TITLE THE SOLENOIDAL DETECTOR COLLABORATION SILICON DETECTOR SYSTEM

AUTHOR(S) Hans-J. Ziock, Michael T. Gamble, William O. Miller,
Andrea P. T. Palounek, Timothy C. Thompson

SUBMITTED TO Fourth Annual International Symposium on the
Super Collider (IISCC), New Orleans, LA, March 4-6, 1992

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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THE SOLENOIDAL DETECTOR COLLABORATION SILICON DETECTOR SYSTEM

Hans-J. Ziock, Michael T. Gamble, William O. Miller, Andrea P. T. Palounek,
and Timothy C. Thompson

Los Alamos National Laboratory
Los Alamos, NM 87545

Representing the Solenoidal Detector Collaboration

INTRODUCTION

Silicon tracking systems will be fundamental components of the tracking systems for both planned major SSC experiments. Fig. 1 shows the central tracking system and the calorimeter of the detector being proposed by the Solenoidal Detector Collaboration (SDC). The small shaded central area is the Silicon Tracking System (STS). Despite its seemingly small size, it occupies a volume of more than 5 meters in length and 1 meter in diameter and is an order of magnitude larger than any silicon detector system previously built.

Fig. 1. The central tracking system and the calorimeter of the detector being proposed by the SDC. The small shaded region in the center is the silicon tracking system. (IP) designates the interaction point where the beams intersect and the events originate.

GEOMETRY

An isometric view of the STS is given in Fig. 2 and a cross sectional view of the system including the various support hardware is shown in Fig. 3. The STS is symmetric about the interaction point, which is located at the center of the detector. It is where the two counter-rotating proton beams collide. The STS consists of a central region in which there are 8 cylindrical detector layers of 30 cm half-length. In addition there are two forward regions each of which contains 13 annular planar arrays of detectors. The system is configured to cover a large solid angle in order to have reasonable acceptance for all the relevant particles in interesting events. The detector also provides a minimum of 6 position measurements over as large a radial extent as possible for any particle that is within its acceptance. The transition from a cylindrical to disk geometry provides a more effective coverage with a minimal amount of silicon, and also reduces the pathlength of the particles through material (*i.e.* the particles never strike the detectors at grazing incidence). The system consists of approximately 17 square meters of silicon microstrip detectors, which are subdivided into approximately 6.5 million independent channels. Considerable effort has gone into optimizing the STS design to ensure that it can perform the required physics measurements while meeting budgetary constraints.

Fig. 2. An isometric view of the STS showing the 8-layer central region and the two 13-layer forward regions.

Fig. 3. A cross-sectional view of the STS showing the various support hardware.

PURPOSE

The STS is one of three components which form the central tracking system of the detector being built by the SDC. The STS will consist of silicon microstrip detectors and possibly silicon pixel detectors. The other two components are an outer barrel tracker, which will consist of straw tubes or scintillating fibers; and an outer intermediate angle tracker, which will consist of gas microstrips. The components are designed to work as an integrated system. Each component has specific strengths, but is individually incapable of providing the overall performance required by the physics goals of the SSC. The STS contributes substantially to all of the functions described below.

Pattern Recognition

End and side views of a typical interesting event are shown in Fig. 4. Each solid line represents a charged particle's track as it traverses the detector. One of the goals of the tracking system is to find all the charged particle tracks shown. Unfortunately, the tracking system is incapable of measuring an entire track, but only measures discrete isolated points on each track. Those points must then be connected with very high reliability and very high efficiency to the other points generated by the same particle. By performing a "connect-the-dot" operation one is able to reconstruct that track. From a first glance at Fig. 4, that appears to be impossible. However, Fig. 5 shows that even the most dense region of tracks is not intimidating when magnified. The trick is to have sufficient magnification, and then to look for a set of points that lie on a constant trajectory through multiple layers. Sufficient magnification is achieved by having a large number of very small detector elements so that two different particle tracks are only rarely intercepted by the same detector element. The verification of a constant trajectory requires a sufficient number of separate layers so that the trajectory is measured many times. These requirements necessitate the large number of channels and the multiple layers of detectors found in the STS.

Fig. 4a - Side view of the tracks in the central tracker for a typical event of interest. Charged particles are represented by solid lines, neutral particles by dashed lines.

Fig. 4b. End view of the tracks in the central tracker for a typical event of interest. Charged particles are represented by solid lines, neutral particles by dashed lines.

Fig. 5. A magnified view of the event depicted in Fig. 4b showing a region of very high track density. This illustrates the low track density at the scale of the individual sensitive elements of the EIS.

Charge determination

The charged particles produced in the collision of the proton beams follow a curved path due to their interaction with the 2 Tesla magnetic field in which the tracker is located. In three dimensions, the particles follow helical paths, which if viewed from the end of the detector, will appear to be a circle, or at least a small part of one. Depending on the direction of the magnetic field and from which end of the detector the event is viewed, positively charged particles will follow a clockwise or counterclockwise arc, while negatively charged particles will curve in the opposite sense. The sense of the arc, hence indicates the charge ($\pm$) of the particle. In contrast, neutral particles are not affected by the magnetic field and furthermore are invisible to the STS. However, these particles are detected by the calorimeter. They are identified as being neutral by a lack of hits in the silicon system along the expected track of those particles from the interaction point to the calorimeter.

Momentum measurement

As mentioned above, charged particles follow a curved path while traversing the tracking volume. By measuring the radius of curvature of a track it is possible to determine the component of the particle's momentum transverse to the magnetic field. The magnetic field is parallel to the beam axis, and, if in addition one measures the angle of a track with respect to the beam axis, one can determine its total momentum. The problem is that high momentum particles follow an arc which has a very large radius of curvature and over the radial pathlength measured by the silicon detector deviates from a straight line by only a small amount (e.g. a particle with a 55 GeV/c transverse momentum has an $\sim 90\text{m}$ radius of curvature and deviates from a straight line by only about $100\text{ }\mu\text{m}$ over a 27 cm pathlength). That again illustrates the need for a very high resolution, finely divided, position measuring device. It can be shown that the deviation of an arc from a straight line increases as the square of the radial extent over which one follows the path of the particle. That is one of the primary reasons for having the other two components of the overall central tracking system. They provide measurements of the position of the particles at large radii.

Impact parameter measurement

Although the primary interaction occurs in an extremely short time ($\sim 10^{-24}$ sec), some of the exotic particles created in the reaction live for relatively long periods of time ($\sim 10^{-12}$ sec), and in that time can travel hundreds of microns. (Special Relativity helps in that the particles have such a high velocity that from our point of view they exist on the order of ten times as long as if they were at rest.) The STS has sufficient position resolution to show that some of the particles originated from a particle that decayed a finite distance away from the primary interaction point. An example of this is shown in Fig. 6. By measuring the distance the parent particle travels from the interaction point to its decay point, and the parameters of the particles into which it decayed, the initial particle can typically be identified, and its lifetime measured. The ability to determine the origin of the particles also helps in separating events from one another. Often when the two proton beams interact, there is more than one primary interaction. The multiple interactions are typically separated by relatively large distances, centimeters, from each other. By identifying where the particle tracks originated, one can clearly assign them to one interaction or the other.

Time stamping

The two counter rotating proton beams at the SSC will cross and collide with each other at the heart of the detectors once every 16 nsec and produce an average of 1.6 interactions or events. The vast majority of these are uninteresting interactions and are called minimum bias events. The preceding values translate into 100 million events every second. In addition, each minimum bias event has on the average 40 charged tracks each of which produces on the average 4 hits per layer in the silicon detector system. The interesting events that we keep for further study occur at rates on the order of 1000 per second, while the truly interesting Higgs events are expected to be produced at rates of only ~ 100 per year. In order to unravel this mess and have a chance of assigning tracks to a unique event one would like to be able to assign every event to a particular beam crossing. That requires the silicon system to measure

Fig. 6. A reconstructed detached decay vertex. The point (P) is the interaction vertex, and the point (S) is where one of the primary particles decayed as indicated by the intersection of the projected tracks from its decay products.

the time of a hit with a total accuracy which is better than the time between beam crossings, namely 16 nsec. From the above, it is evident that the silicon tracker generates a tremendous amount of information, namely $(4 \text{ hits/layer/track} \cdot 8 \text{ layers} \cdot 40 \text{ tracks/event} \cdot 100,000,000 \text{ events/second})$, or about 0.1 trillion hits every second.

THE DETECTORS

The basic component of the STS is a silicon microstrip detector. A detector for the central region is shown in Fig. 7. It consists of a $300 \mu\text{m}$ thick piece of a single crystal of high resistivity ($\sim 5000 \Omega\text{cm}$) silicon approximately 3.4 cm wide and 6 cm long. A bias voltage of approximately 100 V is applied between the top and bottom surfaces of the detector. When a charged particle passes through the $300 \mu\text{m}$ thickness of the detector it ionizes a number of the silicon atoms, creating about 24,000 electron-hole pairs. The positively charged holes are attracted to the negatively biased top surface of the detector, while the electrons are attracted to the positively biased bottom surface. The collected electrons and holes are the detected signals. Position information is obtained by using photolithography to subdivide both the top and bottom surfaces into a series of fine strips. The spacing, or pitch, of the $10 \mu\text{m}$ wide strips is $50 \mu\text{m}$. The strips span essentially the full 6 cm length of the detector. There are 640 strips that cover the 3.2 cm active width of the detector on both the top and bottom surfaces. The bias voltage is actually applied only to the strips which therefore alone collect the generated electrons and holes. The electrons and holes move respectively to the closest strip or pair of strips on the bottom and top surfaces and thus generate a signal only on those strips. By reading out each strip individually one can isolate where the charged particle passed through the detector. The signals collected on a single strip are amplified and compared to a threshold value and only a hit (1) or miss (0) value is stored. There is a unique amplifier, comparator, and data storage array assigned to each strip. This is done using very large scale integration (VLSI) electronics which are mounted on the detectors and have the same $50 \mu\text{m}$ pitch as the strips. If a strip is hit, the position of the center of that strip is assigned to that hit. Thus the maximum position error is half the strip pitch or $25 \mu\text{m}$, and on the average the error is even less. The resolution of the

Axial Strip Side Structure

Fig. 7. a) A top view of a silicon microstrip detector. b) A side view of the detector illustrating the collection of the generated electrons and holes.

position measurement from a single side of the detector is about 14 μm in one dimension. The coordinate in the second dimension is determined by having the strips on one side at a small "stereo" angle with respect to those on the other side. The value of the coordinate in the second dimension is given by the the region over which the hit strips on the top and bottom sides of the detector overlap. That, and the concept of ghost hits are illustrated in Fig. 8. The maximum resolution in the second dimension would clearly be best if the stereo angle were 90°. This, however, also maximizes the problem of ghost hits.

For example, when 3 particles strike a detector, 3 strips on both the top and bottom surface of the detector are hit. If the stereo angle is 90°, the 3 hit strips on the top surface cross the all 3 strips on the bottom surface and one has a total of 9 places where the strips overlap. There are thus 3 real top bottom combinations, together with 6 ghost combinations. Since there is no way to correlate a specific hit on the top surface with a given hit on the bottom surface, there exists a very large ambiguity. By reducing the stereo angle, a strip on the bottom surface crosses only a few strips on the top surface, greatly reducing the chance of producing ghost hits. The undesirable consequence of reducing the stereo angle is the reduction of the resolution in the second dimension, as now a given strip on the top surface overlaps a given strip on the bottom surface over a longer distance. However, since the required resolution is much poorer in the second dimension and it is very important to

Fig. 8. An illustration of a double sided detector and the concept of ghost hits. Note that the small angle stereo detector has no ghost hits, while the 90° stereo angle detector has 6 ghost hits.

minimize the number of ghost hits, a small stereo angle is chosen. The SDC STS stereo angle is 10 milliradians, which corresponds to a resolution of approximately 1 mm for the second coordinate. The position in the third dimension is determined by the accurate placement of the detector. To obtain sufficient accuracy in the different dimensions, it is required that the detectors be positioned to an accuracy of $25\ \mu\text{m}$ and that they maintain that position to an accuracy of $5\ \mu\text{m}$ over long periods of time.

CHALLENGES

The large particle fluxes, the short times between beam crossing, the high channel count, and the required very high position measurement accuracy pose challenging problems that must be solved. Furthermore, to avoid degrading the measurements, the solutions must be achieved using only a minimal amount of material. An additional constraint is that only low-Z materials are allowed. If that were not difficult enough, the solutions must also be affordable. The requirements and problems facing the STS group include:

- The large particle fluxes expose the detectors and electronics to radiation doses of several Megarads over the lifetime of the experiment.
- The 6.5 million channels of amplifiers, comparators, data storage, and readout are required to fit on the ends of the detectors. As the signals are very small, the electronics must produce very little noise and be immune to noise. Furthermore, they must operate at speeds in excess of 60 MHz and consume very little power; the design goal is 1 mW/chan.
- The 6.5 million channels of electronics, even at 1 mW / channel, require a total of $\sim 2000\ \text{A}$ of low voltage current, and generate 6.5 kW of waste heat which must be removed.
- In addition to removing the waste heat, the STS must operate at approximately 0°C to reduce some of the effects of radiation damage and improve the detector performance.
- The detectors must be placed with an accuracy of approximately $25\ \mu\text{m}$ and must remain positionally stable at $\sim 5\ \mu\text{m}$ for periods of many months. The stability must be achieved over the entire 5 m tracker and must include freedom from vibrations.
- The detector must be maintainable and repairable.

CONCLUSION

Because of the formidable problems and large list of secondary issues associated with each one, an incredible amount of work remains. Nevertheless, several years of research and development work, summarized in references 1 and 2, has significantly assisted in developing solutions to these problems. The next several years of research and development will go to implementing and testing the solutions on a wide variety of prototypes.

REFERENCES

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