A modular straw drift tube tracking system for the Solenoidal Detector Collaboration experiment
Part I. Design

Y. Arai\textsuperscript{e}, J.G. Arnold\textsuperscript{g}, J.W. Barkell\textsuperscript{m}, B. Bevensée\textsuperscript{h}, B. Broomer\textsuperscript{a}, J.W. Chapman\textsuperscript{f}, M. Chiba\textsuperscript{k}, T. Collins\textsuperscript{d}, M.J. Corden\textsuperscript{j}, D. Craig\textsuperscript{a}, D.M. Davis\textsuperscript{e}, N. Dressnadt\textsuperscript{h}, A. Dunn\textsuperscript{f}, W.L. Dunn\textsuperscript{i}, T. Ekenberg\textsuperscript{h}, M.S. Emery\textsuperscript{g}, T. Emura\textsuperscript{f}, E. Erdos\textsuperscript{a}, W.T. Ford\textsuperscript{a}, T.A. Gabriel\textsuperscript{g}, A.T. Goshaw\textsuperscript{c}, S.V. Greene\textsuperscript{a}, M. van Haaren\textsuperscript{i}, D.T. Hackworth\textsuperscript{m}, R. Hamatsu\textsuperscript{k}, G. Hanson\textsuperscript{d}, T. Hirose\textsuperscript{k}, M. Ikeno\textsuperscript{e}, Q.P. Jia\textsuperscript{b}, D. Johnson\textsuperscript{a}, T. Kageya\textsuperscript{k}, P. Keener\textsuperscript{b}, S. Kitamura\textsuperscript{k}, A.M. Lee\textsuperscript{c}, R.M. Leitch\textsuperscript{g}, Z. Li\textsuperscript{d}, F. Luehring\textsuperscript{d}, J. Mann\textsuperscript{f}, T. Marshall\textsuperscript{d}, B. Martin\textsuperscript{d}, C. Miao\textsuperscript{f}, T. Murata\textsuperscript{f}, F.M. Newcomer\textsuperscript{h}, S. Odaka\textsuperscript{e}, F. O’Foghudha\textsuperscript{i}, H. Ogren\textsuperscript{d}, S.H. Oh\textsuperscript{c}, T.K. Ohska\textsuperscript{c}, W. Robertson\textsuperscript{c}, D.R. Rust\textsuperscript{d,*}, O. Sasaki\textsuperscript{c}, G. Schultz\textsuperscript{a}, K.D. St. Onge\textsuperscript{g}, F. Sudo\textsuperscript{f}, R.L. Swensrud\textsuperscript{m}, B.R. Thompson\textsuperscript{a}, W. Toki\textsuperscript{b}, R. Van Berg\textsuperscript{h}, D.H. Vandergriff\textsuperscript{g}, S. Vejcik\textsuperscript{f}, C. Wang\textsuperscript{c}, D. Warner\textsuperscript{b}, Y. Watase\textsuperscript{c}, C.R. Watson\textsuperscript{a}, E. Wente\textsuperscript{d}, H.H. Williams\textsuperscript{b}, R. Wilson\textsuperscript{b}, A. Winningham\textsuperscript{a}, D. Xiao\textsuperscript{j}, K. Yamauchi\textsuperscript{k}, B. Zou\textsuperscript{c}, C. Zuechler\textsuperscript{d}

\textsuperscript{a} Department of Physics, University of Colorado, Boulder, CO 80309, USA
\textsuperscript{b} Department of Physics, Colorado State University, Ft. Collins, CO 80523, USA
\textsuperscript{c} Department of Physics, Duke University, Durham, NC 27706, USA
\textsuperscript{d} Department of Physics, Indiana University, Bloomington, IN 47405, USA
\textsuperscript{e} Physics Division, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305, Japan
\textsuperscript{f} Randall Laboratory of Physics, The University of Michigan, Ann Arbor, MI 48109, USA
\textsuperscript{g} Oak Ridge National Laboratory, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-654, USA
\textsuperscript{h} Department of Physics, University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19104, USA
\textsuperscript{i} Quantum Research Services, Alston Technical Park, 101 Capitol Drive, Durham, NC 27713, USA
\textsuperscript{j} Supercomputer Computing Research Institute, Florida State University, Tallahassee, FL 32306, USA
\textsuperscript{k} Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji-shi, Tokyo 192-03, Japan
\textsuperscript{l} Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei-shi, Tokyo 184, Japan
\textsuperscript{m} Westinghouse Science and Technology Center, 1310 Beulah Rd., Pittsburgh, PA 15235, USA

Received 15 April 1996

Abstract

We have developed the baseline design for a straw drift tube tracking system for the Solenoidal Detector Collaboration (SDC) detector. The system was designed to operate in the high-rate environment of a high luminosity hadron collider. We present an overview of the tracking system and the requirements it was expected to fulfill. We describe the construction and properties of the straw drift tubes. We discuss the design of the carbon-fiber foam-laminate shell, which supported the wire tension and held the straws in alignment. We also present descriptions of the designs of the front-end and digitization electronics as well as the electronics associated with the level 1 track trigger.

1. Introduction

The design for the tracking system for the Solenoidal Detector Collaboration (SDC) detector consisted of an inner silicon tracker, an outer straw tube tracker, and a gas microstrip intermediate angle tracker. The straw module outer tracking system was designed to operate in the high-rate environment of the Superconducting Super Collider (SSC). The ability of straw tube drift cells to operate in high rate environments, their long lifetime operating in high radiation conditions, and their ability to provide high spatial resolution, all contributed to the adoption of straw drift cells for this application.
areas, and their low cost per unit volume make them useful as tracking elements also in future detectors. Straw tube tracking arrays are being planned for Large Hadron Collider (LHC) experiments and for Tevatron upgrades. The design details presented here can assist in these future designs. A companion paper to this one [1] describes several measurements to support and prove this design. It also describes the operation of a full size straw chamber module in a test beam.

2. Overview of the detector and tracking system

2.1. The SDC detector

The design goals of the SDC detector were $e/\mu$ identification, energy and sign of charge measurement, detection and measurement of isolated photons, measurements of jet energies and directions, identification of jets containing b-hadrons, determination of charged particle multiplicities, and detection of non-interacting neutrals. In order to accomplish these goals, the detector was designed around the concept of a large-volume solenoidal magnet containing precision tracking detectors for measurement of the momenta of charged particles produced in the pp interaction. The tracking system was intended to operate in the flux of particles produced at a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$, and to measure the trajectories of all charged particles with high transverse momentum with respect to the beam direction ($p_T$). It is described in more detail in Section 2.2. The detector is shown schematically in Fig. 1 and is described in much more detail in Ref. [2]. The solenoid coil, centered on the beam, produced a magnetic field of 2.0 T along the z direction, which was the direction parallel to the beam. The dimensions of the tracking volume inside the magnetic field were 1.7 m radius and 8.6 m total length.

The solenoid and tracking system were surrounded by hermetic calorimetry. The central calorimeter covered $|\eta| < 3$, where $\eta$ is the pseudorapidity. It consisted of scintillating tiles with wavelength-shifting fiber readout interspersed with lead absorber in the electromagnetic section and iron absorber in the hadronic section. The electromagnetic calorimeter also contained a fine-grained shower maximum detector. High-pressure gas or liquid scintillator calorimeters were being considered for the forward region, $3 < |\eta| < 6$.

Muon identification, triggering, and momentum measurement were accomplished with a large system of magnetized-iron toroids with wire chambers and scintillation counters. For $|\eta| < 2.5$, the muon momenta were determined by a combination of measurement in the central tracking system and deflection in the iron toroids.

2.2. The SDC tracking system

The tracking was designed to satisfy the following requirements [3]:

(i) Reconstructed (as opposed to parametric) vertex constrained momentum resolution for isolated charged tracks of $\sigma_{p_T}/p_T^2 < 20\% \ (\text{GeV/c})^{-1}$ for $|\eta| \leq 1.8$, allowed to rise to $\sigma_{p_T}/p_T^2 \rightarrow 100\% \ (\text{GeV/c})^{-1}$ as $|\eta| \rightarrow 2.5$.

(ii) Reconstruction efficiency within this acceptance $\geq 97\%$ for isolated tracks having $p_T \geq 10$ GeV/c, with $\leq 0.1$ false tracks of $p_T \geq 10$ GeV/c per trigger. (Efficiency greater than 90% for detecting all four leptons from $t \rightarrow d^+ \rightarrow 4$ charged leptons, exclusive of lepton identification and trigger cuts.) This requirement is specified for design luminosity, but with occupancy assumed twice that calculated by Monte Carlo for $pp \rightarrow X$.

(iii) Material $\leq 15\%$ of a radiation length ($X_0$) (allowing for $3\%$ $X_0$ equivalent effect of internal bremsstrahlung), $\leq 7\% X_0$ inside 50 cm (average over $|\eta| \leq 2.5$), for efficiency of electron identification ($E/p$ cut).

(iv) First level trigger with momentum resolution $\sigma_{p_T}/p_T^2 \leq 10 \ (\text{GeV/c})^{-1}$ implies a 10% error for a 10 GeV/c lepton.

The innermost layers of the tracking system, at radii between 8 and 50 cm and covering $|\eta| < 2.5$, were composed of double-sided silicon microstrip detectors [4]. The barrel section contained 8 layers of 6-cm-long wafers, bonded together in pairs to form 12-cm-long readout units. The strip pitch was 50 $\mu$m on both sides of the wafer. The strips on the junction (p) side of the wafers had a 10 mrad stereo angle. The wafers were 300 $\mu$m thick and were tilted at an angle of 7.5° to the radial direction to compensate partially for the Lorentz angle. In the forward region, the 6-cm-long wafers were wedge-shaped and were also bonded into 12-cm readout units. The strips were tapered to give a pitch ranging from 28 to 58 $\mu$m over the radial extent of the unit. The stereo strips were also tapered and had an effective stereo angle of 10 mrad at the outer edge. Thirteen disks on each end were used to cover the specified $\eta$ range effectively.

The straw tube tracking system consisted of 5 concentric cylindrical superlayers of straw drift tubes, at radii between 80 and 165 cm and covering $|\eta| < 1.8$. It is shown in Fig. 2. Each superlayer was supported by a carbon fiber epoxy and foam laminate cylinder. The straws were all 4 mm in diameter. The straw tubes were arranged in modules of approximately trapezoidal cross section, each containing about 200 straws. The arrangement of modules in the five superlayers is shown in Fig. 3. Each straw module was essentially an independent tracking chamber, with its own gas and power connections and its own electronics. Three of the superlayers had straws running parallel to the beam direction (axial superlayers) and had 8 layers of straw tubes; these superlayers were used to form the high-$p_T$ track trigger (Section 5.6). The other two superlayers had straws at a small angle, $\pm 3^\circ$ to the beam direction (stereo superlayers), and had 6 layers of straw tubes. All superlayers were divided in half at the $z$ position of the interaction point, $z = 0$, with electronics
located at the ends towards the endcap calorimeters. The superlayers each provided local track segments characterized by an azimuthal angle $\phi$ and a slope in the $r$-$\phi$ plane. The azimuthal offset of segments in the stereo superlayers provided the $z$ measurement. The straw tube tracking system is discussed in much more detail in the rest of this paper.

The intermediate angle tracking detector (ITD) [5] consisted of gas microstrip detectors positioned symmetrically on both sides of the interaction point between the silicon tracker and the endcap calorimeters. Each half of the ITD consisted of 6 superlayers. Each superlayer consisted of a carbon fiber-foam disk supporting axial/stereo pairs of wedge-shaped detector tiles arranged in 4 annuli, with alternating annuli on opposite sides of the support disks. Each pair of superlayers had the same tile structure (number of annuli, number of tiles per annulus, tile size, etc.), but each annulus of the second superlayer was rotated azimuthally by half a tile to avoid overlaps of the dead areas at the sides of the tiles. The strip pitch varied from 200 to 500 $\mu$m, and the stereo angle was 100 mrad.

The performance of the overall SDC tracking system has been studied in great detail by computer simulation [6]. According to this simulation, the baseline tracking system design met the requirements listed here.

3. Straw drift tubes

3.1. Introduction

Small drift cell structures have found many applications in high energy physics. The straw drift tube array is one way to produce such a structure. The cathode is formed from a very thin conductive tube that surrounds the anode wire. These tubes are packed together in a close-packed structure. By using a thin metal coating deposited on a plastic substrate for the tubular cathode structure, the mass of the array can be kept very small. Arrays of these drift cells have been operating successfully in detectors in high energy physics over the course of the last ten years. Although many of the original detectors were small high-precision vertex detectors used in colliding beam experiments, there have been a number of large straw arrays used recently in fixed-target experiments [7].

There are some important advantages of the tube structure over an open cell design with wire cathodes. One is its greater ease of construction and the greater isolation between cells both electrically and mechanically. Also the amount of tension which needs to be supported is reduced by a large factor because it is unnecessary to support cathode wires. These considerations were discussed thoroughly in the 1986 Snowmass report [8].

The time between bunch crossings at the SSC was designed to be 16 ns with an average of 1.6 interactions per bunch crossing at design luminosity. Confusion in each event is minimized if most of the drifting electrons from one bunch
The tracking system. One quadrant is shown, including the silicon, gas microstrip, and straw systems.

The superlayer structure of the straw tracking system. A detail of the modules in a superlayer is shown in a magnified view.

A section through a part of the wall of a 4 mm Kapton straw of the type used in our tests. (A) Outer wrap 13 μm Kapton; (B) Bonding resin; (C) Inner 13 μm Kapton; (D) Copper metallization ~ 0.25 μm.

crossing are collected before the next one occurs. A straw tube with a diameter of 4 mm operating with a gas that has a drift velocity of ~0.1 mm/ns fulfills this requirement to a large extent.

The SDC detector would have significantly expanded the technology that has already been applied to straw drift tube chambers:
- The straw tube diameter had to be reduced from the usual 7–8 mm to 4 mm.
- The wall thickness had to be reduced to minimize material.
- The length of the tubes had to be increased from less than 1 m to 4 m.
- Many more tubes were required than had been used in such a system before.
- Fast gases had to be used instead of the usual argon-based gases or slow gases.
- The tubes would have been exposed to a higher radiation dose over their lifetime than other detectors of this type.
- The tubes would have operated with higher rates and occupancy and higher current per unit length than before.

3.2. Straw design

3.2.1. Straw dimensions for SDC tracking

The diameter of the straw tubes had to be small to reduce the hit rate in the straws and to reduce the drift time. Both requirements dictated a straw tube diameter as small as possible, but there is a lower bound on the straw diameter that comes from the amount of ionization deposited by the track and the difficulty of packing connections to the electronics into a small space.

This lower bound on the straw diameter is set by the distance between ionization electron clusters in the gas and the resolution requirement. At small drift distances, where the track passes close to the central anode wire, there is poor resolution because the charge arriving at the wire is spread out over a length of time close to the maximum drift time. Thus the variance of the time to collect a certain number of electrons is large. At larger track distances the variation in time is smaller for the same amount of collected charge. Diffusion starts to affect the resolution at larger radii but the resolution worsens slowly from this effect as the drift distance increases.

The diameter of the tube was taken to be 4 mm. This somewhat arbitrary round number was smaller than most previous straw tube chambers but gave a short enough drift time (with a fast gas) and sufficiently good resolution. The difficulty of making electronic connections was satisfactorily overcome. (See Section 5.)

The thickness of the straw wall was determined from the practical considerations of working with very thin films. The thinnest standard gauge film that could be wound into a straw was 13 μm. Although a thinner gauge existed it was too fragile to use. The average radiation length of a straw made from two layers of plastic film of this thickness was 0.04%.

The length of the outer tracking system for the SDC detector was planned to be 8 m. There was to be a split in the middle, however, so that the maximum tube length would be 4 m. Tubes of this length were found to be close to the limit of the capability of the tube manufacturers [9]. Nevertheless, thousands of satisfactory tubes were produced, and the machinery existed to generate the full number for the SDC in the space of about two years.
3.2.3. Wire and signal attenuation

We used gold plated tungsten wire for the anode in the straw tubes. Both 25 and 38 μm diameter wire were tried. The resistance of the anode wire and the straw cathode caused a loss of signal pulse amplitude with an attenuation length of about 5–7 m. The attenuation length was measured by direct observation of the amplitude of signals using an $^{55}$Fe source [1]. For the proposed 4 m long straw tracker, using a 25 μm wire, the signal from the end farthest from the electronics was attenuated by a factor of 0.45.

3.2.4. Electrostatic stability and wire supports

The straw tubes were operated at around 2000 V to achieve gas gains that gave suitable signal pulses. The ideal case in which the anode wire is exactly centered within a perfectly cylindrical cathode is electrostatically stable. Practically, however, the anode wire cannot be exactly centered due to positioning error and gravitational sag, and the straw cathode is neither perfectly cylindrical nor perfectly straight. Therefore it was important to determine the conditions under which an operational straw tube detector element would perform satisfactorily. The electrostatic force per unit length $F_c$ due to the offset of the anode wire in the straw tube can be calculated from the formula for the capacitance $C(x)$ between two cylindrical conductors [10] by

$$F_c = \frac{V^2}{2} \frac{\partial C(x)}{\partial x},$$

where $x$ is the distance between the axes of the cylinders and $V$ is the anode wire potential. In MKS units this is very well approximated by

$$F_c \approx \frac{2\pi\varepsilon_0 V^2 \delta x}{R^2(\ln(R/r))^2},$$

for $r, \delta x \ll R$, where $\delta x$ is the offset of the anode wire from the center of the straw tube, $R$ is the radius of the straw tube cathode and $r$ is the radius of the anode wire. We define the linear restoring constant $k$ by

$$k = F_c/\delta x.$$

Solving the second order differential equation for the wire displacement with the symmetric boundary conditions of an offset $\Delta$ on both ends of the straw, we arrive at the equation for the displacement $x$ of the wire at a distance $y$ from the middle of the wire,

$$x = \Delta \frac{\cos \sqrt{k/T^2L^2}}{\cos \sqrt{k/T^2L^2}/2},$$

with $T$ the wire tension and $L$ its length [11]. The calculation of the maximum deflection is shown in Ref. [1] compared to measurements. Both the calculation and the measurements showed that wire supports were required conservatively every 80 cm in order to keep the offsets small and the wires stable.
The wire supports had to center the wire in the straw tube and at the same time not restrict the gas flow through the tube. One design for the wire support consisted of a plastic cylinder 7.7 mm long with a helical groove. The groove was one cylinder radius plus one wire radius deep, had a circular shape at the bottom and made one complete revolution around the cylinder. The anode wire under tension was forced against the bottom of the groove and thus lay along the axis of the cylinder. A schematic drawing of this wire support design, called the “twistor”, is shown in Fig. 5. About 10000 twist wire supports were produced at a cost of $0.60 per piece [12].

Another design, called the “double-V”, is shown in Fig. 6. It was made of two pieces each with a V-shaped slot cut out. The apex of each V was on the center of the straw, but one V was rotated by 180° with respect to the other. The wire was centered because it was forced into the apexes of the V’s by its tension. The pieces were made by injection molding, and about 10000 double-V wire supports were produced at a cost of $0.80 per piece. The self-centering error of each double-V with respect to its ideal position was measured in a matrix of straws which had been glued together while held in a precise clamp. The positions of the vertices of the double-V’s were determined by sighting with an optical comparator having a measuring accuracy of about ±25 μm. We concluded from our measurements that the error at each wire position was less than ±30 μm. This is an upper limit because it includes some sighting error. This error was well within the requirements set for the tracking precision in the SDC. Thus, instead of requiring multiple parameters to specify the location of each wire, it was sufficient to specify the position and orientation of the bundle of straws and the use the same location for a particular straw in any bundle.

3.2.5. Electrical termination of the straw tubes

The long tubes acted as electrical transmission lines for the pulses generated by the passage of charged particles. A termination was designed for the end of the tube opposite to the electronics to absorb the pulse on that end and prevent it from returning to the electronics. Thus the hit rate would not be increased unnecessarily.

The termination also reduced a source of cross talk. The pulse height for pulses generated near the end of the terminated tube was double the value generated over most of the straw, because the pulse traveling away from the electronics reflected off the open end and added to the signal that started out towards the electronics. The extra pulse height caused double cross talk signals, and these were large enough to cross the threshold [1]. A prototype termination was used in some of our test modules. It consisted of a resistor and a capacitor in series connecting the anode wire to the cathode. The resistor was the correct value to terminate the 280 Ω transmission line. The capacitor not only blocked the voltage on the anode wire but also compensated for the lossy nature of the transmission line. The correct value of capacitance to match the reactive component of the characteristic impedance of a lossy transmission line at high frequency is 2/Rc, where R is the resistance per unit length of the line and c is the velocity of light [13]. The required capacitance was 50 to 80 pf.

The actual realization of the termination used a very small surface mount resistor and a capacitor made of a short length of straw tube with metallization on both sides. The resistor-capacitor combination was integrated with the wire support at the far end of the wire to reduce the mass. The resistor was mounted radially on the end of the wire support. A bump of conductive epoxy was placed on the surface of the wire support in a place where it contacted the wire but did not disturb the position of the wire in the tube. The bump was connected to one side of the resistor and the other side of the resistor was connected to the capacitor also with conductive epoxy. The termination made pressure contact from its outside surface to the straw wall. The prototype design is shown in Fig. 7. This design, which was used in the tests described in Ref. [1], was labor intensive to construct and a future design would have used a wire support molded out of a resistive plastic as the resistor.
Fig. 7. The electrical termination of a straw. The wire is centered in the tube on the left-hand side, and electrical contact to the wire is made against a thick coating of conductive epoxy on the right-hand side. The impedance matching resistor is labeled R.

Fig. 8. Gain as a function of anode voltage for 25 and 38 μm wires in a 4 mm diameter straw tube containing 80% CF₄ and 20% isobutane. This gain is the product of the true gain on the wire and the non-attachment probability.

3.3. Operating characteristics of straw tubes

We chose a gas mixture consisting of 80% CF₄ and 20% isobutane for most of our work with straw drift tubes. A considerable amount of experience with this mixture had already been accumulated by other groups so that its properties were quite well known. The properties which most recommended this mixture were its high drift velocity and its usefulness in high radiation rate applications [14].

The gain vs. voltage curve for 80% CF₄ and 20% isobutane is shown in Fig. 8. The exact operating point depends on resolution, efficiency, cross talk tolerance and the allowable value of chamber current. A typical operating point was at a gas gain of about 6 × 10⁴. We have calculated the resolution we expect as a function of distance from the wire in a drift chamber with no magnetic field. This is shown in Fig. 9. Measurements of resolution are shown in Ref. [1]. As indicated in Section 2.2, the straw tracking modules were located at radii ranging from 0.80 to 1.65 m from the beam. We calculated the rate of charged particles hitting each straw at design luminosity using the SDC Monte Carlo simulation [6]. This simulation indicated that rates as high as 4.3 MHz were to be expected at the inner radius of the tracker. The predicted rates are shown in Table 1. At design luminosity for the inner layer of the tracker we estimated that the total current flowing in one straw would be about 3.5 μA, assuming a gas gain of 6 × 10⁴. We thus expected that the total charge accumulated over ten years of running would be about 350 C for a 4 m straw. Our prototype tests indicated that this would not be a problem. A detailed discussion of aging and radiation hardness is given in Section 3.4.

3.3.1. Electron drift characteristics

The straw drift tubes were intended to operate inside the superconducting solenoid of the SDC. The design field was 2.0 T parallel or nearly parallel to the straws. In this configuration the drifting electrons in the cylindrical drift tubes experience a Lorentz force as they move toward the central anode wire. We studied a number of effects that are due to the Lorentz force.

The principal effect is the reduction of the radial drift velocity due to the Lorentz force acting on the drifting electrons. In this case the electron trajectory is a spiral as shown in Fig. 10.

We have calculated the drift time from any point in the straw drift tube to the wire using a CERN based program called MAGBOLTZ [15]. This program is used to calculate
the Lorentz angle and drift velocity as a function of electric field well beyond the values that could be measured in our test cell [1]. It generally reproduces the dependence of the electron drift velocity and Lorentz angle on the electric field in the 80% CF$_4$ and 20% isobutane gas mixture where it can be compared with our measurements; however, the CF$_4$ gas constants are not yet well determined, so there is not perfect agreement.

The radius vs. time function is shown in Fig. 11 for magnetic field values of 0.0 and 2.0 T. This calculation used the measured velocity and Lorentz angles with an extrapolation to high fields aided by MAGBOLTZ. The effect of the magnetic field is to increase the maximum drift time from 18 ns at zero field to 27 ns at 2.0 T.

### 3.4. Aging and radiation damage

The radiation environment in the tracking volume was expected to be severe enough that special care was needed to make sure that the straw drift tubes would be able to survive for the estimated ten year lifetime of the apparatus.

The charged particle flux originating at the interaction point was expected to be the major source of radiation. The rate of charged particle hits in a straw was calculated using a GEANT-PYTHIA simulation designed for the SDC detector [6]. The results are shown in Table 1 and include the effect of multiple passes of low energy particles spiraling in the magnetic field and conversions of gamma rays in the material in the tracking region. The current density caused by radiation from the interaction point is also given in the table. In addition to the charged particle flux there was expected to be a significant flux of neutrons produced in the calorimeters. These neutrons would migrate back into the tracking region and cause current in the straws from knock-on protons and ($n$,γ) conversions followed by Compton scattering. One of the characteristics of the neutron induced signals is that they are often many times minimum ionizing. Energy deposits could in some cases be in the MeV range instead of in the keV range expected from the passage of a charged particle. Thus even though the flux was expected to be relatively small, the amount of current could be important. The estimated contribution of neutron induced ionization current is also shown in Table 1.

The radiation dose expected in the detector is not serious for most materials although some especially sensitive materials would be damaged. The straw material, Kapton, which was chosen for its high temperature capability, was very resistant to radiation damage, with mechanical properties good to $10^3$ Gy. The basic cyanate ester carbon fiber composite material of the shells was also resistant to radiation damage to about the same level of dose. Other materials for the smaller components and the electronics were also

---

**Table 1**

<table>
<thead>
<tr>
<th>Super-layer</th>
<th>Hit rate [MHz]</th>
<th>(Chg. Part.) [nA/cm]</th>
<th>(Neutron) [nA/cm]</th>
<th>(Total) [nA/cm]</th>
<th>Chg. accumulated for ten SSC years [C/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.3</td>
<td>5.8</td>
<td>3.1</td>
<td>8.8</td>
<td>0.88</td>
</tr>
<tr>
<td>2</td>
<td>2.7</td>
<td>3.6</td>
<td>3.1</td>
<td>6.7</td>
<td>0.67</td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
<td>2.5</td>
<td>3.1</td>
<td>5.6</td>
<td>0.56</td>
</tr>
<tr>
<td>4</td>
<td>1.3</td>
<td>1.7</td>
<td>3.1</td>
<td>4.8</td>
<td>0.48</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>1.2</td>
<td>3.1</td>
<td>4.4</td>
<td>0.44</td>
</tr>
</tbody>
</table>
4. Straw outer tracking system design

4.1. Overall design

The proposed outer tracking system consisted of five superlayers of straw tubes, three axial superlayers and two stereo. The modules in the axial superlayer were aligned parallel to the axis of the tracking system and were therefore parallel to the beam. The stereo modules were rotated $\pm 3^\circ$ with respect to the tracking system axis. The superlayers were divided in half at $z = 0$ with the electronics located on the outer ends. The design is shown in Fig. 3. As is indicated in Table 2, five superlayers were placed at approximately equally spaced radial distances. The inner superlayer was placed at 0.80 m radius. This layer consisted of axial modules with each module containing 8 straw layers. The second superlayer was a stereo layer and was located at a radius of 1.107 m. Each of the modules in this stereo layer was rotated $+3^\circ$ with respect to the axis of the tracker. The stereo modules had 6 straw layers each. The third and fifth superlayers were axial layers located at 1.345 and 1.618 m, respectively. The fourth layer was a stereo layer making an angle of $-3.0^\circ$. The innermost axial layer was placed at a radius close to half the maximum tracking radius, where the occupancy is still small enough to allow good segment finding efficiency. Momentum measurement was accomplished by using both the inner silicon and the outer straw tracking systems in an integrated manner.

The three axial superlayers were needed for a high $p_T$ track segment trigger. Within the axial modules the eight layers of straws were arranged on concentric cylindrical surfaces. The modules were alternately staggered in radial position by two straw diameters to allow close packing of the modules with full coverage for high momentum tracks. This is shown in Fig. 12. In the stereo modules the six layers of straws were close-packed in a trapezoidal arrangement. The stereo modules were also staggered radially to get full coverage. With the stereo modules individually rotated about their centerpoints by $\pm 3^\circ$, (2.9$^\circ$ for the staggered layer), the resulting module to module separation at the ends was compensated by the radial stagger to get full coverage for most tracks.

Each superlayer of modules was supported by a carbon fiber foam composite cylinder. The cylinder was 6.3 mm in thickness. High modulus carbon fibers gave the cylinders the needed stiffness over the 8 m span, and the foam sandwich supplied the local strength against deformations.

The modules were attached to the cylinders by pinning the support feet into hoops, called shim rings, that circled each support cylinder at 80 cm intervals along its length. This allowed the modules to be individually inserted and removed from the cylinders from each end of the detector. The support cylinders were attached to the end support frame by a ring shaped flange fabricated from carbon composites. The end support frame, called the space frame, was a web work of carbon composite tubes that held the support flanges and cylinders in rigid alignment, attached to the external tracker supports, and, in addition, supported the inner silicon tracking system. In the radial direction there was 0.75% of a radiation length of material for each stereo superlayer (including the support cylinder), and 0.83% for the axial superlayers. There were a total of 744 modules and 141,404 straws.

4.2. Modules

The module concept evolved as a method of assembling several hundred thousand drift cells into a tracking system. This necessitated mass production techniques, quality control, and repairability, as well as low cost. In the module concept the straws are grouped into six or eight layer pack-
ages with a strong outer cover. The basic module design is shown in Fig. 13. This manner of construction allows the modules to be mass-produced and tested before they become part of the superlayer system.

There were two critical aspects of the module design: the outer shell and the endplate. The outer shell held the straws rigidly in a close-packed position, maintained the alignment along the length of the module, and took the compressional load of the wire tension, which was about 12 kg force. Since the straws had an internal support every 80 cm, they could be forced into a rigid close-packed array at these points and bonded before insertion into the shell. The unsupported 4 m external shell did not have to be straight to a high degree of precision over its entire length since there was a free span over only the 80 cm between the module mounting points. We required, however, that the shell hold the straw concentric to the wire over this 80 cm span within 50 μm; that is, the trapezoidal cross section of the shell had to be accurately maintained between the 80 cm support points. The endplate structure and the bonded straw bundle determined this shape at the support points. The endplate served as the hold-down point for the wires. It also served as the gas manifold for flowing gas through the straws and the interface for the high voltage and electronics. An independent alignment method was used to attach the modules to the cylindrical support structure and provide the overall straightness with a minimum of force.

Four full-length modules were constructed for a beam test at Brookhaven National Laboratory in July, 1993. The results of the beam test are discussed in Ref. [11]. After the beam test three more pre-production modules were constructed.

4.2.1. Carbon fiber shell

The straw tubes were not naturally straight. They had an average bowing of 2–4 cm over a 4 m length. They also had a very weak bowing resistance and could not support the wire tension by themselves, even if glued in large arrays. Therefore, the straws needed to be held straight and formed into regular arrays. Also the wire tension had to be transferred to some external support structure. The external carbon fiber shell satisfied these requirements.

A design of the carbon fiber epoxy and foam laminate straw module shell is shown in Fig. 13. During the design work it was found that the major loads on the shell were the thermal loads that develop as it cools back to room temperature from the maximum curing temperature. The induced compressive stresses in the thin laminates caused warping and waviness of the shells. Such warping and waviness was unacceptable in the module; consequently a design was found which involved laying up the thin laminates on a rigid closed cell foam. This enormously increased the flexural modulus and buckling strength of the laminate while imposing very little material penalty on the module. The design utilized a light weight foam [16] in the lid and base structure to increase the transverse strength and eliminate any buckling. The side walls contained about 1 mm of a denser foam [17]. This was included for both buckling strength and for additional strength against straw pressure from the inside.

The shells were fabricated by a company with extensive experience in carbon fiber composite manufacture [18]. Each side of a foam panel was covered with a 100 μm thick carbon fiber prepreg material that was specially woven for our purposes. This material had different properties in the two dimensions. The carbon fiber designed to go in the direction of the long module axis had a modulus of 410 GPa [19], while in the transverse direction it had a modulus of 138 GPa [20]. The lower transverse strength was designed to reduce the insertion stresses on the module mounting fixtures when the modules were inserted into the support frame. The resin used to impregnate the material was a cyanate ester resin [21] with a curing temperature of 250° C.

The lid and base of the shell were formed separately using matched graphite molds [22] which were machined to strictness and flatness tolerances of ±25 μm. The axial module shells were formed to hold the straws on cylindrical surfaces. The base section of the module shell and the lid were cylindrically shaped on their inside surfaces to match the radius of curvature of the individual superlayer. Close packing of the straws on the inner radius established the correct spacing. The outside surfaces of the module shells were flat. These features of the axial module can be seen in Fig. 14. The resulting module shell had an average thickness of 0.36% of a radiation length. Thus for an eight layer module the straws and the shell contributed equal amounts to the total thickness of a module.

4.2.2. Endplate and connections

The module shells were terminated at the ends by bulkheads that closed the gas volume, held the wires, and provided electrical and gas supply connections. To minimize the material in the detector we made these plates of glass–epoxy laminate plated with copper to provide electrostatic closure. In several of the full-scale prototypes, however, the endplates were built of aluminum, due to schedule constraints. A drawing of a typical endplate is shown in Fig. 15.

The readout end of each straw cathode was terminated by a copper plated ABS plastic extension piece, bonded to the
Fig. 15. Diagram of the endplate showing the attachment points and the holes in the ABS plastic feedthroughs that hold each wire.

Fig. 16. Detail of the ABS plastic feedthrough, the taper pin, the cathode connection, and the final wire support.

inside of the straw by conducting epoxy. The extension piece was secured by a light press fit into the readout endplate to assure a common ground for all cathodes in the module. A section view of the endplate assembly is shown in Fig. 16. A pair of 1 mm diameter holes in the cathode extensions (not shown) allowed gas to flow into the straw. The cathode extensions were omitted from the straws around the periphery as they interfered with the sealing lip of the endplate. Instead, conducting epoxy applied around the margin of the module end provided the ground for these cathodes.

Stepped holes in the outside surface of the endplate accommodated ABS plastic feedthroughs. During assembly the wires were pulled through the module before the feedthrough was threaded over the wire. The feedthrough was then lightly painted with sealant and inserted into the endplate. Finally a gold-plated brass taper pin was pressed into the feedthrough to secure the wire. This taper pin contained a press-fit spring-loaded contact to provide connections to pads on the removable printed circuit boards which supplied high voltage to the anodes and signal amplifiers. Note that the precise wire placement depended only on the wire supports inside the cathodes, not on the feedthrough location. A long term test was performed to demonstrate that the brass/plastic junction formed by the taper pins in the plastic feedthroughs would be sufficient to secure the wire without slippage. This test was accomplished by securing several wires into feedthroughs using the taper pins. Weights were hung from the wires and, after one month, the positions of the wires with respect to the feedthroughs were rechecked using a micrometer. No measurable slippage was observed.

The end of the module away from the readout had an identical endplate. Differences in the assembly were the omission of the cathode extensions and of the spring contacts in the taper pins.

Two ports penetrated the longest side of the endplate on the readout end to provide the gas supply and return. The readout endplate contained a septum to divide the gas volume into two sections. With a free-flow volume at the far end, the straws thus formed a U-path for gas so that the supply and return were at the same end. This feature was included in some of the prototypes and successfully tested.

Flanges extended along the longer sides of the endplates into the space available between superlayers and were drilled to accommodate mechanical connections for the readout boards.

5. Electronics

5.1. Overview of electronics and system requirements

The success of the straw based tracking system for the SDC detector was expected to depend on the performance of the electronic systems as much as the particle detection systems. Consequently, an extensive program was carried out to plan and develop the various parts of the electronics to incorporate the most recent industrial advances available to us. It was possible to design printed circuit boards and custom integrated circuits which allowed dense, reliable connections together with low noise, high gain amplifiers. The details of these developments are described in the following sections. Various measurements of chamber performance obtained using these circuits are given in Ref. [1].

The straw electronics can be divided into various logical or physical blocks. The logical blocks, arising from the basic design requirements, are:

- High voltage connection and distribution system – the means of applying high voltage to the detector elements and providing the interface between the anode and cathode and the active electronics section.
- Preamplification, shaping, and tail cancellation – the initial analog processing steps serving to maximize the signal-to-noise ratio ($S/N$) and minimize the double-pulse resolution time.
- Discrimination – the generation of a digital pulse with leading edge synchronized to the rise of the analog signal.
- Time measurement – the digitization of the time of occurrence of the leading edge of the discriminator output pulse.
- Level 1 storage – the temporary storage of data during the Level 1 trigger processing time (about 4 $\mu$s).
- Level 2 storage – the temporary storage of data satisfying the Level 1 trigger during the Level 2 processing time (from 10 to 50 or more $\mu$s).
- Trigger generation – local generation of track segments for use in the Level 1 Trigger system and the drivers to send the information there.
Trigger interface – receivers and buffers to distribute the minimum set of signals from the trigger system; e.g., clock, Level 1 accept, Level 2 accept, and Level 2 strobe.
- Data readout – buffers, drivers, and interfaces to the data acquisition system (DAQ).

The design consisted of two major physical blocks connected with high performance cables:
- The assembly located on the end of each straw tracking module that provided high voltage distribution and amplification, shaping and discrimination for the straw signals.
- The regional crates located on the outside of the tracking volume that housed the time measurement and trigger generation electronics as well as the interfaces to the DAQ and trigger systems.

In what follows the basic ideas of the front-end analog signal processing are discussed, and then the high voltage distribution, the amplifier-shaper-discriminator (ASD), the time memory cell (TMC), and the tracking trigger electronics are described.

5.2. Front-end electronics and analog signal processing

For a high precision straw tracking system, it is necessary to measure accurately the time of arrival of the first cluster of electrons at the anode. It is also desirable to operate with as low a gas gain as possible to minimize the amount of current flowing in the drift tubes. Taken together this implies the use of a low-noise preamplifier with risetime sufficiently fast to provide the desired time resolution, but sufficiently slow to provide an acceptable signal-to-noise ratio. In addition, because of the high pulse rate, excellent double-pulse resolution is very important.

The straw tracker offered the benefit of high-resolution high-rate tracking with low mass and low channel count, but in order to realize this benefit a significant effort was required to develop sufficiently good signal processing electronics. Table 3 summarizes the principal requirements for the front-end electronics.

Electrons liberated by the passage of a charged particle through a straw tube drift to the anode wire where their number is multiplied in an avalanche process. The current induced on the anode by the avalanche process is due mostly to the motion of positive ions produced along with the electrons. As these ions travel from the wire to the cathode they induce a signal current whose decay is proportional to $1/(t + t_0)$, where $t_0$ is a characteristic time proportional to the ratio between the wire radius and the ion drift velocity [23]. For the SDC straws, this signal lasts about 25 µs, much longer than the time between beam crossings.

A common procedure in high rate systems has been to shorten this slowly decreasing detector tail using hand tuned discrete component cancellation circuits. In this method a minimum measurement time is selected, usually based on the amount of signal that must be accumulated to make a reliable measurement. Only the earliest charge arriving on the anode contains useful timing information for position measurement and the rest can be cancelled. The double-pulse resolution is then at least twice this measurement time. We have implemented a variant of this method adapted to integrated electronics. For good efficiency together with good double-pulse separation, we have adopted the specific goal of having the return to baseline for a single cluster be less than 15 ns.

5.3. High voltage distribution

The straw tubes are close packed in the tracking system to generate as much information as possible from a limited amount of space and to hold the straws in alignment. Thus the cathodes are tightly coupled electrically and almost all of the charge stored in each module, which is about 15 µC at a nominal 2000 V operating voltage, is available to each wire. It was decided that a front-end amplifier should be coupled to each anode through a capacitor, which would have to store only about 0.1 to 0.2 µC, so that an amplifier input would be subject to less stress if a high voltage breakdown occurred in a straw.

In this situation it was then more convenient to apply the voltage to the wires and keep the tube walls at ground potential, as shown in Fig. 17, rather than the reverse. The coupling capacitors had to withstand the 2 kV operating potential for the ten-year life of the detector with a capacitance large enough to pass most of the signal of interest. Practical values ranged from 80 to 150 pF, and custom surface-mount high voltage ceramic capacitors small enough to mount comfortably on 4 mm centers were obtained [24]. The high voltage feed resistors were less critical, and we determined that two standard 1/4 W, surface mount resistors of size 3.2 mm × 1.6 mm in series would withstand a temporary 2 kV overload as in the case of a discharge across a straw. Custom 2 kV, 2 MΩ surface mount resistors [25] were also available. They were smaller than a pair of standard devices and represented somewhat less mass.

Two styles of high voltage distribution were used for the prototype modules built for the test run at Brookhaven National Laboratory. First was a “Folded” design with high voltage elements assembled separately from the ASD electronics (Fig. 18). The capacitors were arranged in a cord-
Table 3
Principal requirements of the straw electronics

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution</td>
<td>&lt;0.5 ns</td>
</tr>
<tr>
<td>Maximum rate</td>
<td>~5 MHz</td>
</tr>
<tr>
<td>Double pulse resolution</td>
<td>&lt;2 crossings</td>
</tr>
<tr>
<td>Level 1 storage</td>
<td>4 μs</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>&gt;1 Mrad, &gt;10^{14} n/cm²</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;30 mW/wire</td>
</tr>
<tr>
<td>Volume</td>
<td>&lt;1 cm³</td>
</tr>
<tr>
<td>Material</td>
<td>&lt;0.3 X₀ per superlayer</td>
</tr>
</tbody>
</table>

Set mainly by position resolution of <150 μm
Set by luminosity and length of inner layer
Average drift time plus pulse width at base
Time for trigger decision
To allow >10 yr of operation
Minimum with available technology

Fig. 18. The endplate/connector assembly used for cross talk tests. This is a prototype of the “folded” design described in Section 5.3: the vertical PC boards are of flexible Kapton and would be bent 90° above and below as installed in SDC.

wood array between a high voltage feed board and the ASD board. Second was an “Aztec” design (Fig. 19) with the high voltage components on the same board as the active electronics. Both systems worked well in beam and bench tests and further work would have been required to select the most robust and least expensive scheme. In both cases the packing density was much higher than in most previous systems. For instance, in the case of the Aztec design we mounted on a 0.7 mm thick printed circuit board less than 7 cm × 10 cm in size:
- 64 high voltage feed resistors,
- 64 signal capacitors (4 kV, 100 pF),
- 8 ASD chips mounted in commercial packages (individually testable prior to assembly),
- input connectors and high voltage filtering,
- threshold distribution and filtering,
- DC power distribution and filtering,
- output connectors for ribbon cables carrying 64 differential output signals plus power and threshold inputs.

5.4. Amplifier-shaper-discriminator

Building on signal processing concepts and experience of the late sixties and early seventies [26], we designed an amplifier-shaper-discriminator circuit adapted to modern semiconductor manufacturing capabilities. A prototype version with one channel of amplification, shaping and discrimination has already been described in the literature [27]. The chip used for our tests combined eight similar channels plus tail cancellation [28] on the same die. This chip, the ASD-8, was fabricated in an advanced analog bipolar process, SHP, offered by Tektronix Microelectronics [29]. A summary of the performance specifications of the ASD-8 is given in Table 4. A detailed statement of the design goals for the circuit, a description of the circuit itself and results of measurements on the circuit can be found in reference [30].

To minimize the risk of pickup and oscillation, each channel had dual inputs and programmable-current differential outputs. Thresholds could be programmed individually, and this feature could be used to disable a noisy channel. The ASD-8 was compared with commercial electronics and was shown to achieve the same good resolution at a wire potential 200 V lower than that required by the commercial system. The performance at high rate is described in Ref. [31].
Tracks were reconstructed with good efficiency in a full size straw module using this ASD in an environment with up to 7.5 MHz of background signals.

While the original design goals for the ASD have been met, two areas for improvement have been identified. One is the need for baseline restoration to compensate for the threshold shift at high rates caused by the recharge current into the high voltage coupling capacitor. A second area has to do with the processing of very large input signals. A small number of neutrons and high energy gammas will convert within the straw, depositing signals on the order of a thousand times larger than those left by minimum ionizing particles. These large pulses can overwhelm the linear tail cancellation network, allowing a large portion of the long detector tail signal to pass to the discriminator. This results in a long pulse on the output, followed by several microseconds where the state of the output is uncertain.

Both of these problems have been addressed in a subsequent design in which the DC path between the shaper and the discriminator is broken by a capacitively coupled baseline restorer circuit. SPICE calculations [32] show that this improved circuit will have a negligible DC threshold shift as a function of rate up to 20 MHz. It also will fully recover after a 1 pC input so that it can trigger efficiently on a 2 pC signal after less than 150 ns.

5.5. Drift time measurement

The time digitizing device for the straw tube system was required to be low-power, high-resolution, high-density, and deadtimeless. A time memory cell (TMC) VLSI circuit was developed [33] as a key element to realize these requirements. This custom VLSI was planned to be used in both the SDC straw and muon systems, which have about 140,000 and 90,000 channels, respectively. The TMC recorded the state of the input digital signals every 1 ns and stored the data inside the memories serially first along a row of cells and then along the next row, etc. From this data the time of the transition of the input signal was found by first coding its position in the row, and then combining the result with the row address. The row length is compatible with the input pulse width. The basic architecture of the TMC is shown in Fig. 20.

The first generation TMC chips (TMC1004) were developed in a full-custom integrated circuit layout in collaboration with NTT LSI laboratories using 0.8 μm CMOS technology. This chip demonstrated good timing resolution (0.52 ns rms), high density (4 channels/chip), and low-power consumption (7 mW/channel for 100 kHz trigger rates). This performance met almost all of the requirements of the straw system, although the buffer depth was 1 μs instead of 4 μs, which was the final requirement for the first level trigger latency.

A 32-channel CAMAC module having 8 TMC1004 chips was developed [34] for use with prototype modules. As a next step, a 64 channel 9U VME module was also developed [35]. The VME module had additional FIFOs at the output of the TMC and had a buffer depth of 64 μs.

In the original baseline design, we planned to locate the time digitizing system in a "Microcrate" [36] near the straw detector where the components had to survive a dose of more than 10 kGy to guarantee operation for 100 years under the nominal SSC luminosity. In view of this for the next generation TMC design we changed to the Toshiba 1 μm CMOS Sea-of-Gates gate array, which is radiation-hard up to 10 kGy [37], and increased the buffer length from 1 to 4 μs [38].

At a later stage of the detector design, however, for ease of access and cooling and greater reliability, it was decided to
transfer the discriminated signals out of the tracking volume to an accessible area on the back side of the calorimeter. In order to realize this configuration, a thin twisted-pair cable and a thin flat-cable were developed [39].

Although the time digitizer was located outside of the calorimeter in the final design, the use of the gate array still gave us the advantages of shorter turn-around-time and lower cost compared with the full-custom process.

The development work on the TMC chip continued after the module tests were completed. As a result an upgraded chip was produced using the 0.5 μm Sea-of-Gates technology [40]. It achieved a time resolution of 0.25 ns.

5.6. Triggering electronics

The goal of the trigger electronics was first to identify track segments, called primitives, in each superlayer with good efficiency for tracks with high-$p_T$ while rejecting hits due to noise and tracks with lower $p_T$. The second step involved the association or linking of the identified segments into high-$p_T$ tracks originating from the beam collision point resulting in a further rejection of hits generated by softer tracks. The identification and linking of primitives was required to be beam-crossing specific. A development of custom integrated circuits incorporating digital mean timers [41] (DMT) that could be mounted close to the front-end electronics was proposed to accomplish these goals.

Fig. 21 shows how the trigger chips were to be connected. Tracks with high-$p_T$ are straight and nearly radial. They leave a series of highly correlated arrival times in radial columns of tubes within a single superlayer. Any set of two adjacent columns offset from each other by one tube radius is referred to as a trigger unit. The trigger circuitry examines the signal times in adjacent pairs of tubes, requiring that these times be consistent with what is expected from good high-$p_T$ tracks. In practice, only a fraction of the eight possible tubes in a trigger unit traversed by a high-$p_T$ track contain hits. This is due to tube inefficiencies and shadowing from prior hits. Of the surviving hits from high-$p_T$ tracks, a large fraction fall within a single trigger unit, whereas for soft tracks the surviving hits tend to distribute over neighboring trigger units. It is this difference that is exploited by the trigger circuitry. The DMT imposes a set of coincidence requirements on the tube-pair signals that are only satisfied by nearly radial tracks. The circuit simultaneously determines the particle passage time to identify from which beam crossing it came. Fig. 22 shows how the DMT circuit is used with a single pair of tubes. For an eight layer straw superlayer, up to seven DMT coincidence pairs could respond. In order to sustain good trigger efficiency into high luminosity (occupancy) environments, the trigger circuits require the count of responses to exceed a minimum number. The minimum count for good efficiency was found to be two or three of the seven possible pairs.

Segments are linked into tracks by imposing a coincidence requirement between trigger units that are nearly radially aligned in different superlayers. For a 10–15 GeV/c threshold, trigger units in the middle trigger superlayer must be associated within a span of four units on each side of a straight line drawn between the two outer superlayers as illustrated in Fig. 23. A combinatorial logic chip was assumed for this function but no chip fabrication was performed. The three axial superlayers permit three such coincidences. A two-out-of-three requirement was envisioned.

A procedure was devised to provide a fourth trigger superlayer by combining trigger signals from the two stereo superlayers. The stereo superlayers can be instrumented with the same trigger circuits as used in the axial superlayers with
the limitation that only five adjacent tube pairs are available in the six layer superlayers. The essential difference between the stereo superlayer trigger primitives and the axial primitives is the mild coupling that exists between the $z$ position of the track and the axial location of the resulting primitive. The coupling in one stereo superlayer is of opposite sign to the coupling in the other. This difference can be exploited to form a "pseudo" axial superlayer at the mean radius between the stereo superlayers. The logic required to form one "pseudo" trigger unit is a simple OR of the AND of all stereo trigger units symmetrically disposed in $\phi$ on each side of the mean position of the "pseudo" trigger unit. With this additional axial superlayer a 3-out-of-4 coincidence is possible. Rejection of spurious high-$p_T$ tracks is enhanced with this additional superlayer.

Monte Carlo studies were performed to assess the usefulness of the various options for the trigger. Comparison was made of the effectiveness of requiring two out of seven with respect to three out of seven tube-pair DMTs. Also a comparison was done between the requirements that two out of three and three out of four superlayers (including the additional "pseudo" superlayer) have a successful segment linkage. Acceptable performance was indicated for the range of options described for $p_T > 15 \text{ GeV}/c$. On the basis of these results, track sensing efficiencies above 95$\%$ were anticipated with satisfactory background rejection for luminosities up to ten times the design luminosity.

Prototypes of chips using the DMTs were fabricated for the purpose of testing both the efficiency and timing properties of the scheme. Each prototype chip contained three DMT circuits (Fig. 24) capable of responding to triplet and quartet hit patterns as well as the tube-pair hit patterns referred to above. A two-stage device is required for triplet or quartet hit patterns. The first stage forms the coincidence between signals from radially projective pairs of wires while averaging their times. A $\Delta t$ restriction between the times is also imposed that eliminates tracks beyond a maximum angle relative to the superlayer normal. The second stage provides the coincidence requirement for the signals from the half-cell staggered columns and averages their output times as required to obtain a precise beam crossing time.

Fig. 25. Arrival times in ns for signals from straw tubes to the front end electronics of sublayer 5. The width of the distribution includes the effect of varying signal propagation time over the length of a tube. This effect is expected to dominate the width and is largest for superlayers 3–5 which subtend the largest $z$-interval.

Used in the tube-pair mode the first stages are not required. To negate their effect the ASD outputs from each member of the half-cell staggered pairs are directed to both inputs of the first stage DMTs. The first stage outputs enter the second stage where the coincidence and time averaging functions are performed as well as the $\Delta t$ restriction on the maximum angle of the track.

It is important to note the various contributions to the time dispersion from these tube-pair patterns. The largest contribution to the variation comes not from the track $\phi$ angle through the superlayer but from differences in particle and signal flight times for tracks passing through the central region of the detector compared with those passing through the extreme ends of the detector. This difference is $\sim 6$ ns in the proposed SDC tracker. The second largest variation is due to the track deviation from a radial trajectory. This is $\sim 3$ ns for $10 \text{ GeV}/c$ tracks. A third variation results from time-walk with amplitude which is on the order of $1.3$ ns in the proposed tracker. Fig. 25 shows the simulated output times in superlayer 5 of trigger signals for high-$p_T$ tracks. A 12 ns gate accepts all tracks of interest and uniquely identifies the beam crossing that gives rise to the track.

6. Summary and conclusions

We have designed a straw drift tube tracking system for the Solenoidal Detector Collaboration (SDC) detector for the SSC. We have developed 4-m-long straw modules with
carbon fiber epoxy and foam laminate shells to position and align the straws and take the compressional load of the wire tension.

We have designed front-end, time-digitizing and trigger electronics for the straw modules. Further design and prototype efforts were begun to develop the fast baseline restoration and very high dynamic range required for high-rate operation.

Acknowledgements

We are also pleased to acknowledge the support of the following agencies: Department of Energy, USA, Texas National Research Laboratory Commission, Superconducting Super Collider Laboratory, Program for Japanese-United States Cooperation in the Field of High Energy Physics, sponsored by the Ministry of Education, Science and Culture, Japan and the Department of Energy, USA, National Laboratory for High Energy Physics (KEK), Japan.

References

[2] Solenoidal Detector Collaboration, SDC-92-0201, SSCL-SR-1215, Revision 1, April 01, 1992;
Outer Tracking Group of SDC, SDC-91-00125, IUHEP-91-10, Revision 1, January 21, 1992;
S. Bhaduri et al., Nucl. Instr. and Meth. A 268 (1988) 92;
M. Frautschy et al., Nucl. Instr. and Meth. A 307 (1991) 52; and
N.M. Hamann et al., Nucl. Instr. and Meth. A 346 (1994) 57.
[9] Stone Industrial Division, College Park MD, USA; Lamina Dielectrics Ltd., Billingshurst, W. Sussex, UK.
[12] The spiral wire supports were fabricated by A.F. Leis of Columbus, OH.
[16] Rohacel 31-IG from Rohm GmbH.
[17] Rohacel 51-IG from Rohm GmbH.
[18] Composites Horizons, Inc., Covina CA.
[19] M40 carbon fiber from Toray Ltd.
[20] T300 carbon fiber from Toray Ltd.
[21] Resin number 954-3 from Fiberte Corp., Winona MN.
[22] Coast Composites, Inc., Irvine CA.
[25] Victoreen, Inc., Cleveland OH.