A new Transition Radiation detector based on GEM technology

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Abstract

Transition Radiation Detectors (TRD) have the attractive feature of separating particles by their gamma factor. Classical TRDs are based on Multi-Wire Proportional Chambers (MWPC) or straw tubes, using a Xenon based gas mixture to efficiently absorb transition radiation photons. These detectors operate well in experiments with relatively low particle multiplicity. The performance of MWPC-TRD in experiments with luminosity of order $10^{34} cm^2 s^{-1}$ and above, is significantly deteriorated due to the high particle multiplicity and channel occupancy. Replacing MWPC or straw tubes with a high granularity Micro Pattern Gas Detectors (MPGD) like Gas Electron Multipliers (GEMs), could improve the performance of the TRD. In addition, GEM technology allows to combine a high precision tracker with TRD identificator. This report presents a new TRD development based on GEM technology for the future Electron Ion Collider (EIC). A first beam test was performed at Jefferson Lab (Hall-D) using 3-6 GeV electrons. A GEM-TRD module has been exposed to electrons with and without a fiber radiator. First results of test beam measurements and comparison with Geant4 Monte Carlo will be presented.

Keywords: Transition Radiation Detector, TRD, GEM, Tracking detector

1. Introduction

Transition radiation (TR) is produced by charged particles when they cross the boundary between two media with different dielectric constants [1]. The probability to emit one photon per boundary crossing is of order $\alpha \sim 1/137$. To increase the transition radiation yield, multi-layer dielectric radiators are used, typically a few hundred of mylar foils, polyethylene foam or fibers (fleece) [2]. The energies of transition radiation photons emitted by relativistic particles are in the X-ray region with a detectable energy range of $3 - 50\,\text{keV}$ [3]. These photons are extremely forward peaked (within an angle of $1/\gamma$). The total transition radiation energy emitted (E_{TR}) is proportional to the γ-factor of the charged particle. Typically, in particle physics, TRDs are used for electron identification and for electron/hadron separation.

The detector we are developing combines a high precision Gas Electron Multiplier (GEM) tracker with the TRD functionality optimized for electron identification.

2. The GEM-TRD concept

In order to convert a standard GEM tracker [4] into a transition radiation detector and tracker, the operational gas mixture has to be changed from Argon to Xenon based, as heavy gases are required for efficient absorption of X-rays. The drift region also needs to be increased from ~3mm to 2-3cm in order to detect more energetic TR photons. A TR radiator has to be installed in front of the GEM entrance window. The standard GEM readout with APV25 [5] is relatively slow and has to be replaced with Flash ADC (FADC).

A standard GEM with a high granularity (400 μm strip pitch) also provides high resolution tracking. The GEM-TRD concept is shown on Fig.1

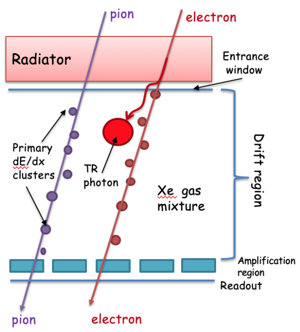

Figure 1: GEM-TRD operation principle

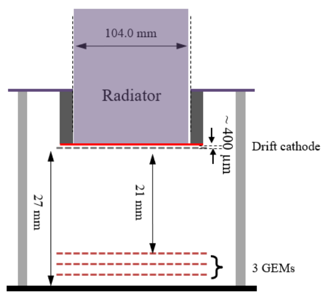

Figure 2: Schematic of GEM-TRD prototype

3. GEM-TRD prototype

A test module was built at the University of Virginia with a drift distance of 21 mm (Fig.2). For the entrance window, we use a 25 μm Kapton foil. The gas gap between the entrance window and the cathode was reduced to about 400 μm to minimize the dead volume absorbing TR photons. As a drift cathode

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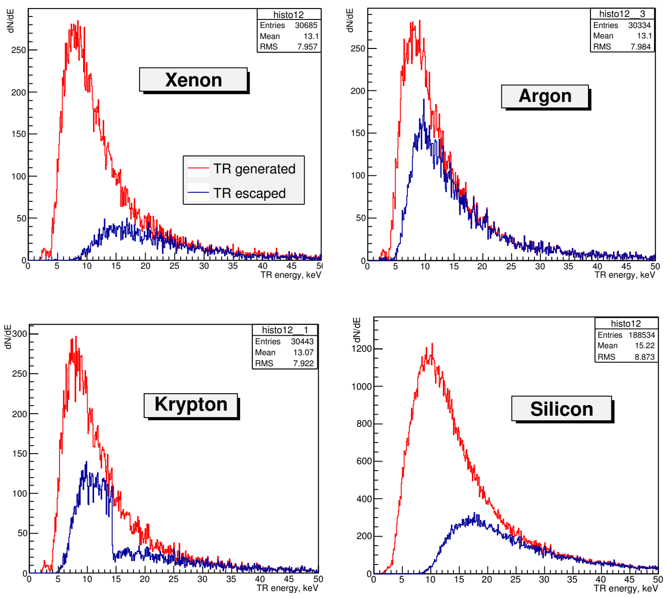

Figure 3: TR absorption efficiency for different gas mixtures

a 50 μm Kapton foil with an ultra-thin (0.2 μm) Chromium (Cr) layer has been used, which significantly improved the detection efficiency of the TRD photons by reducing the photon conversion inside the drift cathode itself. The readout board of the standard CERN triple-GEM [6] is used and modified to control the high voltage separately for the GEM and the drift volume, which allowed independent control of the gas gain and drift velocity. To improve the field homogeneity within the drift volume the side of the drift volume is also at high voltage decreasing towards the GEM detector section. In addition to the standard 7 electrodes needed to supply voltage to the GEM foils, 6 additional electrodes were needed in order to supply voltage to the 21 mm drift volume.

Gas selection. As mentioned, a standard GEM tracker uses an Argon mixture, while TRD requires a heavy gas to efficiently absorb TR-photons. Fig.3 compares various noble gases and silicon in terms of their absorption power of TR photons (red incident photons, blue escaped TR-photons) for a 20 mm gas thickness and 500 μm silicon. The best gas, in terms of TR absorption is found to be a Xenon. Argon-based mixtures do not absorb a large part of the photon spectrum. The shape of the Krypton absorption spectrum reflects the shell structure of the Kr atoms and could be used for efficient absorption of high-energy TR photons (>15 keV) with large TR-radiators (>20cm). Silicon could be used as an alternative to Xe-based gases [7]. A Xenon based mixture differs from an Argon mixture in two important practical aspects. First, a Xenon based gas mixture requires higher electric fields ($\sim$ 2000V/cm) for similar drift velocity as Argon ($\sim$ 1000V/cm). Second, the high cost of Xenon $\sim$ \$20/l demands a closed loop gas system with re-circulation and purification (which is not available for this test).

Radiator. The theory of transition radiation predicts the best radiator to be a stack of regular foils: $20-30\mu$m mylar foils and $200-300\mu$m air gap. The ATLAS experiment for their TRD/T uses foils and spacers between foils to provide the air gaps [8]. ZEUS and many other experiments use fleece radiators (Fig.4). Fig.5 shows the GEM-TRD test module with a fleece radiator in front.

Figure 4: ZEUS radiator

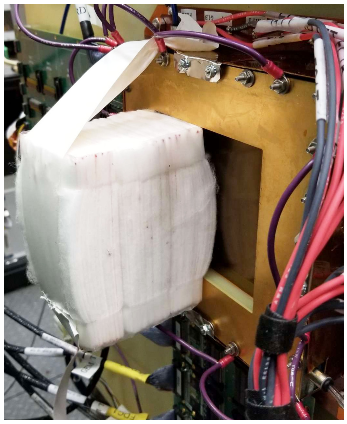

Figure 5: GEM with radiator

Readout electronics. The standard readout for GEM detectors, are typically based on an APV25 chip and measures the peak amplitude [5]. The TRD needs additional information about the ionization along the track, to discriminate TR photons from the ionization of the charged particle. In tests with the GEM-TRD prototype we use a precise (125 MHz, 12 bit) flash ADC, developed at JLAB, with VME-based readout. Flash-ADCs have a readout window (pipeline) of up to 8μs, which covers the whole drift time of the GEM-TRD prototype. Pre-amplifiers have GAS-II ASIC chips, providing 2.6 mV/fC amplification with a peaking time of 10 ns. A typical waveform signal, analyzed with the flash ADC system is shown in Fig. 6.

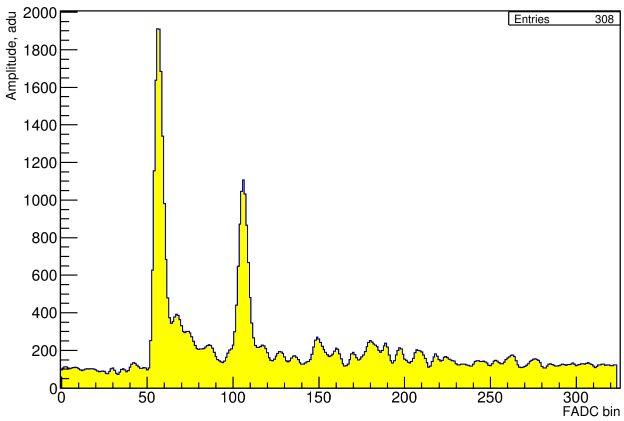

Figure 6: Typical flash ADC waveform

4. Beam test and results

Beam test setup. The first beam test has been performed at Jefferson Lab (CEBAF,Hall-D) using 3-6 GeV electrons, produced in a photon converter of a pair spectrometer. The pair spectrometer provides a precise determination of incident photon spectrum and hence electron/positron energies. The TR-radiator (~ 10 cm thick) is mounted in front of the GEM-TRD module and covers about half of the sensitive area (Fig.5) . Since we do not have a hadron beam in this setup, the effect of electron/hadron separation has been evaluated by comparison of data from electrons with and without radiator, assuming that hadrons start to emit TR-photons only above ~ 100 GeV/c momenta [2].

Beam test results. TR photons are emitted at very small angles within $1/\gamma$, practically along the path of the original particle, and are detected on top of ionization energy loss of the particle. There are several methods that could be used to discriminate TR photons against ionization: a) A cluster counting method using one threshold on the signal amplitude , assuming that the energy deposition from TR photons is point like and produce clusters with high amplitude. This method is widely used for straw-based TRDs [8]. b) A separation in space method requires high position resolution detectors (silicon pixels) to see a natural angular distribution of TR photons [7]. Or, it requires a strong magnetic field to deflect the charged particle from the TR photon trajectory [9]. c) In case of measurements of ionization along the track, a likelihood or neural network method could be used for separation of electrons and hadrons [10]. This GEM-TRD setup does not have the granularity to see the angular distribution of TR photons. Therefore we used the last method for TR identification.

With our readout setup (flash ADCs), we have about 60-200 points of energy measurements along the particle trajectory (Fig. 6), depending on drift velocity. However, most of soft TR photons are absorbed in the part of the GEM-TRD (see Fig.7), close to the entrance window. The presence of additional ionization from TR photons along the particle trajectory is used for TR-identification.

The measured dE/dx profile Fig 8 is in good agreement with the Monte Carlo simulation. The presence of TR photons is clearly visible in the data with the TR-radiator. The negative slope in the energy loss measurement without radiator is not seen in the current Monte Carlo simulation, but can be explained by diffusion and the relatively high threshold applied to the cluster finding. Fig 7 shows the ionization of 3 GeV pions to be less than for 3 GeV electrons due to relativistic rise, therefore the distinction between electrons with and without radiator can not be directly compared to electron/hadron rejection, but could be used as input-reference for Monte Carlo to estimate the electron/hadron rejection.

Data analysis and machine learning. To determine the electron identification efficiency and pion rejection power we tested several methods: total energy deposition, cluster counting, comparison of ionization distribution along a path using maximum likelihood and neural network algorithms. The latter one

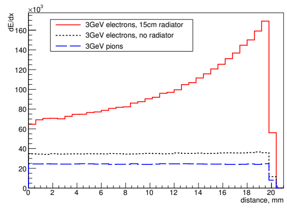

Figure 7: Geant4 simulation of dE/dx vs. drift distance for 3 GeV electrons with (red) and without (black) radiator compared to 3 GeV pions (blue).

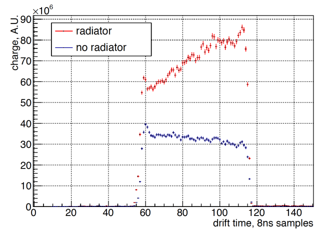

Figure 8: The measured dE/dx vs. drift distance distribution for 3 GeV electrons with (red) and without (blue) radiator.

demonstrates similar performance as a maximum likelihood and has an advantage in practical application for various test parameters. Neural network algorithm was used as the main one for analysis. The ionization along the track was used as input to a neural network program (JETNET [11], ROOT-based TMVA [12]). The particle track drift time of 60 bins (~ 480ns) has been subdivided into 10 slices (sum of 6 FADC samples), and fed into the neural network as an input layer, Fig.9. Layout of NN also has 2 hidden and one output layers. Fig.9 shows a trained network where the connecting lines represent the weights of the nodes.

Both, Monte Carlo and test beam data, were evaluated using the same code. Data was split into two parts: one part was used for ANN training, and the second (independent) part was used for final decision evaluation. Fig 10 shows the output of the neural network for a single GEM-TRD module (red - electrons with radiator, blue electrons without radiator). For a given electron efficiency, the hadron rejection factor can be extracted.

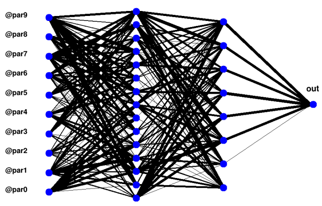

Figure 9: Neural network layout

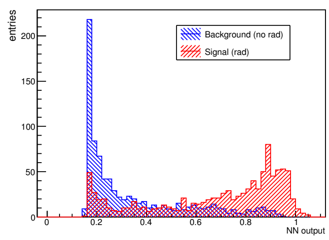

Figure 10: Neural network output for e/e_{norad}

Comparison of data with MC. The current GEM-TRD prototype has a ~ 10 cm radiator and 21 mm drift gap. To understand the optimal configuration, two Monte Carlo scans have been performed: a) for a fixed gas thickness of 20 mm the radiator length has been varied between 5 cm and 30 cm (Fig. 11). b) for a fixed radiator length of 15 cm the gas thickness has been varied between 5 mm and 30 mm (Fig. 12). The measured data (star in Fig 11) is found in good agreement with the Monte Carlo prediction. The MC scans show, that the current setup is able to provide an e/π rejection factor of ~ 5.5. The used detector gas thickness is close to the optimal, and with increased radiator length of 25 cm a e/π rejection of ~ 16 could be achieved with a single module (90% electron efficiency).

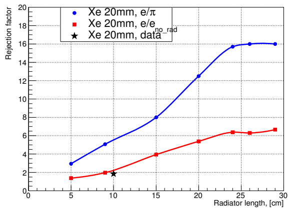

Figure 11: Radiator length variation

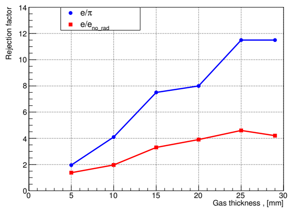

Figure 12: Gas thickness variation

Tracking with a GEM-TRD. A standard GEM plane can only provide an X-Y position of the track, while, the GEM-TRD with a 21 *mm* drift path and Flash ADC readout allows to reconstruct track segments in 3D, similar to a TPC mode (see Fig.13, where two examples of the particle track are shown: upper plot is a single particle trajectory, lower plot is a charged particle track with δ-electron). Fig 14 shows the measured angle of incoming electrons in the X-plane.

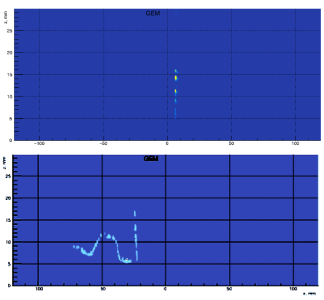

Figure 13: Single track (top) track with δ-electron (bottom)

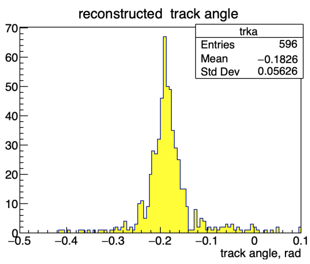

Figure 14: Particles angle measured by GEM-TRD

5. Conclusions

Future high luminosity experiments require high granularity detectors, capable to handle high occupancy and multiplicity. High granularity transition radiation detectors are currently under active development. For the high luminosity Electron-Ion collider (EIC) electron identification is very important. Due to an expected large hadron background in the forward (Hadron-endcap) region, a high granularity tracker combined with TRD functionality (GEM-TRD/T) will provide additional electron identification power. We performed a GEANT4 simulation of a GEM-TRD setup with different configurations of the detector and radiator volumes. First test beam measurements have been performed and show good agreement with MC simulations. Our results are also in a good agreement with other high granularity TRD projects (GasPixel with a TimePix chip readout) [13]. With the relatively large drift gap and FADC readout, GEM-TRD is able to provide 3D track segments like a micro TPC. Xenon gas mixture produces higher ionization density on the track, which also improves tracking accuracy. The GEM-TRD provides better tracking functionality compared to a standard GEM tracker. A strip-based readout would allow to cover large volumes, minimizing cost.

An e/π rejection factor of 5 can be achieved with a single module and can be boosted up to 16 using thicker radiators (up to 25 *cm*).

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