A fast spatial resolution optimizing method for track-ion using a GEM detector based on the time information

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\textbf{Abstract:} This work proposes a fast method of vertex reconstructing for incident ions in GEM detectors. Inspired by the Time Projection Chambers (TPC) approach, the time information of consecutive signal samples from Front End Electronics (FEE) is utilized. The method is demonstrated with a 2D-readout THGEM detector coupled with an APV-25 FEE. Using only one experimentally dependent parameter in the analysis, the proposed method resulted in a spatial resolution of 0.45 mm, compared to a value of 9.10 mm for the traditional center of gravity method.

\textbf{Keywords:} Particle tracking detectors; Vertexing algorithms; Pattern recognition, cluster finding, calibration and fitting methods; Time projection chambers

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1 Introduction

GEM (gas electron multiplier) detectors are widely used in high-energy physics and nuclear physics as spatially sensitive detectors for the detection of both photons and charged particles due to their good performance (high count rate, high effective gain, high spatial resolution, good plasticity: fast neutron detector with PE conversion layer, thermal neutron detector with boron-coated cathode) [1–3]. The spatial resolution for photon detection is typically less than 100 µm with the traditional center of gravity method [4]. However, the spatial resolution is significantly lower for charged particles because ion-electron pairs are produced along the charged track and the center of gravity of the track cannot correctly represent the incident vertex of the particle. This is particularly the case when the charged particles enter the detector at a large angle. A TPC-like analysis method could be used to reconstruct the incident vertex [5, 6].

In recent years, several fast on-line reconstruction technologies based on FPGA chips have been developed. It is difficult to achieve a complex reconstruction algorithm due to the limitation imposed by the inability of FPGA to adequately address non-logical operations [7]. Therefore, the reconstruction algorithm is often simplified to reduce the consumption of chip resources. As such, a fast method for ion incident vertex reconstruction is proposed in which only one of the parameters used to reconstruct the incident vertex of ions is dependent on the experimental conditions.

2 Reconstruction principle

The principle of vertex reconstruction is illustrated in figure 1. An alpha particle enters the detection volume with an angle and generates a track with ion-electron pairs in the drift region of the GEM detector. The velocity of the alpha ions with an energy of a few MeV is much larger than the drift velocity of the electrons in the detector. Therefore, with respect to the drift of the electrons, the track can be considered to be instantly generated. The electrons at different positions of the track drift along the direction of the electric field lines with a slight transversal diffusion. The electrons at the end of the track (point A in figure 1) are multiplied by the GEM foil and enter into the induction
region where they initially fire the strips. On the contrary, the electrons at the beginning of the track (point B in figure 1) travel through the drift region and enter into the induction region and fire the strips finally. The time information of the track can be used to achieve the ion incident vertex reconstruction. The typical signal duration time is 300 ns. APV-25 front-end-electronics with a 25 ns sampling period was used to sample the signal on each strip [8, 9]. A total of 30 consecutive samples can be acquired by the data acquisition system with a typical rise time of 150 ns, which allows the entire waveform of the alpha ion to be recorded.

![Figure 1](image)

**Figure 1.** Reconstruction principle. Point A is the end of the track and initially fires the readout PCB, while point B, which defined the beginning of the track, fires the readout PCB at the end. The relative time between point A and point B can be used to determine the incident vertex using the sampling integrated pre-amplifier.

### 3 Experimental setup

The reconstruction principle was tested using a single-layer THGEM detector which is schematically shown in figure 2. It consists of one THGEM foil (Au-coated with a thickness of 200 µm, pitch of 600 µm, a hole diameter of 200 µm, and a rim of 80 µm), a cathode plate and a read-out anode with the pitch of 600 µm in each dimension [10]. The intrinsic spatial resolution of the detector was approximately 173 µm (600/√12 µm). The detector was operated with a continuously flushed Ar/CO₂ gas mixture (90/10 percentage in volume) and had a square sensitive area of 100 mm × 100 mm, a 4 mm drift region, and a 2 mm induction region. Three voltage dividers were employed to power the detector, while three resistors and capacitors were used to reduce the noise due to the voltage dividers. The work bias voltages were -1830 V, -1350 V and -600 V, respectively. The voltage on the THGEM was 750 V, the electric field of the drift region and induction region were 1200 V/cm and 3000 V/cm, respectively. The lower layer of the GEM film provides a trigger signal, which was supplied to the APV chip via a CF8000 Octal Constant-Fraction Discriminator.

The cathode was made of a 2 µm thick aluminized Mylar foil, which minimized the energy loss of alpha ions from a 2⁴¹ Am source to allow the alpha ions to traverse through the entire drift region. A 100 µm thick FR4 foil, which could completely block the alpha ions except for the three slits it contained, was placed on the cathode. The widths of the slits were 100 µm, 200 µm, and
300 $\mu$m, respectively. The distance between the slits was 30 mm. Three alpha sources were placed directly right on the slits, and an alpha ion could enter the drift region at a maximum of 71°. The readout system was built on APV-25 front-end boards and an FPGA-based data acquisition system which reads 30 consecutive samples in one trigger signal. The velocity of a 5.29 MeV alpha ion was approximately 15.9 mm/ns given by LISE++ [11], and the velocity of electrons in the drift region was approximately 0.05 mm/ns, which was calculated by Garfield++ [12]. Compared with the electron drifting time, the time to generate a track was negligible. Thus, it was reasonable to assume that all electrons in a track were generated and started to drift at the same time.

Figure 2. Experimental setup. Two-dimensional position sensitive THGEM detector with one THGEM foil and 600 $\mu$m pitch in each dimension. Alpha ions from the $^{241}$Am source enter the drift region with a maximum angle of 71°. The signal on the lower side of the THGEM foil provided a trigger signal for the DAQ system.

4 Results and discussion

For a track generated by an alpha particle traversing the detector, signals are induced in several adjacent electrodes and readout by the FEE at 40 MHz frequency. In figure 3 several histograms are represented that show the signals associated with the 6 adjacent electrodes. For a given electrode, the signal is sampled for 30 FEE working periods. It is obvious that the signals on different electrodes arrive at different times. Electrode 43 receives the signal the earliest. This signal is associated with the electrons that are ionized at the end of the track. Accordingly, electrode 48 is the last to receive the signal. This signal is associated with the electrons that are ionized at the beginning of the track.

Since the entire signal induced by a proton track lasts for several FEE readout periods, the DAQ deals with only a part of the signal. To correctly reconstruct the vertex of a track, it is necessary to first determine which FEE periods contain the entire signal of the track. figure 4 shows the signals for a track sampled over several FEE periods. The upper panel shows the sum of the signal amplitude of all electrodes within one FEE period. Since a constant pedestal subtraction was applied, the sum of the signal amplitude in the FEE periods in which there is no real signal but only noise, varies around 0. In figure 4A it is clear that the signal starts in period 15 and ends at approximately period 24, as indicated by the two red lines. In the experiment, an amplitude cut was set on each FEE
Figure 3. The signals on the 6 adjacent electrodes, it is obvious that the signals on different electrodes arrive at different time.

In a typical analysis, the track vertex is determined by the center of gravity of all the signals induced by the entire track. For the track shown in figure 4B, the result should be a position at approximately 55, which would exhibit an obvious deviation from the real vertex. For comparison, the result of this analysis method on the experimental data is shown in figure 5. Although the alpha particles can travel into the detector through the 3 slits in the experiment, only the data from one slit are plotted in figure 5. In figure 5 the left panel shows the 2-D distribution of the track vertexes as determined by the center of gravity. Since all the alpha particles in the figure are from one slit,
the real vertex distribution should represent the shape of the slit. The obvious difference between the pattern shown in figure 5A and the shape of the slits clearly shows the failure of the normal analysis method. Figure 5B shows the center of gravity distribution in the x-direction, which is perpendicular to the direction of the slits. In order to evaluate the position resolution of this normal analysis method, a convolution of a rectangular function with a Gaussian function is applied as the fitting function on the histogram shown in figure 5B. The fitting result is shown as the red curve in figure 5B and the position resolution of 9.1 mm was determined.

Figure 4. A typical signal of an alpha ion. A: signal waveform of an alpha ion. B: the samples order against the center of gravity for each sample. The center of gravity gradually approaches the incident vertex (48.5) but there still is a deviation.

Figure 5. A: position spectrum in two-dimensions. B: position spectrum in x dimension.
As illustrated in figure 4 and figure 5, neither the center of gravity of an entire track nor the signal in any FEE period can represent the track vertex. It is therefore necessary to identify another approach for the reconstruction of the vertex. Figure 6 shows a clear correlation between the weighted average center of the track for a slit and the weighted average center of gravity interval, in one dimension of the track. The weighted average center of gravity interval refers to the weighted average of the center of gravity interval and the integral of the signal, which is defined as:

\[
\frac{\sum_{sa=1}^{n} (\alpha_{sa} + 1 - \alpha_{sa}) \times (\beta_{sa+1} + \beta_{sa})}{2 \times \sum_{sa=1}^{n} \beta_{sa}},
\]

(4.1)

where \(\alpha_{sa}\) represents the center of gravity for the sample period \(sa\), and \(\beta_{sa}\) represents the integral of the signal in the sample period \(sa\). The symbol \(i\) represents the start period of the signal where the amplitude of the \(i\)-th period is about 10% of the maximum signal amplitude, and \(n\) represents the end period of the signal where the amplitude of the \(n\)-th period is also approximately 10% of the maximum signal amplitude.

The ratio of the center of gravity to the weighted average center of gravity shift is a constant, which can be obtained from the linear fitting in figure 6. In this case, the value is -11.55, which means that the reconstructed vertex for each track is determined by the following formula:

\[
\text{Position} = A + 11.55 \times B,
\]

(4.2)

where \(A\) represents the weighted average center of the track, and \(B\) represents the weighted average center of the gravity interval.

![Figure 6](image-url)  
**Figure 6.** Linear correlation between the center of gravity and the weighted average center of the gravity interval.
The spatial resolution after correction with eq. (4.2) is shown in figure 7, the resolution has an FWHM of 0.45 mm which was achieved based on the convolution with a Gaussian-distribution. Large-angle incident ions mainly contribute to both sides of the position spectrum, primarily because the level of noise is increased due to the large number of fired readout strips. When compared to the traditional method, this method achieves an improvement in the spatial resolution by an order-of-magnitude.

**Figure 7.** Spatial resolution after correction. A resolution of FWHM of 0.45 mm was achieved by convolution with a Gaussian-distribution.

The same processing was performed on the ions emitted from the other two slits and the results are shown in figure 8. The parameters obtained by fitting the data of the two slits are 11.43 (figure 8A) and 11.40 (figure 8B), respectively. Distortion signals were removed during the processing of the right slit data. This was necessary because distortion is induced by the detector’s drift field in the fringe region. The parameters of the three slits are almost the same under the same working condition, which indicates that for any track under experimental conditions, these phenomenological parameters can be determined and applied to reconstruct the incident vertex. The main factor that affects these parameters is the electron drift velocity, which depends on the electric field of the drift region. If the electron drift velocity increases, the electronic response is relatively slow, and the movement of the center of gravity for each sampling period decreases, which leads to a larger parameter. This parameter is independent of the incident angle of the tracks, the counting rate, the slit width, etc.

The correction parameter of the first slit is used to reconstruct the incident vertex of the tracks from all three slits. The result is shown in figure 9. The center of the three slits are located at 48.47 (600 μm), 98.10 (600 μm) and 148.02 (600 μm), respectively, and the distances between the slits are 29.78 mm and 29.98 mm. Compared with the physical value of the distance which is 30 mm, this impressive coincidence is unambiguous evidence of the efficacy of the proposed reconstruction method.
Figure 8. A: center of gravity as a function of the weighted average of the gravity interval for the middle silt. B: center of gravity as a function of the weighted average of the gravity interval for the right silt.

Figure 9. Alpha ion reconstructed position spectrum of three slits using the center of gravity technique (in red) and the TPC technique (in blue).

5 Conclusion

In this work, a fast method of vertex reconstruction for incidental ions in GEM detectors is proposed. The analysis revealed that using an experimental dependent parameter, the method facilitates a spatial resolution of 0.45 mm. Compared with the result of 9.10 mm obtained using the traditional gravity method, there is an improvement in excess of one order of magnitude. The parameter, which depends on the configuration of the detector and is independent of the incident track, can be extracted by a linear fit of predefined signals during a calibration process. Experimental evidence that unambiguously demonstrates the capability of this method is described.

The analysis in this work assumes the incidental tracks generates signals in a linear manner and higher order effects are ignored. It is possible to achieve superior precision by taking non-linear effects into account, but this will increase the complexity of the reconstruction process. The current method significantly reduces the overall complexity and facilitates implementation in FPGA-based online DAQ systems.
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