be π^0. These neutral pions will decay to two photons (blue line), $\pi^0 \rightarrow \gamma\gamma$, before having a chance to interact hadronically, and they will induce an electromagnetic cascade. The two photons appear as a single photon in the electromagnetic calorimeter, unless the latter has a fine enough granularity to be able to detect two distinct close-by showers. In the high charged particle multiplicity environment (hadron endcap), that could lead to misidentification of such neutral pions as electrons.
For such a high occupancy region **an additional identification device combined with a high granularity tracker is needed**.

3. Transition radiation

The transition radiation (TR) is emitted when a particle moves across the interface of two media with different dielectric constants [9]. The energies of transition radiation photons emitted by relativistic particles are in the X-ray region with a detected energy interval 3–50 keV. The total transition radiation energy emitted (ETR) is proportional to the γ factor (γ=E/m) of the charged particle. These characteristics could be used to discriminate between particles that have similar energies but different masses. Due to the large mass difference between electrons and hadrons, detecting transition radiation can be used to identify electrons effectively in the momentum region from 1-100 GeV/c . This is very important, because other methods like time of flight methods or detection of Cherenkov radiation no longer work in the higher energy ranges.

4. Detector concept

Traditionally, transition radiation detectors are made with Xenon-filled gas detectors (straw tubes or wire chambers). As an example, Fig. 13 (left, middle) shows the principle of operation of the ALICE transition radiation detector (TRD) [10]. As expected, most of the transition radiation photons are observed close to the entrance of the drift volume. Note that the TRD performance of wire chambers depends on the occupancy. At EIC, in the high occupancy environment in the forward region a high granularity detector would be required. The possible solutions could be segmented straw, cathode readout, silicon detectors etc. Silicon detectors could be used as a detectors for transition radiation [11], see Fig13 (right), but due to the large cost, it would not be possible to cover the large area of the end-cap region with such detectors.

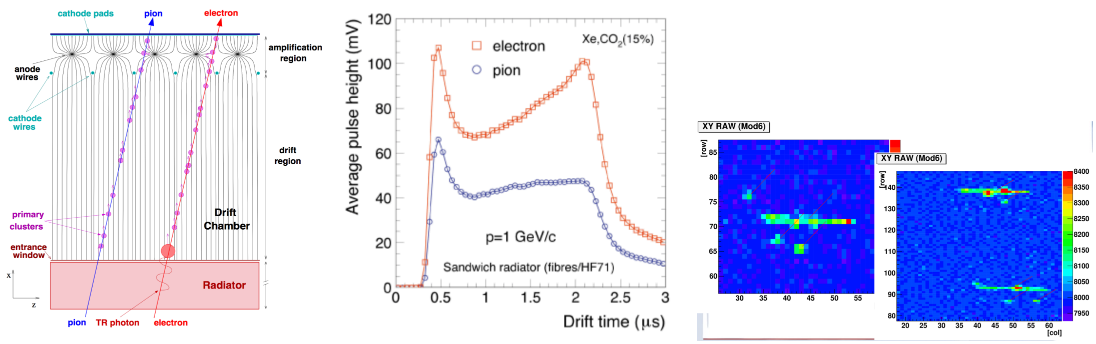

Fig. 13 ALICE multi-wire TRD principle of operation (left). Average pulse height as a function of the drift time for ALICE TRD (middle). Particle tracks surrounded by transition radiation clusters as measured by DEPFET silicon pixel detector (right).

A more natural solution would be to use GEM technology. GEMs could provide high enough granularity at relatively low cost. All detector designs for the Electron-Ion Collider, it is envision using GEM technology in the end cap region. We propose to combine a high presition GEM tracker with TRD functionality and optimize the performance of this detetcor for the use of this device as an additional tool for electron identification.

5. Prototype and test beam measurements

In order convert the standard GEM tracker into a transition radiation detector and tracker, we propose to place the 5-10cm of transition radiation radiator in front of the entrance window. Traditional gas TRDs use a heavy gas for efficient absorption of X-rays. Therefore, we need to change the operational gas mixture from Argon to Xenon. Also we propose to increase the drift region up to 2-3 cm to allow registration of more energetic TR-photons. The number of layers would depend on the needs, but we expect that 3 layers could provide e/pi rejection at level of 100 with a reasonable electron efficiency.

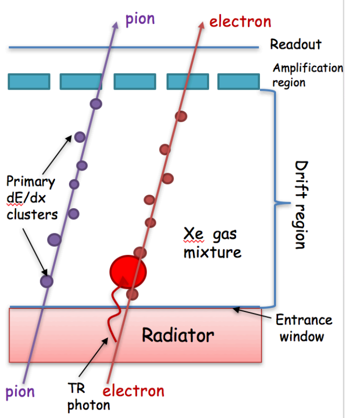

Fig.14 GEM TRD/T concept

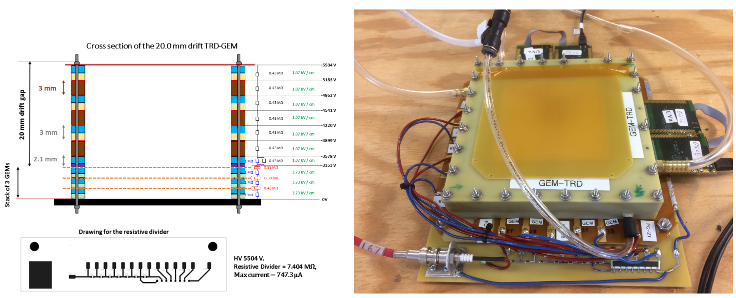

Fig.14 GEM TRD/T prototype built at UVA

In the Fall 2016 a preliminary prototype (Prototype-0) was built at UVA (Fig14). It is a modified version of a standard CERN 10 cm × 10 cm triple-GEM with a 21 mm drift gap. This drift gap corresponds to ~1.2μs drift time with an Ar gas mixture.

The first test was performed at JLAB (HALL-D) using the 3-6 GeV electrons coming from the pair spectrometer Fig.15. A 10cm of radiator material composed of fleece(fibers) was placed in front of the entrance window. This type of radiator was used for the production of the ZEUS transition radiation detector (based on multi-wire chamber). This material showed very good performance for the production of transition-radiation photons and will be used as a reference during all tests. Unfortunately, production of this material has been stopped. R&D tests for new materials will be needed.

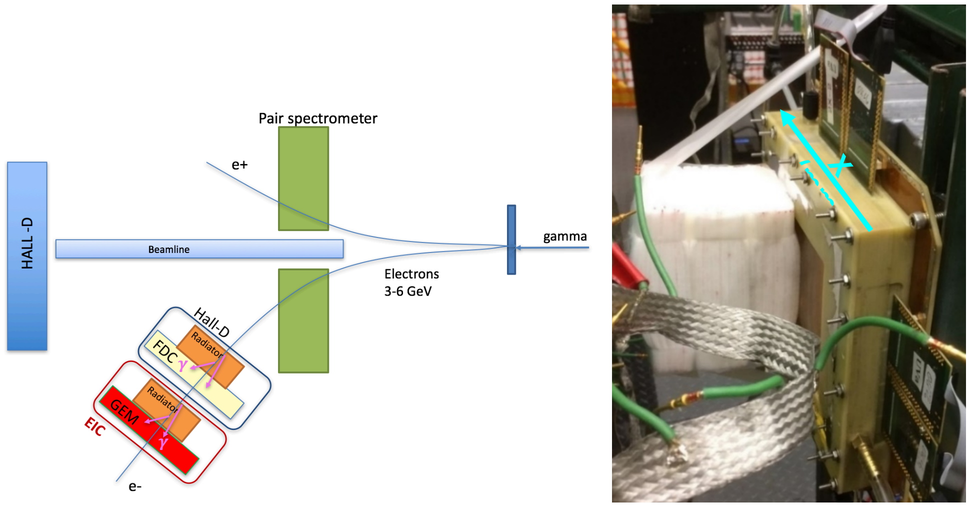

Fig.15 Experimental setup at JLAB (HALL-D) using 3-6 GeV electrons.

The first preliminaty results with Argon gas mixtures and the GEM-TRD prototype-0 show the expected behavior (Fig.16) . The excess of the avarage pulse height at the area close to the entrance window (larger drift time on the left plot) shows the presence of transition radiation photon clusters. A simillar effect can be seen in the Monte Carlo data (right plot). Note that this test has been performed with an Argon gas mixture. We are expecting segnificant impovement in the TR-absorbsion with a Xenon based gas mixture. Unfortunatelly beam operation unexpectedly stopped one week before official shutdown and we didn't have a chance to test our chamber with the Xe-mixture. We are planning to continue our measurements during the next possible beam period.

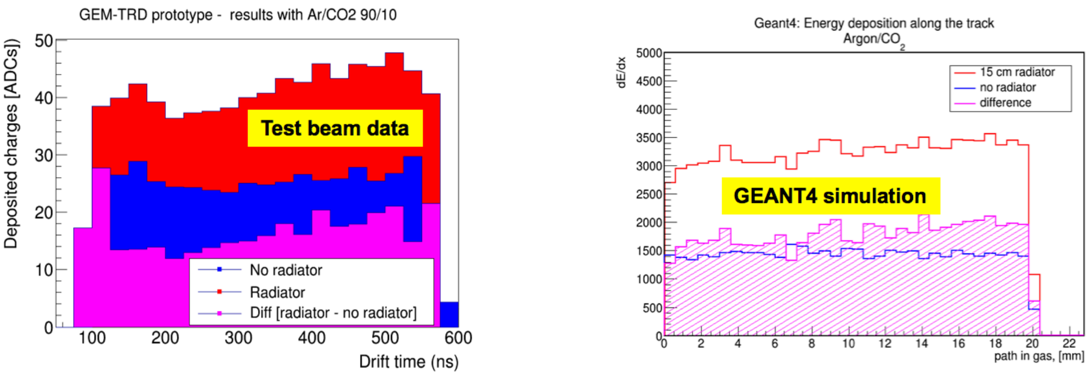

Fig.16 The first preliminaty results with Argon gas mixtures shows the expected behavior. The access of the avarage pulse hight at the area close to the entrance window (larger drift time) shows the presence of transition radiation photon clusters.

6. Proposed program of work and deliverables.

We propose to perform the following work:

1. Perform a detailed Geant4 simulation of the TRD setup with the GEM detector. This includes:
   - Estimation of the e/π rejection factor for different configurations.
   - Optimization of a number of layers/modules needed to achieve necessary rejection power and available space.
   - Check the performance of the detector with different gas mixtures, with different gas-gains and drift-times.
   - Optimization of the electron efficiencies.

2. Made modifications to implement lessons learnt from the preliminary prototype (prototype-0). Build and test two (one) new GEM based transition radiation detectors and optimize their performance to work in a transition radiation detector operation:
   - Thinning down the material for an entrance window to allow more transition radiation photons to penetrate into the Xe-gas volume.
   - Remove or minimize the dead gas gap between the entrance window and the cathode, which would allow to minimize the absorption of TR photons before the actual working detection length.
   - Replace Cu with Al or Cr to minimize the amount of material in front of the chamber.
   - Optimize HV to increase the drift velocity and decrease the drift time. Optimize the gas gain to get a better energy resolution.
   - In case of available funds, change/upgrade the readout electronics (DAQ) to allow readout of a 1-2 μs long signal.

Prototype-I will be built with standard GEM foils and Prototype-II will be built with Chromium GEM foils. The following pieces will be needed for production:

Table 1. Prototypes production needs

	Prototype I (standard)	Prototype II (Chromium)
Window: 25 micron Kapton foil	Available @UVA	Available @UVA
Drift Cathode: Kapton with 100 nAChromium (Cr-Drift)	$400	$400
Foils	3 standard GEM foils $400 = $1200	Available @UVA
Readout layer 2D COMPASS	$1300 (design and production)	$1000 (production)
Dedicated Gas box and support for radiator	$1500 (design and production)	$500 (production)
Field cage parts + custom divider design	$1000 (design and production)	$500 (production)
Total	$5400	$2400

3. Design and build a gas system, which consists of gas flow control, CO_2, temperature and pressure monitors.

4. Perform test-beam measurements using the existing setup in HALL-D(JLAB) with the pair spectrometer. Compare results with Monte Carlo simulation. Extract the e/π rejection factor for a single module.

5. Perform the test of different materials for the transition radiation radiator (foil with a spacer, fleece, foam, preferably with self-supported structure)

7. Optimization of the GEM-TRD prototypes.

For GEM-TRD Fig.14, we will implement the modifications listed below derived from the lessons learnt during the operation of GEM-TRD prototype-0 (Fig.15) used in the beam test setup in HALL-D @ JLAB in spring 2017.

a) The detector gas volume and room for the radiator

For GEM-TRD prototype-0 Fig.14, we used existing gas volume box for the chamber that was not design for a 20-mm drift. This lead to some issues with gas leakage that are critical for drift time measurement and the overall quality of the signals. In addition, the gap between the entrance window and the drift cathode was as high as 3 mm, which lead to very low efficiency for TRD photon detection. For the next prototypes we plan to build a dedicated gas tight box with less than a 0.5 mm gap between the entrance window and the drift cathode to address all these issues. The gas box will also be designed to easily accommodate the radiators.

b) GEM and drift cathode and entrance window foils

We plan to get three new GEM foils as well as a very low mass foil for the drift cathode made of a 50 µm Kapton layer with a 100 nm (0.1 µm) Chromium layer as the drift electrode from the CERN PCB workshop. For the entrance window, we are using 25 µm Kapton foil. The field cage will basically be a replica of the one we designed and used for the first prototype.

c) New design for the 2D strip readout board

The readout strip layer is the anode layer of triple GEM and is usually the layer with the electric pad for applying voltage to create the electric field across the GEM foils in the other regions of a triple-GEM detector. In the TRD configuration, in addition to the 7 voltages, we would need to add the field cage into the HV scheme in order to maintain a uniform electric field in the large drift region of the chamber. This leads to some modification of the standard readout foils that we usually get from CERN. We will work with experts at CERN to implement these modifications.

d) Redesign of the voltage divider and HV power supply scheme

In order to be able to operate the GEM-TRD prototypes in the optimal condition (maintain stable gain) we need during to adjust the electric field in the drift region to tune the drift time. To do so we would need to apply the HV in drift region independently from the HV in the GEM amplification layers. This required to move away from the traditional divider for one HV channel to distribute the voltage to all seven electrodes of a standard triple GEM. The new scheme would require at least two inputs for the HV.

Two new prototypes (Prototype I with standard GEM foils and Prototype II with Chromium GEM foils) will be built and fully tested at UVa before installation in Hall D @ JLab for beam test in Spring 2018 or Fall 2018. Given the current uncertainty of the JLAB-beam schedule, we will consider using other test beam facilities, preferentially in the US.

8. Gas system.

We are planning to build a gas system, which will be developed and built at Temple University. This system will serve for controlling and monitoring gas mixture conditions, such as gas flow, pressure, temperature and a CO_2 monitor. At the moment, no recirculation or purification systems are required.

9. Readout.

For readout of the GEM-TRD prototype a standard APV25 frontend was used. Unfortunately, the design of APV25 does not allowed to cover a full drift length (the maximum possible is ~600ns). With a Xe-based gas mixture we are expecting the drift-time to be 1-2μs. We are planning to adjust the high-voltage to fit the drift-time into a readout window. If we will find out that it is not possible, we are planning to use DAQ based on a flash-ADCs (FA125) developed at JLAB. All equipment, including boards, a VME crate, a trigger board, a signal distribution board and a computer will be borrowed from JLAB for 1-3 months. Special adapter board from GEM detector to preamplifier or to flash ADC needs to be developed.

Manpower

(with tasks assigned at paragraph " Proposed program of work and deliverables")

JLAB: (tasks 1, 4, 5)
Dr. Yulia Furletova
Dr. Sergey Furletov
Dr. Lubomir Pentchev
UVA: (tasks 2, 4, 5)
Dr. Kondo Gnanvo
Prof. Nilanga K. Liyanage
Temple: (tasks 2, 3, 4)
Dr. Matt Posik
Prof. Bernd Surrow

Proposed Budget for FY18

	Request	-20%	-40%
Xe/CO_2 (70/30) gas volume 54ft3 Pressure 820psig @70F	2x8k=16k$	8k $	8k $
Gas system	5k $	4k $	3k $
Detector prototype	8 k $(2prototypes)	8k $ (2 prototypes)	6k $ (1 prototype)
Radiators	2k $	2k $	1k $
Other material	3k $	3k $	2k $
DAQ	10k $	10k $	5k
Travel*)	16k $	14k $	13k $
Undergraduate student	5k $	5k $	5k $
Total	65k $	54k $	43k $

*) Travel includes travels to CERN for prototype production and to JLAB testbeam.
In case of travel to CERN or to DESY for testbeams (electron beam) a travel funds needs to be significantly increased.

Proposed Budget for FY18 by institutes
JLAB

	Request	-20%	-40%
Xe/CO_2 (70/30) gas volume 54ft3 Pressure 820psig @70F	2x8k$= 16k$	8k $	8k $
Radiators	2k $	2k $	1k $
DAQ	10k $	10k $	5k $
Other material	3k $	3k $	2k $
Travel	6k $	5k $	5k $
Total	37k $	28k $	21k $

UVA

	Request	-20%	-40%
Detector prototype	8k $ (2prototypes)	8k $ (2prototypes)	6k $ (1 prototype)
Undergraduate student	5k $	5k $	5k $
Travel	5k $	5k $	5k $
Total	18k $	18k $	16k $

Temple

	Request	-20%	-40%
Gas system	5k $	4k $	3k $
Travel	5k $	4k $	3k $
Total	10k $	8k $	6k $

Talks and Publications

"*Preliminary Results of GEM based Transition Radiation Detector/ Tracker in Test Beam at JLab*", by Kondo Gnanvo, conference talk at the 5th International Conference on Micro-Pattern Gas Detectors (MPGD2017)

References

[1] INT Workshop Report: http://arxiv.org/abs/1108.1713
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