A modular straw drift tube tracking system for the solenoidal detector collaboration experiment
Part II. Performance


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Abstract
Several investigations were conducted to demonstrate the capabilities of a straw drift tube outer tracking system for the SDC detector as described in the previous article. These include electrical properties and aging properties of the tubes as well as measurements of electron drift times in a 2 T magnetic field. Measurements characterizing the radiation hardness of the processes used to fabricate the front-end electronics are also included. We present the performance characteristics of prototype straw modules read out through this front-end electronics as well as some data on the performance of the track trigger system.

1. Introduction
This paper describes many tests that were performed to demonstrate various capabilities of the the SDC outer tracking system. For a description of the design of the SDC outer tracking system see the companion paper [1]. Measurements of the straw tube properties include pulse attenuation, drift properties in a magnetic field and aging. A method of measuring accurately the dimensions of the modules is described. Then the performance characteristics of the drift
tube modules as a whole are presented. Finally the performance of the proposed track trigger circuits is given.

2. Straw drift tubes

2.1. Measurement of the signal attenuation along the straw tube

The attenuation of the electrical pulses generated by the passage of charged particles through the straw tube was a concern because of the extreme length of the straws (4 m). Loss of signal amplitude occurs in both the anode wire and the cathode coating on the straw. Both 25 μm wire and 38 μm wire with resistances of 115 Ω/m and 52 Ω/m, respectively, were used. The resistance of the copper cathode coating was, for different batches depending on our specifications, from 25 to 50 Ω/m. The thickness of this coating was estimated to be between 0.2 and 0.3 μm.

The attenuation length was measured by direct observation of the amplitude of signals using an 55Fe source. A special straw 7 m long was constructed to enhance the attenuation. The source was placed at several positions along the straw and the peak amplitude of the signal from the source was measured at both ends of the straw. The attenuation length was determined from the ratio of the two pulse amplitudes as a function of distance from one end. This quantity has an exponential dependence with characteristic length twice the attenuation length. Although there was some variation between tubes, an average attenuation length of 5.0 m was obtained. The measurements with 38 μm wire gave an increased attenuation length of 7.0 m.

For a 4 m long straw tube, using a 25 μm wire, the signal from the end farthest from the electronics was attenuated by a factor of 0.45.

2.2. Measurements of electrostatic stability

We constructed a straw tube model using a stainless steel tube that was held straight by accurately machined mounting brackets on a 2 cm square steel backbone. The tube had an inner radius of 1.95 mm and was placed in a horizontal orientation. A manifold on one end allowed gas to flow to purge the air. We used CO₂ and CF₄ as filling gases to quench discharges when voltage was applied to the wire.

The displacement of the wire was measured as a function of voltage. This was done by drilling a small hole in the middle of the steel tube to observe the position of the wire with a traveling microscope as the wire potential was raised.

We used the following procedure. First the wire was positioned off center horizontally by a known amount, and then the wire potential was increased. The deflection of the midpoint of the wire from its initial position was measured for several different potentials. There was also a vertical offset in the middle due to gravitational sag. For a 50 g tension, the amount of sag was about 25 μm; since this was considerably smaller than the offsets that we were measuring, we ignored the gravity effect.

Fig. 1 shows measurements of the wire deflection vs wire potential for tensions of 50 and 100 g. The lower set of data in each case is with an initial offset of 100 μm and the upper set of data is for an initial offset of 200 μm. The solid curves are predictions for the deflection at the midpoint. The measurements agree quite well with the calculations used for the design [1].

2.3. Electron drift characteristics in magnetic fields up to 2 T

We have made direct measurements of the Lorentz angle and drift velocity at magnetic fields up to 2.0 T for the nominal gas mixture 80% CF₄ and 20% isobutane. These measurements were made in a test cell with a 2.5 cm drift distance in a uniform electric field that could be raised to 4 kV/cm. The design of this cell was similar to the one described in Ref. [2] but was smaller and used a different method to generate the ionization. The cell is shown in Fig. 2. The drift electrons were generated by a 2 ns light pulse from a nitrogen laser passing through the cell at its outer edge. The time reference was provided by a photodiode in the laser beam. A series of cathode pads spaced 2.54 mm apart measured the deflection of the drift electron trajectories in the magnetic field. The magnet was a laboratory magnet of a type often used for NMR observations. It had a uniform field region of about 15 cm diameter. The measurements of the Lorentz angle are shown in Fig. 3 and the total drift velocity along the direction of motion of the electrons in Fig. 4.

The chief source of systematic error in these measure-
Fig. 2. Diagram of the drift cell used to measure the drift velocity and Lorentz angle of drifting electrons in CF$_4$ based gases. An N$_2$ laser generates ionization at a point near the edge of the cell. The electrons drift to the anode wire and generate a signal there. Cathode pads also pick up the signal at the point along the length of the wire where the electrons hit the wire. The optical components in the light are not shown in this diagram.

ments was in the absolute value of the mixing ratio of the gas mixture. In these measurements the amounts of gas were measured with mass flowmeters with ±2% full scale accuracy, but considering also zero drifts, temperature dependence and making measurements at a fraction of full scale, the errors were larger. Thus the amount of isobutane with respect to the total amount of gas was 20±2%. The Lorentz angle and velocity are quite sensitive to the ratio of the components in the mixture. The small difference between our measurement and the one from Ref. [3] can be attributed to a slight difference in the mixture ratio.

The error bars on the points reflect the reading errors of the drift time in the velocity measurement and the deflected avalanche position in the Lorentz angle measurement.

2.4. Comparison with different gases

Most of the tests carried out with the straw tubes used mixtures based on CF$_4$. The reasons for the choice of these gas mixtures were that the drift velocity is large and the aging effects are minimal. Other gas mixtures such as 90% Ar and 10% CO$_2$ show minimal aging but do not have as large a drift velocity. There are three important points against CF$_4$, namely 1) it tends to attach electrons to a region near the wire just before the avalanche region so that the efficiency and resolution are not as good as one would expect from such a dense gas; 2) the Lorentz angle is relatively large; and 3) it is expensive so that one usually leads to some sort of recirculation system. Another small disadvantage is that the operating voltage is 10–15% higher than with argon-based gases. A point in its favor, however, is that it is difficult to initiate a breakdown and one can run with large gas gain.

The most commonly used mixture of CF$_4$ is 80% CF$_4$ and 20% isobutane. Another gas that we have used is 50% CF$_4$ and 50% ethane. The drift velocity for this gas with no magnetic field is shown in Fig. 5. The shape is similar to that of 80% CF$_4$ and 20% isobutane but the peak occurs at lower electric fields and the velocity minimum is deeper and wider so that the time vs distance relationship is more nonlinear.

The search for a more ideal gas is not finished, and it may

Fig. 3. The Lorentz angle measurement vs electric field for several magnetic fields in a gas mixture of 80% CF$_4$ and 20% isobutane.

Fig. 4. The drift velocity along the drift direction vs electric field for several magnetic fields in a gas mixture of 80% CF$_4$ and 20% isobutane.
be hoped that some of the disadvantages of the standard CF$_4$ mixtures might be removed by altering the ratios and adding other components.

2.5. Aging and radiation damage

Recently an extensive series of measurements on anode wire degradation were done by Kadyk and his co-workers [4]. The anode wires develop coatings in most hydrocarbon-rich gases after a certain amount of charge has been collected. If a certain amount of CF$_4$ is mixed with the hydrocarbons, however, the anode wire is continually cleaned by the etching action of the reactive fluorine compounds generated in the electron avalanche process that occurs near the wire. This plus other operational experience with a mixture of 80% CF$_4$ and 20% isobutane [5] caused us to select this mixture for most of our tests. It is expected, however, that the etching action occurs for most hydrocarbons mixed with CF$_4$ within a range of mixing ratios so that other mixtures would also be satisfactory.

The alteration of the cathode surface has received less attention but was found in our tests also to be a serious problem in some circumstances. A straw tube with an aluminized inner surface is often used because it is very easy to aluminize a plastic film and the resulting coating is relatively resistant to chemical degradation. It was found, however, that after a certain amount of current had flowed in a straw with an aluminum cathode, the straw developed a tendency to draw large amounts of current in the presence of a radiation source. The amount of current drawn was limited mainly by the power source. The discharge would occur if the radiation level and/or the gain was high. An explanation which fits the observations is that an insulating coating develops on the surface of the aluminum and charges landing on it are trapped. The charges produce high electric fields in the thin insulating coating and this causes local breakdowns through the insulating coating. Electrons generated in these discharges drift to the wire and multiply causing even more charge to land on the insulating patch. Thus the discharge is self-sustaining.

Other metals that did not show this discharge problem could be deposited on plastic. In particular we tried both copper and gold and found them to be free of this behavior up to levels of integrated ionization current of 1–2 C/cm. The radiation length of a straw increased by about 10% for the copper coating as compared to an aluminum coating. The difficulty with the copper coating was that it was subject to corrosion in damp atmospheres where ionic impurities exist. Thus we had to be careful in shipping and storing the straws, and we maintained a dry atmosphere inside a finished straw module. The copper was also attacked by sulfides. Sulfur compounds are often present in commercial hydrocarbon gases. This is particularly true of ethane. Isobutane is, however, obtainable in a purity for which sulfur compounds are much less of a problem. By paying attention to these difficulties we were able to operate straw tubes over long periods of time. A long term test was conducted on a small section of module which could be irradiated with one or two 10 mCi $^{90}$Sr sources. A total of 17 m of 4 mm diameter straws were irradiated at levels up to about 50 nA/cm corresponding to about 5 times the current expected at design luminosity. The test was run for about one calendar year. At the end of the test 1.4 C/cm of charge had been accumulated corresponding to about 15 SSC years (1 SSC year $= 10^7$ s) at design luminosity. At the end of the test the chamber did not experience the breakdown seen with aluminum cathodes and when examined the copper cathodes had the same surface resistivity as unirradiated tubes. This implies that to a level of 5% there was no loss of copper from the cathode surfaces.

3. Measurements of shell and module straightness

Measurements of the shell and module were made with a coordinate measurement machine [6] capable of measuring the full length of the 4 m shell with an accuracy of $\pm 5$ $\mu$m. The shells were constrained to lie on a flat fixture but were allowed to take their natural shape transversely. The lid and the base were separately quite flat and without any gross distortions. Individual measurements on the shells indicate that the thickness of the lid and the base components of the module were precise to $\pm 60$ $\mu$m for several different lay-up configurations. This was within the required tolerance. Also, the best individual straightness measurements on the shell components indicated that the tolerance of $\pm 300$–$400$ $\mu$m maximum deviation from a straight line over a length of 1.6 m could also be accomplished. The prototype lids showed somewhat greater variation than our specification. During the assembly procedure, however, the lid and base sections were clamped and glued in jigs to force
straightness so that the final module was straighter than its individual components. A glued base and lid measurement is shown in Fig. 6. These measurements indicate the modules are within the ±200 μm tolerance required by the module holding fixtures.

4. Electronics

4.1. Radiation hardness

It is well known that certain high speed bipolar processes can tolerate large doses of radiation with only small changes in their operational characteristics. In a detailed series of measurements on the AT&T CBICU [7] and the Tektronix SHPI [8] processes we have found acceptable performance for exposures up to 50 kGy of gamma irradiation and up to 10^{14} neutrons/cm^2 [9]. Fig. 7 shows the current gain of an SHPI transistor as a function of collector current before and after exposure to 10^{14} neutrons/cm^2. At TRIUMF powered amplifier-shaper-discriminator (ASD) circuits have been exposed to 3 \times 10^{13} protons/cm^2. Shifts in thresholds of less than 1 fC have been observed with otherwise unchanged operational characteristics [9].

4.2. Electrical noise and interference

Low noise is an important criterion in making precise position measurements in the straw drift chambers and operating the chambers at high rate with low gas gain. We took care to reduce the noise as much as we could during the tests described in this paper.

The design of the ASD chip incorporated some special noise reduction features. The pseudo-differential input connection to the amplifier allowed us partially to cancel noise signals present near the amplifier input, and the use of low level differential digital output lines resulted in low cross coupling between the input and the output.

The amplifier boards were provided with ground planes and ground tabs to connect the chamber grounds to reduce pickup. There was shielding around the transition from the endplate to the amplifier. It was also beneficial to wrap each module with aluminum foil because the module shell and the straw cathodes are not good shields in themselves for frequencies around 100 MHz. A similar shield would have been provided in the final system. Finally there was improvement in the noise if the output cables carrying the low level digital signals were shielded.

With all these measures to reduce noise the threshold could be reduced to 2 fC without having an excessive noise rate of discriminated signals. The low noise rate also reduced the amount of time jitter on the time signals. With a fast drift velocity this was important to maintain good position resolution.

5. Performance of straw modules

5.1. Test setups and time evolution of modules

5.1.1. Cosmic ray test setups

Preliminary tests of the straw modules were conducted using cosmic rays. Simple arrangements of a straw module together with scintillation counters for a trigger were adequate to determine rough efficiencies and resolutions as functions of chamber voltage.

5.1.2. Beam test setup

In July 1993 we conducted a system test of four straw modules at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS). The primary purpose of the beam test was to demonstrate that the modules and the highly sensitive ASD readout electronics could perform successfully as a system during accelerator running conditions. In addition, the beam test provided an opportunity to study chamber performance for tracks at oblique angles, such as would be expected during collider operation for tracks at large values of pseudorapidity. Thus the data set included both runs taken with the beam perpendicular to the plane of the modules and with the beam 60° to the perpendicular.

The apparatus for the beam test consisted of two axial modules and two stereo modules mounted on an aluminum frame. These four modules are described in Table 1. The axial modules were prototypes with the correct dimensions for the innermost superlayer of the SDC tracking system [1] in every way except that they were a full 4 m in length. The stereo modules were of the type intended for superlayer
4. The mounting frame rested on a motor-driven table that allowed the precise and reproducible location of the modules with respect to the beam axis. The method of mounting the modules to the frame was designed as a prototype of the alignment and mounting procedure proposed for the final detector configuration.

The beam was primarily negative pions at momenta ranging from 2 to 8 GeV/c with a 5% contamination of electrons. The flux was about $10^5$ particles per 1 s spill, over a 4 s duty cycle. Because of a shortage of ASD chips in high density packages, two of the modules were only partially instrumented. A total of 483 ASD channels were digitized using CAMAC based Time Memory Cell (TMC) modules [1]. The chambers were operated mainly with a mixture of 80% CF$_4$ and 20% isobutane. The readout electronics and HV distribution were operated in a nitrogen atmosphere to reduce the effects of high humidity and temperature.

A typical online event display is shown in Fig. 8.

5.1.3. Time evolution of module design

Improvements were built into later modules based on experience with the earlier ones. The modules for the beam test had both 25 μm and 38 μm wire. It was apparent from the tests that the lower attenuation with 38 μm wire did not overcome the disadvantages of worse resolution and higher operating voltage. The modules for the beam test did not have terminations and therefore had rather large cross talk. Previous attempts to terminate the straws with external component resistors and capacitors aggravated the cross talk because of the added leads. After the beam test, modules were built with the terminations described in the companion paper [1]. In the new prototypes we also built spring signal contacts into the taper pins that hold the wires under tension, whereas the earlier prototypes used separate double-ended spring contacts. This improved the reliability of the connections and also reduced the coupling between the wires by reducing the length of unshielded signal line. In the following sections the results of both the beam test modules and the later modules will be presented.

5.2. Efficiency and resolution

The beam test provided us with a large set of data from the modules at various voltages and positions along the modules. The high energy minimum ionizing particles in the beam gave a reliable concentrated source of particles with low multiple scattering.

To study efficiency, noise, and resolution we reconstructed track segments in each of the four modules. We set the assumed wire resolution to 200 μm, and required that the pattern recognition and fitting program find exactly one track segment of four or more hits in a module. To measure efficiency and classify hits as signal or noise, we tagged the cells that should contribute to the segment by projecting the segment to each layer in turn. This established a trial for calculation of the efficiency of the tagged cell. A hit in that cell contributed to the numerator of the calculation. A hit in any other cell in the layer was a noise candidate. We corrected, however, for cases in which the projection missed the edge and pointed to the neighbor of the cell actually traversed [10].

The resulting efficiency plateau and noise curves for module 1 from the beam test are shown in Fig. 9. The efficiency is reduced from 100% because of the space taken up by the straw wall and, in the case of the axial modules, by the extra space between the straws in the rows with larger radius of curvature. These geometric effects lead to a maximum efficiency for the stereo modules of 98% and 96% for the axial modules. The data show that the efficiency approaches the geometrical limit as the voltage is increased. The noise hit rates shown in Fig. 9 are for hits that are in time with the trigger within the drift time range. Delayed noise hits can be separated and ignored, although they contribute to pileup in a high rate environment. Both types of noise hits are discussed in Section 5.3.1.

Measurement of the resolution via track residuals depended upon a careful calibration of the distance-time relation for each module, including individual time offsets for the TMC channels [11]. We used an iterative procedure,
alternating an averaging of individual channel time residuals with fits to the drift velocity and a global time origin. Deviations from a constant drift velocity model were small and ignored. The drift velocity fits yielded values around 120 µm/ns, depending slightly on the anode voltage and the straw diameter. This agreed with the measurements described in Section 2.3.

We measured the resolution by three different methods. Since the tracks were all very nearly normal to the wire planes, they lay on the same side of the wires in alternate-layer triplets (see Fig. 8). The difference between the middle wire's drift time and the average drift time to the outer members measured the resolution in time. Then the resolution in position was obtained by multiplying by the drift velocity \( v_d \): \( \sigma = \sqrt{2/3} v_d \sigma [t_2 - (t_1 + t_1)/2] \) [12,13]. This depended on an independent determination of the constant \( v_d \) (Section 2.3). A second method was based upon segments reconstructed in the modules by least squares fitting of the hits to a straight line. We varied the assumed resolution and plotted the confidence level (\( \chi^2 \) probability) distribution at each point; a uniform distribution (ignoring an excess at very low confidence level from delta rays, tracking errors, etc.) indicated that the assumed resolution had the true value. The third method was to measure residuals from global track fits spanning three (or four) modules, and then to fit a Gaussian function to their distribution. We found consistency among the results of these measurements to within about 10%.

Fig. 10 shows the resolution measured by the confidence level method vs anode voltage for three of the modules for normal incidence at two positions, and for 60° incidence at one position. Parameters and operating conditions for the three detectors are listed in Table 2.

The best resolution values obtained were about 150 µm at 0° and 130 µm at 60°. The optimal operating point to include this range of angles was about 1850 V for 25 µm wires and 2050 V for 38 µm wires. This is 100 V lower than the optimum for 0° alone, to avoid excessive noise attributable to cross talk with the higher signal levels produced at 60°.

The TMC digitizer introduced an rms uncertainty in the drift time measurement of 0.52 ns [14]. For the beam test this error occurred twice, because in the long spill the arrival times of beam particles were measured with a scintillator read out in the TMC's; we confirmed that this measurement was uncorrelated with that of the drift electrons' arrival [15]. With \( v_d \approx 120 \mu m /ns \) the second time measurement contributed about 62 µm that would not occur in a collider environment.

Other contributions to the time measurement error included variations in pulse height leading to time walk in the discriminator and random variations in signal level (noise). The position resolution also depended on the measurement of the diffusion distribution centroid (\( \propto 1/\sqrt{n} \), where \( n \) is the number of primary ionization electrons) and the cluster spacing along the track. The former makes only a small contribution but the latter is relatively important for small

<table>
<thead>
<tr>
<th>Module</th>
<th>( a [\mu m] )</th>
<th>( N_{layers} )</th>
<th>Gas mixture</th>
<th>( v_d [\mu m/ns] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>6</td>
<td>CF₄–IC₄H₁₀ (80–20)</td>
<td>130 at 1950 V</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>8</td>
<td>CF₄–C₂H₆ (50–50)</td>
<td>105 at 1950 V</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>6</td>
<td>CF₄–IC₄H₁₀ (80–20)</td>
<td>135 at 2150 V</td>
</tr>
</tbody>
</table>
cells such as these.

The average resolution over the length of a module at 1850 V in 80% CF₄ 20% isobutane in a module with 25 µm wire is 145 µm after the contribution of the extra TMC measurement, mentioned above, is removed. This takes into account the variation in resolution due to the angle of incidence of a track from 0° at z = 0 to 60° at z = 4 m using superlayer 3 as an example. Another difference between the beam test and SDC operation is the effect of the 2.0 T magnetic field. This acts to reduce the drift velocity by about 25% on the average and thus we would expect the average resolution in the magnetic field to be about 110 µm.

5.3. Cross talk

A challenge that arises with closely spaced cells of long wires is to minimize intercell cross talk. Although the wires are completely enclosed over the active length of the detectors by cylindrical conductors, they are only imperfectly shielded because of the limited thickness of copper that can be deposited on the plastic straw wall, or be desired from considerations of material. Coupling of signals between the connections to the electronics where the conductors are unsheilded can be troublesome as well.

The system aspects for the SDC tracker exacerbated the problem by imposing a large dynamic range requirement on the detector performance. This occurred because tracks traversing the straws at the largest incident angles had path lengths inside the straws nearly 3 times those for tracks normally incident. Further, these long path tracks occurred near the readout end of the straws so that their signals arrived unattenuated at the preamps. Over the full length of the straw the attenuation loss was about 55% (Section 2.1). Altogether then the requirement for dynamic range includes a factor of nearly 6 over and above the variation of pulse height from Landau and cluster fluctuations.

5.3.1. Beam test observations

Data taken in the test beam covered a range of operating voltages, track distance from the preamps, and two rather extreme track incidence angles (0° and 60°). Generally speaking, we found that for operation at high enough gain to provide good resolution for normally incident tracks, the noise rate associated with 60° tracks was high. The observed close proximity of noise signals to valid track responses suggests that cross talk was the dominant cause of this noise.

From our analysis of the test beam data we found that there were three components of noise [16,10]: the first was present even at low gain (sufficient for reasonable efficiency) and could be attributed to track interactions in the material of the straws or shells, producing delta rays and other ionizing radiation. The second component increased with gas gain and with distance from the amplifier. Since pulse attenuation alone would instead diminish the signals with distance, we suspected that cross talk in the straws themselves was responsible. The remaining component increased with gain but slightly decreased with distance, and could have been caused by cross talk in the connections to the electronics. This is discussed further below.

5.3.2. Cross talk in the straws

We conducted an extensive series of bench tests to analyze the mechanisms for cross talk and guide design improvements [17]. To measure the effect in the detectors themselves we set up a pair of straws with anode wires connected through 4 cm long coaxial cables to a pulse generator and an oscilloscope. The use of very short connecting cables and a clean coaxial mating of the cable to the straw minimized the potential confusion from impedance mismatches between the 93 Ω cable, 50 Ω pulser output impedance, and 280 Ω sample impedance. The active straw was pulsed with a step function of 2.0 ns risetime (appearing as a 2.8 ns risetime pulse at the output end of the active straw). Ignoring a slow bipolar response believed to be caused by ground currents, we observed a response in the passive detector of about 5 ns width, opposite polarity to the driving signal, and about 3.5% of its magnitude. This signal was reduced if we increased the risetime of the driving pulse, increased the separation of the straws, or added an aluminum foil shield between the two straws. This behavior was consistent with magnetically induced coupling.

5.3.3. Cross talk in the readout connections

The readout assembly and ASD board input traces were probed for the "folded board" [1] by connecting a pulse generator directly to the input face of a spare endplate. A bare readout board was equipped with terminating resistors, for a few channels, placed so as to allow us to separate the effects caused by neighboring straws from those due to neighboring electronics channels. The driving waveform was as before a step of 2 ns risetime.

The observed cross talk signal had a width of about 3 ns, was of the same polarity as the driving pulse and 3.5% of its magnitude. No reduction was seen on a second channel connected to a nearest neighbor connector pin via a trace well separated on the readout board, indicating that most of the cross talk occurred upstream of the readout board. The cross talk signal from a well separated connector pin was, by contrast, an order of magnitude smaller. It was possible, no high voltage being involved in this test, to remove the high voltage feeder board and blocking capacitor assembly of the "folded board" [1], about half of the connector length, and as expected this reduced the cross talk signal by a factor of two.

We tested the effect of adding ground feed pins interspersed among the signal lines. The effect was to reduce the cross talk signal only slightly, from 3.5% to 3.1%, and to reduce a smaller trailing oscillation presumably caused by ground currents by a factor of 2 to 3. This represented a very small improvement in view of the difficulty of operating with such close proximity between high voltage and
ground electrodes.

We measured the contribution of the blocking capacitors separately by interrupting the ground braid of a pair of coaxial cables, inserting the capacitors in line with the center conductors, and pulsing one while observing the pickup on the other. This cross talk was about 0.4% (with the same polarity as the driving pulse), compared with 0.1% for a length of unshielded center conductor alone, and with 3.5% for the connector assembly as stated above. This indicated that the contribution to cross talk of the closely spaced capacitors was small though not negligible.

We concluded that the connector cross talk could be reduced by shortening the paths that were not coaxially shielded, to the extent allowed by mechanical constraints. Simple ground leads were not very effective, and we did not have a practical design for a fully coaxial connector.

5.3.4. Termination tests

In general two conductive lines may be coupled through their mutual capacitance and inductance. Signals propagate in both directions from the point of coupling. Assuming the signal in the driving line is positive and forward going, the forward going component in the driven line will be negative if it is dominated by the inductive contribution. The backward going component may reach the receiver after reflecting from the far end if the line is not terminated there. These considerations can explain our observation of opposite-polarity cross talk in the straw tests, and further suggest that back termination of the lines may reduce cross talk.

We built four straw bundles of seven straws each for testing a range of termination schemes. One of the bundles was equipped with a mechanism to add or remove termination while preserving the coaxial ground. Another contained the custom terminator described in the companion paper [1]. Two others were unterminated, one having the cathodes connected together at the non-readout end. These were fully operable detectors.

We induced signals in these test detectors with a $^{55}$Fe X-ray source and detected them with the ASD circuit described in the companion paper [1]. (A gas mixture of 50% Ar and 50% ethane was used for convenience in these cross talk tests.) To estimate cross talk rates with this system we recorded the fraction of X-rays detected in the direct channel that were accompanied by pulses in the neighboring one. Only the discriminator output was available, and the shaping circuit was designed to minimize the time over threshold for the signals. Nevertheless the length of the output pulse reflected the amplitude of its input to a useful degree. Traces from a direct and a cross talk signal induced near the readout end of the detector are shown in Fig. 11. The direct signals from the monoenergetic X-rays have a consistent large width, while the cross talk pulses are much narrower.

Corresponding signals from the away end of the detector are shown in Fig. 12. In this case, the cross talk signal arrives near the trailing edge, suggesting that the input is of opposite polarity from the direct pulse and triggers the discriminator by means of an overshoot.

Cross talk of both timings is plotted in Fig. 13, where we see a falloff of the leading edge component and growth of the trailing edge component with distance from the am-

Fig. 11. Measured waveforms at the ASD output with a $^{55}$Fe source: (above) direct signal and (below) cross talk pickup for the source 5 cm from the ASD.

Fig. 12. Measured waveforms at the ASD output with a $^{55}$Fe source: (above) direct signal and (below) cross talk pickup for the source 4 m from the ASD.
plifier\textsuperscript{1}. A threshold control voltage of $-1$ V corresponds to charge sensitivity of about 4 fC. The pickup that grows with distance from the amplifier and triggers the discriminator on its trailing edge can be explained by magnetic inductive coupling, which has opposite polarity from the driving pulse and grows with the distance of travel. The leading edge component probably comes mainly from the connections, since it does not grow with propagation distance, but drops off because of resistive attenuation.

We might expect to suppress the trailing edge component by terminating the straw at the far end in its characteristic impedance, at least to the extent that reflection doubling of the driving signal is eliminated. We tested this, again using the X-ray source, with results shown in Fig. 14. We see that the termination reduces the trailing edge cross talk (lower plot) by a factor of two, as indicated by the data at 1550 V, and more according to the two points at 1650 V. The (smaller) leading edge component is actually somewhat larger with the terminator, although with additional uncertainty in the measurements caused by variation in noise levels, this difference may not be significant.

Points measured with the X-ray source in the new prototype built with internal terminators are included in Fig. 14. The 50\% cross talk sensitivity for a source placed near the electronics is similar to the better of the two curves measured in the comparison test. For the source at the termination end we have estimated the equivalent threshold voltage for an operating point corresponding in gain to 1550 V in the earlier prototype (lower plot), and we find again that the cross talk reduction exceeds our expectation.

We show in Fig. 15 the drift time distribution for cosmic ray triggers near the termination end of the module for the first (Module 3 of the beam test) and second generation prototypes. The distribution for hits attached to tracks is shown to indicate the shape expected from true track crossing responses. The strong peak at late times in data from the earlier test beam prototype without terminations is caused by the trailing edge cross talk. This has been eliminated by

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\textsuperscript{1} We can not use the same high voltage settings for both components because of the limited dynamic range of these observations based on fractions of events that trigger the discriminator.
the terminators in the new prototype as shown in the lower graph in Fig. 15.

6. Performance of the trigger

6.1. Trigger simulation

A full GEANT simulation was carried out so that the performance of the proposed trigger [1] could be assessed and the options compared. Several important characteristics of the trigger were studied: the efficiency for tracks above a preselected minimum momentum perpendicular to the beam (p_T), the sharpness of the p_T threshold, and the rejection of minimum-bias backgrounds.

The sharpness of the p_T threshold is displayed in Fig. 16 for isolated muons. The threshold variation can be characterized by a width $\Delta p/p = 0.07$ at 12 GeV/c. Since the p_T threshold is programmed by linking segments across superlayers, a few discrete values are available: 8, 12, 15, and up to 36 GeV/c with decreasing resolution. Thresholds of 12 or 15 GeV/c were anticipated. The efficiency and background rejection properties of the trigger were evaluated in terms of the tradeoff between selectivity and efficiency. The integrated percentage of high-\(p_T\) muons found among minimum-bias background events is plotted in Fig. 17 against the number of false triggers alone. The trajectories on this plot are defined by four data points at the luminosities 1, 3, 6, and 10 times the SSC design luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$. Each trigger option is exhibited on this plot as a separate curve connecting the four data points at the four luminosities. The number of falsely sensed "fake" triggers is represented as the number of matches these fakes can have with the calorimeter. For the SDC the azimuthal match with the calorimeter was in 128 bins, 64 at each end of the detector. An event with four fake tracks would then correspond to approximately a 1/32 chance of a random coincidence with a calorimeter trigger.

6.2. Performance of the trigger chips

In this section, we describe the results of testing the basic algorithm and electronics of the prototype chips described in the companion paper [1] using both cosmic ray data and data from the test beam run at Brookhaven.

Previously recorded data was read from the storage medium and routed to a test setup as shown in Fig. 18. A 32 channel programmable pulser with a 1 ns/count granularity produced differential signals at times specified by the data. For each event these signals were recorded by a LeCroy 1879 FASTBUS TDC. The 1879 has a way of sending the input data lines to the auxiliary backplane. From there the signals were sent to a custom designed board holding seven digital mean timer (DMT) chips where the signals were processed. The outputs of the DMT chips were then sent back to the TDC to be recorded for off-line analysis.

Data taken with cosmic rays was used to verify the basic operation. This set of data describes tracks with a large range of incident angles. Fig. 19 shows the segment finding efficiency as a function of the equivalent p_T in the SDC detector corresponding to the incident angle of the track. The efficiency for very stiff tracks is 92.0±4.0%. In a configuration of three straw modules, such a segment finding efficiency would imply an efficiency for passing two of three layers of 98%.

In a collider environment, the actual distribution of DMT
output times is expected to be sensitive to a number of factors, the largest being the pseudo-rapidity of the track. In the SDC, this results in a 7 ns shift in the width of the time distribution of the signals. We find that additional dispersion inherent in the DMT electronics is small compared to these factors and, more importantly, small relative to the 16 ns beam crossing interval. Therefore the ability to identify uniquely a beam crossing is not compromised.

The performance of the trigger chips was also studied with data taken from the test beam run at Brookhaven. The test beam environment, described earlier, provides much higher rates and better measured tracks than could be obtained with cosmic rays. The efficiency for tracks normally incident to the straw tubes was measured to be $94 \pm 3\%$. The performance near tube boundaries was also studied and no loss of efficiency was observed.

In summary, the DMT chips proposed for the SDC straw trigger performed as expected with both cosmic ray and with test beam data. No unforeseen effects were observed which might, for instance, be due to the geometry of the tubes. At the same time, some effects intrinsic to the SDC environment, such as high occupancies, remain unstudied except in Monte Carlo simulations.

7. Summary and conclusions

We found a way to measure the dimensions of the modules with high precision and found that they met their specifications. The electron drift velocity and Lorentz angle in a 2.0 T magnetic field were measured in a gas mixture of 80% CF$_4$ and 20% isobutane. The measured single-wire position resolution using this gas mixture averaged 145 $\mu$m with no magnetic field over the full 4-m length of the module at a high voltage that gave a cross talk of less than 10%. The resolution was expected to improve in a magnetic field of 2 T. The cross talk in the final modules, with internal terminations, was not due to coupling between the straws themselves, but originated instead in the connection between the end of the straws and the ASDs and possibly could have been reduced further. The trigger based on finding high momentum track segments in the superlayers was found using a GEANT simulation to be about 98% efficient while rejecting minimum bias events that accidently pass the primary calorimeter trigger.

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