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CHARGED PARTICLE TRACKING AND VERTEX DETECTION GROUP SUMMARY REPORT*

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Summary

Charged particle tracking is essential in order to investigate the new physics expected at the SSC. The Tracking Group studied radiation damage and rate limitations to tracking devices, vertex detectors, and central tracking. The Group concluded that silicon strips and large wire tracking chambers with small cells can probably survive at the design luminosity of 10^{33} cm^{-2} sec^{-1}; however, the presently designed electronics for silicon strip vertex detectors can withstand a luminosity of only 10^{31} cm^{-2} sec^{-1}. Wire chambers at a radius of less than about 25 cm can withstand a luminosity of $\leq 10^{32}$ cm^{-2} sec^{-1} only. Actual tracking and pattern recognition in central tracking chambers at a luminosity of 10^{33} cm^{-2} sec^{-1} will be very difficult because of multiple interactions within the resolving time of the chambers; detailed simulations are needed in order to decide whether tracking is indeed possible at this luminosity. Scintillating glass fibers are an interesting possibility both for vertex detectors and for central trackers, but much research and development is still needed both on the fibers themselves and on the readout.

Introduction

Physics Motivation

The major reason for building the SSC is to discover what new particles, discussed elsewhere in these Proceedings, exist in this energy régime. Some of the reasons why charged particle tracking is important in studying this new physics are the following:

(1) Detection of secondary vertices to search for new particles which decay to known long-lived particles and to measure the lifetimes of the new particles;
(2) Separation of multiple interactions within the same bunch crossing;
(3) Track matching to calorimeter or muon detector elements;
(4) Photon and π^0 rejection for electron identification;
(5) Charged particle multiplicity measurement;
(6) Help in determining jet directions;
(7) Identifying unusual event topologies;
(8) Determining whether particles go through calorimeter cracks as a cross check;
(9) Momentum measurement;
(10) Invariant mass measurement;
(11) Energy-momentum matching for electron identification;
(12) Charge determination.

Whether in a magnetic or nonmagnetic detector, some type of charged particle tracking will be needed in order to investigate competently this exciting new physics.

SSC Environment

The design luminosity of the SSC is 10^{33} cm^{-2} sec^{-1} at an energy of 40 TeV in the center of mass.[1] The inelastic cross section is about 100 mb which gives 10^8 interactions per second at the design luminosity. There are expected to be six charged particles per unit of rapidity for minimum-bias events. The design bunch spacing is 10 m which gives bunch crossings every 33 ns with an average of 3.3 interactions per crossing at the design luminosity.

Limitations to Tracking Devices

Radiation damage and rate limitations impose severe constraints on charged particle tracking detectors at the SSC, as described in a contribution to this Workshop by M. G. D. Gilchriese.[2] We will summarize some of these considerations here for completeness.

The limitation on silicon strip detectors is increased leakage current after irradiation. Damage has been detected at the level[2,3] of $10^{12} - 10^{14}$ particles/cm^2. Silicon strip detectors may be able to be placed as close as ~ 2 cm from the beam for a lifetime of one year at a luminosity of 10^{33} cm^{-2} sec^{-1}, although more study and testing is needed. The situation with the electronics for silicon strip detectors is, however, much more pessimistic. For reasons of space it is best to integrate the readout electronics with the silicon strips so that it is at the same distance from the beam as the strips. Presently planned electronics of this type ($nMOS$) is known to fail at a level of $\sim 10^4$ $rads$ (1 $rad = 3.5 \times 10^7$ minimum ionizing particles/cm^2) with power on.[4] Radiation-hardened MOS electronics may be able to survive 10^6 $rads$, but even this is not sufficient for operation close to the beam at 10^{33} cm^{-2} sec^{-1}.

Radiation damage to wire chambers is quantified by the average current drawn by a wire and by the deposited charge per unit length of wire. The additional assumption made in order

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to calculate limitations on wire chambers was that 10^6 electrons are collected per particle, which corresponds to a relatively low gain of a few $\times 10.^4$ A simple rate calculation leads to a current of $\sim 300\ \mu A/N_{wire}$ for a chamber covering a rapidity range $|y| < 1.5$, where N_{wire} is the number of wires, for $10^{33}\ cm^{-2}\ sec^{-1}$ luminosity. A current of 1 μA/wire may be possible before breakdown. This leads, for example, to a minimum radius of 25 *cm* for a chamber with 5 *mm* cell width (2.5 *mm* drift distance). Chamber lifetimes greater than 10^{18} electrons/*mm* have been observed, depending on the gas. A chamber with 5 *mm* cells at 25 *cm* would collect 7×10^{16} electrons/*mm* in one year of operation at a luminosity of $10^{33}\ cm^{-2}\ sec^{-1}$ which should not be a problem. Changes in gain for wire chambers have been observed at the level of 10^4 particles/*mm–sec* due to space charge build-up. A 1-*m*-long chamber layer with 300 wires would have a flux of 6×10^3 particles/*mm-sec* at a luminosity of $10^{33}\ cm^{-2}\ sec^{-1}$.

Electronics on the end of a vertex drift chamber close to the beam would receive a radiation dose of $\sim 2.5 \times 10^3$ *rads* per year at a luminosity of $10^{32}\ cm^{-2}\ sec^{-1}$, which would require some care in design. A large central tracking chamber would receive ~ 600 *rads* per year at $10^{33}\ cm^{-2}\ sec^{-1}$, which is probably not a limitation.

Another limitation relevant for all types of tracking detectors is occupancy. This is not a problem, however, for silicon strip detectors because of their high segmentation ($\sim 25\ \mu m$ strip width). The problem for wire chambers is severe. A 5 *mm* cell has a resolving time of 50 *ns* for a typical drift velocity of 50 $\mu m/ns$. During that time it is sensitive to two bunch crossings with an average of 6.6 interactions at a luminosity of $10^{33}\ cm^{-2}\ sec^{-1}$. The occupancy for such a cell at 25 *cm* radius is therefore 30% for a minimum-bias event.

Backgrounds from beam-gas interactions and beam losses are estimated to be much less than those from collisions at $10^{33}\ cm^{-2}\ sec^{-1}$.

Vertex Detectors

The primary purpose of a vertex detector is the observation of short-lived particles by their decay vertices. The technique is particularly applicable to the heavy flavors (bottom and charm as well as top quarks via b decay) plus the τ lepton. It might also find use in identifying heavier quarks or other exotics. A second use at high luminosity could be in matching tracks with events when there are multiple events within the resolution time of the main detector. The good time and position resolution characteristic of most vertex detector designs could be helpful in this matching. A third possible application is to make use of the very high resolution inherent in some vertex detector techniques to make a very compact high-momentum-resolution device to supplement or replace the central tracking chamber.

Vertex detectors are becoming relatively common in colliding beam experiments. For precision in reconstructing vertices a general design aim is to start the active region of the detector as close to the beam as possible since there is a limit to the precision of reconstruction set by multiple scattering in the innermost layer. However, $\gamma c\tau$ can be a number of centimeters at TeV energies for the heavy quarks so that detector elements cannot be too close. At a 5 *cm* radius a 10 GeV/c particle traversing 1% of a radiation length of silicon acquires an impact parameter uncertainty of $\sim 8\ \mu m$ due to multiple scattering compared with $c\tau$ for a b decay of $\sim 400 \mu m$ and attainable detector resolutions (silicon strips) of $\sim 6\ \mu m$. Unfortunately, because of the high luminosities needed to investigate TeV physics a number of problems arise that make it advantageous to keep the detectors at large radii.

In order for a vertex detector to function as a useful device at the SSC it must satisfy certain criteria:

(1) It must be sufficiently radiation resistant to survive the environment near an interaction point.

(2) It must have high enough segmentation to assure a low occupancy rate for pattern recognition at the design luminosity.

(3) It must respond fast enough that events do not pile up on each other and cause confusion.

(4) It should be thin enough (a few per cent of an interaction length) that secondary interactions do not cause confusion.

(5) It should have good spatial resolution.

With present technology all devices considered — drift chambers, silicon strips, and scintillating glass fibers — encounter problems with at least one of these criteria at a luminosity of $10^{33}\ cm^{-2}\ sec^{-1}$. The accompanying chart (Fig. 1) shows the radius at which detector materials can be placed and survive radiation damage under various operating conditions. The allowed radius is approximately independent of the z–coordinate (distance along the beam direction). Since it is very desirable for a large system to have electronics mounted on the silicon strips, the innermost layer for such a detector must be at least 14 *cm* away, even for radiation-hardened electronics, to assure one year survival. Wire chambers are limited to the same radius due to radiation damage to electronics placed on the chamber. There were reports that we could not verify of military electronics which will withstand a factor of 3 – 10 more radiation than hardened electronics. These should be investigated since the electronics is the most radiation-sensitive element in most systems.

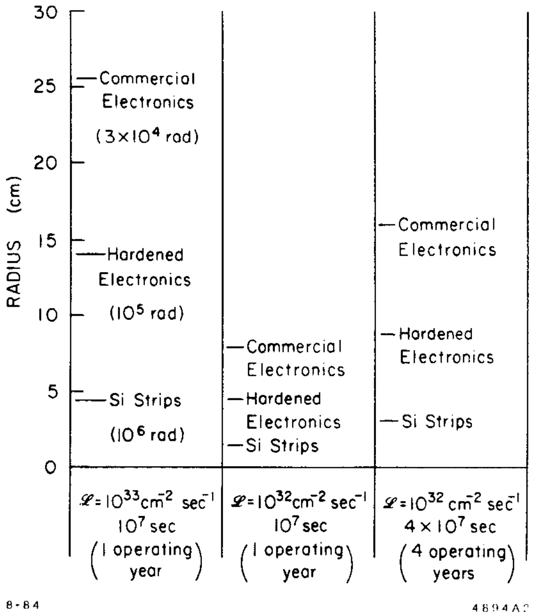

Fig. 1 Mininum component radii for radiation damage at luminosities of 10^{32} and $10^{33}\ cm^{-2}\ sec^{-1}$.

Scintillating glass fibers are discussed in a contribution to this Workshop by R. Ruchti.[5] Plans for a glass fiber system must be speculative at present. There may be problems with radiation resistance and the decay times of the light from the fibers and phosphors could pose a problem under criterion (3). The thickness of glass required depends on the light collection efficiency and has yet to be determined for a realistic system. Conditions (2) and (5) should be easily satisfied.

Wire chambers have great difficulty with criterion (2) at small radii because of the required close wire spacing. Condition (1) limits wire chamber use to the same minimum radius as silicon strips due to radiation damage to electronics placed on the chamber. Particularly as the gas gain will have to be held low, the spatial resolution will also be much inferior to that obtainable from silicon or glass fibers.

Faced with a hierarchy of technical uncertainties and possible technical advances, for the purpose of this report, we decided to look in some detail at a conservative design in which we assume a luminosity of 10^{32} cm^{-2} sec^{-1} and a rapidity range $-1.5 < y < 1.5$. As scintillating fibers are at an early stage of development we use silicon strips anticipating technology by assuming electronics to withstand 10^5 *rads* integrated with the strips and strips 10 to 20 *cm* long. We chose silicon strips over drift chambers because of their inherently better spatial resolution. In the final part of our report we indicate the R & D work that must be done before higher luminosity detectors become a possibility.

At a luminosity of 10^{32} cm^{-2} sec^{-1} there is an average of one interaction every 3 bunch crossings. Thus, except for statistical fluctuations, criterion (3) is easily satisfied. Radiation damage is reduced to the point where silicon strips can be placed relatively close to the beam and strip occupancy is negligible. The complexity of the resulting system and the requirement for a small interaction length (criterion (4)) suggests a limit of 3 or 4 layers of detector. Such a number does not, however, provide enough redundancy for pattern recognition. Rather than depend on the main tracking chamber we prefer to supplement the high-resolution silicon with a vertex wire chamber to achieve the needed redundancy.

On the average there will be 20 charged particles per event between $-1.5 < y < 1.5$. The inner radius of the wire chamber is at 10 *cm*, consistent with a four year life for the hardened electronics on each wire. For a 6% occupancy the chamber would have 300 cells/layer which means each cell would be 2 *mm* wide. Twenty layers of cells, making a total 10^4 in all, should be sufficient for pattern recognition since this chamber is meant to supplement the main tracker. For a bunch separation of 33 *ns* it is worthwhile maintaining the 2 *mm* cell dimension throughout the chamber as tracks from the previous crossing will have been swept away. Assuming a resolution of 100 μm wire, with up to 20 layers this chamber could also be a useful backup if the silicon system should start to fail.

As an example of a complete vertex chamber see Fig. 2. Three layers of silicon strips each with a pitch of 25 μm are placed at 3, 6 and 9 *cm*. These are closer to the beam than necessary for vertex reconstruction of high momentum tracks mainly to reduce the number of strips and the consequent readout problems. Even so, the total length of the outer cylinder is ~ 50 *cm* and we would propose to split this with separate readout from the two ends; with this assumption the total number of strips to be readout would be $\sim 70,000$. The drift chamber extends from 10 to 20 *cm* in radius and is ~ 1 *m* long.

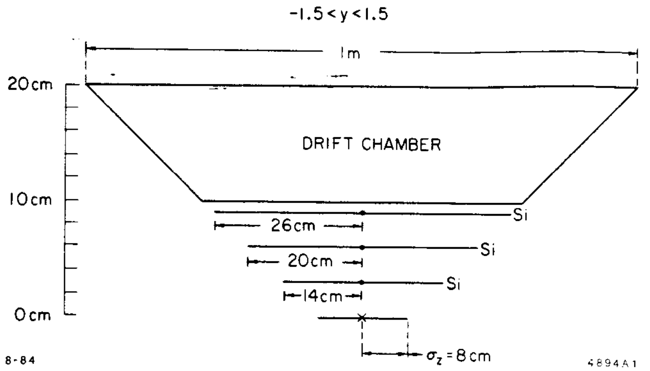

Fig. 2 An example of a complete vertex detector system for use at a luminosity of 10^{32} cm^{-2} sec^{-1} or less.

We do not discuss the z-coordinate. One approach, possible at 10^{32} cm^{-2} sec^{-1}, would be to concentrate all the efforts in the x–y plane and rely on the main tracking chamber for z information. Otherwise, stereo silicon strips or vertex chamber wires would have to be considered.

The electronics to read out the strips would contain one amplifier feeding a shift register on each strip. The registers would be advanced at each crossing so that successive interactions would not be superimposed. The registers would have to have enough places to store an event until the trigger was formed. The individual strips would then be read out serially in convenient-sized blocks so that only about 1000 cables would be needed for connection to the outside world. The electronics, while basically simple, would dissipate several kilowatts of power and some means of cooling would have to be provided. Also, the sheer volume of circuitry would require large-scale integration. A possible alternative would be an LED light fiber system to pipe the signals out and reduce the electronics on the silicon strips.

Not enough is known to make better than ballpark guesses at the cost of such a system but $\$ 5 \times 10^6$ is probably not unreasonable. Such a device could operate in a detector with or without a magnetic field. It is small enough that it could be surrounded by a main tracking chamber or transition radiation detector and still allow a compact calorimeter design.

Central Tracking

Some form of central tracking is needed in any type of general-purpose detector in order to examine carefully the new physics expected at the SSC. Central tracking systems are assumed to cover the rapidity range $|y| \lesssim 1.5$. Much interesting physics is expected to occur in this rapidity range, including the production of the heaviest new particles. Current technology dictates that a central tracking system be based on wire chambers, specifically drift chambers, of some type. Newer technologies under development may lead to other types of central trackers. For drift chambers, small cells ($\lesssim 5$ *mm* drift distance) are needed because of rates, radiation damage, resolving time, and occupancy, as discussed in the Introduction and in Ref. 2. Carefully executed small-cell designs should be able to survive at a luminosity of 10^{33} cm^{-2} sec^{-1}.

Pattern Recognition

Central tracking at a luminosity of $10^{33}\ cm^{-2}\ sec^{-1}$ must deal with the problems of high interaction rates. For a drift distance of 5 mm, the resolving time of a drift chamber is 100 ns for a typical drift velocity of 50 $\mu m/ns$. At 10 m bunch spacing, bunch crossings occur every 33 ns and there are an average of 3.3 interactions per bunch crossing. Thus there are 10 interactions during the resolving time for a 5 mm drift. These multiple interactions, both in the same and different bunch crossings, pose a very difficult pattern recognition problem. The process of linking drift chamber hits to form tracks and associating the tracks with interactions is what we refer to as pattern recognition.

Staggered or tilted jet cells, as shown in Fig. 3, may help to separate tracks from different bunch crossings. (Tilted jet cells are an advantage in large magnetic fields because of the large Lorentz angle; both staggered cells and tilted jet cells resolve left–right ambiguities.) Tracks from earlier or later bunch crossings than the triggering event suffer displacements as they cross cell boundaries in the case of staggered cells or as they cross sense–wire planes in the case of tilted jet cells. These tracks can, in principle, be eliminated from the event of interest, provided that they can be clearly identified. However, if such a track occurs in the same cell as one from the event of interest, one must deal with the further complication of double hit resolution, which is typically 3–4 mm. The pattern recognition problems caused by tracks from different bunch crossings are further discussed by G. H. Trilling[6] in a contribution to this Workshop. The resolving time for a given drift distance may be reduced by using a fast gas, but this would worsen the double hit resolution. Another implication of the resolving time problem is that one is restricted to small cells even at large radii.

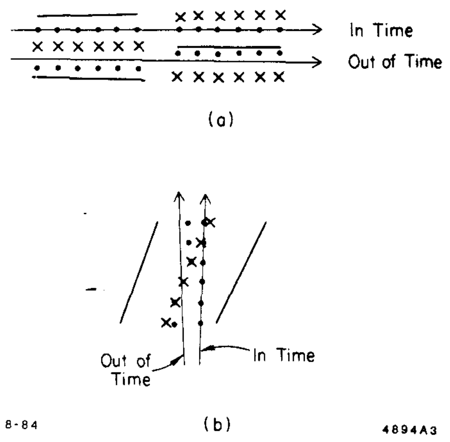

Fig. 3 (a) Staggered or (b) tilted jet cells, showing displacement of out-of-time tracks from bunch crossings earlier or later than the triggering event.

Events from the same bunch crossing can be separated only by finding different vertex positions along the beam direction (z coordinate). The design[1] luminous region has $\sigma_z = 7\ cm$. For chambers with wires running parallel to the beam direction, the z coordinate can be measured in three ways: small–angle stereo wires, charge division, and cathode strips running azimuthally. Another solution is to have the wires running azimuthally so that the drift is in the z direction; this method would give the best resolution in the z coordinate but is not suitable for measuring momentum. Of the methods for wires running in the z direction, small angle stereo gives the best z resolution, typically a few mm. However, reconstruction errors can give large errors in the measured z coordinate at the beam axis, as discussed in Ref. 6. Charge division in the best cases gives z coordinate resolution $\sim$ 1% of the length of the wire. At the SSC this resolution would be worse because the chambers would need to run at low gain. Segmented cathode strips running azimuthally can give a spatial resolution of 1 mm for isolated tracks[7] and could be used as an aid to pattern recognition in conjunction with small angle stereo. It is probably better to have bunch crossings every 10 ns rather than the 33 ns of the Reference Design Report[1] with an average of one interaction per bunch crossing; this would give additional timing information to separate multiple interactions.

On a somewhat more encouraging note, a study done for this Group by H. Williams indicates that tracking within jets may be possible. He ran a Monte Carlo simulation of $t\bar{t}$ jets at p_T = 500 GeV/c at 90° to the beam direction in the CDF drift chamber. The decay mechanism for t–mesons was $t \rightarrow b\ e\ \bar{\nu}$. The maximum drift distance in this chamber is 3 cm, much larger than would be possible at the SSC; however, the effect of this should be negligible if the double hit resolution is the same. The CDF chamber has 84 layers. The mechanism for loss of hits for a track is the 3.5 mm double hit resolution – if two tracks in a cell are closer than this distance, then only the hit from the closest track is recorded. Tracks were not actually reconstructed, but one can obtain a rough estimate of reconstruction efficiency by measuring the number of hits per track. The events had $\sim$ 500 particles each, including photons.

Figure 4 shows the distribution of number of hits for all charged tracks within the active area of the chamber. (Some tracks have more than 84 hits because they have low momentum and spiral around in the chamber.) For all tracks, the mean number of hits is 65. The distributions are also shown for the high–momentum tracks in the core of the jet (p_T > 5 GeV/c) and for electrons with p_T > 5 GeV/c. The high–momentum tracks have fewer hits with a mean of 51. The high momentum electrons have a larger mean of 61 because they have a larger transverse momentum to the jet direction. One cannot estimate the tracking efficiency precisely without a tracking algorithm, but one can guess that a track with half the total possible hits available might be reconstructible. Using this criterion, 85% of all tracks, 69% of tracks with p_T > 5 GeV/c, and 83% of the electrons with p_T > 5 GeV/c could be reconstructed. In this study the drift chamber contained tracks from only one event; the effect of multiple interactions within the chamber remains to be studied.

Central tracking at a luminosity of $10^{32}\ cm^{-2}\ sec^{-1}$, with an average of one interaction within the resolving time of the chamber, is probably not too difficult a problem. Simulations would be needed for any specific design to optimize track reconstruction efficiency. Experience will be available from tracking in the CDF chamber at the Fermilab Tevatron Collider, for example. Track reconstruction at $10^{33}\ cm^{-2}\ sec^{-1}$ is another matter: *much detailed simulation of tracking and pattern recognition must be done to determine whether tracking is really possible in this multiple interaction environment.*

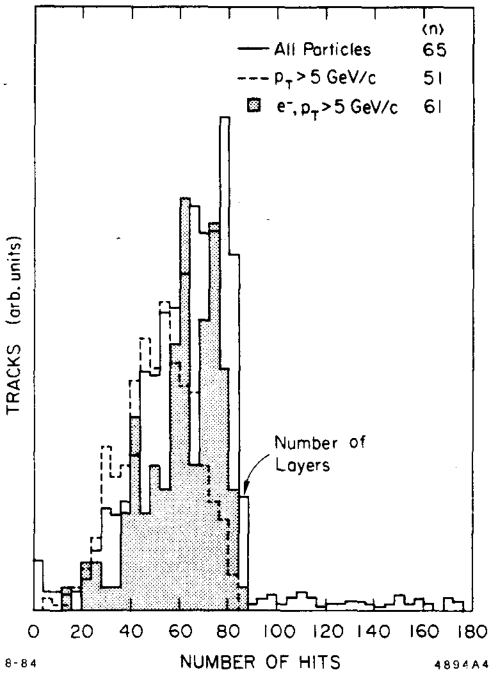

Fig. 4 Distribution of number of hits for charged tracks in CDF drift chamber simulation for 500 GeV/c $t\bar{t}$ jets.

Momentum Measurement

There seems to be no clear consensus as to whether momentum measurement in the central tracking system is really needed at the SSC. Some of the functions of tracking, listed in the Introduction, can obviously be performed without momentum analysis. A nonmagnetic tracking system can be made more compact so that detector elements outside the central tracker, such as calorimeters and muon detection systems, can be made smaller and cheaper. However, the difference in cost for total detectors turns out to be not very great (see the Summary Report of the 4π Detector Group[8]).

On the other hand, when first studying physics in a new energy region, it would seem that one should have as complete a detector as possible to search for and identify unexpected new phenomena. Momentum measurement is needed to make optimal use of vertex detectors, to help in determining invariant masses, to make momentum cuts which are often needed in analyses, to determine the sign of particle charges, and to aid in muon and electron identification.

Momentum resolution is determined by the following well-known relation:

$$\frac{\sigma_{p_T}}{p_T^2} \propto \frac{\sigma_x}{BL^2\sqrt{N}}, \qquad (1)$$

where σ_x is the spatial resolution, B is the magnetic field, L is the track length, and N is the number of measurements. For example, for 200 μm spatial resolution, 1.5 Tesla magnetic field, $2-m$ track length, and 100 measurements, the momentum resolution would be 30% for a 1 TeV particle, which would allow charge determination. The actual momentum resolution obtained would depend, for example, on constraints on the origin of the track.

Spatial resolutions of ~ 100 μm can probably be obtained, particularly with a small drift cell. The drift chamber might also operate at high pressure in order to improve the spatial resolution. However, in a large central tracking system the momentum resolution may be determined more by the geometrical accuracy of wire positioning than by the single-wire spatial resolution. To take advantage of 100 μm spatial resolution the systematics would have to be very well controlled. A 1.5 T superconducting solenoid magnet can be built using current technology; the CDF magnet, for example, has a 1.5 T magnetic field. One might consider a larger magnetic field, perhaps 3.0 T, although tracking in such a high magnetic field may be difficult. One of the major objections to momentum measurement in a central tracker at the SSC is the large tracking length needed for adequate momentum resolution at such high momentum. A cylindrical drift chamber of the type familiar in colliding-beam detectors would have inner radius of 0.5 m, outer radius of 2.5 m, and *length of* 10.6 m to cover a rapidity range $y < |1.5|$. This is a very large chamber! Problems of electrostatic stability would probably impose severe constraints on wire length, particularly for closely-spaced wires. Some means of mechanical support for the wires would be needed. In addition, other detector components must start at radii larger than 2.5 m.

Electronics

The density of signals from a drift chamber would be quite high because of the small cell requirement. In addition, the large number of channels, ~ 10^5 sense wires, would necessitate cost-saving measures. The signal density might be handled by the conventional means of hybrid or integrated circuit preamplifiers followed by a cable or twisted-pair line for each signal; a multiplexed readout scheme using local storage of time and pulse-height information would be preferred but would require much more development. Problems of power dissipation by 10^5 preamps on the chamber (many kilowatts) would have to be solved.

Fast multihit timing measurement would be required. The LeCroy 1879 TDC, based on a 250 MHz silicon-on-sapphire shift register, with a 1 ns time resolution, would be suitable, but the cost would be high. A double hit resolution of 3 - 4 mm can be achieved with a discriminator and TDC; 2 mm might be achieved with Flash ADC's or fast analog storage devices. Measurement of dE/dx on some channels might be useful in order to detect overlapping tracks; dE/dx for particle identification would not be useful in this energy range.

The cost of electronics will dominate the cost of a drift chamber system.

Examples of Central Trackers

Several different approaches to solving some of the problems mentioned earlier in this Section were discussed. The following examples of central tracking systems were developed in collaboration with the 4π Detector Group.[8]

D1 Detector. The D1 Detector (named in analogy to the D0 Detector) is a nonmagnetic detector. The central tracking system of the D1 Detector is shown in Fig. 5 and consists of 4 groups of 5 layers each of drift chambers interspersed with transition radiation detectors. The drift chambers have azimuthal sense wires at 5 mm spacing. The system is arranged in octants azimuthally. The drift is along the beam direction to obtain the best resolution in that direction in order to separate multiple interactions. The central tracking system is compact, located within 1.2 m from the beam axis. The occupancy is typically

4%, with a maximum of 8%, for minimum-bias events at a luminosity of 10^{33} cm^{-2} sec^{-1}. The sense wires must be read out from the spaces between the octants, so some dead space would be required. There are forward-backward tracking chambers ~~(not~~ shown) which extend the tracking coverage to the rapidity range $|y| \lesssim 5$. The total number of sense wires is 1.8×10^5.

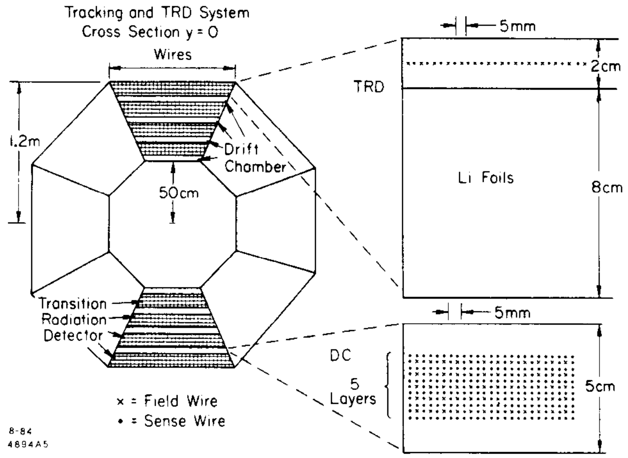

Fig. 5 D1 central tracking system.

SCD Detector. The Super Collider Conventional Detector (SCD) is a magnetic detector based on conventional technology. The tracking system is located inside a large 1.5 T superconducting solenoid. The goal of this central tracker was to determine the sign of the charge of a 1 TeV particle, so the momentum resolution is estimated to be $\sigma_p/p = 3 \times 10^{-4}p$ (GeV/c). A brute force approach was used to design the central tracking system. Small cells were used to solve the problems of radiation damage, rates, resolving time, and occupancy.

The central tracking system design evolved from the large cylindrical drift chambers in common use in colliding-beam experiments. Because of the large number of sense wires and mechanical problems due to the large size, a modular design was thought to be more practical. The SCD central tracking system, shown in Fig. 6, consists of four cylindrical modules. Each module is self-supporting and contains its own gas volume. The inner and outer cylindrical walls of each module are made of plastic hexcell between aluminum or graphite-epoxy sheets or a foam graphite-epoxy laminate; the amount of material in the walls would hopefully be less than 1% of a radiation length per module.

Module 1 contains 24 layers of staggered small cells with 1 mm drift distance. The innermost layer of wires is located at 50 cm radius and has an occupancy of 4% for minimum-bias events at a luminosity of 10^{33} cm^{-2} sec^{-1}. Each pair of staggered sense wire layers is alternately parallel to the beam direction (axial) or at a small stereo angle. Module 1 covers $|y| \leq 1.5$.

Module 2, the central part of Module 3, and Module 4 contain tilted jet cells with 5 mm drift. Each module contains 3 layers of jet cells, each with 8 sense wires. The layers of jet cells are alternately axial and small-angle stereo. The innermost jet cell layer would have an occupancy of 29% at a luminosity of 10^{33} cm^{-2} sec^{-1} for minimum-bias events. This may be too high. However, the pattern-recognition capabilities of jet cells, because of their ability to contain track segments, is degraded for narrow tilted cells because tracks from the center of the chamber cross at angles; in fact, 5 mm may already be too narrow. Tilted jet cells, as opposed to radial jet cells, were chosen because of the high magnetic field. Modules 3 and 4 cover only $|y| < 1$ because we limited the total length to 6 m for reasons of mechanical practicality and electrostatic stability. Even so, central mechanical support of such closely-spaced wires would probably be required. The outer radius of Module 4 is 2.5 m.

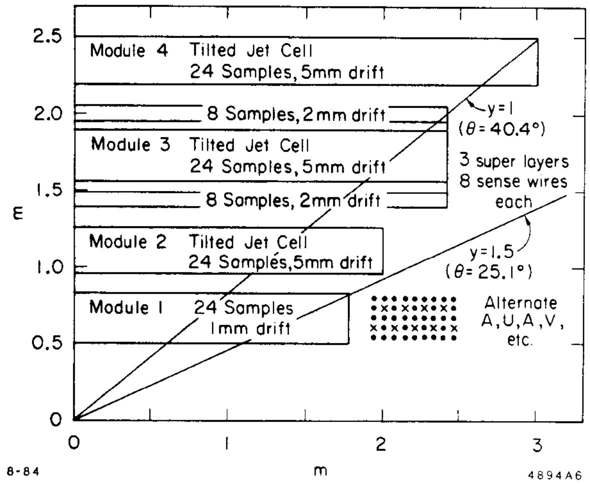

Fig. 6 SCD central tracking system.

The inner and outer portions of Module 3 consist of 8 layers of staggered small cells, similar to Module 1, except that the drift distance is 2 mm instead of 1 mm. These should be useful to help with pattern recognition because their resolving time is less than for the jet cells, so their occupancy is lower. Making all of the layers small cells is probably impractical because of the increased number of sense wires. The total number of sense wires in the central tracker as described is 1.7×10^5.

The central tracking system provides 112 measurements for each track which traverses the full radial extent of the system. Half the wires are axial and half are small-angle stereo, as recommended in Ref. 6. Additional aid in measurement of the z-coordinate is provided by segmented cathode strips at the edges of small-cell layers. A spatial resolution of 200 μm was assumed in calculating the quoted momentum resolution. One needs to worry about alignment of the four modules. Systematic effects in mechanical location of the wires will probably dominate in such a large system, so an intrinsic drift chamber spatial resolution of 100 μm would probably be too optimistic to use in calculating the momentum resolution.

Both staggered small cells and tilted jet cells were used in an attempt to optimize pattern recognition. The details of the design might well change after a full Monte Carlo simulation is carried out. However, the ideas used here would probably be the basic ingredients of a conventional drift chamber design for a central tracking system.

SciFiD Detector. The Scintillating Fiber Detector (SciFiD) is a magnetic detector with a central tracking system made of scintillating glass fibers. The magnet is a 1.5 T solenoid, as in the SCD. The very good spatial resolution (10 μm) of scintillating glass fibers is used to obtain the same momentum resolution within a much smaller tracking volume. Scintillating glass fibers have been reported to withstand a radiation dose of 10^6 *rad*. Occupancy is not a problem because of the fine segmentation.

The SciFiD central tracker is shown in Fig. 7. Cylindrical layers of 10 μm scintillating glass fibers[5] are placed at 10, 30, 60, and 90 *cm* radius from the beam axis. The layer at 10 *cm* has 2 *mm* thickness (0.02 radiation lengths) of fibers running parallel to the beam direction; it also serves as a vertex detector. The layers at 30 and 60 *cm* are each made up of four 2-*mm*-thick layers, two of which are stereo and two of which are axial. The layer at 90 *cm* is a 1.6-radiation-length-thick microconverter. Transition radiation detectors are placed between the layers at 30 *cm* and 60 *cm* and between the layers at 60 *cm* and 90 *cm*. The central tracker covers $|y| < 1.5$.

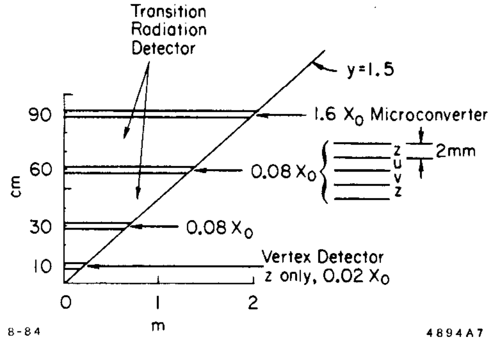

Fig. 7 SciFiD central tracking system.

The spatial resolution is expected to be 10 μm. The double-hit resolution is estimated to be 50 μm. The number of hits per track is 210. The tracking algorithm proposed is to find short track segments in each detector layer and then to link the track segments. The rather large amount of material may pose problems for tracking because of multiple scattering and conversion of photons. The momentum resolution is calculated to be $\sigma_p/p = 2.5 \times 10^{-4} p(\mathrm{GeV/c})$ plus 1.6 % due to multiple scattering. The impact parameter resolution is expected to be less than 20 μm at the origin for momenta greater than 10 GeV/c.

The fibers are read out through photodiodes which provide gain and shift the blue light to red. The light is transmitted over glass fiber bundles to gated image intensifiers, which are read out by liquid-nitrogen-cooled CCD's.

This novel solution to central tracking is very attractive; however, scintillating glass fibers are in a very early stage of development and so far have been used only in very limited detectors. There are many problems to solve. The radiation hardness needs to be verified for the fibers as well as for the readout system. To take advantage of the small spatial resolution, the fibers must be very precisely aligned, positioned, and calibrated. The decay constant for the fibers and the phosphors in the photodiodes is rather long and may lead to pile-up problems. The amount of light may not be sufficient. Production of the fibers needs development, as does the readout system. Much more research and development is needed before a proposal for such a system could be taken seriously.

Research and Development Recommendations

Considerable research and development will be needed before tracking detectors for the SSC at a luminosity of 10^{33} cm^{-2} sec^{-1} can be built. While much of this will occur naturally in connection with present or planned experiments at existing accelerators, operation at the SSC highlights particular problems deserving of special study. These are centered around the problems of component lifetimes in a high-radiation environment, the need for techniques to handle the very large number of electronic channels foreseen, and the difficulties arising from the short time interval, less than 33 *ns*, between bunch crossings. There are several areas that could benefit greatly from a directed research effort. We itemize these as follows:

(1) Drift Chambers — Limitations to chamber lifetimes and operating currents should be studied. These are dependent on the gases used; perhaps gases can be found which will enable chambers to operate at higher currents or collect more charge without degrading spatial resolution or double hit resolution. Operation with very small cells should be studied. Fast gases may decrease the resolving time of drift chambers for fixed drift distances. R & D efforts to solve the mechanical problems associated with very large drift chambers are needed.

(2) Silicon Strips — Radiation damage to silicon strip detectors should be studied. Efforts should be made to increase the maximum length of the strips. Methods for precisely positioning the strips should be developed.

(3) Electronics — Development of radiation-hardened electronics is crucial to the operation of any vertex detector at the SSC at a luminosity of 10^{33} cm^{-2} sec^{-1}. Present electronics limits the use of silicon strip detectors close to the beam to luminosities of 10^{31} cm^{-2} sec^{-1} or less. Continued work on integrated readout circuits for silicon strip detectors is needed. Design of electronics for both drift chambers and silicon strip detectors to minimize power consumption, costs, and volume would be worthwhile. Integrated, fast multihit electronics for drift chambers is also needed.

(4) Scintillating Glass Fibers — The understanding and use of scintillating glass fibers has barely begun. Research on the fibers themselves, in particular, the light output and attenuation, the radiation hardness, and the manufacturing problems to be overcome in attaining the required geometrical precision, is needed. R & D on the production of long (~ 30 *m*) image-preserving fiber bundles and on the implementation of a readout system to handle the information should be pursued. Success in these efforts could lead to a real breakthrough by making available a high-resolution system with an enormous number of channels at a reasonable price.

(5) Monte Carlo Simulations — Detailed simulation of pattern recognition and tracking are needed to determine whether tracking is really possible in the multiple interaction environment expected at the SSC at a luminosity of 10^{33} cm^{-2} sec^{-1}.

Research and development is needed on these detector ideas beginning now, before the actual detectors are designed and proposed, if experiments are to be ready to run at the SSC in ten years. Funds should be made available for SSC detector R & D projects. Finding the people to carry out the R & D may also be a problem since so many of the best physicists are already committed to large projects. The SSC promises to be a real challenge for innovative new detectors.

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References

1. Report of the Reference Designs Study Group on the Superconducting Super Collider, May 8, 1984.
2. M. G. D. Gilchriese, "Radiation Damage and Rate Limitations in Tracking Devices," in these Proceedings.
3. T. Kondo, in these Proceedings.
4. S. Parker and J. T. Walker, PSSC Proceedings.
5. R. Ruchti, in these Proceedings.
6. G. H. Trilling, "Tracking Efficiency in SSC Tracking Detectors," in these Proceedings.
7. CLEO II Proposal, CLNS 84/609, Cornell University Report.
8. G. Feldman and J. Kirkby, "4π Detector Group Summary Report," in these Proceedings.