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REPORT OF THE CENTRAL TRACKING GROUP*

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I. Summary

The Central Tracking Group addressed the issues involved in building a realistic central tracking system for a general-purpose 4π detector for the SSC. We assumed that such a central tracking system must be capable of running at the full design luminosity of 10^{33} cm^{-2}s^{-1}. We also assumed that momentum measurement was required in a general-purpose 4π detector.

Limitations on charged particle tracking detectors at the SSC imposed by rates and radiation damage are reviewed. Cell occupancy is the dominant constraint, which led us to the conclusion that only small cells, either wires or straw tubes, are suitable for a central tracking system at the SSC. Mechanical problems involved in building a central tracking system of either wires or straw tubes were studied, and our conclusion was that it is possible to build such a large central tracking system. Of course, a great deal of research and development is required. We also considered central tracking systems made of scintillating fibers or silicon microstrips, but our conclusion was that neither is a realistic candidate given the current state of technology.

We began to work on computer simulation of a realistic central tracking system. Events from interesting physics processes at the SSC will be complex and will be further complicated by hits from out-of-time bunch crossings and multiple interactions within the same bunch crossing. Detailed computer simulations are needed to demonstrate that the pattern recognition and tracking problems can be solved. Because of the time limitations of this Summer Study, we were barely able to begin this work, although some of us are planning to continue with the effort.

Our general impression of central tracking at the SSC is optimistic, but it is clear that a great deal of work needs to be done.

II. Introduction

A. Physics Motivation

Interest in the SSC is based on the expectation that it will lead to new discoveries — Higgs particles, heavy W's or Z's, new heavy fermions, supersymmetric particles, or composite particles. In order to fully investigate the physics opportunities in this regime, a general-purpose detector which includes a central tracking system is needed. The central tracking system would perform the following functions:

1. Trajectories of charged particles would be measured and linked to tracks in a microvertex detector where long-lived particles can be detected. Long-lived known particles can be used to tag decays of new particles, and the lifetimes of new particles can be measured.
2. Charged particle tracking is useful for separating multiple interactions within the same bunch crossing.
3. It is necessary to follow tracks from the central tracking system into calorimeters or muon detectors in order to determine, for example, whether these tracks came from the interaction under study or from decays of long-lived particles.
4. Charged particle tracking is required to separate electrons detected in an electromagnetic calorimeter from photons and π^0's.
5. Charged particle multiplicity measurements can be useful in studying new physics.
6. Charged particles can be used to help determine jet directions.
7. Charged particle trajectories are useful in identifying unusual event topologies.
8. For measurement of total energy, it is essential to know whether there are charged particles which go through calorimeter cracks.
9. For many types of physics analyses it is useful or necessary to measure the momentum of a charged particle.
10. Reconstruction of the invariant mass of a group of charged particles may be required.
11. Matching of charged particle momentum measurement with energy measurement in a calorimeter improves electron identification.
12. Determination of the electric charge of a particle is needed for charge asymmetry measurements and is useful in determining the quark content of a parent particle. Charge determination is useful in reducing and understanding combinatoric backgrounds and in studying multileptonic events.
13. Charged particle tracks may be useful in the trigger.

The Central Tracking Group has concentrated on a central tracking system in a magnetic field because we thought that a general-purpose 4π detector would require momentum measurement. This view was shared by the Detector Cost Model Advisory Panel,[1] among others. They suggested two versions of a 4π all-purpose magnetic detector – Model A and Model B. Central tracking was essentially the same in both versions. Our goal for this Summer Study was to try to design a realistic central tracking system for the SSC. By "realistic", we mean that we have also tried to address mechanical problems so that the resulting central tracking system could actually be built. We have also begun the effort to determine whether we will be able to solve the pattern recognition problems and find tracks in such a chamber.

We have chosen to work with a solenoidal magnetic field. This choice is conventional in e^+e^- storage ring experiments. In hadron colliders, it is not obvious that a solenoidal field is better than a dipole field since it is more difficult to achieve acceptance at large rapidity in a solenoidal field. On the other hand, it is very difficult to achieve azimuthal symmetry in a

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central tracking system in a dipole field. Given the time constraints of a summer design study, with the design of a realistic central tracking system as the primary goal, the more conventional solenoid choice was more appropriate. No doubt, some groups that try to organize an actual proposal for an SSC experiment will study designs using dipole fields more carefully in order to emphasize acceptance at large rapidity.

B. SSC Accelerator Parameters

The performance of tracking devices at the SSC is critically dependent on the accelerator parameters because of the high interaction rate and small bunch separation. The design luminosity, $\mathcal{L}$, of the SSC is 10^{33} cm^{-2}s^{-1} with an energy of 40 TeV in the center of mass.[2] We have assumed that the central tracking system in a general-purpose 4π detector must be capable of operating at the full design luminosity in order to study the highest accessible mass scales. The bunch separation is 4.8 m, so the time between bunches, t_B, is 16 ns. Since this is much shorter than reasonable detector resolving times, this implies that any detector must be capable of handling multiple bunch crossings in any event.

C. Total Cross Sections and Multiplicities

The inelastic cross section, σ, at 40 TeV is expected to be about 100 mb, which gives 10^8 interactions per second at the design luminosity. With bunch crossings occurring every 16 ns, the average number of interactions per bunch crossing, n_I, is 1.6 at the design luminosity. The number of interactions per bunch crossing has improved since the Reference Design of 1984 where the bunch spacing was 10 m, resulting in an average of 3.3 interactions per crossing. We now have more help from the time between bunches to separate multiple interactions within the resolving time of the detector.

For relativistic particles, the rapidity variable is given by

$$y \approx -ln\ (tan\ \theta/2), \tag{1}$$

where θ is the angle relative to the beam direction. For minimum-bias events, particle production is expected to be uniform in rapidity, and the average number of charged particles per unit of rapidity, n_c, is expected to be six. The central tracking system that we have studied covers a rapidity range $|y| \leq 1.5$, so there will be only about 18 particles from a minimum-bias event in the detector. However, the high interaction rate with multiple events within the resolving time of the detector results in a much higher effective multiplicity.

III. Requirements for an SSC Central Tracking System

In addition to the requirements imposed on a central tracking system by any specific physics goal, there are severe constraints imposed by the event rates expected at the SSC and the nature of the specific device chosen. We have chosen to investigate these constraints for a central tracking system consisting of a vertex detector surrounded by a large drift chamber. In this chapter we discuss how these constraints led us to a specific design. In Chapter IV we discuss some details of the design of a "realistic" drift chamber system, and in Chapter V we present our current thoughts on the pattern recognition problem. Some alternatives to a drift chamber are mentioned in Chapter VI. Many of the considerations in this chapter can be easily translated to these and other devices.

A. Rates and Radiation Damage

Radiation damage and rate limitations impose severe constraints on charged particle tracking detectors at the SSC, as described in several references.[3] We will summarize these calculations here since they are necessary considerations for the design of a central tracking system.

A central tracking system for the SSC is assumed to be made up of wires running (nearly) parallel to the beam line. The width, w, of the cell is assumed to be equal to the height, h, and the drift distance, d, is half the cell width. The ionization rate, α, in the gas is assumed to be 100 electrons/cm. The gas gain, G, is assumed to be 2×10^4.

Since particles are produced uniformly in rapidity for minimum-bias events, the flux of particles per unit length (ℓ) of wire in a cell at radius r is given by

$$\frac{d^2n}{d\ell\ dt} = \frac{n_c\, w\, \sigma\, \mathcal{L} \sin\theta}{2\,\pi\, r^2}. \tag{2}$$

The ionization produced by a charged particle at angle θ is $h\alpha/\sin\theta$, so the ionization per unit length of wire is independent of θ. Thus the current draw per wire, I, for a layer of wires of length L at radius r is given by

$$I = \frac{n_c\, w\, h\, \sigma\, \mathcal{L}\, G\, e\, \alpha\, L}{2\,\pi\, r^2}, \tag{3}$$

where e is the electron charge. A layer of 4 mm wide cells at a radius of 25 cm covering $|y| < 1.5$ (L = 106 cm) will draw 0.83 μA/wire, which is just below the limit of acceptable current draw before breakdown will occur.

Wire chamber lifetimes are measured in deposited charge per unit length of wire before a decrease in gain occurs. The decrease in gain is due to the buildup of material on the wires. For the above example of a 4 mm cell at 25 cm radius covering $|y| < 1.5$, the collected charge in one year (10^7 s) would be 0.078 C/cm. Chamber lifetimes of 1.0 C/cm have been measured under very clean laboratory conditions.[4] For the purposes of a realistic experiment, it is probably best to assume a chamber lifetime about an order of magnitude below this. Cells of 4 mm width at a radius of 50 cm would collect four times less charge than at 25 cm radius for the same rapidity coverage and would collect only 0.098 C/cm in five years, which should be safe.

Changes in gain for wire chambers have been observed at the level of 10^4 particles/mm-s at a gas gain of $\sim 4 \times 10^5$ due to space charge buildup.[5] The particle flux is given by Eq. 2. For the above example of 4 mm wide cells at a radius of 25 cm, the flux would be 6×10^3 particles/mm-s at $\theta = 90°$ where the flux is maximum. Since the gas gain is much smaller in our design, space charge should not be important.

The hit rate per wire, R, for SSC central tracking chambers is quite large and is given by

$$R = \frac{n_c\, y_{max}\, \sigma\, \mathcal{L}\, w}{\pi\, r} \tag{4}$$

for chambers covering $|y| < y_{max}$. Thus a 4 mm cell at 25 cm radius covering $|y| < 1.5$ would have a hit rate per wire of 4.58 Mhz. Existing electronics can probably handle rates of $\sim$ 10 Mhz.

The dominant limitation for central tracking chambers at the SSC is occupancy. The occupancy, O, is given by

$$O = \frac{2\, n_c\, y_{max}\, n_I\, n_B\, d}{\pi\, r}, \tag{5}$$

where n_B is the number of bunch crossings during the resolving time of the cell. n_B is given by

$$n_B = 1 + \text{int}\left(\frac{t_R}{t_B}\right)\left[2 - \frac{t_B}{t_R} - \left(\frac{t_B}{t_R}\right)\text{int}\left(\frac{t_R}{t_B}\right)\right], \tag{6}$$

where t_R is the resolving time of the cell, d/v_D, where v_D is the drift velocity, and int(x) is the largest integer $\leq x$. $n_B \approx t_R/t_B = d/(v_D\, t_B)$. A 4 mm wide cell (2 mm drift) has a resolving time of 40 ns for a typical drift velocity of 50 μm/ns and is therefore sensitive to 2.6 bunch crossings. A layer of such cells at a radius of 25 cm and covering a rapidity range $|y| < 1.5$ would have an occupancy of 19% per cell. The same cell at a radius of 50 cm would have a more reasonable occupancy of 10%. Occupancy is the criterion which determines the cell width at any radius of a central tracking system since, even at larger radius, as one increases the cell width the cell becomes sensitive to more bunch crossings. In fact, since $n_B \approx d/(v_D t_B)$, the occupancy increases quadratically with d and decreases linearly with r. Hence, the maximum cell size can increase only as the square root of the radius. A faster gas, such as mixtures[6] of CF_4 with a saturated drift velocity of 125 μm/ns, would improve the situation considerably by allowing wider cells and thus fewer wires for a given occupancy. However, little is known about the suitability of CF_4 or other fast gases for use in a high rate and radiation environment, so we will not assume that drift velocities substantially larger than 50 μm/ns are realistic.[7]

One pleasant feature of the SSC is that backgrounds from beam-gas interactions and beam losses have been estimated to be much less than the rate from collisions at a luminosity of 10^{33} cm^{-2}s^{-1}, except for the possibility of dumping an entire beam in an interaction region. Tracking chambers and their electronics would presumably be turned off during injection.

B. Tracking System Characteristics

In this section we summarize the general characteristics of a central tracking system which we developed in discussions in the Central Tracking Group.

1. Momentum Measurement. We have assumed that an SSC central tracking system should be able to determine the charge for a particle with momentum up to 1 TeV/c, which means $\sigma_p/p \leq 0.3\,p$ (TeV/c). Momentum resolution is determined by the following well-known relation:[8]

$$\frac{\sigma_p}{p^2} = \frac{A_N\,\sigma_x}{0.29979\,q\,B\,D^2\,\sqrt{N}}, \tag{7}$$

where p is the momentum of the particle in GeV/c, q is the charge in units of the electron charge, σ_x is the spatial resolution in m, B is the magnetic field in Tesla, D is the track length in m, and N is the number of measurements. A_N varies very slowly with N and depends on the spacing of the N measurements. For a large number of equally spaced measurements,

$$A_N^2 = \frac{720}{1+5/N}. \tag{8}$$

The optimal grouping of measurements for momentum measurement (1/2 of the measurements concentrated in the center and 1/4 concentrated at either end) yields a value of A_N a factor of 1.68 smaller. Reasonable grouping of layers will result in values of A_N between these two values. We have taken advantage of this optimization by grouping our layers accordingly, leaving room for transition radiation detectors (TRD's) between the center and outside groups of layers. However, we have used the value for A_N in Eq. 8 to estimate momentum resolution because our layers are more nearly equally spaced than concentrated at the center and ends of the detector. For example, 200 μm spatial resolution, 1.5 Tesla magnetic field, 2 m track length, and 100 equally spaced measurements will give 30% momentum resolution for a 1 TeV/c particle, depending on constraints on the origin of the track. The magnetic field probably cannot be higher than $\sim$ 2 T, or the coil will be too thick for effective calorimetry. A 1.5 T superconducting solenoidal magnet can be built with current technology. Spatial resolutions of $\sim$ 100 μm have been achieved in central tracking chambers, and it is probably reasonable to assume this value. Some have suggested that 50 μm can be achieved, for example, with pressurized straw tube chambers. However, all examples of straw tube chambers which have achieved this resolution have been small vertex chamber devices. In a large central tracking system the effective position resolution is probably determined more by systematic errors in wire location than by the intrinsic single-wire spatial resolution. Track lengths of 1.5–2.0 m are needed to achieve the required momentum resolution. Since high cell occupancies force the minimum radius to be greater than 35–50 cm for an occupancy less than 10%, the outer radius of the central tracking system would be 1.85–2.50 m. The number of measurements is driven more by pattern recognition considerations than by momentum resolution; more will be said about this later, but ~100 is a reasonable number.

2. Cell Size and Shape. As discussed in Section A, the cell width is determined by the occupancy. We have assumed that the cell occupancy should be less than 10%. This means that the maximum cell width at a radius of 50 cm is 4 mm, increasing to 9 mm at a radius of 2.35 m for a central tracking system covering $|y| < 1.5$. These widths correspond to drift distances of 2 mm to 4.5 mm.

The minimum practical cell size is determined by a number of considerations:

1. If the cells are too small, it is very difficult to string the wires.
2. There must be adequate space for high voltage, readout electronics, and cooling.
3. Electrostatic instability becomes worse as cell size decreases.
4. The number of wires increases at least linearly as the cell size decreases.

Although the difficulties resulting from small cells are obvious, it is not so easy to determine the minimum practical size. We chose a drift distance of 2 mm as the lower limit for a cell size that could be used in a large scale detector. In order to achieve this size, some hard work will have to be done to integrate the readout electronics and package the high voltage supply and cooling. As indicated above, if this is the minimum cell size, the inner radius of the drift chamber cannot be much smaller than 50 cm if the occupancy is to be limited to about 10%.

We considered two types of cell geometry: small cell and jet cell. By "small cell" we mean a single sense wire surrounded by field wires or by a cathode surface, as in straw tube chambers. By "jet cell" we mean a multi-sense-wire cell which also contains field-defining wires, as shown in Fig. 1. Since we have concluded that cell widths of 4–9 mm are needed to keep occupancies at a reasonable level, the jet cell must be quite narrow compared to the several cm width used in present jet-cell chambers. This means that the uniform electric field which is generally obtained at a distance of a few mm from the sense-wire plane and is one of the advantages of the jet-cell geometry is not established. In addition, since the Lorentz angle in a 1.5 T magnetic field is large, it would be desirable to tilt the jet cell so that the electron drift trajectories are perpendicular to the sense wire plane. Then, since the jet cell is so narrow, a radial track will produce signals on only a few of the sense wires, as illustrated in Fig. 1. Hence, another of the attractive features of the jet cell, the long track segment in one cell, is lost. We therefore concluded that from a tracking and pattern recognition aspect, we might as well have small cells. Also, the ratio

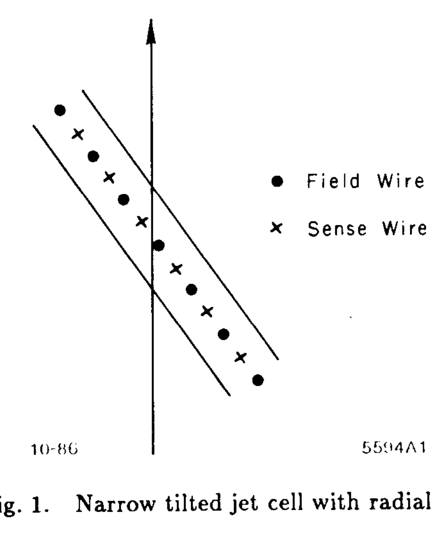

Fig. 1. Narrow tilted jet cell with radial track.

of field wires to sense wires is higher for a jet-cell geometry, so there are more wires to string and there is more force on the endplates from wire tension for each sense wire in a jet cell. The conclusion was that only small cells, either wires or straw tubes, were suitable for a central tracking system at the SSC.

3. Rapidity Coverage. Although particle production for minimum-bias events is expected to be uniform in y, very heavy particles, such as Higgs bosons, are expected to be produced more copiously in the central region, $|y| \lesssim 2$.

We would like to be able to cover the region $|y| \leq 1.5$ completely with central tracking; however, at a radius of 2 m a tracking chamber would have a length of 8.5 m in order to cover $|y| \leq 1.5$. We have decided to limit the length of a tracking chamber to 6 m; even this length provides a number of challenges in its mechanical and electrical design. Thus our compromise is a central tracking system that would cover $|y| \leq 1.5$ to a radius of 0.7 m, would cover $|y| \leq 1.2$ to a radius of 1.6 m, and would cover $|y| \leq 1.0$ to a radius of 2.4 m. The ends of the central tracking system can be covered with planar endcap chambers to improve the $|y|$ acceptance.

4. Gas Gain. As discussed in Section A, the gas gain must be kept relatively low in order to keep the current draw per wire, the chamber lifetime, and space charge effects at a reasonable level. The gas gain we have assumed is $G \sim 2 \times 10^4$.

5. z-Reconstruction. We have assumed that wires in the central tracking system run parallel, or nearly parallel, to the beam direction or z-axis. Good z-reconstruction of tracks is needed to separate particles coming from multiple interactions within the same bunch crossing, to measure total momenta and invariant masses, and to extrapolate tracks to other detector components. There are three conventional methods for measuring the coordinate along a wire: charge division, small-angle stereo, and azimuthal cathode strips.

Charge division, at best (high gas gain $\sim 10^5$), gives z-coordinate resolution of about 1% of the length of the wire. Since the wires in an SSC central tracking system would be quite long (3–6 m), the resolution would be only 3–6 cm. In addition, at lower gas gain, this resolution would be even worse. Also, charge division requires electronics readout at both ends of the wire, and the electronics must simultaneously measure charge and drift time. For these reasons we do not think that charge division is a practical method for measuring the z-coordinate. If providing additional electronics is not a serious problem, rough current division might be useful in reducing the ambiguities inherent in our preferred choice, small-angle stereo wires.

Small-angle stereo wires typically give z-coordinate resolution of a few mm. The resolution is approximately the drift distance resolution divided by the stereo angle. This can be accomplished using the same electronics for all wires. However, because of the complexity of SSC events, it might be difficult to associate the hits on stereo wires with the correct tracks.

Cathode strips in the azimuthal direction can give a z resolution of better than 1 mm. However, they are difficult to build and read out. It would be particularly difficult to install them in a straw tube chamber. In a conventional wire chamber, they could be installed at every radial mechanical boundary in the tracking system to give accurate z measurements to assist the pattern recognition.

6. Pattern Recognition Considerations. Even small cells with drift lengths of 2–5 mm will be sensitive to tracks from several bunch crossings. To remove tracks from out-of-time bunch crossings, several adjacent layers of small cells with cells in every other layer staggered by one-half the cell width can be used. Hits from tracks from bunch crossings which are earlier or later than for the event of interest will be displaced from possible tracks by at least 16 ns, or 0.8 mm for a drift velocity of 50 μm/ns, as shown in Fig. 2. In the pattern recognition stage, track segments would be found in these adjacent groups of layers (superlayers), thereby rejecting the out-of-time hits. Since there will be inefficiencies caused by the high occupancy and double-hit resolution (probably equal to half the cell width), the number of adjacent layers in a superlayer will probably need to be at least six in order to have a high efficiency for finding track segments. This problem should be studied quantitatively using Monte Carlo simulations.

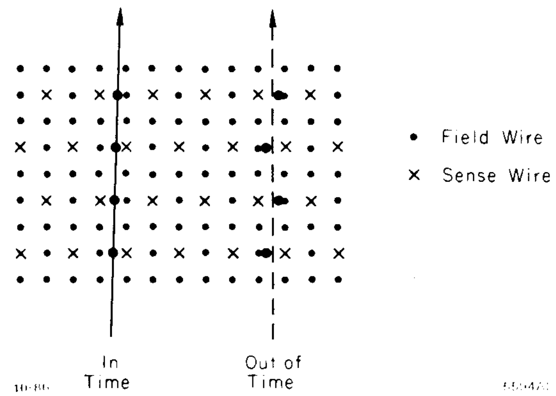

Fig. 2. Layers of small cells staggered by one-half the cell width, showing displacement of hits from track from out-of-time bunch crossing.

Our central tracking system would be built of superlayers consisting of adjacent layers of small cells. In order to be able to link hits in stereo layers appropriately with hits in axial layers, it is best to have them nearby. We expect that a reasonable structure for a central tracking system would be alternating axial and small-angle stereo superlayers.

7. Modularity. Building the central tracking system out of several radial modules would help alleviate some of the mechanical difficulties involved in the design of such a large system. For example, if the cathodes of the central tracking system are wires, there would be 80–100 tons of force on the endplates due to wire tension. If this is built in 4 or 5 modules, then there would be only about 20 tons on the endplates of each module. Such a system would have much better mechanical properties, as will be discussed in more detail in Chapter IV.

Modular construction, however, would introduce more systematic errors in wire position due to uncertainties in locating the modules relative to each other. Means to align the modules very accurately and measure the positions once the modules are in place would have to be devised. We are not sure how this could be accomplished; laser alignment may be a useful tool. The technique developed by the OPAL group[9] of using two parallel beams from a split laser beam to determine velocity and position simultaneously is especially attractive. Also, one would need to take great care to minimize the number of radiation lengths in the material forming the walls of the modules in order to keep multiple scattering errors small and reduce photon conversions.

Building the central tracking system in modules also allows the possibility of locating other detector elements, such as transition radiation detectors, between the modules, as long as they do not degrade the central tracking system performance to an unacceptable level.

8. Electronics Considerations. We feel that the only cell design suitable for an SSC central tracking system is a small-cell design, using either field wires or straw tubes, with drift distances from 2 to 5 mm, and a low gas gain of $\sim 2 \times 10^4$. This means that careful pulse shaping within the cell is probably not available. The width of the pulses due to the charge collection region will be approximately equal to the drift distance divided by the drift velocity. This implies that it will be very difficult to instrument these cells with multihit capability. This problem is important enough to merit further study. A pole-zero filter to suppress the $1/t$ tail will at least allow the cell to be able to recover from hits in previous beam crossings. Beyond that, recording the time at which a pulse crosses a threshold is most likely acceptable and all that can be achieved. A constant-fraction discriminator would help to reduce the effects of time-slewing. There is probably not much to be gained by digitizing pulses for most of the wires, so Flash ADC's or fast analog storage devices may not be helpful. Again, this needs further study. However, maybe this is good, since all of the designs considered have $\sim 10^5$ sense wires; keeping the electronics simple will be essential. Pulse-height measurement for some layers may be useful to detect the presence of overlapping tracks even if they cannot be resolved.

Preamps must be fast and have low noise because of the high rates and low gas gain. It is assumed that as much of the electronics as possible will be located on the chamber endplates.

IV. Design of a Drift Chamber Central Tracking System

A. Design of the Drift Chamber

In order to explore the problems that will be encountered in building a realistic drift chamber for the SSC, we went through the exercise of designing one, given the parameters, limitations, and design goals described in the previous chapters. For convenience, the important parameters are summarized in Table I, and the design goals are summarized in Table II.

Table I. Summary of Accelerator and Drift Chamber Parameters

Luminosity	$\mathcal{L}$	10^{33} cm^{-2} s^{-1}
Inelastic Cross Section	σ	100 mb
Charged Particle Multiplicity	n_c	6 /unit of rapidity
Ionization Rate	α	100 electrons/cm
Gas Gain	G	2×10^4
Drift Velocity	v_D	50 μm/ns
Minimum Drift Distance	d_{min}	0.2 cm
Minimum Radius	r_{min}	50 cm
Magnetic Field	B	1.5 T
Spatial Resolution	σ_x	200 μm
Running Time in a Year		10^7 s

Table II. Summary of Drift Chamber Design Goals

Momentum Resolution	σ_p/p	$\leq 0.3\,p$ (TeV/c)
Rapidity Range Accepted	$\lvert y_{max}\rvert$	1.5
Maximum Length	L_{max}	6 m
Maximum Current per Wire		1 μA
Maximum Charge per Wire		0.02 C/cm/yr
Maximum Occupancy	O_{max}	0.1

Our drift chamber is divided into four modules, with five superlayers per module and six layers per superlayer, giving a total of 120 layers. Within a superlayer, the number of cells per layer is constant to permit half-cell staggering from one layer to the next to simplify the pattern recognition problem. In addition, the nominal or average cell size is constant within a module. The superlayers within a module are intended to be A, S+, A, S−, and A, where A refers to an axial superlayer, S+ refers to a stereo superlayer, and S− refers to a stereo superlayer with the opposite sign for the stereo angle. We have chosen to surround each stereo superlayer with axial superlayers in order to improve the local definition of the r-ϕ track which, in turn, improves the z-resolution of the stereo layers and makes pattern recognition in the stereo layers much easier. We have counted the stereo layers as axial layers for estimating momentum resolution. This is a reasonable approximation, given the large spatial resolution we have assumed. The stereo superlayers do not seriously affect the radial geometry, except for the fact that the stereo wires are at a smaller radius in the middle of the chamber than at the ends. In order to accommodate this, we have left 1 cm of radial space between superlayers.

We have assumed the minimum space we can imagine, 5 cm, between modules 2 and 3. In an actual chamber, this space may be larger, especially if cathode strips are included at the inner and outer radii of the modules to improve the z-resolution. In addition, we have left 40 cm between modules 1 and 2 and between modules 3 and 4 in order to accommodate transition radiation detectors for electron identification. Table III summarizes the organization of the drift chamber geometry.

Table III. Organization of the Drift Chamber Geometry

Number of Cells per Layer is Divisible by	16
Number of Layers per Superlayer	6
Separation Between Superlayers	1 cm
Number of Superlayers per Module	5
Number of Modules	4
Separations Between Modules	1 - 2 : 40 cm
	2 - 3 : 5 cm
	3 - 4 : 40 cm

The consequences of these design choices were studied using a spreadsheet program[10] on an IBM PC/XT[11] computer. The minimum radius, the nominal cell size in each module, and the organization described in Table III were used to determine the radial geometry. Working outwards in radius, the number of wires in each superlayer was chosen to be the multiple of 16 which gave a cell size nearest to the nominal for that module. This led to a well-defined radial geometry, given in Table IV. For each superlayer, the average current per unit length of wire and the average occupancy per wire per unit of rapidity were then calculated. The maxima of these variables for each module were then used to calculate the maximum charge collected per centimeter per year, the maximum current per wire, and the maximum occupancy of a wire. The latter two quantities and the chamber length, L, were calculated for a number of different values of $|y_{max}|$. The nominal drift distances in each module were then adjusted to try to achieve the design goals. Spreadsheets provide a framework in which this sort of calculation can be quickly organized and an "optimum" choice can be rapidly found. In addition to the variables specified in the design goals, a number of practical quantities derived from the cell geometry were calculated to explore problems with the mechanical design.

Table IV.
Summary of Drift Chamber Geometry, Current and Occupancy

Module Number	1	2	3	4	Total
Drift Distance (cm)	0.20	0.35	0.40	0.50	
r_{min} (cm)	50	106	135	202	
r_{max} (cm)	66	130	162	235	
Number of Layers	30	30	30	30	120
Sense Wires	27,360	31,680	35,040	43,200	137,280
Average # Wires/Layer	912	1056	1168	1440	
Maximum Q (C/cm/yr)	0.019	0.007	0.005	0.003	
$\lvert y_{max}\rvert$	1.5	1.2	1.2	1.0	
Length (cm)	279	392	489	553	
Maximum Occupancy	0.094	0.105	0.106	0.091	
Maximum Current (μA)	0.528	0.288	0.253	0.194	

The faint-hearted would certainly not try to build such a drift chamber, but they would also not contemplate building the SSC in the first place. On the other hand, the total number of sense wires is only about an order of magnitude greater than the number in the CLEO II drift chamber.[12] In addition, the system is split into four modules which would be built in parallel, possibly even in different laboratories. Each module has only a factor of two or three more wires than this existing drift chamber.

We have done very well in achieving our design goals in occupancy, current draw per wire, and charge collected per centimeter per year. The first module is generally the one with the greatest difficulty, but it is quite satisfactory.

Table V presents quantities related to momentum resolution. The momentum resolution is actually much better than the design goal. This is largely due to the large radial space left for transition radiation detectors. If these were not included, the radius could be decreased and the wire count reduced, while maintaining the design goal of $\sigma_p/p \leq 0.3\,p$ (TeV/c).

Table V. Momentum Measurement

Number of Measurements		120
Magnetic Field Length		185 cm
Momentum Resolution	σ_p/p	$0.19\,p$ (TeV/c)

To the extent that any of the assumptions, e.g., allowable occupancy, are a bit optimistic, there is some room left for compromise, most likely at the expense of increasing the number of wires.

The stereo angles and the z-resolution are not serious issues in the design. For example, for a rather modest stereo angle of 3°, the resolution in z is 3.8 mm (for $\sigma_x = 200\ \mu$m) and the resolution in the slope is 10^{-3}. If this turns out to be inadequate, it is easy to increase the stereo angle by a factor of two or more.

The central tracking system that we suggest is illustrated in Fig. 3. The figure includes transition radiation detectors and space for endcap chambers. The latter would increase the $|y|$ range of the detector. We have not studied the design of the endcap chambers in any more detail.

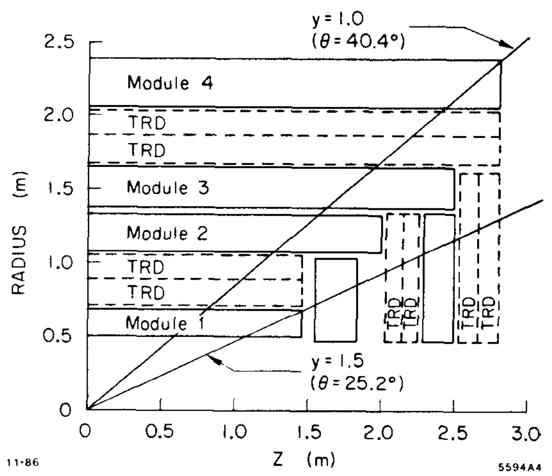

Fig. 3. Example of central tracking system.

We conclude that we can, in principle, do very well in reaching our design goals within the very difficult constraints provided by the high luminosity of the SSC and the large interaction cross section and multiplicity. However, it is still not clear if such a system could be built and operated, given the current state of the art in building tracking systems. In the next two sections we explore some of the mechanical problems and their solutions.

B. Conventional Wire Chambers

By "conventional wire chamber" we mean an atmospheric pressure drift chamber in which the sense wires are strung in a lattice of field wires. Since the drift chambers described in the previous section are a factor of 2 larger than existing drift chambers, it is necessary to study the gross mechanical properties of such chambers to see if they are reasonable. The typical pattern of square cells, illustrated in Fig. 2, has three field wires for each sense wire, neglecting boundaries. A hexagonal close-packed array is an alternate possibility in which there are only two field wires per sense wire, neglecting boundaries. We have chosen to study the square cell array in order to be conservative in the sense that we must deal with more wires, resulting in larger mechanical stresses and more radiation lengths of material.

Since many drift chambers have been built with a variety of techniques for holding the wires, we will not consider that problem here, except to note that cells with 2 mm drift distances will be difficult to string. Following the calculations of wire stability at this workshop,[13] we have assumed that the sense wires are stressed with a mass of 90 g, and the field wires are stressed with a mass of 220 g. These assumptions determine the force on the endplates of each module, which is the source of the major structural problems of the drift chamber. Table VI illustrates the results of these calculations.

Table VI. Summary of Drift Chamber Structural Calculations

Module Number	1	2	3	4	Total
Sense Wires	27,360	31,680	35,040	43,200	137,280
Field Wires	82,080	95,040	105,120	129,600	411,840
Sense Wire Tension (ton)	3	3	3	4	
Field Wire Tension (ton)	18	21	23	29	
Total Wire Tension (ton)	21	24	26	32	103
Endplate Thickness (cm)	1	1	1	1	
Average Shear Stress (N/mm^2)	3	2	1	1	
Total Cylinder Thickness (cm)	0.2	0.2	0.2	0.2	
Compression Stress (N/mm^2)	14	8	7	6	

The total tension of the wires in a module varies from 21 to 32 tons. Of course, these numbers are large since each module contains so many wires. However, it is not difficult to handle these forces. For example, the average shear stress on the endplates at their inner and outer radii where they are supported by support cylinders is one measure of the magnitude of the support problem. Table VI illustrates this average shear stress assuming that the endplates are 1 cm thick. The numbers are about a factor of 100 lower than the maximum shear stress, about 200 N/mm^2, for aluminum. This is due to the large support circumferences at the inner and outer radii. We conclude that stresses on the endplates are no problem in this design.

We assume that the support cylinders would be made of an aluminum-plastic honeycomb composite. Such support cylinders have been successfully used in existing drift chambers, e.g., the HRS and CLEO II drift chambers. Such composites generally consist of two aluminum sheets about 1 mm thick, separated by a honeycomb structure about 8 mm thick. Again, such a structure is far away from the yield strength (about 150 N/mm^2) for aluminum under compression. This is not surprising, since the dominant method for such a structure to fail is by buckling. Making realistic estimates of the buckling strength of such a composite material is beyond our ability in the time available. However, the measured strength of the support shells of the CLEO II drift chamber would be adequate for this chamber.

We conclude that the overall mechanical structure of the proposed drift chamber modules is reasonable, even though the forces are large.

The number of radiation lengths (L_{rad}) in the central tracking system is also an important parameter because high energy photons that convert there could be misidentified as leptons. In contrast to lower energy experiments, the effect of multiple scattering on the momentum resolution is not important since the energies of the interesting particles are very high. In this design, the number of radiation lengths is dominated by either the cylindrical shells or the endplates, depending on the direction a particular particle goes. The total amount of aluminum in the two support cylinders for each module contributes 4.5% L_{rad} for normal incidence, resulting in a total thickness of the cylindrical part of the drift chamber system of about 18% L_{rad}. The 1 cm endplates would contribute 22%

L_{rad} at normal incidence. The contribution of the gas and the (tungsten sense and aluminum field) wires is almost an order of magnitude lower, so it is not important. If the field wires were made of copper-beryllium, the contribution from the gas and wires would still be only a factor of four less than the total for the support cylinders. In addition, the forces on the endplates would have to be about a factor of two higher. In any event, the number of radiation lengths in the central tracking system is larger than is desirable.

The most difficult problems with the conventional drift chamber solution are related to the wire support. The small cell sizes and long lengths of these SSC drift chambers result in a serious electrostatic instability problem. According to estimates at this workshop,[13] cells with drift distances on the order of 2 mm are unstable for lengths greater than about 170 cm, while cells with 5 mm drift are unstable if the length is greater than about 400 cm. Since these lengths are shorter than the lengths of the modules with cells of these sizes, intermediate support of the wires would be required. This is a very serious limitation of the conventional design. For two reasons this may eliminate the conventional wire chamber as a practical means of building and operating such a central tracking system: First, providing such support would make stringing very difficult and time-consuming. Modules with such a large number of wires must be very easy to string or the construction time will be intolerably long. Second, if support is provided, it will be nearly impossible to remove broken wires after the chamber has been installed. With the large number of wires in each module, it is difficult to imagine that no wires will ever break. A broken wire tends to curl around other wires, so it is possible that substantial areas of the drift chamber would be lost to broken wires.

Straw tube chambers are an alternative to conventional drift chambers, and they provide attractive solutions for the problems of wire support, broken wires, and number of radiation lengths in the chamber. We now turn our attention to this possibility.

C. Straw Tube Chambers

High pressure straw tube chambers are common as vertex detectors in storage ring experiments. A very complete design study for such a high pressure straw tube chamber for central tracking at the SSC has been accomplished at this workshop.[14] In this section, we consider the possibility of using an atmospheric pressure drift chamber that closely matches the geometry of Table IV. We refer to the high pressure design study for details of how such a chamber might be built. In the next section, we will comment on the differences between the high pressure and the atmospheric pressure option.

A typical straw tube is made of polyester film (Mylar) or polycarbonate (Lexan) with wall thickness greater than or equal to about 40 μm. The inner diameter of the straw is coated with a thin film of aluminum which is used for the cathode surface. Although only shorter straws have been used so far, the production technique is in principle consistent with producing straws long enough for the proposed drift chamber.

The idea of the straw tube chamber can be summarized as follows: The chamber would be made of straw tubes of appropriate length glued together into cylinders in an approximately hexagonal close-packed array. The wires would be held at both ends by crimp connectors inserted into bushings, which are in turn inserted into the tubes. A sufficiently clever design of the bushing provides the mechanical support of the wire, the electrical connection to the inner aluminum surface of the straw for the cathode potential, electrical insulation between the wire and the cathode surface, and holes for gas flow through the straw. In addition, the wire can easily be supported internally in the straw by inserting small plastic bushings at appropriate intervals. The possibility of using multiple supports for the wire in the straw suggests that the wire could be strung with relatively small tension.

The geometric design given in Table IV assumes that the cells are square. However, the natural lattice for straw tube chambers is approximately hexagonal close packed. Hence, the radial extent of a superlayer with a given cell size would be smaller. We have assumed that the six layers of a superlayer in the straw tube design would be concentrated in the center of the space reserved for the same superlayer in the conventional design. This means that the numbers in Table IV would be essentially the same; the two designs differ only in their mechanical properties, the number of radiation lengths, and the question of wire support.

Assuming that straws of sufficiently high quality and long length can be produced, there is still a serious mechanical problem with handling individual straws. For example, straws for the first module of the drift chamber would be 4 mm in diameter and 279 cm long. If a 100 cm length of the tube were simply supported at each end, the tube would sag about 2.4 cm under its own weight. (This is independent of the thickness of the wall of the tube.) The corresponding theoretical sag for tubes 279 cm long is about 145 cm for simple support at each end. Obviously it will be necessary to support the tube at many points along its length at each stage of construction. This is more of a nuisance than a fundamental problem, but it illustrates the fact that one cannot extrapolate from vertex detector sizes to SSC central detector sizes without doing some work. When the tubes are glued together into superlayers, their rigidity is a completely different story. For example, the theoretical gravitational sag of a superlayer of the same straw tubes in the first module would be on the order of nanometers. Hence, a straw tube chamber would be intrinsically mechanically stable. The only mechanical structures that would be required would be structures to protect the tubes from damage, to hold them in place and to provide support for readout electronics and other services.

Since we are not aware of any experience in working with straw tubes with the long lengths and large diameters required for this detector, we need to make an assumption about the proper wall thickness in order to calculate the number of radiation lengths in the detector. A typical straw tube used so far has a diameter of 4 mm and a wall thickness of 40 μm. As the diameter increases, the strength against collapse of the tube (hoop strength) under its own weight decreases with the fourth power of the diameter. We can use this as a measure of the strength of the tube against collapse during construction. If we wish to compensate for this by increasing the thickness, the thickness would have to increase as the square of the diameter. This results in a rather thick chamber, measured in radiation lengths. The average number of radiation lengths, $< L_{rad} >$, that a particle encounters in traversing a layer of tubes of thickness, t, and radius, d, equal to the drift distance, is given by

$$< L_{rad} > = \pi\, t \left(1 - \frac{t}{2d} \right) . \qquad (9)$$

Table VII presents $< L_{rad} >$ for tubes whose thickness is constant or increases linearly or quadratically with the drift distance, assuming that tubes with 40 μm walls are adequate for 4 mm diameter.

Table VII. Summary of $< L_{rad} >$ for Straw Tube Modules

Module Number	1	2	3	4	Total
Drift Distance (cm)	0.20	0.35	0.40	0.50	
Wall Thickness (μm)	40	40	40	40	
$< L_{rad} >$ (%)	1.3	1.3	1.3	1.3	5.2
Wall Thickness (μm)	40	70	80	100	
$< L_{rad} >$ (%)	1.3	2.3	2.6	3.3	9.5
Wall Thickness (μm)	40	123	160	250	
$< L_{rad} >$ (%)	1.3	4.0	5.3	8.2	18.8

If the wall thickness is constant, a straw tube chamber has about one-fourth as many $< L_{rad} >$ as the conventional chamber. If the wall thickness must increase linearly with drift distance, this ratio is close to one-half, and if the wall thickness must increase quadratically with drift distance, the straw tube chamber is actually slightly thicker than the conventional drift chamber. Only experience with large straw tubes will determine what wall thickness is sufficient for large tubes.

In comparison with conventional wire chambers, straw tube chambers appear to have few disadvantages. The few that were exposed during the workshop were:

1. It is very difficult to see how one would use lasers to calibrate straw tube chambers and locate the modules relative to each other. Thus, the most important potential tool for solving the alignment problem is lost.
2. Cathode strips may be required for measuring the z coordinate, either to improve z-resolution or to help resolve the left-right ambiguity in the stereo layers. It is difficult to see how to achieve this with straw tube chambers.
3. Enough experience in building large conventional wire chambers has been accumulated to insure that the individual modules could be built. There has been no experience with building straw tube chambers of this size. Hence, a major research and development effort would be required.

We conclude that a straw tube chamber is a very attractive alternative to a conventional wire chamber. The mechanical problems appear to be tractable, there is a natural solution to the wire support problem, and it may be possible to build the chamber with half as many L_{rad}.

D. High Pressure Straw Tube Chambers

As mentioned previously, the possibility of using a high pressure straw tube chamber for the entire central tracking system was actively pursued during the workshop. The starting point for this discussion was the notion that the much better spatial resolution, $\sigma_x \sim 50\ \mu$m, achievable at pressures of about 3 atmospheres, could be traded against magnetic length if the outer radius of the drift chamber was determined by the momentum resolution goal. The factor of four decrease in σ_x that might be possible would result in a factor of two decrease in the required magnetic field length. This sort of central tracking system would then be much smaller, which could yield substantial savings in cost and effort in the construction of the outer detectors.

A high pressure chamber would be very difficult to build in the style of a conventional wire chamber because the pressure vessel would be very thick, yielding an intolerably large L_{rad}. The straw tube chamber does not have this problem, since the individual straws are intrinsically strong enough to support pressures of a few atmospheres. Hence, the straw tube option would be the only reasonable option for a high pressure drift chamber system.

In this workshop, the chief criticisms of the high pressure design were the following:

1. The problems of aligning the individual layers, superlayers, or modules of a large straw tube system may result in an effective spatial resolution much larger than 50 μm.
2. In the central tracking detector design presented here, the radial space for transition radiation detectors is approximately as large as the magnetic field length that would be saved by reducing spatial resolution. Hence, the high pressure option does not significantly reduce the size of the detector.

We conclude that the high pressure option for a straw tube chamber is especially attractive in a central tracking system that does not include substantial space for transition radiation detectors or other detectors that should be interleaved with the central detector. Even if other detectors govern the overall size of the central tracking system, the increased resolution may be worth the slight increase in trouble due to maintaining the chamber at high pressure.

V. Central Tracking Simulation

Events from interesting physics processes at the SSC are generally quite complex with many tracks, often in dense jets. In addition, there are tracks from out-of-time bunch crossings and sometimes from additional events from the same bunch crossing. Another problem which will affect pattern recognition is converted photons from the rather large percentage of a radiation length of material in the walls of the drift chamber modules or straw tubes, plus the additional material (about 10% of a radiation length) if transition radiation detectors are added. For these reasons it is necessary to be able to demonstrate that one can solve the pattern recognition problems and find tracks in a realistic central tracking system for simulated SSC events. We have begun to address this problem for a central tracker of our model design.

After much discussion with the Detector Simulation Group,[15] we decided that we should try to use a general-purpose detector simulation package such as GEANT3[16] because so much effort has already gone into it over many years and because it seemed that such a package might be more suitable for a complex SSC detector being worked on by a large number of physicists spread out all over the world. So GEANT3 was chosen to simulate the central tracker.

We found that GEANT3 did not include some of the necessary software tools for simulating drift chambers, for example:

1. Stereo wires do not fit easily into the geometry of tubes.
2. There are no routines to calculate electron drift trajectories or distances of closest approach to tracks in the electric and magnetic fields which exist for particular drift chamber cell geometries.
3. There is no provision for including spatial resolution or double-hit resolution.

GEANT3 seems to be mainly concerned with simple geometrical volumes and intersections of tracks with those volumes. The routine GCDRIF was too trivial to be useful.

Nevertheless, we did make some progress in simulating a central tracker. The central tracker consisted of modules, each of which contained superlayers consisting of layers of small cells with every other layer staggered azimuthally by one-half the cell width. The numbers of modules, superlayers in a module, and layers in a superlayer, as well as radii and lengths of layers and cell widths, could be varied. We digitized the wire number and drift time in each layer for each charged track using a simple linear time-distance relation to convert the distance of closest approach of the track to the wire to a drift time. We used a 1.5 T magnetic field to calculate curvature. We have not yet included:

1. Stereo wires
2. $\mathbf{E} \times \mathbf{B}$ drift
3. γ conversions
4. Multiple Coulomb scattering
5. Adding digitizations from out-of-time bunch crossings
6. Keeping only the earliest hit on each wire (no multi-hit capability)
7. Removing hits in the tails of hits from previous bunch crossings
8. Smearing the drift times by the resolution.

Once the above effects are included we can begin to look at the pattern recognition problems involved in removing the hits from out-of-time bunch crossings and linking the remaining hits to form tracks.

An example of this simulation of a central tracking system is shown in Fig. 4 for a W-pair event with $p_T = 800$ GeV/c. Actually this display is somewhat of a simplification because the GEANT3 display shows only the intersections of the tracks with the drift chamber layers, not the digitized drift times, of which there are two for every wire, and, of course, it displays the produced tracks, not tracks found by a tracking program. However, it does give an indication of the complexity of the event.

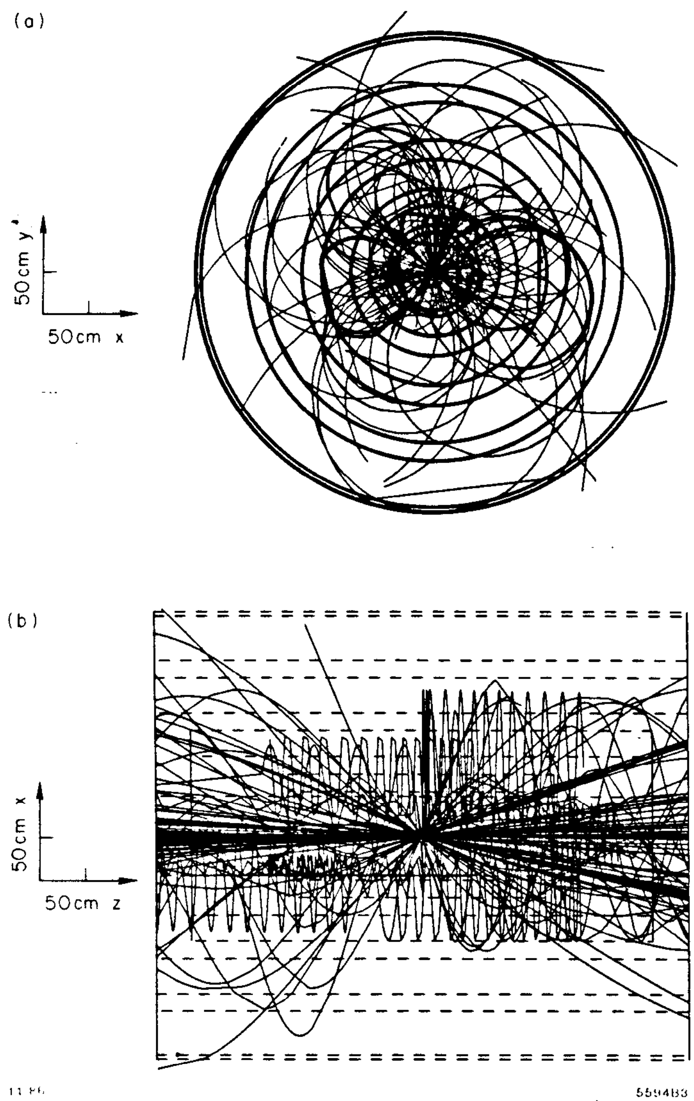

Fig. 4. GEANT3 computer simulation of a model central tracking system for an event from $pp \rightarrow W^+W^-X$ with $p_T(WW) = 800$ GeV/c.

Only after progress is made in finding tracks in realistic central tracking simulations will we be able to say that central tracking at the SSC can be accomplished.

VI. Some Alternate Solutions to Central Tracking

A. Scintillating Fibers

A central tracking system made of scintillating fibers could be a good match to the SSC environment.[17] The most attractive characteristics of scintillating fibers are their radiation hardness, fine segmentation, and excellent resolution. Both glass and plastic fibers can withstand a radiation dose of $\sim 10^6$ rad, with glass fibers being somewhat better. Scintillating glass fibers with a diameter of 25 μm have a measured spatial resolution of 20 μm and a double-track resolution of $\sim$ 80 μm. Since the fibers have a fine segmentation, occupancy is not a problem. Due to their excellent spatial resolution, a central tracking system made of scintillating glass fibers would occupy much less radial space for the same momentum resolution as a wire chamber central tracking system, assuming that the fibers can be positioned accurately. Scintillating fibers could also be used as a vertex detector.

Unfortunately, however, scintillating fibers are still at an early stage of development, and there are still fundamental limitations which must be overcome before they can be considered as a realistic possibility for an SSC tracking device. Scintillating glass fibers, made of cerium-based glass, can be made in small diameter and have the excellent resolutions noted above. However, they have an attenuation length of $\lesssim$ 5 cm. The causes of this are being investigated. Scintillating plastic fibers have an attenuation length of $\sim$ 1 m, but must have diameters of $\sim$ 1 mm in order to obtain usable light output. This larger diameter, of course, degrades the spatial and double-track resolution to a level which is comparable to wire chambers. Another problem with scintillating fibers is that the fluorescence decay times of glass fibers and of the phosphors used in the image intensifiers in the readout system are 50–100 ns, so the fibers integrate over about ten events. Also, an optical delay line would be required to delay the signal during the $\sim$ 1 μs for a trigger decision because the CCD's presently used for a readout take 1 μs to fast clear. In addition, the CCD's require several ms for readout, thus precluding the use of scintillating fibers in the trigger.

Research and development is directed toward solving these problems with scintillating fibers. Several experiments are using or building scintillating fiber detectors. More people and more money are needed. If these problems can be solved, the many advantages of scintillating fibers would make them a good candidate for an SSC central tracking system.

B. Silicon Microstrips

Silicon microstrip detectors have generally been considered only for vertex detectors. Due to their excellent spatial resolution, double-track resolution, and segmentation, they could be a candidate for the central tracking system. We considered such a possibility. In outline, a design using them seems quite attractive.

Silicon microstrip detectors actually have 5 μm spatial resolution[18], but in considering a large central tracking system we increased this to 30 μm to account for positioning errors. In a 2 T magnetic field, spatial resolution of 30 μm, track length of 1 m, and 20 measurements would give 30% momentum resolution for a 1 TeV/c track. Silicon strips are being developed with readout on both sides. This would reduce the number of radiation lengths. Any fraction of the layers could be small-angle stereo.

However, there are severe problems inherent in use of microstrip detectors on a large scale. First, the silicon strip length is limited to 10–12 cm due to the maximum size of available silicon wafers and due to the interstrip capacitance which reduces the signal to noise ratio. This results in a very large number of channels in order to cover the rapidity range needed. If the silicon strips are 10 cm long and have 25 μm pitch and the central tracking system covers $|y| < 1.5$, our hypothetical silicon microstrip central tracking system would have 10^8 strips! Second, the readout electronics, which would be integrated with the silicon strips, may not be sufficiently radiation hard. The radiation dose at a radius of 10 cm, suitable for central tracking, is an order of magnitude lower than at 3 cm, where microstrips might be used in a vertex detector. Third, the CMOS electronics developed at Rutherford Laboratory dissipates 0.4 mW/channel. Even this small dissipation yields a total power dissipation of 40 kW. At this point, even without considering the cost, such a system does not appear to be realistic. In addition, pattern recognition in complex SSC events using only 20 layers would probably be a problem. Hence, our conclusion is that a silicon microstrip central tracking system is not realistic, given the current state of technology.

VII. Research and Development Recommendations

Considerable research and development will be required before a central tracking system for the SSC at the design luminosity can be designed and built. The high-rate and high-radiation environment provides considerable challenges. The major areas in which research and development are needed are the following:

1. Mechanical problems.

   (a) Wire chambers. Detailed mechanical design which includes support for the large wire tension while minimizing the amount of material in the walls is needed. How can the wire support needed for electrostatic stability be provided? How are the wires held and strung? How will broken wires be dealt with? How can azimuthal cathode strips be built and read out? How can the modules be aligned and the wire positions measured?

   (b) Straw tube chambers. How can long straws be held straight? How can long straws be handled? How thick do the walls of large diameter straws have to be? How well can the wires be positioned? Can a chamber be built with stereo straws? How can the wire support required for electrostatic stability be provided? How can cathode strips be implemented? Are pressurized straws a realistic possibility, and if so, how much will the effective spatial resolution be improved? How much of a problem is the material in the walls of the straws?

2. Gases. Fast gases, such as CF_4, could be useful in reducing the occupancy for a fixed cell size by reducing the resolving time. Alternatively, use of a fast gas could reduce the number of wires by a factor of two for the same occupancy. More research is needed on fast gases. How radiation resistant are the gases we might use? What is their contribution to spatial and double-hit resolution?

3. Small cells. Are small cells any more prone to radiation damage than larger cells? What spatial resolution can be obtained at low gain? What is the effect of the large Lorentz angle on the time-distance relation? Is there any double-hit capability?

4. Computer simulation, pattern recognition, and tracking. It is crucial to demonstrate that tracks can actually be found for SSC events given the high multiplicity and density of tracks and the added hits from out-of-time bunch crossings. Pattern recognition studies are needed to help determine the cell and chamber design.

5. $15\ \text{cm} < r < 50\ \text{cm}$. It appears that there is a "no-man's land" between the vertex detector region at small radius and the central tracking region at larger radius. Silicon microstrip detectors have the segmentation needed to handle the rates in this region, but costs, power dissipation, and radiation damage to electronics would probably be prohibitive. Drift chambers have severe problems with occupancy at radii of less than 50 cm. How well can tracks be linked between the vertex detector and the central tracking system?

6. Electronics. Is the simplest, fastest electronics for measuring only drift time the best solution? What is the best scheme for obtaining the best time resolution? Is there any multi-hit capability in small cells? Is pulse digitation useful? How much electronics can be put on the chamber endplates? How much processing of the data can be accomplished on the chamber (the ultimate would be calculation of momentum vectors) in order to reduce the number of cables?

7. Scintillating fibers and silicon microstrips. Solutions to the technological problems, discussed in Chapter VI, could make one of these an excellent candidate for the central tracking system.

These questions need to be answered in the very near future in order to establish the feasibility of central tracking at the SSC at the design luminosity of $10^{33}\ \text{cm}^{-2}\text{s}^{-1}$. Time, money, and interested people are needed.

VIII. Conclusions

The rate problems facing a central tracking system in an SSC experiment are well-known. We have tried to present a coherent discussion of these problems and to suggest directions to pursue in order to solve them. We find that a system involving 137,000 sense wires in 120 cylindrical layers is a plausible solution to these problems. Since this is an extrapolation of an order of magnitude in the number of wires in a central tracking system, more work needs to be done to insure that it is feasible. In the limited time available for this study, we find that a solution involving straw tubes for the cathodes and wire support appears to be the most promising. We are aware that a pitfall of workshops is the fact that there is insufficient time to examine all aspects of a design, and above all, that there is no time or money to build experimental prototypes to see how to solve the problems that may arise. In addition, the concentration required to actually build something is lacking in this environment. Thus it is easy to focus on a new or unconventional solution to a problem and to make an extrapolation that is too large to be practical. The only way to make a design realistic is to do some honest work, that is, to invest time and money in research and development aimed at building prototypes large enough to expose the problems that may arise. In addition, a long-term effort to develop a realistic design should be started. Immediate goals are:

1. The geometry of the system must be carefully studied using Monte Carlo simulations. The geometry must be driven by the pattern recognition considerations while taking account of the realities to be encountered in actually constructing the detector.

2. Substantial work should be done to find suitable faster gases in order to reduce the number of wires and the occupancy and increase the wire spacing to leave more room for electronics.

3. A long prototype straw tube chamber should be built in order to expose the mechanical problems that will arise.

4. Development of electronics focused on achieving the small size and high density required at an acceptable cost and power dissipation level must be started.

We strongly recommend that some of the budget for development of experiments at the SSC be devoted to addressing these questions. We remain confident that a workable central tracking system can be built and can operate at the full-luminosity SSC.

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