# DETECTORS AT THE SUPER ACCELERATOR

Mel Shochet
University of Chicago

This article describes a possible detector at the SSC as well as the nature of each of the major detector systems and some of the difficulties that may come up. The major problem with these detectors is the enormous number of individual detector elements in the system which might be as high as a few hundred thousand. Each element will have to be read-out electronically at high speed, with good precision both in amplitude and in time, and over a large dynamic range. That presents significant design and cost problems.

There are many outstanding problems in elementary particle physics that hopefully will be solved with the SSC. If so, then the understanding of particle physics should be significantly broadened. This could occur, in part, by discovering and studying the properties of very massive particles heretofore undiscovered. Even at the SSC, production of such particles will be relatively infrequent.

Figure 1 is a schematic of what such a collision might look like. When two protons collide, massive particles may be produced in the process. A massive particle will decay essentially instantaneously into a large number of lighter particles. Some of those particles are metastable. In the figure, the massive particles which decay rather quickly have been indicated by dotted lines. The distances for those decays to occur are something on the order of 100 to 150 microns. The particles from the decay are often produced in clusters. In order to discover and then study the properties of the massive particles, it is necessary to measure the characteristics of each of the final-state particles. The detector will thus have to locate secondary vertices with high efficiency. That means that the detector will have to be able to determine that a metastable particle had been produced and that it decayed 100 to 150 microns away from the primary vertex. The detector will also have to accurately measure the directions of all the particles produced in the interactions and accurately measure the energy of each particle or in the case of very tightly clustered particles, the energy of the cluster.

To give a feeling of the environment that this detector will be working in, one is talking about studying processes which are rather rare so that they might occur at the rate of one event per hour or even one event per day or per week. This is to be compared to the total interaction rate of something on the order of ten million per second. In one hour the detector must pick the single most interesting and unusual event out of the ten billion interactions that occurred in that hour. In each of

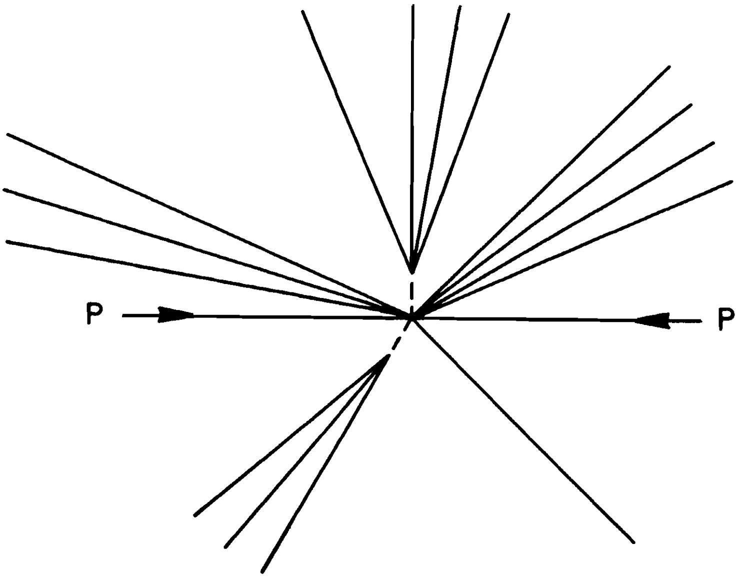

Fig. 1. Schematic of what a typical collision might look like. The incoming protons have arrows on their lines.

these events some 50 or 100 particles will be produced. One will therefore have to build a detector with very good time resolution because of the fact that on an average there will be an interaction every 100 nanoseconds. Very good spatial resolution is needed to detect the secondary vertices and measure the directions of these particles with precision.

Figure 2 is a simulated picture of particles coming out of an interesting interaction superimposed on four other non-interesting events to illustrate the importance of time resolution. Notice that an enormous number of particles come out. Time resolution is really at a premium to reduce the number of events that appear to occur simultaneously.

## General Detector

What might such a detector look like? Figure 3 is an illustration. Notice the distance scale of two meters. There is a vacuum pipe bringing the particles into the interaction region. The particles interact in the center. Very close to the interaction region there is a vertex detector to locate any secondary vertices. Following that is a large region filled with the central tracking chamber. The function of that device is to

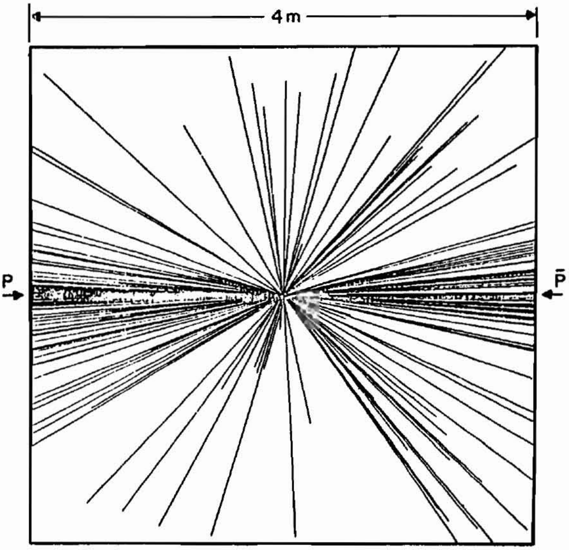

Fig. 2. Simulation of an interesting event superimposed on four dull events.

accurately measure the directions of all the particles produced in the interaction. A superconducting magnetic coil is incorporated to produce a large magnetic field in the center. With the magnetic field the charged particles don't move in straight trajectories but have curved trajectories as they are influenced by the magnetic force. A measurement of the momentum of the individual particles can be made by measuring the radius of curvature of those trajectories. That measurement is also the responsibility of the tracking chamber.

The electromagnetic calorimeter is just outside of the central tracking chamber. The calorimeter is a device which measures the energy of a particle or a very tightly clustered group of particles. The calorimeter will be highly segmented to avoid summing the energy of two particles or clusters that are close together. This segmentation must occur many times in both the axial and azimuthal direction. Individual elements look toward the vertex. The energy of the particle must be measured very well. The general technique is to have the particle interact in a dense material, which is interspersed with detecting layers. In the electromagnetic calorimeter an electron or a photon will interact close to the front end and then produce some additional charged particles. A detector layer then samples how many particles there are. Then there is another layer of very dense material in which additional electrons and photons are produced, thus building up a cascade. As the energy is absorbed

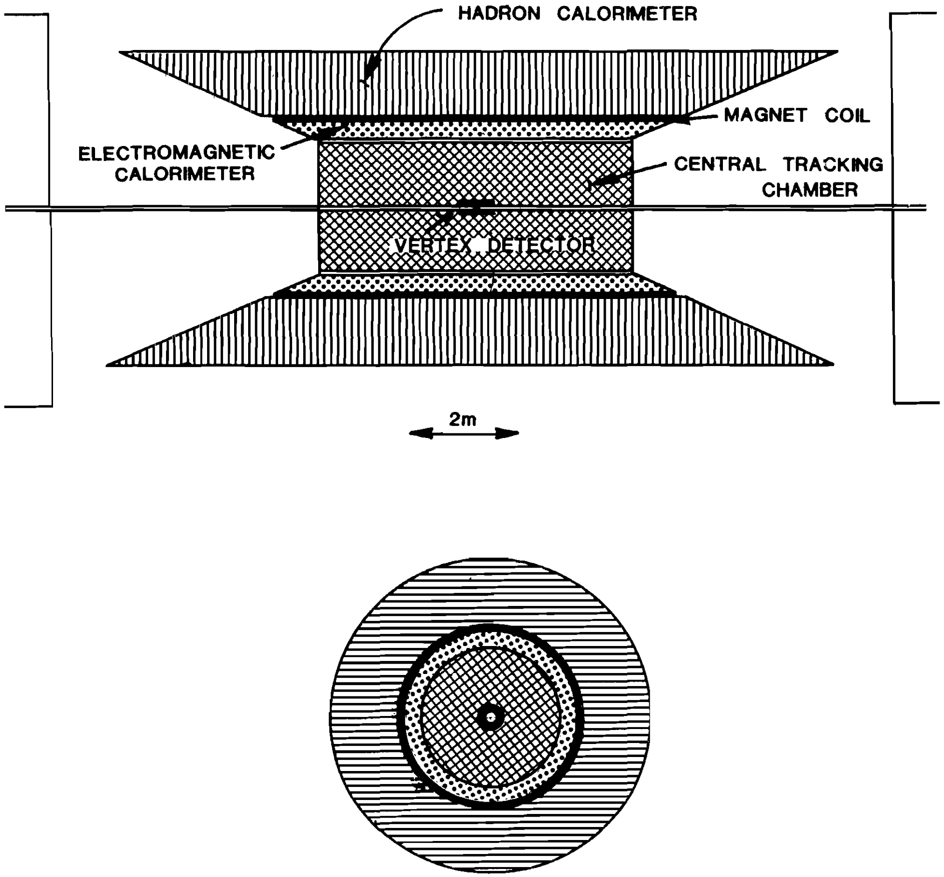

Fig. 3. Schematic of an SSC detector. The upper view is along the direction of the colliding beams, the lower view is transverse to the beams.

the cascade dies out before the back of the detector. By sampling the number of particles at many depths in the calorimeter, it is possible to get a very good estimate of the particle that entered.

Finally, there is a hadronic calorimeter outside the electromagnetic calorimeter. Particles other than electrons and photons will also deposit their energy when they strike heavy material in the same characteristic cascade but the cascade is longer so that more material is needed to measure those particles' energies. Again, the same technique is used with many layers of detectors sandwiched between layers of heavy material.

The regions forward and backward along the beam pipe contain similar kinds of detectors to cover the regions which are left open in the central detector.

## Vertex Detector

At the moment, the detector of choice for the vertex detector is a silicon strip detector which is made out of a depleted semi-conductor layer with metallic conductor on each side. A particle passes through, ionizes the material, and the charge is collected. If very narrow strips of metal electrode can be used, one can get spatial resolution on the order of five to ten microns and can separate two particles that are as close as fifty or one hundred microns apart. With such resolution, one can do an extremely good job of finding secondary vertices which are no more than 100 to 150 microns away from the primary vertex. Figure 4 shows how such a detector might appear. Typically one might have four layers of these detectors. For a small section of the silicon strip detector, 5 millimeters wide by 50 millimeters long, there would be strips every 50 microns. One hundred detector channels would be required for that 2.5 $cm^2$ region alone.

What are the problems associated with such a device? First, with strips (essentially detector elements) every 50 microns and with many layers in a cylindrical system, there are between ten thousand and one hundred thousand channels, depending on the longitudinal segmentation, i.e., whether the strips run the whole length of the detector or are broken up into segments with each segment readout. The signals are low level, thus requiring amplification near the device to avoid noise pickup. There will be problems of having to multiplex these channels for readout since it is not possible to bring out $10^4$-$10^5$ cables from the center of the detector. What is needed is a chip which will amplify with very low noise, will integrate the signal, will store it, and will produce a multiplexed readout. If such a chip could actually be imbedded into the silicon detector itself, that would increase reliability because one would not have to have the problems of external mechanical connections. This would result

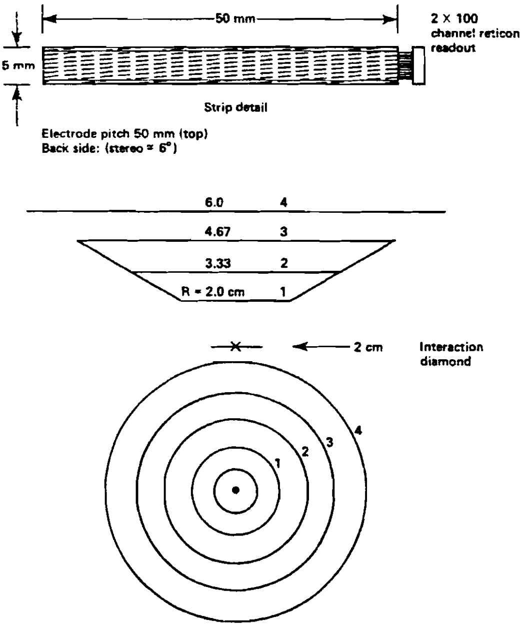

Fig. 4. Silicon strip vertex detector.

in a significant reduction in the number of external connections, and represents both a cost saving and an obvious improvement on reliability.

Second, there is a problem of radiation damage. With this detector as close as it is to the interaction point, the detector will see between $5\times10^5$-$5\times10^6$ Rads of radiation per year. Normal silicon detectors start deteriorating after about $2\times10^5$ Rads, so there is a problem. MOS-based amplifiers usually start to run into trouble after about $4\times10^3$ Rads. Clearly, there is work that has to be done on producing devices which are radiation hardened.

There is one other problem associated with a silicon device of this size and that is the fabrication problem due to the size limitation for a single crystal of silicon. That has led a number of researchers to study the possibility of using non-crystalline semiconductor detectors for such a device. That is research which is in its very early stages.

## Central Tracking Chamber

The next detector element is the central tracking chamber. It is required to measure the directions of all the particles produced in the collision. Figure 5 illustrates the situation as the beam would see it with a typical particle coming out and being bent by a magnetic field. The chamber contains many fine sense wires strung in the volume and connected to a high positive voltage. There are other wires not shown in Fig. 5 which are field shaping wires which carry the negative voltage. As a particle passes through the gaseous atmosphere in the chamber, typically, argon/$CO_2$ or argon/ethane, it ionizes the gas. The electrons that are freed in that ionization drift with a constant velocity toward the nearest sense wire. The length of time that it takes for the electrons to reach the nearest wire measures how far the particle passed from the wire. Thus the time of arrival at a wire measures the angular position of the particle at the radial position of the wire. A third coordinate is also needed, the position along the wire in the direction of the beam. That can be obtained by using wires of finite resistivity so that when charge is deposited at some point along the wire, the resistance from that point to the two ends of the wire are different and the charge which arrives at the two ends will divide accordingly. The charge that is collected is amplified on each end and the ratio of those signals gives the position along the wires. That way, one can get a three-dimensional readout of the particle's position.

There can be a very high local track density due to the fact that there are heavy particles each of which decay into many secondary particles. In addition, the maximum drift time for electrons should be rather small so as not to confuse tracks from one interaction with the tracks from the next interaction which on average occur 100 nanoseconds later. Those two constraints of high spatial density and the need to collect the charge in a short period of time lead to a requirement that the distance between sense wires in the drift direction be less than 1 cm. In addition, a particle should pass at least 100 wires as it moves radially outward from the interaction point. When those numbers are put together with the typical size of the tracking chamber, one finds a requirement of approximately one hundred thousand wires each with amplifiers on both ends.

The electronics must give a time resolution of a few nanoseconds so that the location of the particle can be measured with good precision. Good amplitude information is needed to measure the location of the particle along the wire. Because of high multiplicity, which leads to high track densities, good two particle resolution is also needed. This means that if a signal on the wire appears to show two pulses close together in time, it is desirable to detect the two pulses and to measure their amplitudes and their times of arrival. The net result is a readout system containing flash ADC's which can sample 100 or 200 million times a second. Such a system produces an enormous amount of data. Something like a ring buffer is needed to store all the information, because it takes a finite time to decide that the interaction that occurred was one that should be studied

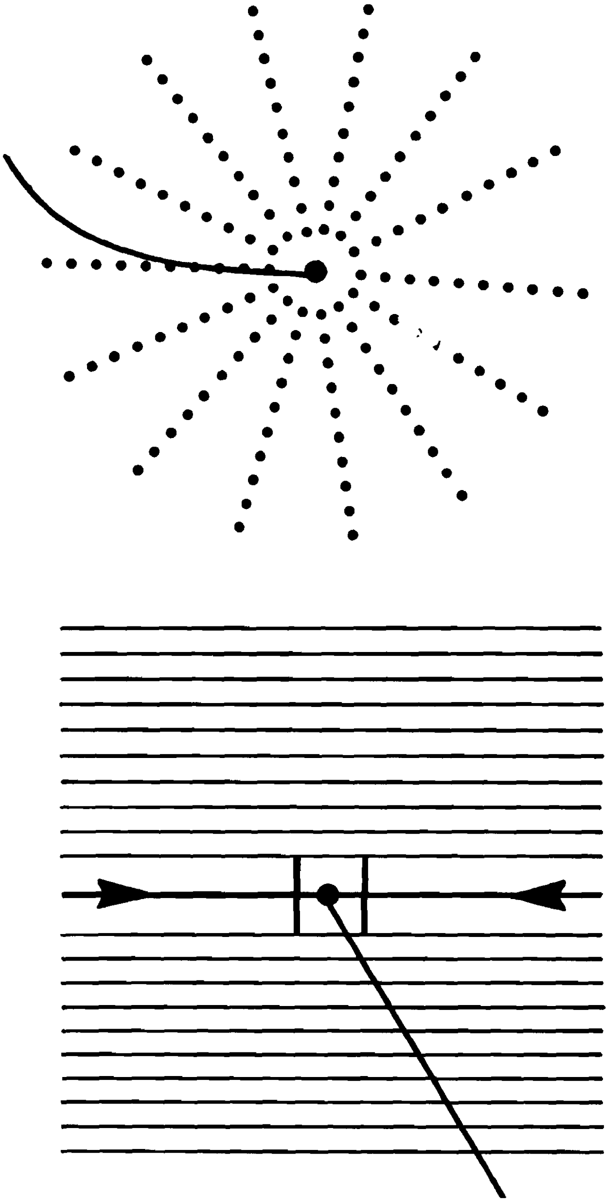

Fig. 5. Wires for central tracking detector. The top view is along the particle beams direction; the bottom view is transverse to the beams.

in more detail. It is not possible to send all of that information up to a computer, because there are one hundred thousand wires each with two amplifiers and each with many samples. A system of data compression is thus needed so that only the channels that have non-zero amplitude are sent up. Again, the main difficulty is that there are approximately one hundred thousand channels of electronics and the requirements on each of those channels is extremely high.

## Calorimetry

The next part of the detector is the calorimetry. This is the device which measures the particle energy. A very fine grain division is needed in the electromagnetic calorimeter. The segments which are individually read-out form a geometry which is projective in depth. This arrangement results in tower-like elements each of which points back to the interaction region. This is done so that an electron produced at the interaction region enters one segment and deposits its energy in that one tower as the shower develops in depth. Projective geometry is needed to avoid ambiguities because of the large number of particles produced in each collision.

Electrons play a crucial role in trying to locate and study very massive particles in high-energy collisions. The ability to find electrons near other particles is important. As noted earlier, electrons and photons deposit their energy in a different characteristic depth pattern compared to hadrons; they deposit their energy early. Other particles deposit energy more uniformly throughout the depth of the detector. Since it is necessary to identify an electron that is close to other particles, it is necessary to have a maximum size for each individual tower of roughly ten centimeters on a side. Three or four segmentations in depth is necessary to see the characteristic development of the shower and be able to separate electrons from other particles.

Since it is important that energy information from the event not be lost, it is necessary to minimize the dead space between the calorimeter elements. Also, very good energy resolution is needed. It is thus necessary to be able to associate a voltage that comes out of one of these detector elements with the energy of the entering particle. The response should be uniform to different types of particles so that thirty millivolts on the detector corresponds to five GeV of energy, independent of the kind of particle that went in. Further, in order to make sense out of the information, the response should be uniform over the surface area so all cells will have the same response or at least a response that can be calibrated and is rather constant in time. A scheme is therefore needed for maintaining the calibration of such a system.

When all of those requirements are put together, the detector that at present seems most feasible is made of uranium and liquid argon. It would consist of plates of uranium separated by thin gaps of liquid argon. The ionization in the liquid argon would be read out with copper pads. As particles go through the uranium and interact, the secondary particles that are produced pass through the liquid argon and produce ionization. The ionization is collected by the copper pad electrodes. The problem here is that very small signals are produced so that the detection system and amplifier system must have low noise. A typical system would contain approximately 25,000 channels, in which the amplitude measurement has to have at least a ten bit dynamic range and an eight bit resolution with very low noise. One has to have a reliable and relatively inexpensive way to maintain the calibration so that each of these 25,000 channels can remain calibrated to one half per cent or better. So again, the requirement on the electronics is not trivial.

## Triggering

Interactions are occurring at the rate of ten million per second and about one per hour is really interesting. How is that one picked out? It should not be at random or someone will to have wait a long time to see the event of interest. Thus we come to the question of triggering. How are the interesting events selected?

How much data is there for each one of these interactions that occurs? First of all, assume a sparse scanning technique that records only those channels containing non-zero data. If no particle struck a given wire at a given sampling time, nothing is recorded for that wire. But there are still as many as one hundred particles in an event. Each of these tracks passes by one hundred wires in the central tracking chamber. Each one of those wires has amplifiers on two ends. Typically there are five samples out of the flash ADC encoders for a track. That gives one hundred thousand bytes of information for the event. However, since it is a sparse scan, it is necessary to indicate which wire produced each signal. In addition, the time of the digitization must be indicated. When all of that is put together it gives something like $4\times10^5$ bytes of tracking information, in addition to calorimetry and vertex detector information. Conservatively, there would be approximately a half a million bytes per event. Just to indicate what that means, two or three events per second would saturate a 6250 BPI, 200 inch per second magnetic tape drive. A three month run, recording two or three events per second, would produce something like $5\times10^{12}$ bytes of data to be analyzed. That is a problem all in itself. (Some of these issues were discussed in last year's Fermilab Industrial Affiliate Round Table on Supercomputers.) What is needed then is a system which can accept events at an average rate of one every one hundred nanoseconds and select the one most interesting event out of each ten million so that about one event per second can be written on magnetic tape.

How is that selection done? It can be understood by focusing on one characteristic of these events. That is the fact that in events of interest there is a local concentration of very high energy deposition in the calorimetry. In a typical uninteresting event, there are lots of particles going in all directions. Generally, each one of those particles deposits relatively little energy. This results in a uniform energy deposition over the whole detector. For events of interest there can be a very high-energy deposition in small local regions. What is done is to locate as quickly as possible each one of these clusters of energy and classify them. One finds out where they are in the detector and whether they are likely to be electrons or whether they are likely to be jets of other particles. Once that information is available for all of the clusters and all of the electrons, it can be put together in a list and the overall topology of that event examined to see if it is one that is likely to be of interest.

The strategy that one employs is to reduce the number of interactions, the number of events that one is looking at in a series of steps. Initially, very fast decisions must be made because the number of events is enormous. Then most of the events are removed and relatively few remain so that one can afford to spend more time thinking about each one of the remaining events. Thus decisions that take more time are left to a period when most of the events have been removed from the data sample.

Table I shows an example of how this might be done in a series of steps. One starts out with ten million events per second. Only those elements of the calorimetry which have energy above some reasonably high threshold are examined. All of the elements of the detector which have low energy deposition aren't even looked at. The energy of all the clusters is then added and that total energy has to be above a certain level. If so, it is a potentially interesting event. That decision can probably be made in about three hundred nanoseconds, but that does not cost live time in the detector because storage elements are used that make it possible to make the decision in real time. That is, delay lines are used for the analog signals, and ring buffers are used for digital signals so that the data is slowly percolating through the system while the decisions are being made. No data has been lost. By the time it gets to the end of the percolator, a decision must be made whether or not to keep that event for further analysis. With such a scheme the number of events per second can be reduced to something on the order of a $0.5\times10^5$.

Table I.

| # of Events/Sec | Criteria | Time Required |
|---|---|---|
| $10^7$ | $\Sigma E_i$ for $E_i > E_{TH}$ | 300 nsec (dc-use delay lines & ring buffers) |
| $1/2 \times 10^5$ | E of highest energy cluster<br>E of highest e-like cluster<br>Missing energy | 1 μsec (5% dead-time) |
| 5000 | Find all clusters<br>Determine their energies, locations<br>Identify as e or jet of particles<br>Find μ's<br>Take "interesting" topologies | 10 μsec |
| 50 | Refine above information | 2 msec (read out all data) |
| 10 | Analyze in dedicated processor | 100 msec - 1 sec |

At that point, it is possible to take about one microsecond to look at each one of those events in more detail. That has a cost; about 5% of the detector real time will be lost looking at interactions. This is something that one can live with. At that point the highest energy cluster in the detector can be located very quickly and its energy accurately determined. The highest energy electron cluster in the detector can also be located and its energy determined. All of the energy in the detector can be added up and compared with the energy of the protons that have collided. There is something that hasn't been seen if the energy in the detector is much less than the energy of the initial particles. It has already been noted that electrons are very important for discovering and studying new massive particles. Electrically neutral relatives of electrons called neutrinos are also important. The neutrinos do not interact in the detector. If they carry a lot of energy, that energy will escape and the detector won't see the full energy of the collision but significantly less. That situation can be detected in approximately one microsecond.

One can make some requirements on those parameters and reduce the event sample to something like five thousand per second. Then one can take another ten microseconds to calculate.

For the collider detector that is being built at Fermilab all of the clusters in the system are found. At the University of Chicago, electronics have been designed which can find arbitrarily shaped clusters of energy in such a system without any prejudice on the shape every 150 nanoseconds. Their energies and their locations can be determined with high precision. Likely electrons or jets of other particles can be identified. The same holds for muons, electron-like objects which are identified in another way which won't be discussed here.

This essentially gives the overall topology of the event. The interesting events are finally defined by the software. What the software accepts as interesting can be adjusted as more is learned about the physics at these very high energies. When some new kind of process is found that wasn't anticipated, the software can be modified so that none of the new events are missed.

At that point the number of events has been reduced to a rate of fifty per second and two milliseconds can be taken to read all the data out of all of the subsystems into a large buffer. During that time the information can be refined, and some additional calculations made to reduce the number of events to ten per second. Each of those ten events could be sent to its own dedicated processor which could take 100 milliseconds per second to analyze the event and determine whether it is really of interest and whether or not one wants to keep it on magnetic tape. It is clear that the problem here is basic design. One is trying to make a decision involving a very large number of channels very quickly with high precision.

These are just a few comments that are based on a preliminary analysis of the problems that will face detector designers for the SSC. It is clear that when serious design of these detectors begins, problems will be found that haven't even been thought of yet. That's when the help of industry will be needed to solve them.