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Track reconstruction based on Hough-transform for nTPC *

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Abstract: A GEM-TPC prototype, which will be used as a fast neutron spectrometer based on the recoil proton method, is designed and being constructed in Tsinghua University. In order to derive the recoil angle of the recoil proton, tracks of recoil proton in the TPC sensitive volume must be reconstructed. An algorithm based on Hough-transform for track finding and least square method for track fitting was developed in this paper. Based on the Monte Carlo simulation data given by Geant4, a detailed track reconstruction process was introduced and the spectrum of induced fast neutron was derived here. The results show that the algorithm was effective and high-performance. With the recoil angle of the proton less than 30°, a 4.4% FWHM neutron energy resolution was derived for 5 MeV induced fast neutron, and the detection efficiency was about 2×10^{-4}.

Key words: fast neutron spectrometer, GEM-TPC, Hough-transform, track reconstruction, Geant4

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1 Introduction

It is very important to measure the energy spectra of fast neutrons in various fields both in science research and engineering applications, such as nuclear physics, neutron-field characterization and thermonuclear fusion plasma diagnostics [1, 2]. A Time Projection Chamber prototype using Gas Electron Multipliers for signal multiplication and readout (GEM-TPC) [3, 4], is designed and being constructed to measure the fast neutron spectrum (herein named nTPC) in Tsinghua University [5]. The energy resolution of nTPC is designed to be less than 5% while the detection efficiency is higher than 1×10^{-5} for 5 MeV induced neutron. The working principle of the nTPC is based on the recoil proton method [6]. Fig. 1(a) shows the scheme of the nTPC, the working gas, argon-hydrocarbon mixture, also plays the role of a convertor for converting neutron to proton and the multiplication gas for GEM. Fig. 1(b) shows the readout pads layout of the nTPC, in order to reduce the readout electron channels, only the first quadrant is designed though the detection efficiency will be reduced 75%. The current signal of each pad will be shaped and amplified by an application specific integrated circuit (ASIC) named CASA-GEM [7], and then sampled by FADC. The proton tracks in sensitive volume of nTPC will be recorded as 3D coordinates, both the x and y coordinates are given by the position of the fired pads, and the z coordinate is given by the relative drift time of the electron.

In the nTPC, after a collimated incident neutron generates a proton by an (n, p) reaction in the working gas, once the energy $E_{\rm p}$, and the recoil angle θ of the recoiled proton are measured, the energy of induced neutron $E_{\rm n}$ can be derived by the equation $E_{\rm n}=E_{\rm p}/\cos^2\theta$. The energy of the recoil proton can be easily derived from the sum of the charge of the fired pads. Then, the other important process is to reconstruct the track of the recoil proton, and get its recoil angle. Hough-transform [8] is

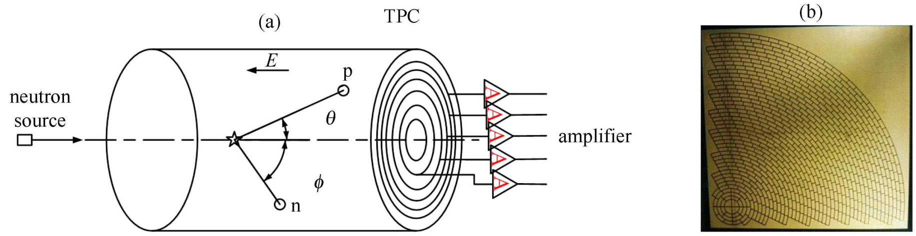

Fig. 1. Scheme of the fast neutron spectrometer (a) and the readout pad layout (b).

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well suited for tracking the charged particle without magnetic field, because the tracks are always described as a straight line model. Here we describe the track reconstruction algorithm, which is based on Hough-transform for track finding and the least square method for track fitting.

2 Monte Carlo simulation

Monte Carlo simulation is carried out with a mixture of argon (50%) and ethane (50%) as the working gas for 5 MeV neutrons using the GEANT4 toolkit. The QGSP_BIC_HP model is selected as the physics list to simulate the neutron scattering, proton recoil and ionization process, and the energy deposited in the gas is recorded. Parameters of working gas used in the simulation, such as the drift velocity, the transverse/longitudinal diffusion coefficient, and the attachment coefficient, are calculated by Garfield. Then, the electrons' transportation in the working gas and signal generation in pads are simulated by the ROOT program using a fast MC method. For simplicity, the charge amplification and electron transfer process in the GEM are skipped. The charge signal waveform of the fired pads is recorded with a time window of 20 μs by a 100 MHz FADC sampling, which means that $2{\times}10^3$ samples are recorded for every charge signal. Some gamma events and electronics noise of CASA-GEM are also added in the simulation process, aiming to imitate the background of the real situation as well as to examine the background avoidance of the reconstruct algorithm. In the simulation, $3{\times}10^6$ fast neutron events with 5 MeV are input and about $1.8{\times}10^4$ recoil proton tracks have been recorded, i.e. that the interaction efficiency of Ar/C_2H_6 (50/50) for a 5 MeV neutron is about 6‰.

3 Data pre-processing

Traditionally, there are three steps to reconstruct particle tracks from measured charge signals: (1) cluster finding, (2) track finding and (3) track fitting. First, before the process of track reconstruction, the FADC raw data of the charge signal from experiment or simulation should be pre-processed. The processing mainly contains threshold (which equals 3σ of electronic noise) determination, pedestal subtraction, pulse finding, induced charge deriving and pulse arrive time determination. Besides, the coordinate definition and the mapping of readout channels to the pad positions are also needed to be saved in a configuration file before the reconstruction process.

3.1 Coordinate system definition

The coordinate system used in this paper is shown in Fig. 2(a). It is a right-handed coordinate system, where the z axis runs along the drift direction of the electrons in the TPC, the x axis and the y axis are shown in Fig. 2(b), whose origin lies in the center of the circular pad of the readout plane.

3.2 Pulse reconstruction

In our design, the pulse appears in the range of the first 16 μs of the 20 μs time window. So, a baseline subtraction is performed using the average of its last 400 samples. A five points moving average method is implemented before the baseline subtraction to reduce the electronic noise. The typical waveform after smooth and baseline subtraction is shown as Fig. 3. Since the data set predominantly contains a single elastic scatter event, we assume in this analysis that each waveform contains only one pulse (here a pulse also means a hit). The start time of the hit is defined as below: (1) the differential coefficients of five consecutive FADC data points are greater than 0 and (2) the value of the 5th data is greater than baseline plus threshold. The threshold equals three times of the electronic noise, which is given by the mean square root of the last 400 samples of each waveform. As shown in Fig. 3, the time of t_5 is defined as t_start. Meanwhile, the end time of a hit, t_stop, is determined

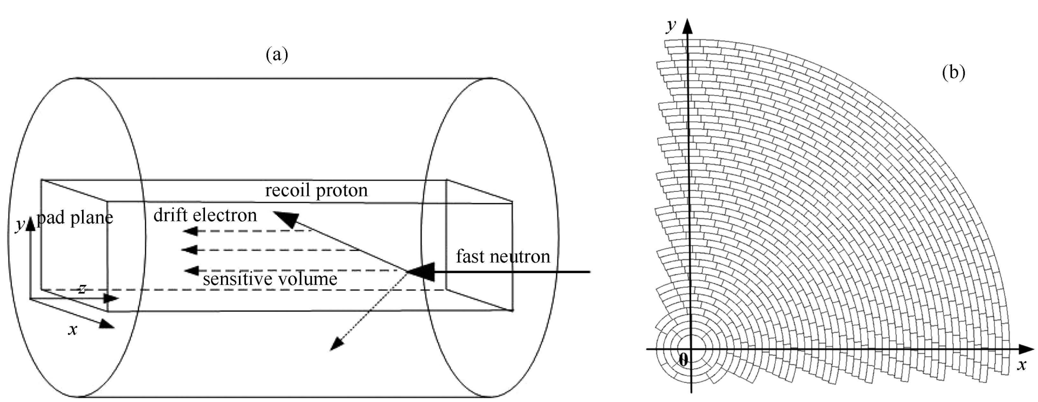

Fig. 2. Coordinate system used in the calculation with a sketch of the TPC prototype (a) and the origin definition in the pad plane (b).

when the differential coefficients of five consecutive FADC data points are smaller than 0 and the 5th data is smaller than the baseline plus the threshold. Then, the time window of the hit is defined as the FADC data between $t_$start and $t_$stop. The arriving time of the hit is calculated using the center of gravity method as follows:

$$T_{\rm hit}=\frac{\sum\limits_{\rm time\ window} t_iQ_i}{\sum\limits_{\rm time\ window} Q_i}. \tag{1}$$

The charge of the hit is defined as:

$$Q_{\rm hit}=\sum_{\rm time\ window} Q_i. \tag{2}$$

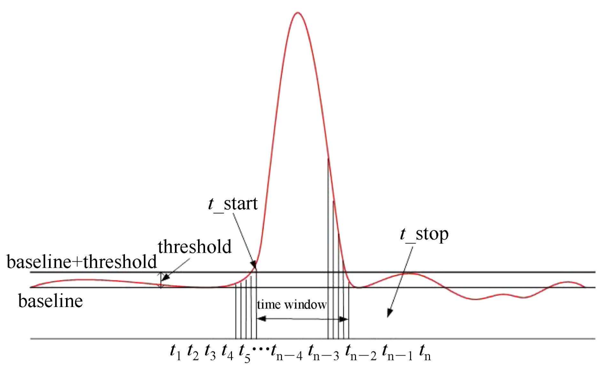

Fig. 3. Pulse reconstruction.

3.3 Cluster finding

The cluster finding process is carried out in ring-wise. The charge and time information of neighboring hits in one pad ring and within a certain time window are integrated, and treated as one cluster, which is originated from the same primary ionization. Then, the charge and 3D coordinates of a cluster are calculated as below:

$$Q_{\rm cluster} = \sum_{\rm hits} Q_{\rm hit}, \tag{3}$$

$$X_{\rm cluster} = R_{\rm cluster}\cos\varphi_{\rm cluster}, \tag{4}$$

$$Y_{\rm cluster} = R_{\rm cluster}\sin\varphi_{\rm cluster}, \tag{5}$$

$$Z_{\rm cluster} = v_{\rm cluster}T_{\rm cluster}. \tag{6}$$

Where

$$R_{\rm cluster}=R_{\rm ring}, \tag{7}$$

$$\varphi_{\rm cluster}=\frac{\sum\limits_{\rm cluster}\varphi_{\rm hit}Q_{\rm hit}}{\sum\limits_{\rm cluster}Q_{\rm hit}}, \tag{8}$$

$$T_{\rm cluster}=\frac{\sum\limits_{\rm cluster}T_{\rm hit}Q_{\rm hit}}{\sum\limits_{\rm cluster}Q_{\rm hit}}. \tag{9}$$

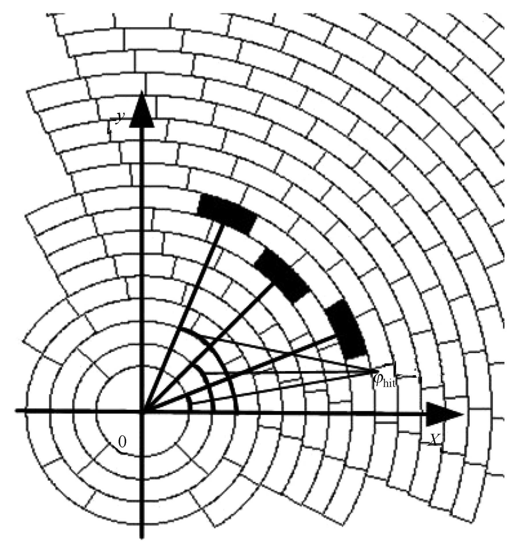

Fig. 4. $\varphi_{\rm hit}$ of the fired pads.

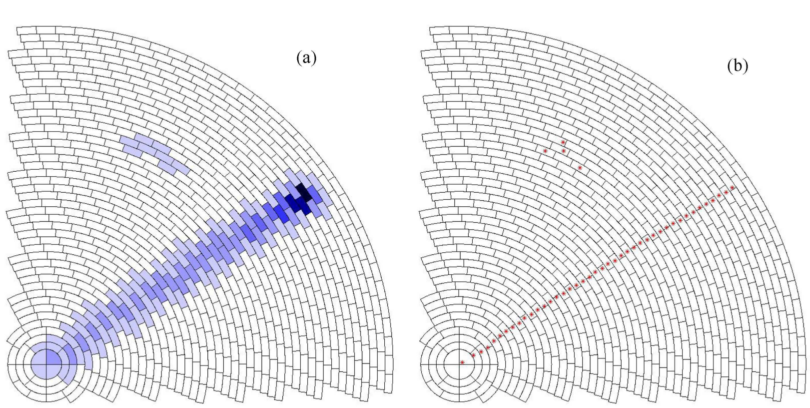

Fig. 5. Hit plot (a) and cluster plot (b) of a recoiled proton.

Where φ_{hit} is the polar angle of fired pads as shown in Fig. 4, and v_{electron} is the electron drift velocity in the TPC working gas, for Ar/C_2H_6 (50/50) v_{electron}=3.89 cm/us. Fig. 5 shows the hit projection (a) and the cluster reconstruction of a recoil proton track (b). The color of the plot in Fig. 5(a) stands for the quantity of energy deposited in the hit: the more energy deposited, the deeper the color. Here, an obvious Bragg peak can be observed at the end of the track. Fig. 5(b) shows the reconstructed cluster by the method mentioned above. Some clusters' projections are far away from the proton track projection in the readout pad plane, and should be produced by gamma ray.

4 Track reconstruction based on Hough-transform

4.1 Hough-transform

The Hough transform is based on a simple transformation of the equation of a straight line in an x-y plane, $y=cx+d$, to another straight line in a c-d plane, $d=-xc+y$. The points along the line in the c-d plane correspond to all possible lines going through the point (x, y) in the x-y plane. Points lying along a straight line in the x-y plane therefore tend to create lines in the c-d plane crossing at the point which specifies the parameters of the corresponding line in the x-y plane. In practice, the c-d space is often discretized, allowing a set of bins to be incremented for each of the measurements in the x-y space. The position of peaks in the histogram provides information about the parameters of the lines in the x-y space.

4.2 Hough-transform for nTPC

In this study, in order to avoid the inaccuracy of inverse trigonometric calculation, the Hough-transform track reconstruction is done in the r-z plane (here r stands for the projection direction of the recoil proton in the pad plane) instead of the x-y plane (the pad plane). Because the track of the recoil proton is a straight line in the space, so it can be described in the r-z plane as below:

$$z=k*r+b. \tag{10}$$

In order to cover all straight lines of the plane, especially lines such as $z=0$, the straight line equation can be transformed as below

$$\rho(\theta)=\cos\theta*r+\sin\theta*z, \tag{11}$$

where ρ and θ are shown as Fig. 6(a). For the nTPC system, $|\rho|\leqslant\sqrt{z_{\max}^2+r_{\max}^2}=\sqrt{500^2+90^2}\approx508$ mm and $-\pi/2<\theta\leqslant\pi/2$, $\Delta\rho$ and $\Delta\theta$ are 1 mm and $\pi/180$ rad respectively. Based on the equation of (11), clusters along a straight line in the r-z plane therefore tend to create sine lines in the ρ-θ plane crossing at the point which specifies the actual parameters of that line in the r-z plane, as shown in Fig. 6(b).

4.3 Track fitting by LSM

Though the parameters of the reconstructed track can be given by the Hough-transform method, the accuracy of them depends on lots of factors such as the rounding of ρ, peak spreading of ρ and θ and the quantization of ρ and θ [9]. In order to improve the accuracy of the parameters, the least square method is used here to fit the parameters of recoil track of the proton in the r-z plane. Firstly, the track parameters are taken from the Hough-transform, and then the distance between the cluster and reconstructed track line in the r-z plane were calculated. A threshold, which is related to the space resolution of nTPC, is set to determine whether a cluster belongs to the track or not. All the clusters considered to be generated by the same proton are fit as a straight line by the least square method in the r-z plane and the parameters of the track are derived.

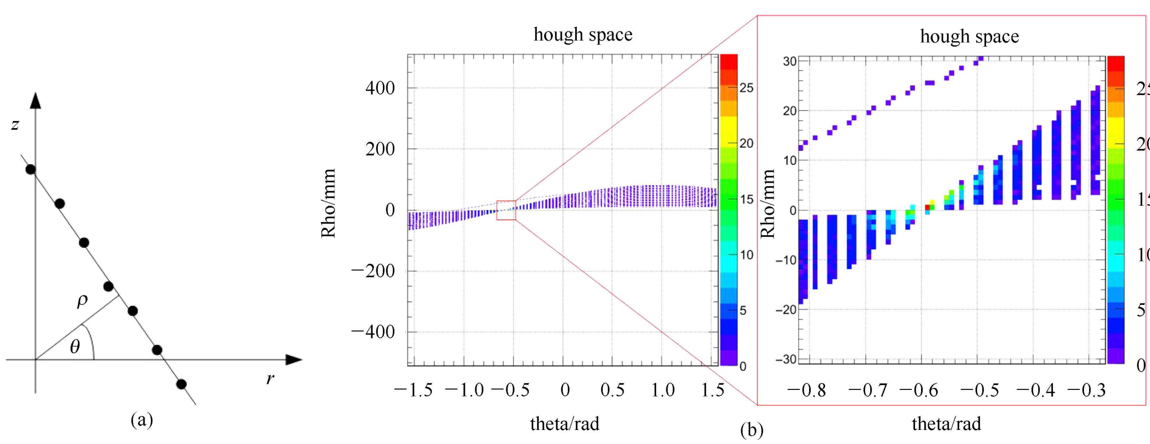

Fig. 6. Hough-transform for nTPC.

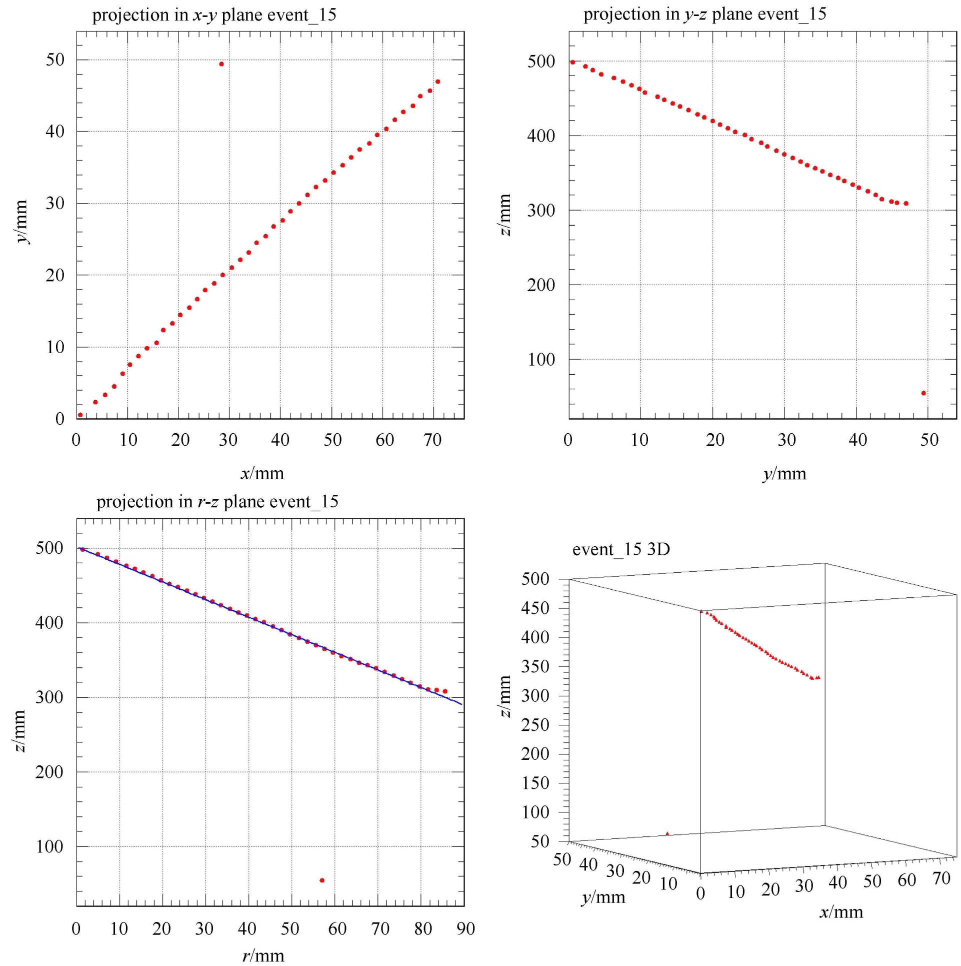

Fig. 7. Event display of track reconstruction.

4.4 Event display

Figure 7 shows a reconstructed track of a selected recoil proton. The display shows the projections in the x-y, the y-z, the r-z plane and a three dimensional view of the event. Though outliers that are generated by the gamma ray can be found in the display, this does not affect the tack fitting process as shown in Fig. 7. It demonstrates that the track construction algorithm used in this paper possesses the excellent ability of background avoidance.

5 Induced neutron spectrum

After the track reconstruction, the spectrum of induced neutron energy is derived and shown in Fig.8 with the recoil angle less than 30°. The energy resolution of the induced neutron will become worse as the increase of the recoil angle. The reason is that with the increase of recoil angle, the energy of the recoil proton becomes smaller, the energy resolution of charge measurement and the accuracy of fitting parameters of the reconstructed track will become worse.

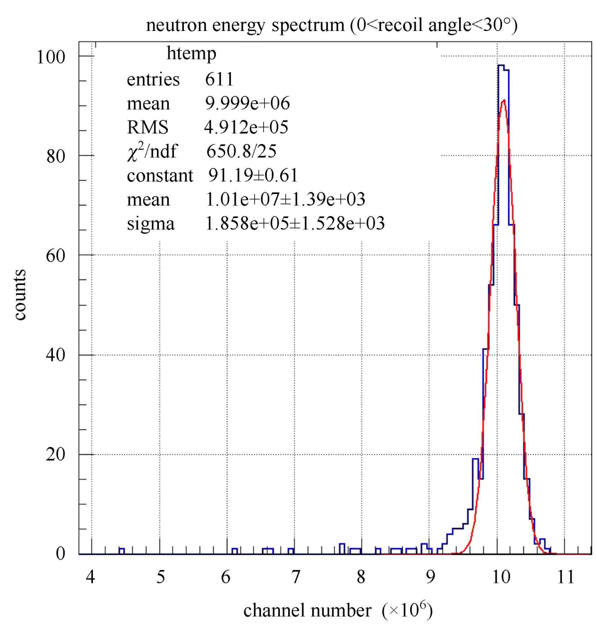

Fig. 8. Neutron energy spectrum with recoil angle less than 30°.

All the 1.8×10^4 proton tracks generated by 3×10^6 fast neutron events are reconstructed here. Among them about 6×10^2 tracks are with a recoil angle less than 30 degrees, so the absolute detection efficiency of the neuron will be 2×10^{-4}. Fig. 8 demonstrates that with the cut of the recoil angle to less than 30 degrees, we can get the FWHM of neutron energy resolution to be 4.4%.

6 Conclusions

Track reconstruction is an important work for nTPC. A detailed reconstruction process based on Hough-transform track finding and least square method track fitting is given in this paper. The results show that with a cut of recoil angle less than 30°, a 4.4% FWHM of induced neutron energy resolution and 2×10^{-4} detection efficiency for 5 MeV fast neutron are derived, which satisfied the demands of the nTPC system perfectly. Though the method mentioned above performed well, lots of tracks of protons with short projections in the readout plane are ignored for their poor accuracy of fitting parameters. So in the future, a reconstruction method based on 3D Hough-transform will be carried out to take full advantage of the nTPC system.

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