Performance of a Multi Anode Straw Tube Detector

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Abstract

We report on the performance of a multi anode straw tube detector using cosmic rays. It is constructed inside a 5 cm diameter straw tube with twelve anode wires. A calibration technique and track reconstruction algorithm is developed for this type of detector, and we calculate the resolution from the residual distribution and show that ~ 170 μm resolution is not difficult to achieve. The technique is general and especially useful for detectors with complex electric fields with or without the magnetic field.

1. Introduction

In an earlier paper [1], we proposed a multi anode straw detector and constructed a prototype to demonstrate its feasibility. Normally there is one anode wire inside a straw tube. The multi anode detector can have several anode wires, and the one we constructed had twelve wires. With the prototype, we measured properties such as the signal shape, cross talk, and gas gain. By having several anode wires in a tube, some of the shortcomings of a single anode straw detector can be overcome. One shortcoming is stereo configuration in a tracking system. This is not a problem for a plane geometry, but when a cylindrical geometry is required, the design becomes complicated because unlike an axial tube, a stereo tube, which has an angle with respect to axial tubes, makes the surface contact only at the center of the tube-supporting cylinder¹. For a multi anode detector, a stereo detector can be simply constructed by slightly rotating one end plug with respect to the other end plug and be stacked like non-stereo detectors on the cylinder. The end plug is where the anode wires are fixed. Another problem is that of excessive material because each anode wire requires a tube, and the amount of tube material can become a problem if low momentum tracking is desired. For the multi anode detector with twelve anodes, the average number of hits per track is about four, implying that the material due to the tubes is lower by a factor of four.

One difficulty of this type of detector is obtaining a relationship between the drift time measurements and the space coordinates with respect to the anode wire because of the complex electric fields. The relationship is necessary for track reconstruction and its quality determines the resolution. For a single anode straw detector it is known as a “V” plot. Any drift detectors with complex electric fields face a similar difficulty and because of this, drift detectors, in general, have many field wires in addition to anode wires to shape the electric field.

We developed a technique to convert the drift times to coordinates for detectors with complex electric fields. With cosmic ray tracks, we demonstrate that the multi anode straw detector can track particles with a good resolution. The technique is quite general and can be used with any drift detectors with or without a magnetic field.

2. Prototype Construction and Operation

For the study, we constructed another prototype, which is similar to the one reported earlier. But there are a few differences. One is that the diameter of the straw tube is increased to 5 cm from 1.85 cm. The tube is called the outer tube. The length of the tube is 30 cm and is made of aluminized Mylar film rather than

¹ The sculpture Tracticiou at Fermi National Accelerator Laboratory is a good example.

stainless steel. The wall thickness of the tube corresponds to $\sim 0.4\%$ radiation length. The changes are to increase the cosmic ray acceptance and to reduce the multiple scattering for very low momentum particles. Another is that the $100\text{ }\mu\text{m}$ diameter center wire is replaced with another straw tube with 5 mm diameter (this one is called the inner tube). This is to reduce the high electric field near the center wire where ions are collected. We occasionally noticed very large signals from the first prototype. The tube is also made of aluminized Mylar film, and the equivalent radiation length of the wall thickness is $\sim 0.06\%$. It is wound such that the outside is conductive. Another is that the disk that positions wires accurately is replaced with precision-made feedthroughs. It simplifies the detector end design. A cross-sectional view of the new prototype is shown in Figure 1.

The anode is $30\text{ }\mu\text{m}$ diameter gold-plated tungsten wire under 0.7 N of tension. An anode wire is grounded through a $300\text{ }\Omega$ resistor (Figure 2) and the negative high voltage is applied to the outer and inner tube independently. Because of an error, the distance from the wire to the outer tube is less than the distance to the inner tube. Ideally, it should be the opposite. This causes a somewhat large difference in operating voltage between the outer and inner cathode tube. The two voltages are adjusted until the efficiency of cosmic ray detection is close to 100% . The final operating voltages are -3080 and -4060 volts for the outer and inner tube, respectively. The ionization gas for the detector is a mixture of argon (83%) and CO_2 (17%) with 1% uncertainty in the proportion. The flow rate is 20 cc per minute.

Figure 1. A schematic of a cross-sectional view of the new prototype. The outer (inner) cathode tube radius is 2.5 (0.25) cm. Twelve anode wires along the tube axis are located at the corners of the dodecagon. The distance to the wires from the center is 1.45 cm . The radial solid lines (black) passing through the wire locations, the radial dotted lines (red) indicating cell boundaries, and the dodecagon connecting wires are to guide the eyes.

Figure 2. A picture of an end of the prototype. The $300\text{-}\Omega$ resistors (blue color) connect the wire ends to the ground. The thin black coaxial cables connect the wire ends to the amplifier-discriminator card. The red tube covers a cylindrical conductor which connects the inner tube to a HV source. This is for safety.

3. Electronics and Cosmic Ray Trigger

Each anode wire is connected to one of sixteen channels of a LeCroy 2735DC card through a $0.4\ \mu\text{F}$ capacitor. The input has to be AC coupled because of the 300-ohm resistor to the ground. 2735DC is an amplifier-discriminator front-end electronic card with an externally adjustable threshold. Our threshold voltage is set at 1.5 volts corresponding to $3\ \mu\text{A}$ of current at the input. With the threshold, the counting rate per channel is about a few hundred Hz dominated by noise. The ECL output from the card is connected to a 32-channel LeCroy CAMAC 2277 TDC via a 150 feet ribbon cable. The TDC with 1 nanosecond least count is read out using Wiener CC-USB CAMAC controller via a LabVIEW program [2].

The cosmic ray trigger is established using two $\frac{1}{2}$ inch thick scintillators in coincidence. The scintillator is coupled to a fast phototube, Phillips XP2262B, operating at 1800 volts. The width and length of the top scintillator are 5 cm and 30 cm respectively and of the bottom scintillator are 25 cm and 45 cm. The two scintillators are separated by 60 cm vertically and the detector is placed about 7 cm below the top scintillator. With this setup, the trigger (coincidence) rate is about 1 Hz and $\sim 75\%$ of triggers are associated with at least one hit in the detector. The triggers without any hits are likely due to the geometrical effect since the false coincidence rate is very low, and the hit efficiency of a wire is over 95%. This is a low rate experiment.

4. Calibration

When a track traverses a straw tube detector with one anode wire at the center, the measured drift time corresponds to the closest approach distance, which is the perpendicular distance to the track. We should note that this is only possible if the combined gain of the gas multiplication and the front-end amplifier is high enough to detect a single ionized electron. This condition is not difficult to meet as demonstrated in several experiments including the ATLAS TRT detector [3], and makes the track reconstruction possible with a good resolution. However, for the multi anode detector, the drift time measured from a wire does not necessarily correspond to the closest approach distance of the track to the wire. Thus, for a given track, it is necessary to find the location where the ionized electron responsible for the measured drift time (or the least drift time) originates. The location is necessary for the track reconstruction.

Finding the location of the least drift time of a track inside a cell is accomplished by a lookup table of the drift time as a function of r and φ in the cell. r and φ are the usual polar coordinates with respect to the center of the detector. Using the table, the location responsible for the least drift time can be easily found by following the path of the track in the cell. This is an important step for getting a good detector resolution as described in the next section. The table is generated as follows. First, the electric field inside the cell and the electron drift speed as a function of electric field are calculated. The former is obtained from GARFIELD [4] and the latter is from reference [5]. Figure 3 shows the magnitude of the electric field in a cell and the drift speed as a function of electric field. Second, a cell is divided into a grid in r and φ coordinates. The dimension of a cell of the grid is $100\ \mu\text{m}$ in r and 0.5 degrees in φ . Starting from an r and φ position, an electron is followed along the electric field line in a step of $50\ \mu\text{m}$. For each step, the drift speed is found using the electric field at the location, and the drift time for the step is calculated. The drift time is summed until the electron reaches an anode wire to get the total drift time. The process is repeated to cover all grid points. Figure 4 shows a contour plot of the drift time as a function of x and y .

Figure 3. Left plot: $\log(E)$ as a function of x and y , where E (V/cm) is the magnitude of the electric field. The wire is at $\varphi = 75$ degrees. Right plot: The electron drift speed as a function of the electric field for our gas mixture [5].

Figure 4. A contour plot of the electron drift time (the time it takes to reach the wire). The cell has the anode wire at $\varphi = 75$ degrees (see Figure 1). Each contour corresponds to about 20 ns.

5. Track Reconstruction and Resolution

The first step in reconstructing a track is to calculate the approximate slope and intercept of the track. The left plot in Figure 5 shows a typical cosmic ray track. The plotted hit distance from a wire is the product of the drift time and the average drift speed ($52 \mu\text{m/ns}$). The drift time (t_{drift}) equals $t - T_0$, where t is the hit time from TDC and T_0 corresponds to the hit time which occurs when a track passes through a wire. One T_0 value is used for all 12 wires.

It is assumed that the hits on a wire are along the radial direction passing the wire location. Each drift time results in two hits because of the left and right ambiguity. The track is reconstructed from a set of hits comprised of one of two hits from each wire. Since there are six wires with a hit in this example, there are $64 (2^6)$ combinatorial data sets and each set has six hits. Each set is fitted with a straight line and the set resulting in the least χ^2 is chosen for further processing. The stars with blue color in Figure 5 are the hits used in the fit with the least χ^2 . The rms shown in the figure is the square root of the average of the sum of the squares of residuals.

Figure 5. Left plot: There are two hits (red and blue) for each drift time because of the left-right ambiguity. To start the track reconstruction, it is assumed that hits are along the radial direction passing the wire location. The blue hits are used in the fit resulted in the least χ^2 , and the line is from the fit. Right plot: Hits are calibrated using the drift-time table and the track parameters (slope and intercept). Compared to the left plot, there is a great improvement. See the text for detail. The rms shown in the figure is the square root of the average of the squares of residuals.

With the approximate slope and intercept, the final calibration begins. We search for the least drift time to the anode wire (Figure 6) in each cell using the lookup table. As we follow the track ($50 \mu\text{m}$ step), the track position is calculated in r and φ coordinates and the corresponding drift time is found from the table. The number of drift times depends on the track length in the cell and the least drift time and its coordinates (called r' and φ') are kept. The least drift time (t_{least}) is compared with t_{drift} . If the two are not the same, a correction is added to r' , which is $\text{sgn} V_D (t_{drift} - t_{least})$. V_D which equals $52 \mu\text{m/ns}$ is the average drift speed and $\text{sgn} = +1$ if r' is greater than the radial wire position and -1 if r' is less than the wire position. The x and y hit coordinates are calculated from φ' , and the corrected r' .

Figure 6. Electron-drift lines from GARFIELD for the track in Figure 5. . Electrons are uniformly produced along the track through ionization. For each wire, we search for the drift line results in the least drift time using the table described in the text. The least drift time is what we measure.

The calibrated hit coordinates are fitted with a linear function and the rms is calculated. The track parameters (slope and intercept) from the fit are used in the next iteration and the process is repeated until the rms does not change more than 10 microns. The right plot in Figure 5 shows the calibrated hit coordinates and the fitted line from the final iteration. There is a great improvement. Figures 7 and 8 show additional reconstructed cosmic ray tracks. It is worthwhile to note that there are virtually no hits not associated with tracks. This is generally true for other events, and it is not unexpected from the cross talk study with our first prototype.

Figure 7. See Figure 5 for a detailed caption. The track passes close to the inner tube.

Figure 8. See Figure 5 for a detailed caption. The track passes the inner tube.

The resolution with respect to the radial direction in the xy-plane is calculated from the tracks with at least four hits. The average number of hits for these tracks is 4.9. The left plot in Figure 9 shows the residual distribution of tracks with $\chi^2/dof < 7.5$ requirement. The region around the peak (1.3 x FWHM) is fitted with a Gaussian function and the standard deviation (σ) is 173 μm .

About 7% of tracks have a hit with a residual greater than 700 μm . These bad hits could be due to delta rays, or noise. If a track has a bad hit, it is dropped and the rest of the hits are refitted. The right plot in Figure 9 shows the residual distribution after dropping the bad hits. We still require that there are at least four hits and $\chi^2/dof < 7.5$. The peak (1.3 x FWHM) is again fitted with a Gaussian function and we obtain 152 μm for the standard deviation.

Figure 9. Left plot: Residual distribution with $\chi^2/dof < 7.5$ requirement. Right plot: Residual distribution after dropping bad hits and with $\chi^2/dof < 7.5$ requirement. The overlapped curves are from Gaussian fits and σ from the fit is 173 (152) μm for the left (right) plot.

The standard deviation of the residual distribution is correlated to the detector resolution, and the resolution is found using a simulation. We start with a track whose slope and intercept are randomly

selected from the cosmic ray data. Using the slope and intercept, the hit positions with respect to wires are calculated and smeared according to a Gaussian function whose standard deviation equals a given resolution. Also included is the T_0 determination uncertainty of 1.5 ns, which is estimated from the time distributions of 12 channels².

The hit and wire positions are inputs to a linear fit. Similar to the real data, the residual distribution is plotted using tracks with at least four hits, and the distribution is fitted with a Gaussian function to find σ of the residual distribution. We plot the relationship between the resolutions and σ and find that if the resolution is 170 μm , the corresponding σ is about 150 μm . Thus we conclude that our resolution is about 170 μm . It is worthwhile to note that if there were also a stereo detector the z-resolution would be $\sim 170 \mu\text{m}/\sin(\theta)$, where θ is the angle between the two end plugs holding wires.

Figure 10. Electron-drift lines from GARFIELD for the track in Figure 7 inside uniform 10 K Gauss magnetic field along the z-axis. Electrons are uniformly produced along the track through ionization.

The calibration technique can be easily applied when the magnetic field is present. Using the electric field lines modified by the magnetic field (Figure 10) and the drift speed (Figure 3), a table of drift time as a function of r and φ can be constructed and used to calibrate the hit positions as previously discussed.

6. Summary

We reported on the performance of a multi anode wire straw tube detector with twelve anode wires and two cathode tubes, 5 cm diameter outer tube and 0.5 cm diameter inner tube. The detector has several advantages over a single anode wire straw tube detector: for example, simpler stereo configuration and less detector material. Using cosmic ray tracks, we showed that about 170 μm resolution is not difficult to achieve. In order to achieve the resolution, we developed a calibration technique converting the drift times to space coordinates. The technique is general and especially useful for detectors with complex electric fields with or without a magnetic field.

² Our measured residual distribution includes the uncertainties in the T_0 determination, wire positions, proportion of gases, drift speed, and the slewing effect of front-end electronics. In the simulation, only T_0 effect is included. In other words, the resolution calculation presented here is somewhat conservative.

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