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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Construction and performance of a 2.7 m long straw drift tube prototype chamber for the SSC

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We report the construction and testing of a 2.7 m long straw tube drift chamber consisting of 60 channels. The straw tubes with 2 mm radius are stacked in a pyramid shape up to eight tube layers. There are two wire supports inside each tube for electrostatic stability. 28 tubes out of 60 are instrumented for measurement of resolution, gas gain, and attenuation length. Resolution of close to 110 μm and attenuation length of 500 cm are obtained.

1. Introduction

The design of the central tracking chamber in a solenoidal detector [1] for the Superconducting Super Collider (SSC) calls for a cylindrical tracking chamber ≥ 6 m long. Using straw tubes with small radii is one of the options [2] for the tracking chamber. Due to the bunch spacing and the occupancy rate, the tube radius should not be greater than 2 mm. The central tracking chamber will likely consist of several cylindrical superlayers, with each superlayer typically made up of about eight layers of tubes. In order to cover a large tracking volume, superlayers are separated by about 10–15 cm from each other. In this chamber, track segments are found in each superlayer first and then the segments from different superlayers are linked to form a complete track.

For a feasibility study, we have constructed a 2.7 m long superlayer on a flat surface. In the prototype, 60 straw tubes with 2 mm radius are stacked in a pyramid shape up to eight tube layers. The tubes used in the prototype have a wall thickness of 50 μm of mylar on a 8 or 12 μm thick aluminum cathode. Because of the length of each cell, sense wires have to be supported and our study shows that the support is needed about every meter. Two wire supports are placed inside each tube in the prototype.

By successfully constructing and operating the prototype, we have verified that the basic design concept is sound and can be extended to a full size cylindrical central chamber. Specifically we have demonstrated the following: First, we showed that layers of tubes can be placed straight with an accuracy better than 100 μm over several meters once a flat base surface is provided. Second, a double-wall endplate designed by our group provides a simple way to supply gas, tension the sense wire and mount electronics. Third, the wires can be supported inside tubes at 1 m intervals to make a long working straw cell. Fourth, a large number of channels can be made operational simultaneously without difficulty. This is important since the expected number of channels for the final tracking chamber is about 200000. Finally, we showed that spatial resolution of close to 110 μm can be achieved and the attenuation length is long enough that signals from the end of the detector farthest from the readout electronics are not significantly degraded.

Although using a tube for a drift cell is not new [3], and there have been efforts to use small radius straw tubes [4], our prototype is the first of its kind in terms of length, tube radius and number of channels.

This article is organized as follows. In section 2, we present results of an electrostatic stability study. We measured the position of the sense wire inside a 2 mm radius tube as a function of high voltage with different tension in the wire and different initial displacement. In section 3, we discuss a design of a wire support. Section 4 contains details of the design and construction of the 2.7 m prototype. In section 5, we present the results of tests to measure the gain, attenuation length and resolution of the prototype. We present our conclusions in section 6.

2. Electrostatic stability

The design for the central tracking chamber in a solenoidal detector at the SSC uses 2 mm radius straw tube detector elements. The sense wire would be oper-

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ated at around 2000 V to achieve gas gains which give suitable signal pulses. The ideal case in which the sense wire is exactly centered within a perfectly cylindrical cathode is electrostatically stable. Practically, however, the sense wire will not be exactly centered due to positioning error and gravitational sag and the straw tube cathode will be neither perfectly cylindrical nor perfectly straight. Therefore it is important to determine the conditions under which an operational straw tube detector element will perform satisfactorily. The electrostatic force per unit length due to offset of the sense wire in the straw tube is given by (mks unit)

$$F_e = \frac{2\pi\epsilon_0 V^2 \delta}{R^2(\ln(R/r))^2},$$

where V is the sense wire potential, δ is the offset of the sense wire from the center of the straw tube, R is the radius of the straw tube cathode and r is the radius of the sense wire.

We have constructed a straw tube model using a stainless steel tube which is held in alignment by a 2 cm square steel "backbone" and machined mounting brackets. The tubing has an inner radius of 1.95 mm. The steel tube is placed in a horizontal orientation. A manifold on one end allows gas flow to purge air. We have used CH_4, CO_2 and CF_4 as stable gases.

We find that the longest cell that is stable above 2.5 kV with a 25 μm sense wire centered in the tube under 50 g tension is about 1 m. The tensile strength of 25 μm diameter gold plated tungsten wire is 150–200 g so the applied tension to the wire should be kept below 100 g. Keeping the wire tension to a minimum will also reduce the mechanical load on the detector assembly.

Using a 1 m long tube, we have conducted a series of tests to determine the effect of the wire offset in the tube on the maximum voltage the cell can sustain before breakdown. A sense wire is positioned in the tube so as to be centered vertically. The horizontal position of the sense wire with respect to the center of the tube is adjustable. The distance from the center of the tube to the position of the sense wire is measured by means of a travelling microscope to an accuracy of better than 20 μm. The wire position was adjusted relative to the center of the tube and the potential on the wire was then increased until breakdown occurred in the cell.

Fig. 1 shows the maximum stable operating voltage that a 1 m long cell filled with CH_4 can sustain as a function of the sense wire displacement from the center of the cathode for wire tensions of 50 and 100 g. Two other gases mentioned earlier give slightly different results. The test shows that the wire offset of up to a few hundred micrometers will not compromise cell operation.

One can study the displacement of the sense wire under increasing electric potential. This has been done by drilling a hole in the middle of the steel tube to observe the position of the sense wire with a travelling microscope as the wire potential is raised.

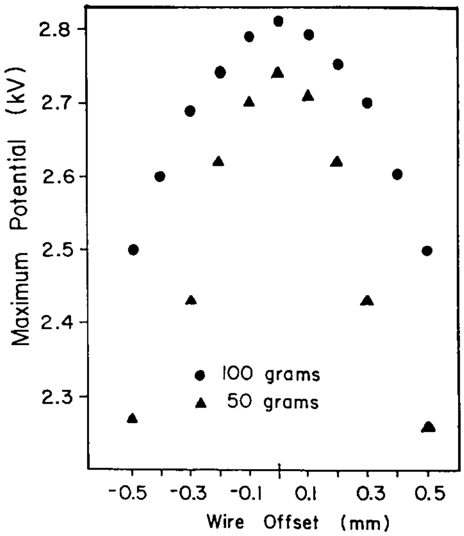

Fig. 1. Maximum stable operating voltage for two different wire tensions of 50 and 100 g as a function of initial wire offset.

In our setup, the sense wire was positioned off center by a known amount (δ) horizontally, and then the sense wire potential was increased. The deflection of the midpoint of the wire (d) from its initial position was measured for several different potentials. This deflection is related to the potential on the wire of length L to good approximation by the expression

$$d = L^2 F_e / 8T.$$

This problem is similar to the wire sag calculation due to gravity. For a 50 g tension, the sag due to gravity at the middle for a 1 m long wire is about 25 μm thus we ignore the gravity effect in this analysis. Using the F_e previously defined, then d can be written as

$$d = \frac{2\pi\epsilon_0 V^2 L^2(\delta + d/2)}{R^2(\ln(R/r))^2}.$$

$d/2$ is added to δ in order to take into account the additional force (approximately) due to the wire deflection d. For 1 m long wire, the displacement is given by

$$d = \frac{\delta(V/V_0)^2}{1 - \frac{1}{2}(V/V_0)^2},$$

where $V_0 = 2700\sqrt{T/50}$, with T the wire tension in grams and V the applied potential in volts.

Fig. 2 shows measurements of the wire deflection versus sense wire potential for tensions of 50 and 100 g. The lower set of data in each case is with an initial

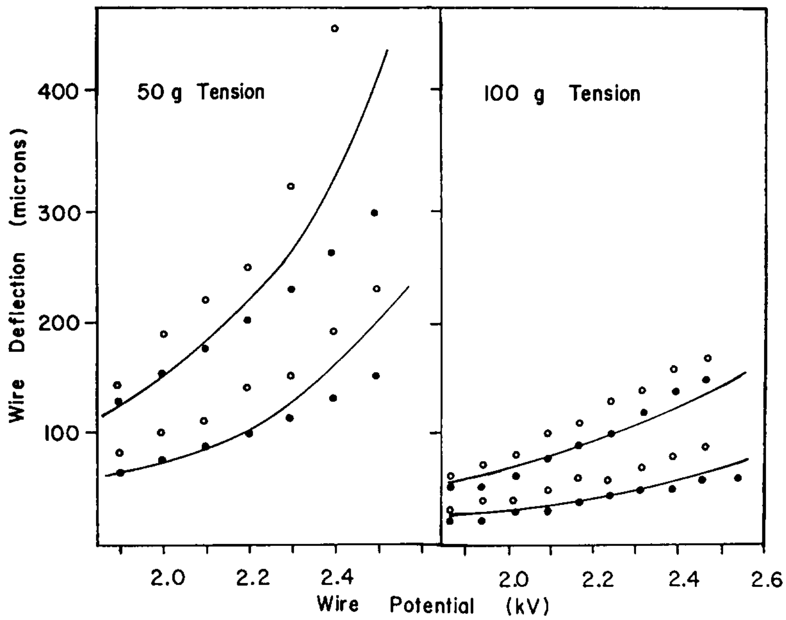

Fig. 2. Wire deflection as a function of voltage for two different initial displacements, 100 (lower set) and 200 (upper set) μm. The left panel is for 50 g tension, and the right panel for 100 g tension. The solid curves are the prediction from the formula in text. The open circle data points are for initial offset in one direction while the closed data points are for initial offset in the opposite direction.

offset of 100 μm and the upper set of data is for an initial offset of 200 μm. The solid curves are predictions from the formula for the wire deflection. The open circle data points are for initial offset in one direction while the closed circle data points are for initial offset in the opposite direction. The discrepancies between the data are indicative of some nonlinearity of the tube. The measurements agree quite well with the predictions of the above calculations.

With 50 g wire tension the amount of deflection of the wire from its initial position is about 80 μm for the initial displacement of 100 μm at potentials at which the straw tubes are expected to be operated. In order to optimize spatial measurement resolution such wire deflection must be minimized. 50 g of tension is probably acceptable with wire supports at distance intervals of 1 m if the initial wire displacement is less than 50 μm.

3. Sense wire support

To achieve adequate geometric acceptance for charged tracks the SSC central tracking chamber will have to be 6 m long at an outer radius of 1.7 m. Some designs consist of two 3 m long chambers. In this case there is a gap in the middle of the chamber. In either case it will be necessary to provide centering support for the sense wires in the straw tubes at about 1 m intervals to ensure electrostatic stability, and minimize the wire deflection.

The wire supports must center the wire in the straw tube while at the same time not restricting gas flow through the tube. Our design for the wire support consists of a plastic cylinder with a helical groove which is a cylinder radius deep and makes at least one complete revolution around the cylinder in a length of

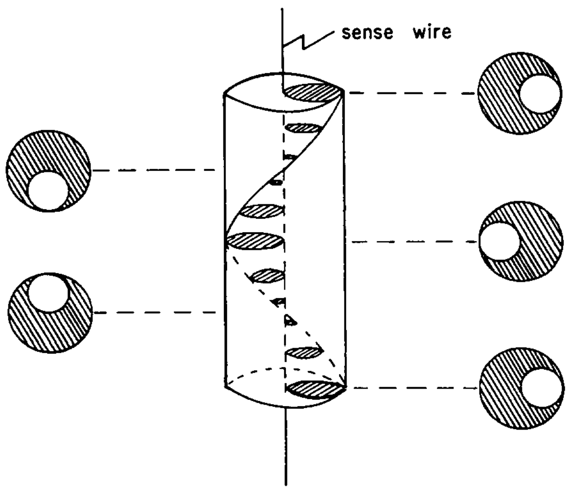

Fig. 3. Duke wire support design. A helical hole is made inside a plastic cylinder.

less than 1 cm. Such a device will provide gravitational support regardless of the orientation of the tube. A schematic drawing of the wire support design with cross section views is shown in fig. 3. We have produced a few samples using two methods, injection molding and using a milling machine to make the groove. In the latter case the plastic cylinder translates as well as rotates while being cut. The cutting method seems to produce better pieces with lesser cost.

The wire supports will be attached to the straw tube. The wire will then be threaded through the tube. This has the advantage that if a wire should break during installation in a straw tube it will be easy to remove the broken wire and re-string the tube.

4. The construction of the prototype

We have successfully constructed a 2.7 m long prototype chamber with eight layers of tubes. In this section, we present the construction of the prototype. The geometry of the tubes in the prototype is shown in fig. 4. The 60 tubes are arranged in a pyramid shape with eleven tubes at the bottom and four tubes at the top. The radius of each tube is 2 mm.

The construction of the prototype starts with a sturdy base. The base could be an optical table or a rail. It is important that the base has a flat surface that tubes can be placed on. Our base looks like the bottom third of a disk. It is 3.3 m long with a 7 cm wide machined face. The surface was scanned with a survey telescope and found to be flat to better than 25 μm over the entire surface. Present design concept for our final tracking chamber for SSC requires a cylindrical surface for each superlayer, which is constructed out of carbon fiber. Preliminary study [5] shows that a 6 m long cylindrical surface constructed with carbon fiber thickness of less than 0.3% of radiation length has a

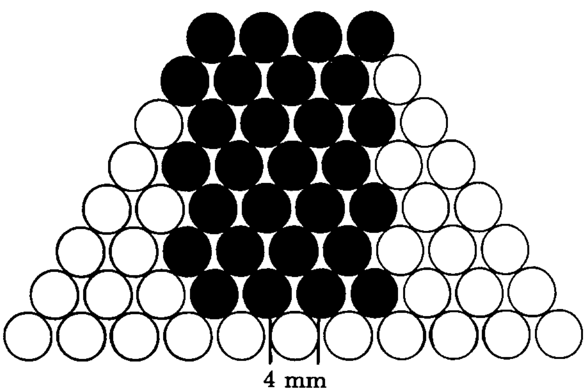

Fig. 4. Cross section of the straw tube superlayer in the prototype. The shaded tubes were instrumented.

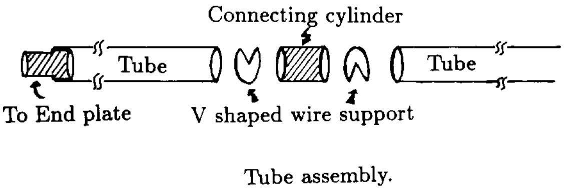

Fig. 5. Tube assembly with tube connector and wire support.

maximum deflection of less than 25 μm at the center when the ends are fitted with endplates.

On the top of the base, four aluminum plates with machined grooves are placed. The grooves on the plates are to guide the tubes. The plates are aligned among themselves using the survey instrument. The plate simulates the cylindrical base to be used in the final tracking chamber.

Straw tubes were assembled prior to placing them on the aluminum plate. The tubes used in the prototype have a wall thickness of 50 μm and were made of mylar strips wound on top of 8 or 12 μm thick aluminum foil (cathode) strips [6]. Although we have chosen the aluminum cathode for convenience, it is not clear whether that was the best choice. It has been known that a cell with aluminum cathode will draw a large continuous current when it is exposed to a high radiation. The speculation is that the aluminum cathode becomes oxidized and results in the buildup of positive ions on the oxide layer. Eventually the potential across the oxide layer becomes large enough to extract electrons from the cathode, which causes the continuous current draw. This effect is known as the Malter effect [7]. We are investigating different cathode materials such as a several hundred ångströms thick copper.

Three tubes of 90 cm length were joined. Before the tubes were connected together using thin aluminum sleeves, wire supports were inserted inside tubes as shown in fig. 5. Because we were not able to obtain the wire support described above in time for use in the prototype, we instead used two V-shaped disks back to back. Although the disks were machined carefully, measurements using a microscope showed that they were about 75 μm in tolerance. As we have discovered, joining tubes was not the best approach since the tube joints introduced alignment errors along the vertical direction at the joint. In the next prototype different techniques will be tried, for example, the wire supports will be inserted from the ends of continuous straws.

Once enough tubes are assembled for a layer, they are inserted to the endplates (fig. 6) and placed on the grooves of the aluminum plate. The endplate design is very important since straw tubes, electronics, gas and high voltage connections and cooling are done through endplates. Our endplate consists of two plates with

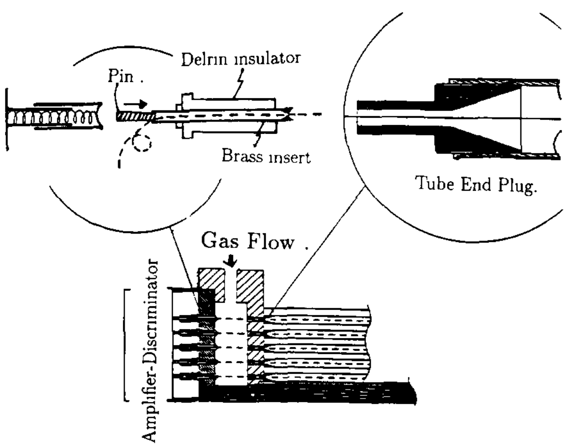

Fig. 6. The endplate used in the prototype. The details of the tube end plug and feedthrough are shown.

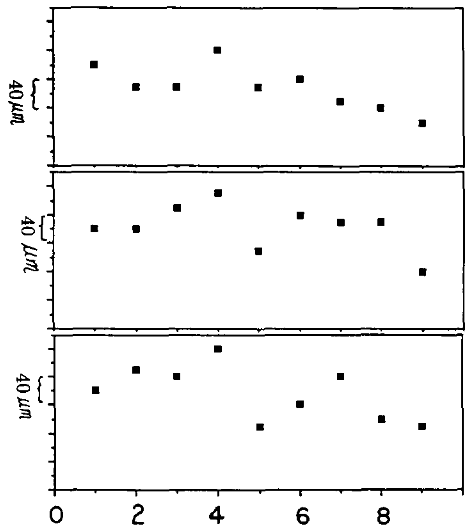

Fig. 7. Horizontal position of straw tubes in the third layer as a function of straw tube number. The plotted points are the difference between the measured position and the expected position with respect to the first tube. Each plot is taken at a different distance from one end along the length of tubes. The measurement error in each point is about 25 μm.

space between them. Tubes are fitted to the inner plate, and feedthroughs are inserted from the outer plate for sense wire, high voltage and amplifier connection. The space between the plates serves as a plenum to provide gas flow to the straw tubes. The gas may be cooled to reduce ohmic heating inside the tubes. In order to attach the tubes to endplates, the tubes were bowed slightly.

After all tubes for a layer are placed, the tubes are glued to the layer below (or on the aluminum base plate for the first layer). To obtain better placement accuracy, the tubes are pressed slightly using finger-shaped jigs from the top. After the tubes are properly placed, a small amount of fast drying glue (cyanoacrylate) is used to glue the tubes. The gluing has two purposes. First, the fixed tubes act like the grooves on the aluminum plates, so that the next layer of tubes can be aligned accurately. Second, it straightens the tubes. The tubes from the factory are not only very flexible but also are slightly bent. Tubes are glued about every 10–20 cm depending on the quality of tubes.

As we assembled each layer, the vertical and horizontal position of the tubes was measured. Fig. 7 shows the horizontal position of the tubes in the third layer at three different locations along the tube length. The plotted points are the difference between the expected tube position and measured tube position with respect to the first tube. The figure shows that tubes can be positioned to an accuracy of bettern than 100 μm. Fig. 8 shows the vertical position of the top layer (eigth layer) measured along the tube length from one end. As we mentioned earlier, the tube joint at 90 cm is out of place by about 100 μm.

After all tubes were placed and glued, sense wires were strung. To accomplish this, high pressure air (we used 20 psi air from a tube with 1.5 mm radius) was blown from one end of a tube to string a guide wire with 100 μm diameter. A gold plated tungsten sense wire with 25 μm diameter was attached to the guide wire and pulled through. (The procedure can be done without the guide wire.) The sense wire was passed through a feedthrough and then tensioned to 50 g, pinned, and soldered. The feedthrough design shown in fig. 6 consists of three pieces: a cylindrical insulator made of delrin, a brass insert which fits inside the insulator and a pin. At the end of the brass insert there is a 60 μm diameter opening which positions the sense wire accurately.

Each cell was tested for high voltage. Out of 60 tubes, we instrumented 28 of them (shaded tubes in fig. 4). Of these, we found that only one tube does not hold an operating voltage (1800 V). For the rest of the tubes, we were able to raise the high voltage to at least

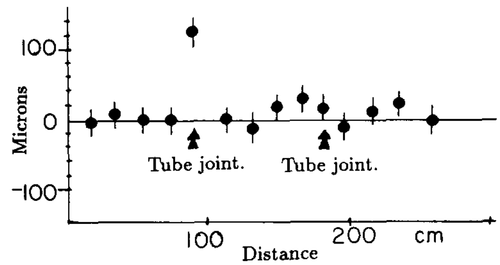

Fig. 8. The vertical position of straw tubes on the top layer as a function of distance from one end.

2500 V. It is not clear why one cell is bad, but we think that the wire support inside the cell may not be positioned properly or was moved by high pressure air. In this one tube, we strung another wire with 100 g tension, and were able to raise the voltage to 1900 V.

5. Performance of the prototype

In this section, the tests performed with the prototype chamber are described. We studied the attenuation length, gas gain and resolution. to eliminate signal reflection, one end of the sense wire was terminated. Since the impedance of a 2 mm radius tube with 25 μm sense wire is about 300 Ω, one end of the sense wire is terminated to ground through a 150 pF capacitor and 300 Ω resistor in series. By comparing the time difference between the reflected signal and unreflected signal, we obtain $(2.9 \pm 0.1) \times 10^8$ m/s for the propagation velocity.

Fig. 9 show the averaged signal using ^{90}Sr. 1000 signals are averaged in the plot. The gas used for the plot was a mixture of CF_4–Ar–ethane (33–33–33) and the high voltage was set at 1800 V. Although different gas mixtures show slightly different decay time, the typical signals (using ^{90}Sr) into 50 Ω from the chamber have a rise time of about 2–3 ns. About 30 ns later, the signal is reduced to about 15% of its maximum.

Fig. 10 shows plateau curves obtained using a Lecroy 2735DC amplifier–discriminator with a 3 μA threshold. A ^{90}Sr radiation source is used. One curve is taken with the source near the readout end and the other with the source 250 cm from the readout end. The gas used is CF_4–Ar–ethane (33–33–33) mixture. As expected, the knee of the plateau curve measured at the far end location moves compared to the other curve. The shape of the signal from the near end compared to the far end (with respect to the readout end) is very similar although the height is down by about half (i.e. the dispersion is small).

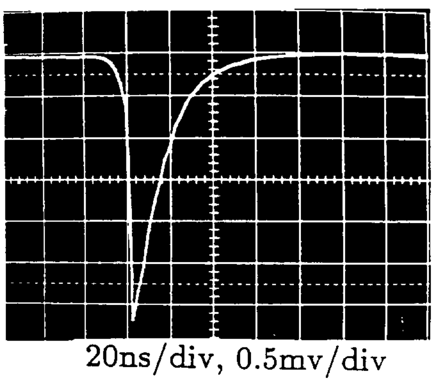

Fig. 9. The averaged signal using ^{90}Sr source. The gas mixture is CF_4–Ar–ethane (33–33–33) and high voltage is 1800 V.

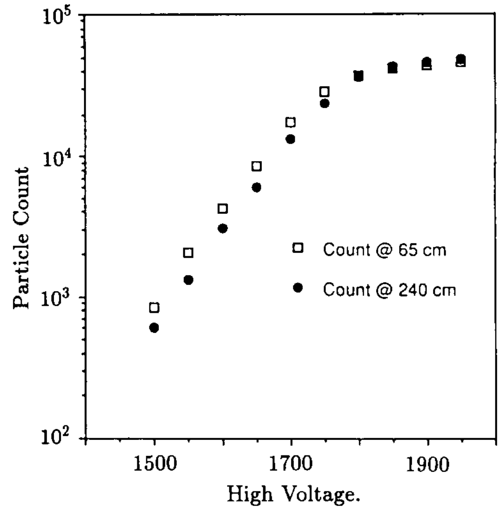

Fig. 10. Plateau curves obtained using ^{90}Sr source at two different positions from the end of tubes. The gas mixture is CF_4–Ar–ethane (33–33–33).

The attenuation length (λ) is measured using a ^{55}Fe source. Because of the variation of gas gain near the straw tube joints, the peak of the signal is measured from both ends of the chamber. From the ratio of the two peaks as a function of distance from one end, the attenuation length is calculated. Fig. 11 shows the

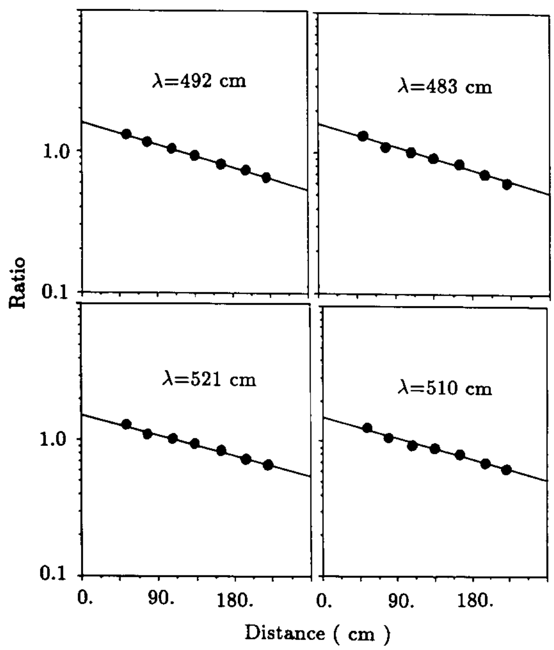

Fig. 11. The ratio of amplitude from one end to the other end using ^{55}Fe source. The attenuation length is obtained from the slope. See text for detail.

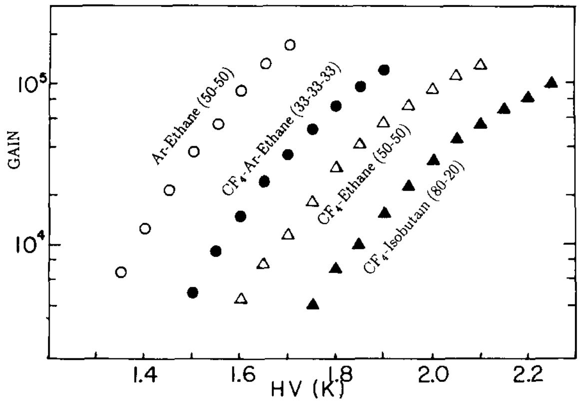

Fig. 12. The gain as a function of high voltage for several gas mixtures.

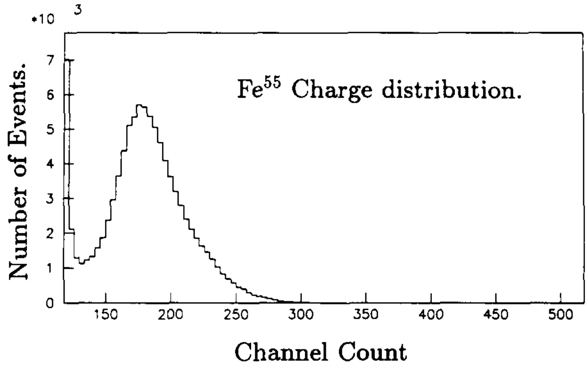

Fig. 13. Typical ^{55}Fe spectrum measured from a cell using a multichannel analyzer.

plotted ratio for several channels. The overlapped curves are fits using an exponential function. Although there is some variation between tubes, an average attenuation length of 500 cm is obtained. (The attenuation length calculated this way is one half of the true attenuation length. The 500 cm and the numbers in fig. 11 are already multiplied by a factor of 2.) The signal attenuation is likely due to the resistance in the sense wire. The resistance of the sense wire is about 100 Ω/m which is much larger than the resistance of the cathode, which is less than 1 Ω/m. Our value is somewhat higher than a previously reported value of 450 cm [4]. The difference may be due to the different cathode thickness.

Fig. 12 shows the gas gain as a function of high voltage for several different gases using a ^{55}Fe source. The output from a cell is connected to a charge amplifier and then to a multichannel analyzer. Fig. 13 shows the typical charge spectrum from the multichannel analyzer. The rms width of the peak is about 35%. The absolute calibration is accomplished by inserting a known amount of charges into the amplifier. However, due to the uncertainty in the calibration, we expect about 10–20% systematic error in the absolute gain values. We have tried several different mixtures in an attempt to find a mixture with high electron drift velocity and high gas gain. It is desirable to lower the sense wire voltage as much as possible since the earlier electrostatic stability study showed that the wire deflection increases as a function of V^2.

The 28 channels were instrumented with electronics for the resolution study using a cosmic ray trigger. The outputs from the chamber were connected to the LeCroy 2735DC amplifier–discriminator with 5 μA threshold. The discriminated outputs were connected to LeCroy TDCs (2229). Fig. 14 shows the raw time distribution for several different gases; Ar–ethane (50–50) mixture with the operating voltage = 1700 V, CF_4–ethane (50–50) mixture with the operating voltage = 2100 V, and CF_4–isobutane (80–20) mixture with the operating voltage = 2200 V. The average electron velocity inside tubes for the gases are 51, 89, and 110 μm/ns, respectively. Because the bunch crossing of

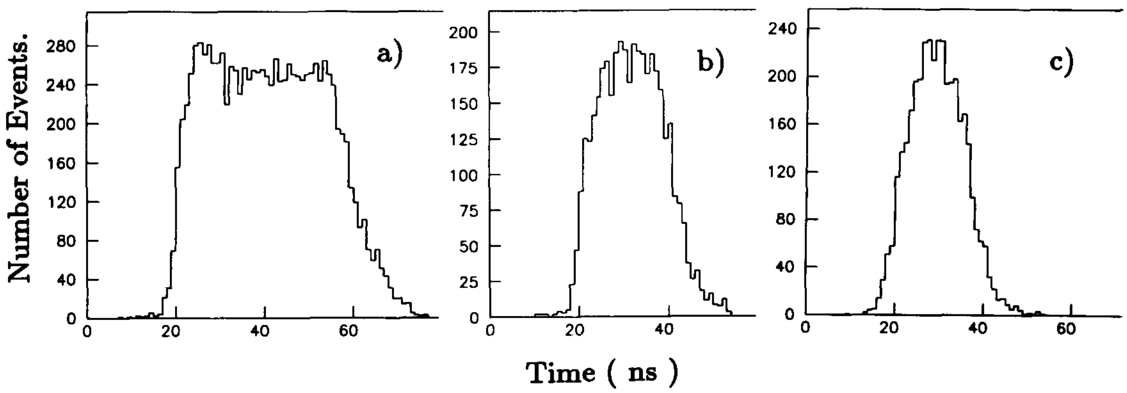

Fig. 14. Raw time distributions measured using different gas mixtures: (a) Ar–ethane (50–50), (b) CF_4–ethane (50–50), (c) CF_4–isobutane (80–20).

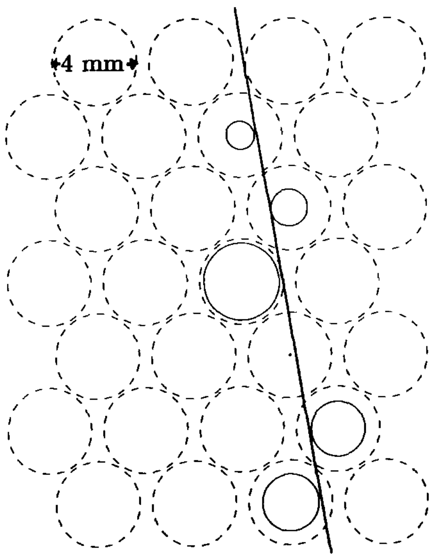

Fig. 15. A triggered cosmic ray track traversing the superlayer.

the SSC is 16 ns, and the average number of interactions is 1.5 per crossing at the design luminosity of 10^{33} cm^{-2} s^{-1}, the fast electron drift velocity is necessary in order to reduce the occupancy rate.

Fig. 15 shows a triggered cosmic ray track traversing the straw tube array. Using the tracks, the sense wires are aligned among themselves before residuals are calculated. The amount of correction to align sense wires is consistent with the deviation of the tube positions shown in fig. 7. Using the fitted tracks, the residuals are calculated and plotted in fig. 16 for the gas mixture of Ar–ethane (50–50) with operating voltage of 1700 V. The residuals are calculated using tracks with six or more hits. A sigma of 110 μm is obtained by fitting the distribution with a Gaussian curve. Several different gas mixtures are tried for comparison. For CF_4–ethane (50–50 mixture, operating voltage = 2100 V) a sigma of 120 μm, and for CF_4–isobutane (80–20 mixture, operating voltage = 2200 V) a sigma of 125 μm is obtained.

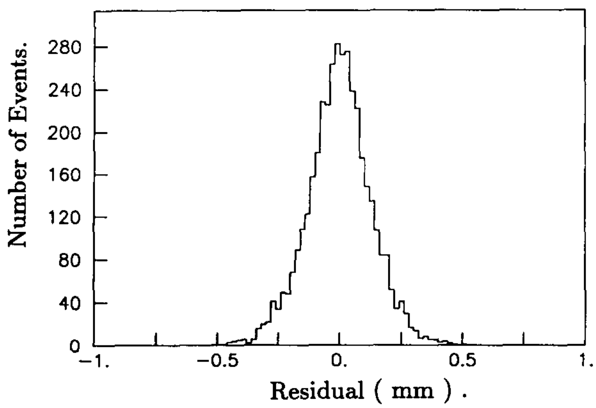

Fig. 16. Residual in mm obtained using cosmic ray tracks. Only tracks with six or more hits are used. Sigma of 110 μm obtained from a Gaussian fit to the curve.

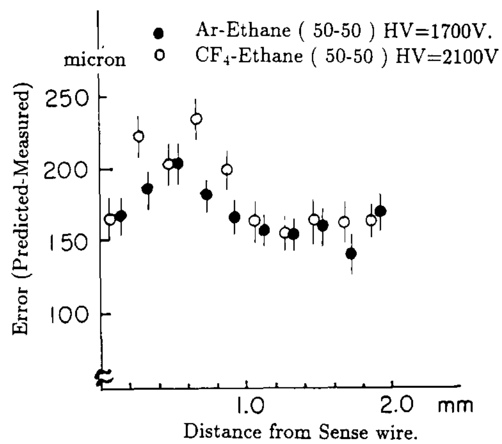

Fig. 17. The error as a function of distance from the sense wire. See the text for the definition of the error.

The resolution is also measured as a function of distance from the sense wire. Fig. 17 shows the error plotted for two gas mixtures. The error is calculated like the residual calculation except the hit from the cell of interest is not used in the track fit. In order to increase statistics, any tracks with more than four hits are used. As seen in the figure, the resolution is worse near the wire.

Presently we are studying long term aging effects. The expected radiation level at 50 cm distance from the interaction region causes about 0.05 C/(cm yr) charge deposit on a sense wire at the design luminosity with the gas gain of 5×10^4. It is essential to find a proper gas mixtures which results in a good resolution, high gain, fast electron drift velocity and a long chamber lifetime. Results of these tests will be reported when available.

6. Conclusion

For a feasibility study of using small radius tubes for a central tracking chamber for a SSC experiment, we have constructed and operated a 2.7 m long prototype straw tube drift chamber. The prototype consists of eight layers of tubes with a total of 60 channels. 28 channels were instrumented with readout electronics. By doing so we have demonstrated the following: First, we showed that layers of tubes can be placed straight with an accuracy better than 100 μm over several meters once a flat base-surface is provided. Second, an endplate designed using two plates provide an easy way to mount tubes, supply gas, string wire and mount electronics. Third, the wires can be supported inside tubes with proper wire supports to make a long working straw cell. Fourth, a large number of channels can be made operational simultaneously without difficulty. Using the prototype, we obtain about 500 cm for the attenuation length and about 110 μm for the resolution. We believe that the design and construction concept can be extended to a full size cylindrical central tracking chamber.

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