PROCEEDINGS OF SCIENCE

Simulation of silicon strip detector and charge measurement based on Allpix Squared

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Charged particles passing through the silicon detector will generate electron-holes pairs along their path by ionization process. Positive and negative charge carriers are drifted in opposite directions to the electrode by the applied electric field. Allpix Squared, an open-source software, is able to simulate the physical processes of particles inside the silicon strip detectors, and generate electrons/holes at each electrode, the digital signal (or ADC) is simulated according to the response of the readout electronics. For silicon strip detectors, the ADC signal exhibits large dependences on the impact position and impact angles of the incident particle. To optimize the charge resolution, the effects concerning particle impact position and angle dependencies are taken into account in this paper, finally the charge measurement method, and the reconstructed charge distribution will be presented.

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1. Introduction

There are many advantages of semiconductor in the field of particle detectors, such as precise position, low material, fast readout speed, and small size. Due to these advantages, silicon detectors are used for many large-scale detector experiments. For example, AMS(Alpha Magnetic Spectrometer), which is currently the only detector in space equipped with a magnet, utilizes silicon tracker for charge measurement and measuring energy deposition of charged particles [1]. A silicon–tungsten tracker–converter(STK), one of the four subdetectors of DAMPE(Dark Matter Particle Explorer), is made up to charge reconstruction and track reconstruction [2]. STK is also the key to AGILE(Light Imager for Gamma-ray Astrophysics), which is a scientific satellite for the detection of cosmic γ-ray sources in the energy range 30 MeV–50 GeV [3].

Allpix Squared (Allpix^2), developed by the European Organization for Nuclear Research, is a generic and lightweight simulation framework for semiconductor tracker. Allpix^2 can be used to gauge effects from charge transport, digitization and track reconstruction on the detector performance[4].

In this paper, a silicon charge detector (denoted as SCD hereafter) is used for the study of detector digitization and charge reconstruction. Data are generated by a Monte Carlo simulation software and are digitized, details of SCD digitization can be found in reference [5]. The data sample in this paper includes isotropic samples of proton, helium, boron, and carbon nuclei with an energy range of 10-1000 GeV, and the energy spectra follows a power-law distribution.

2. SCD Digitization

2.1 The detector

The silicon strip detector typically consists of a reverse biased PN junction, with p+ implanted diode strips and aluminum contacts located on one side of the silicon detector. In this paper, the SCD consists of an N-type silicon substrate with a thickness of 0.15 mm.The sensitive region of the detector is coated with p+ implanted strips and aluminum contacts. There are 180 strips implanted with a spacing of 100 µm between each strip and a width of 50 µm. One of every two implanted strips is readied out by electronics.

2.2 Allpix^2 method

Allpix^2 can simulate the process of the silicon detectors when an incident particle passing through the detector. When a charged particle passes through the sensitive area of the detector, electron–hole pairs are generated. Electrons are drifted to the ground plane and holes are drifted to the metal aluminum strips by an applied electric field. The electrons and holes also undergo a diffusion process. In these processes, the deposition energy of the particle that incidents into the detector is obtained from a Monte Carlo simulation software named Geant4, the processes of electrons and holes are simulated by Allpix^2 software.

3. SCD Charge Reconstruction

The principle of charge measurement by SCD is based on the well-known Bethe-Bloch formula [6], as shown in Equation 1,

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right] \tag{1}$$

where x is the amount of traversed material in g/cm^2, K $\approx 0.307MeVg^{-1}cm^2$. Z, A and I are characteristics of the traversed material and correspond to the atomic number, the mass number and the mean excitation energy, z, β, T_{max} are the incoming particle charge, speed and maximum energy transferable in a collisions with an electron, $\delta(\beta\gamma)/2$ is a density effect correction.

There are four effects concerning particle impact position and angles dependence, velocity dependence, and electronics saturation effects that affect the charge resolution[7]. All these corrections contributed to optimal charge resolution. However, since particle impact position and angles are the primary influencing factors, this paper primarily focuses on correcting those two effects.

3.1 Position and $\theta_\perp$ corrections

First of all, to evaluate the impact position, an estimator η, as shown in Equation 2, in the unit of reading strip distance is used, which ranges from 0 to 1. Where i is the serial number of the readout strip and ADC corresponds to the ADC signal of the i^{th} strip, n means the the number of strips of the layer at SCD which has signal.

$$\eta = \frac{\sum_{i=1}^{n} i \times ADC_i}{\sum_{i=1}^{n} ADC_i} \tag{2}$$

The distribution of η for carbon is shown in Fig. 1. The peaks with η close to 0 and 1 correspond to readout strip incidence, while the peak with η close to 0.5 corresponds to un-readout strip incidence. The η dependency is mostly attributed to the capacitances of SCD [3] and diffusion radius [8].

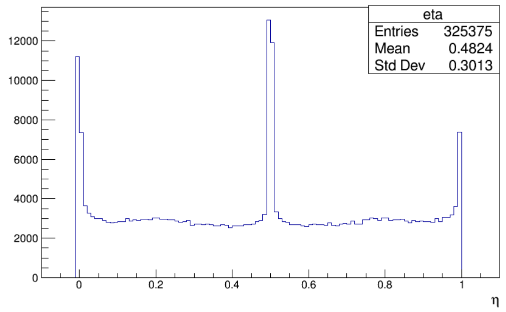


Figure 1: The distribution of η for a carbon nuclei sample

The inclination angles are divided into $\theta_\perp$ and $\theta_\parallel$, which are measured in the plane perpendicular and parallel to the strips, respectively. $\theta_\perp$ is also the angle of incidence along the direction of increasing number of strips. In this direction, both the position and angle of incidence have an effect on the charge distribution, and they are correlated. It's common to correct them together.

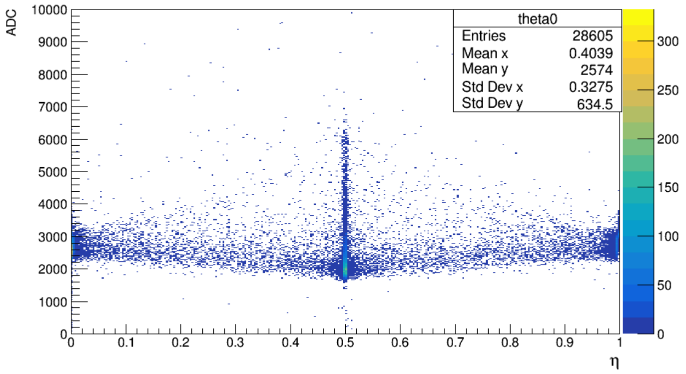


Figure 2: The relationship between position(or eta) and ADC for incident particles with angle from 0 to 5 degrees. ADC is the sum of all signal strips.

$\theta_\perp$ was divided into five angular bins(0-5° , 5° -15° , 15°-25° , 25°-35° , 35° -45°). At 0 to 5° (plots for other angle ranges are similar), The relationship between the reconstructed impact position and ADC for carbon sample is shown in Fig. 2, where ADC is the sum of all signal strips. As can be seen, the ADC is lower for un-readout incident position, and the ADC is higher for readout incident position, which is due to the charge loss for un-readout incident position, which affects the charge resolution.

In Fig. 2, the η is uniformly divided into 15 bins, the ADC distribution for one η bin is shown in the left panel of Fig. 3, and the MPV (Most Probable Value) values inside each η bin are extracted to obtain the position dependencies, which is shown in the right panel of Fig. 3. which was fitted with a constant plus Gaussian function (Equation 3), where p0 is the peak of Gaussian function, which is fixed at 0.5, p1 is the sigma of the Gaussian function, p2 is the amplitude of Gaussian function, and p3 is the constant value.

$$MPV = p_3 + p_2 * e^{-\frac{(\eta - p_0)^2}{2p_1^2}} \tag{3}$$

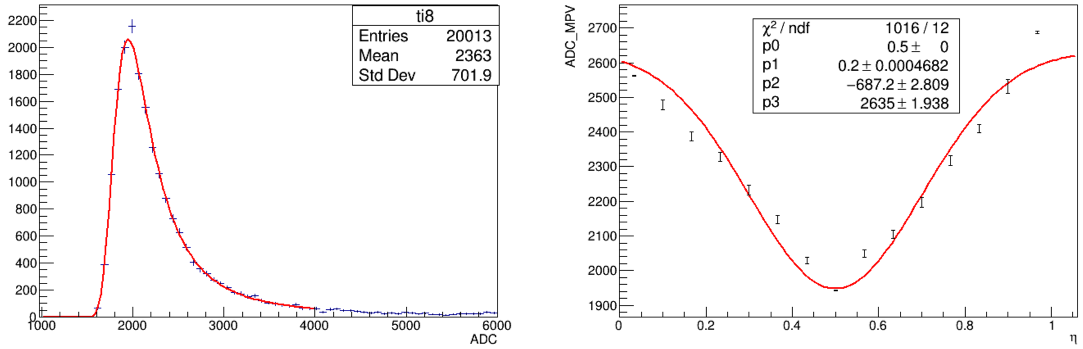
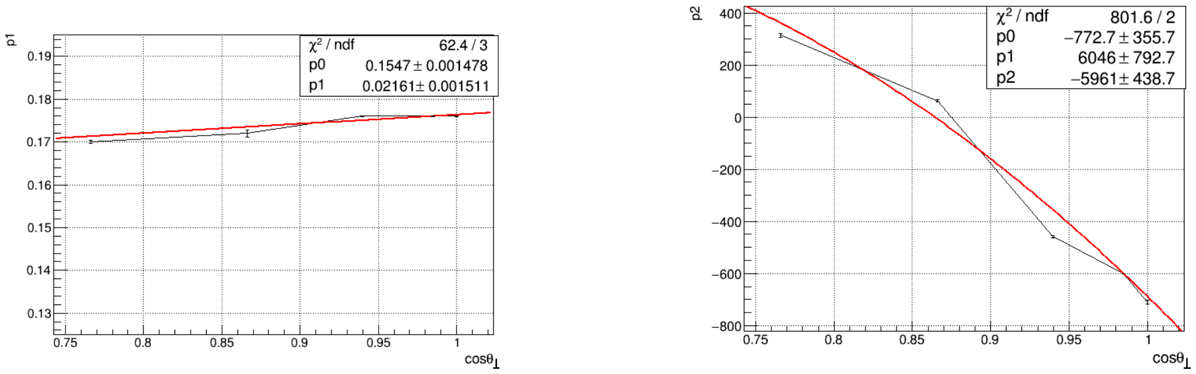
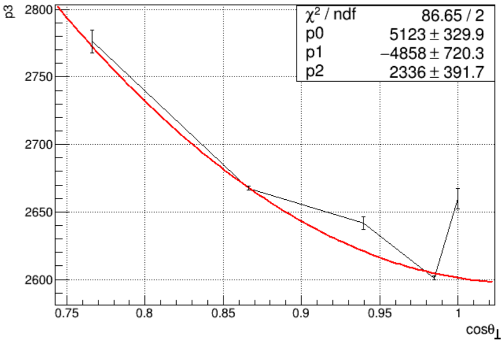


Figure 3: Left: The ADC distribution in one η bin, the red line is the fitting with a Landau convoluted with Gaussian function. Right: The relationship between η and MPV of ADC for the carbon nuclei sample with $\theta_\perp$ ranging from 0 to 5°, the red line is the fitting with a constant plus Gaussian function.



(a) p1 **(b)** p2



(c) p3

Figure 4: The fitting of the parameters vs $\theta_\perp$. p1 is the sigma of the Gaussian function, p2 is the amplitude of Gaussian function and p3 is the constant value.

Since ADC is different for different $\theta_\perp$, the fitting parameters are also evolving with $\theta_\perp$. Fig. 4 shows the relationship between the fitting parameters and $\theta_\perp$. By combining the fittings in Fig. 3 and Fig. 4, a smooth two dimensional surface was reconstructed to describe the impact position and impact angle dependencies of ADC for each Z. Then for a giving impact position η and impact angle $\theta_{\perp}$, a converting line between ADC and Z^2 was reconstructed to calculate charge from ADC, the converting line is shown in Fig. 5 for η = 1 and cos$\theta_{\perp}$=1. After the impact position correction and $\theta_{\perp}$ correction, charge is derived instead of ADC.

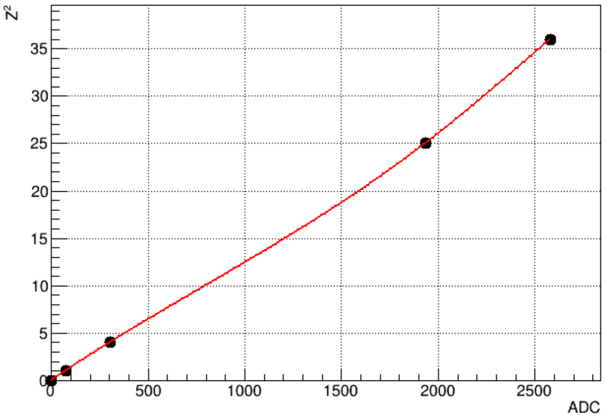
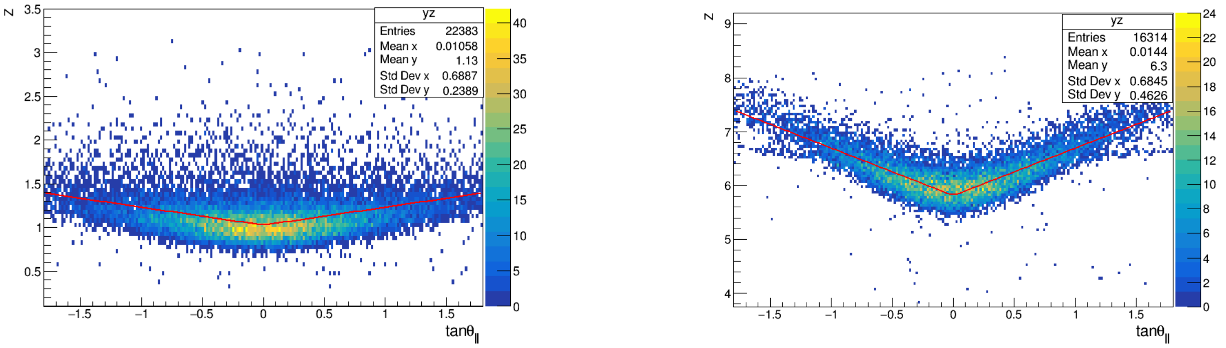


Figure 5: The converting line of ADC vs Z^2 for η = 1 and cos$\theta_{\perp}$=1.

3.2 $\theta_{||}$ corrections

Considering the effect of the path length of the particle inside the silicon sensor, $\theta_{||}$ should also be corrected. The relationship between tan$\theta_{||}$ and charge after impact position and $\theta_{\perp}$ correction is shown as Fig. 6. The charge is corrected for the $\theta_{||}$ dependencies according to the fitted straight lines in Fig. 6.

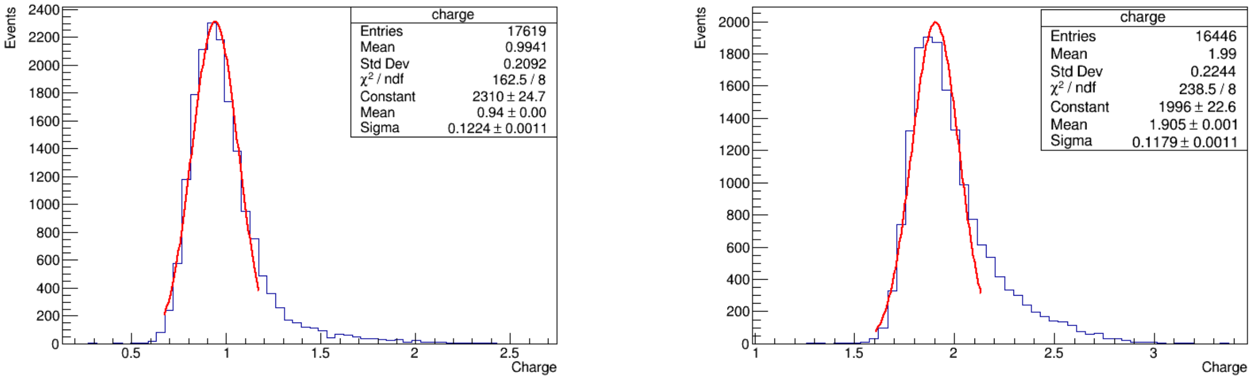


(a) Proton **(b)** Carbon

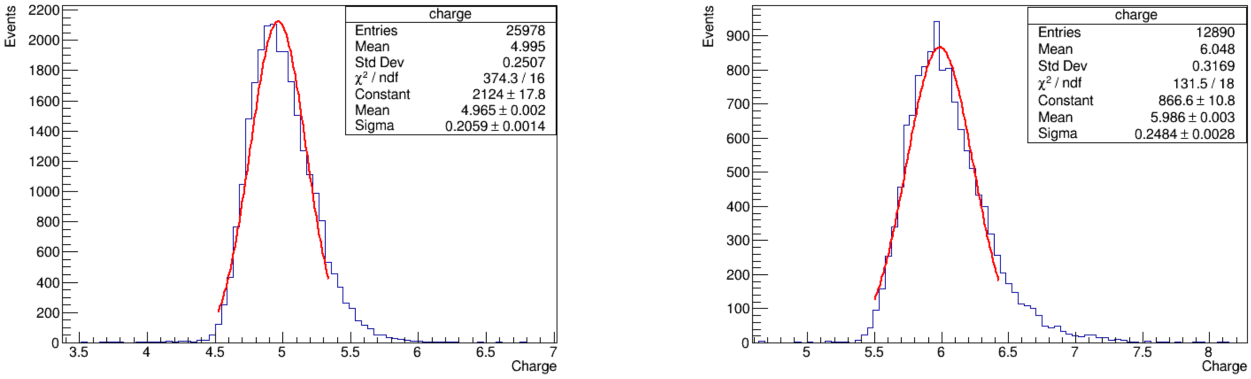
Figure 6: The relationship between $\theta_{||}$ and Z of proton and carbon nuclei samples.

3.3 Charge resolution

After the incidence position and angle dependency correction, the charges from SCD were finally reconstructed, the charge distributions are shown in Fig. 7, where the red lines are the fitting with a Gaussian function. As seen in Fig. 8, the charge resolution from SCD is 0.12 charge units for proton, 0.12 charge units for helium, 0.21 charge units for boron and 0.25 charge units for carbon. The reason that the charge resolution of helium is better than that of proton is that probably due to the fact that proton is more affected by noise.



(a) Proton **(b)** Helium



(c) Boron **(d)** Carbon

Figure 7: Reconstructed charge distribution for proton (a), helium (b), boron (c) and carbon (d), the red lines are the fitting curve with a Gaussian function.

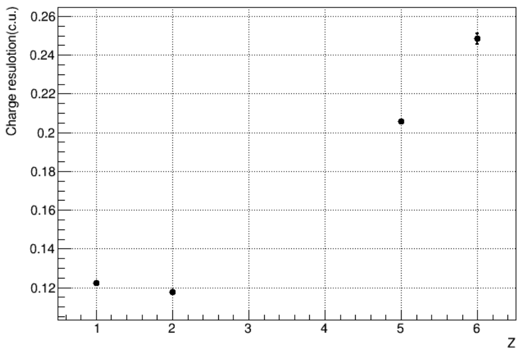


Figure 8: Charge resolution vs Z.

4. Summary

The method and performances of the SCD charge measurement have been studied with several MC simulation samples digitized with Allpix^2. The simulated samples include proton, helium, boron, and carbon nuclei with a power-law spectrum of energies from 10 GeV/n to 1 TeV/n and with isotropic incidence distribution. After correcting for the impact position and angles, a charge resolution of 0.12 charge unit for proton and helium, 0.21 charge unit for boron, and 0.25 charge unit for carbon were obtained.

Acknowledgement

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