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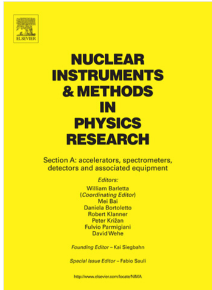

A new Transition Radiation detector based on GEM technology

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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^2s^{-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 one to combine a tracker with TRD identification (GEM-TRD/T). This report presents a new TRD development based on GEM technology for the future Electron Ion Collider (EIC). The first beam test was performed at Jefferson Lab (Hall-D) using 3-6 GeV electrons. A GEM-TRD/T module has been exposed to electrons with and without a fiber radiator. First results of test beam measurements and comparison with Geant4 Monte Carlo are presented in this article.

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 several hundred 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 keV [3]. These photons are extremely forward peaked (within an angle of $1/\gamma$). The total transition radiation energy emitted is proportional to the γ-factor of the charged particle. Typically in particle physics, transition radiation detectors (TRDs) are used for electron identification and for electron/hadron separation.

The detector that is discussed in this paper combines a Gas Electron Multiplier (GEM) tracker with the TRD functionality optimized for electron identification.

2. The GEM-TRD/T design

A standard GEM tracker [4] with high granularity (400 μm 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 ~3 mm to 21 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 (based on the APV25 [5]) was replaced with one based on the relatively faster, JLAB developed, flash ADC (FADC) [6]. The GEM-TRD/T concept is shown in Fig. 1.

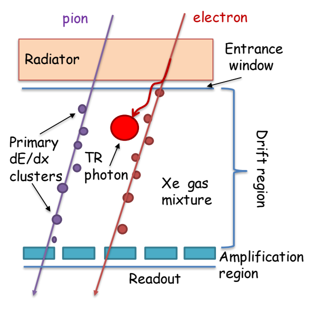

Figure 1: GEM-TRD/T operation principle

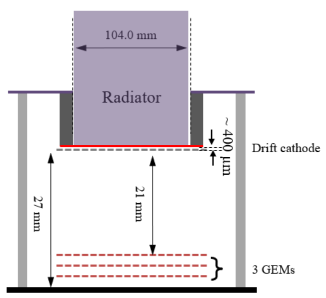

Figure 2: Schematic of GEM-TRD/T prototype

2.1. GEM-TRD/T prototype

A GEM-TRD/T prototype module was built at the University of Virginia with a drift distance of 21 mm (Fig.2) and three

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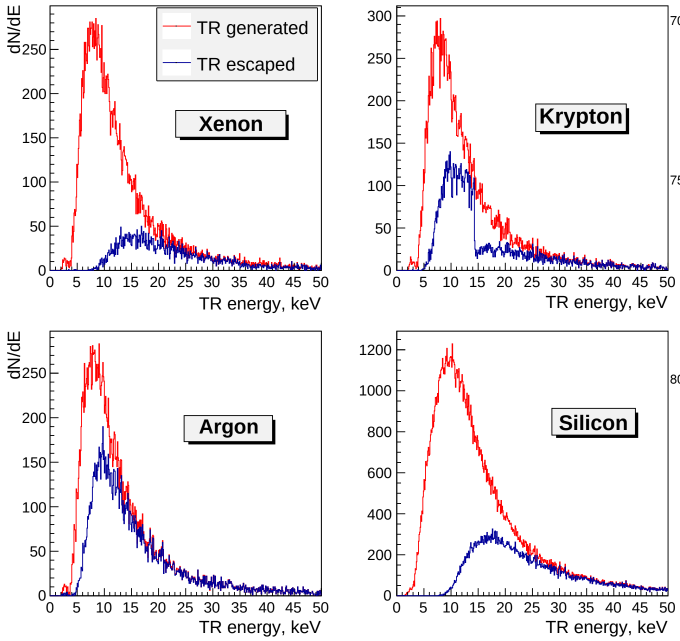

Figure 3: TR absorption efficiency for different gas mixtures and silicon

single-mask GEM foils for the amplification. A 25 μm thick Kapton foil was used for the entrance window and 50 μm thick Kapton foil, which had one side coated with 0.2 μm thick Chromium (Cr) layer, was used for the drift cathode. The thin Cr layer was used in place of a standard 5 μm Copper layer in order to reduce the absorption of TRD photons inside the drift cathode itself.

The gas gap between the entrance window and the cathode was also reduced to about 400 μm to minimize the dead volume absorbing TR photons. The transfer gap (between the GEM foils) as well as the induction gap (between the third GEM and the anode readout layer) are equal to 2 mm and the electric field in each gap was held at approximately 3 kV/cm. A 1 MΩ protection resistor was used for the GEM foils. A new resistive divider board with two HV inputs was developed in order to independently control the field in drift region and the GEM amplification. This HV power supply scheme allowed us to set the detector gain at about 5000, while independently scanning the HV in the drift volume in order to optimize drift field. The standard 2D strip readout [7] with 400 μm strip pitch is used.

2.2. *Gas selection*

As mentioned, a standard GEM tracker uses an Argon mixture, while a TRD requires a heavy gas to efficiently absorb TR-photons. Figure 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 of silicon. The best gas, in terms of TR absorption is found to be 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 (> 20 cm). Silicon could be used as an alternative to Xe-based gases [8]. A Xenon based mixture differs from an Argon mixture in two important practical aspects. First, a Xenon based gas mixture requires higher electric fields (~2000 V/cm) for a similar drift velocity as Argon (~1000 V/cm). Second, the high cost of Xenon demands a closed loop gas system with re-circulation and purification (which was not available for this test). In this test, we used a two-component mixture of *Xe* and CO_2 as a quencher, in the ratio of 70:30.

2.3. *Radiator*

The theory of transition radiation predicts the best radiator to be a stack of 20-30 μm mylar foils with a 200-300 *mu*m air gap between them. The ATLAS experiment for their TRD/T uses foils and spacers between foils to provide the air gaps [9], while ZEUS and many other experiments use fleece radiators (Fig.4). Figure 5 shows the GEM-TRD/T prototype module with a fleece radiator in front of it.

Figure 4: ZEUS radiator

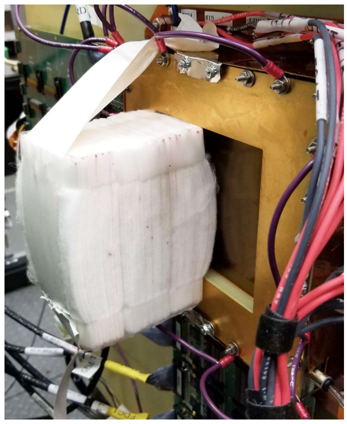

Figure 5: GEM with radiator

2.4. *Readout electronics*

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

3. Beam test

3.1. *Beam test setup*

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 pair spectrometer provides a precise

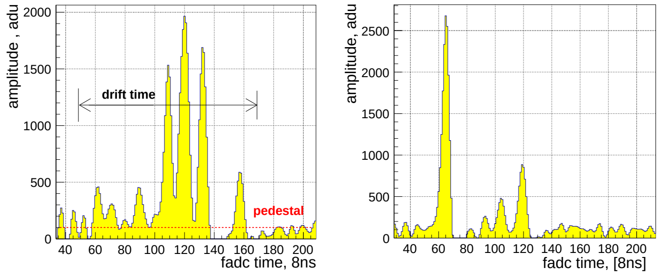

Figure 6: Typical flash ADC waveform

determination of the incident photon spectrum and hence electron/positron energies. The TR-radiator (made of ∼10 cm thick fleece) was mounted in front of the GEM-TRD/T module and covered about half of the sensitive area (Fig.5) . Since there was no hadron beam in this setup, the effect of electron/hadron separation had to be evaluated by comparing data from electrons with and without the TR-radiator present, assuming that hadrons only start to emit TR-photons above ∼100 GeV/c momenta [2].

3.2. 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. One method is known as the cluster counting method, which uses one threshold on the signal amplitude , assuming that the energy deposition from TR photons is point like and produces clusters with large amplitudes. This method is widely used for straw-based TRDs [9]. Another method known as the separation in space method, requires high position resolution detectors (silicon pixels) to see a natural angular distribution of TR photons [8]. Alternatively, a strong magnetic field can also be used to deflect the charged particle from the TR photon trajectory [10]. In the case of measurements of ionization along a track, a likelihood or neural network method could be used for the separation of electrons and hadrons [11]. This GEM-TRD/T prototype did not have a high enough granularity to see the angular distribution of TR photons, therefore the neural network method was used for TR identification.

The FADC readout setup was able to provide about 60-200 energy measurements along each particle trajectory (Fig. 6), depending on drift velocity. However, most of the soft TR photons were absorbed in the part of the GEM TRD/T (see Fig.7) close to the entrance window. 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. 8). The measured dE/dx profile shown in Fig. 8 is in good agreement with the Monte Carlo simulation. 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 algorithm. Figure 7 shows that the ionization of 3 GeV pions is less than that for 3 GeV electrons, due to a relativistic rise. Therefore the distinction between electrons with and without the TR-radiator could not be directly compared to the electron/hadron rejection. Nevertheless, this information was able to serve as an input-reference for Monte Carlo to estimate the electron/hadron rejection.

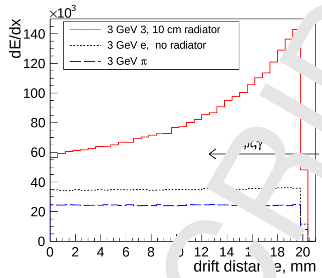

Figure 7: Geant4 simulation of dE/dx vs. drift distance for 3 GeV electrons with and without radiator compared to 3 GeV pions.

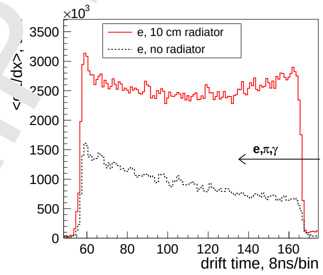

Figure 8: The measured dE/dx vs. drift time for 3 GeV electrons with (red) and without (black) radiator, drift distance is 21 mm.

3.3. Data analysis and machine learning

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 [12], ROOT-based TMVA [13]). The particle track drift time of 60 bins (∼480 ns) was subdivided into 10 slices (sum of 6 FADC samples) and fed into the NN as an input layer. Both Monte Carlo and test beam data were evaluated using the same code. The data was split into two parts: one part was used for the NN training, while the second (independent) part was used for final decision evaluation. Figure 9 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.

3.4. Comparison of data with MC

The GEM-TRD prototype had a ∼10 cm radiator and 21 mm drift gap. To understand the optimal configuration, two Monte Carlo scans were performed. The first used a fixed gas thickness of 20 mm and had the radiator length varied between 5 cm and 30 cm (Fig. 10). The second configuration used a fixed radiator length of 15 cm and varied the gas thickness between 5 mm and 30 mm (Fig. 11). The measured data (star in Fig 10) was found to be 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 detector gas thickness that was used in the beam test was close to the optimal value, and with an increased radiator length of 25 cm an e/π rejection of ∼16 should be achieved with a single module (90% electron efficiency).

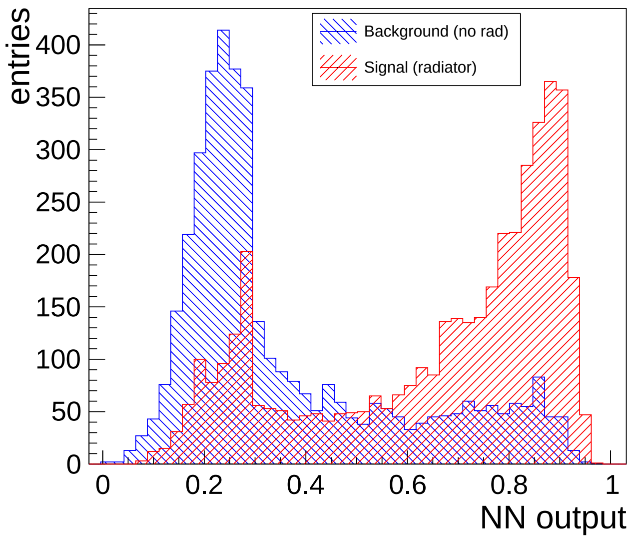

Figure 9: Neural network output for e/e_{norad}

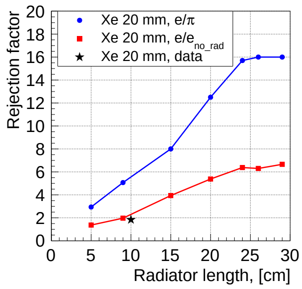

Figure 10: Radiator length variation

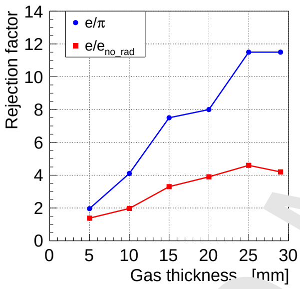

Figure 11: Gas thickness variation

3.5. Tracking with a GEM-TRD/T

A standard GEM plane can only provide the 2D X-Y position of a track, while the GEM-TRD/T with a 21 mm drift path and Flash ADC readout allows for 3D track segments to be reconstructed, similar to that of a μTPC. Figure 12 shows an example of a reconstructed 3D track measured with the GEM-TRD/T prototype. The left panel shows the 2D Z (reconstructed from the electron drift time) vs. X position, while the right panel shows the corresponding 2D Z vs. Y position.

4. Conclusions

Future high luminosity experiments will require high granularity detectors, capable of handling both high occupancy and multiplicity. In particular, for the high luminosity Electron-Ion collider (EIC) electron identification will be very important. Due to the expected large hadron background in the forward (Hadron-endcap) region, a high granularity tracker combined with TRD functionality can provide high resolution tracking, as well as additional electron identification power. We have performed a GEANT4 simulation of a GEM-TRD/T setup with different configurations of the detector and radiator volumes.

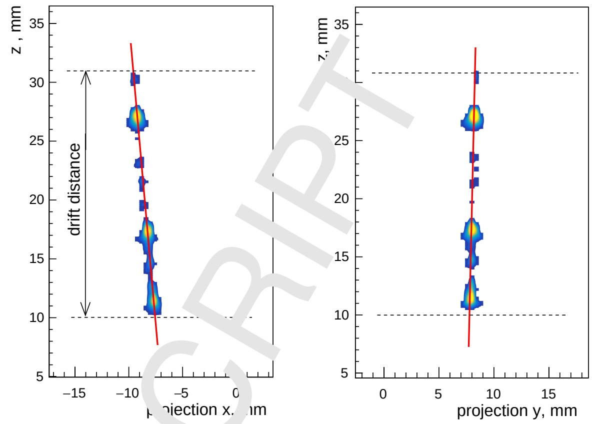

Figure 12: Single track reconstruction

The first test beam measurements from GEM-TRD/T prototype using a Xenon based gas mixture, 21 mm drift gap, and a Flash ADC readout have been performed and show good agreement with MC simulations. These results show that an e/π rejection factor of 5 can be achieved with a single GEM-TRD/T module and can be increased up to a factor 16 by using a thicker radiator (up to 25 cm). We have also demonstrated the μTPC like tracking functionality of the GEM-TRD/T by successfully reconstructing 3D track segments. These results are also in good agreement with other high granularity TRD/T projects, such as the GasPixel with a TimePix chip readout [14].

5. Acknowledgment

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Research Highlights

New development of a transition radiation detector based on GEM technology

The first results of beam test measurements and comparison with Geant4 Monte Carlo

Neural network algorithms for extracting the electron/pion rejection power