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SSC Subsystem R&D Proposal to Develop a Silicon Tracking System

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SSC Subsystem R&D Proposal to Develop A Silicon Tracking System

I. Introduction

We are proposing a program of R&D aimed at developing a large-scale charged particle tracking system matched to SSC physics, and to the challenging SSC environment. The tracking system is based on silicon detectors and associated VLSI electronics. The system has fine spatial precision, granularity and two-track resolution allowing superb pattern recognition and momentum measurement. Substantial multiplexing is provided in the detector. Our proposal builds on substantial silicon detector experience from experiments at SLAC, FNAL and CERN, as well as more than two years of work on detector/event simulations, development of silicon electronics and radiation studies for the SSC.

The silicon tracker for the SSC is a non-trivial extension of existing silicon systems. Significant progress must be achieved in the area of radiation hardness, low power electronics, cooling/heat dissipation, mechanical supports/alignment for large systems, and integration of the silicon into the experiment trigger. Research on most of these issues is already well underway. More progress is needed; and these issues are central to the major milestones/goals of our proposal.

To identify the critical physics/tracking issues, and to address/solve the technical issues, we propose the following program of R&D:

(1) Monte Carlo study of the physics potential of a good tracking system, especially for Higgs detection.

(2) Design of a tracking system matched to the physics potential of the SSC and consistent with the limitations of the technology and the engineering complexity of a large system. This includes the development of a detector-tracking simulation, leading to a pattern recognition program and track-fitting program which allows careful assessment of the detector efficiency, the impact on tracking of the detector configuration and the effect of material on system performance.

(3) We plan to undertake a realistic engineering design of the mechanical structure needed to hold and cool all of the detector elements and associated electronics and cabling.

(4) We plan to continue ongoing work on electronics readout schemes and on the development of sufficiently fast, radiation resistant, electronics. This is an area in which industry is moving forward rapidly and where we have done generic R&D to familiarize ourselves with the technical questions. We plan to assess critically what can be expected in the future and how to best make

decisions to utilize the latest technology while maintaining a conservative detector completion schedule.

(5) The detection system we envision consists of pixel detectors at small radii ($r \lesssim 10$ cm) and strip detectors covering larger radii ($r \lesssim 50$ cm). R&D on the development of suitable pixel detectors is part of a separate generic R&D proposal. We plan, within the scope of this proposal, to look at the physics potential and integration of pixel detectors into a tracking system. We include within the proposal the development of double-sided strip detectors in conjunction with silicon-detector manufacturers, a study of single-sided strip detectors with short strips, with hits recorded digitally, and a joint effort with Westinghouse to produce detectors and integrated readout. The strip detectors would make up the bulk of a large-scale tracking system. Along with the mechanical engineering work, the development of optimized production quality detectors is our major technical objective.

(6) We plan to begin work on second-level trigger possibilities using strip detectors. Since the momentum precision is inherent in the geometrical hit pattern, it should be possible to have available track information for triggering by using hit patterns.

(7) A result of our work will be a plan on how to build the tracking system, a cost estimate, and milestones for a realistic program. It will include a verification of the mechanical design and cooling using prototypes.

We discuss below in more detail, each of the areas outlined above. We include a list of the individuals committed to work on each area of the R&D. The proposal includes industrial participation in the area of fast bipolar electronics (Silicon Dynamics), rad-hard CMOS (UTMC), detector development (Hamamatsu in Japan, SI in Oslo and MBB in Germany), and mechanical engineering (Westinghouse). We also plan to use some unique facilities for prototype detector production at LBL and the Stanford Center for Integrated Systems and some unique engineering skills available at LANL. We expect the whole group to meet periodically and review progress in all areas and that the groups working on the different areas will submit written progress reports to the group as a whole.

II. Physics Capabilities and Goals

We envision the silicon-tracking system as a part of a large solenoidal detector whose dimensions are mainly determined by calorimetry requirements. The role of the silicon tracker is to provide charged particle track finding and momentum measurement over a rapidity range $|y| \lesssim 2.5$. Some explicit goals are listed below. These physics goals are based on several studies, in particular the work at last summer's Snowmass Workshop.

(1) Measurement of dE/dx in a few inner layers to search for oddly ionizing particles and to reject overlapping electron-positron pairs from photon conversions.

(2) Precision vertex reconstruction to look for long-lived particles and to study B decays in the central region. The intermediate mass Higgs decay to $b\bar{b}$ may be measurable above backgrounds for masses near 100 GeV. We expect to investigate this more carefully as part of our simulation effort.

(3) In the past, leptons have often been indicative of new physics and we design our tracking device in anticipation of a similar role at the SSC. The tracking detector allows excellent momentum measurement for electrons and muons and powerful background rejection by matching the track parameters of the leptons with information of the other detector systems: for the electrons, the energy E from the calorimeter is matched to the momentum p measured with comparable accuracy in the tracker in the few hundred GeV momentum range; for muons, the track seen in the outer muon identifier is matched to the track found in the precision tracker.

(4) A mass resolution for $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ comparable or better than the spreading from the Z width, allowing maximum background rejection for Z's originating from decay of a Higgs of mass up to about 1 TeV. This requires $\sigma_{P_\perp}/P_\perp \sim 10\%\ P_\perp$ (TeV) for $|y| \leq 2.5$.

(5) The simplest Standard Model Higgs to four charged-lepton decay typically results in only about 100 useful events per SSC year. To avoid losing valuable data it is essential to have a very good tracking efficiency for these events, especially since all four tracks have to be correctly measured. The silicon tracker should have as a goal a tracking efficiency $\geq$95% per lepton for this channel in the rapidity range $|y| \lesssim 2.5$.

(6) For the case of several Higgs bosons, the number of events expected for each Higgs decaying to four leptons is reduced compared to the simplest Standard Model. For this case, each Higgs particle is correspondingly narrower. Thus, a system with sufficiently good mass resolution will provide a fixed signal-to-noise ratio in the Higgs invariant mass—where the reduction in events is compensated by the narrower width. Thus, good mass resolution allows sensitivity to a wider range of models. We will look at this issue in more detail and expect to set as a goal for the detector a Higgs mass resolution a few times smaller than the simplest Standard Model width for Higgs in the few hundred GeV range.

(7) The use of tracking and event multiplicity measurement should be a useful tool in separating the decay of a very heavy Higgs to $\underset{\hookrightarrow \ell\nu}{W} + W \rightarrow 2$ Jets

and $\underset{\hookrightarrow \ell^+\ell^-}{Z} + Z \rightarrow 2$ Jets from mixed Electroweak-QCD backgrounds. These signal processes have much higher rates than the decays involving leptons only. We expect to complete a detailed simulation of the signal and background processes in order to better understand the potential of this technique for Higgs discovery.

(8) Silicon provides the ability to reconstruct most of the tracks in very high multiplicity high $P_\perp$ events, up to 1 TeV in $P_\perp$. This could be important in understanding jets and searching for new physics. It will allow reconstruction of leptons in jet environments. In addition, it provides the ability to select leptons from primary or secondary vertices.

(9) In order to use the multiplicity or other event characteristics it is necessary to reject tracks from second events in cases where a time bucket contains two or more events. This can be done efficiently using the tracking vertex information.

(10) If the calorimetry integrates over more than one time bucket, the silicon tracking, which provides excellent bucket separation, can be used as a cross check that potentially interesting physics signals are not due to unusual multiple event overlaps.

III. Geometrical Detector Arrangement

A. Simulations

We have been looking at the organization of a silicon tracker for the past two years. This has resulted in a set of scaling rules to guide the geometrical design of such a tracker, as presented at last summers Snowmass conference and enclosed as Appendix 1. We have begun a Monte Carlo study of such a design and plan to use our simulation to evaluate the proposed design more thoroughly, including a study of the effects of material on electron tracking and other features of the detector. We have included a pixel vertex detector and a straw outer chamber in our simulation, and plan to study the effects of misalignment and individual component resolutions. We also plan to look at alternative arrangements including tower geometries, to see how much simplification can be accomplished while maintaining performance. In general, our philosophy is to look for the simplest configuration consistent with our physics goals.

The tracker from our initial study is shown in Fig. 1. It consists of eight pairs (superlayers) of double sided-detectors, providing 32 measurements per track. The longitudinal coordinate is resolved using small angle stereo. Such a detector offers position resolution $\sim 5\mu$m, two-track separation $\sim 100\mu$m, and would have an

occupancy of about 10^{-3} at the SSC design luminosity. In a 2.5 Tesla magnetic field it provides a mass resolution for leptons from Z decay shown in Fig. 2 and a mass resolution for Higgs to four leptons shown in Fig. 3. It will provide a mass resolution for the Z^0 matched to the Z^0 intrinsic width and a Higgs mass resolution typically a few times better than the Higgs width in the simplest Standard Model to allow the search for a more complicated Higgs sector.

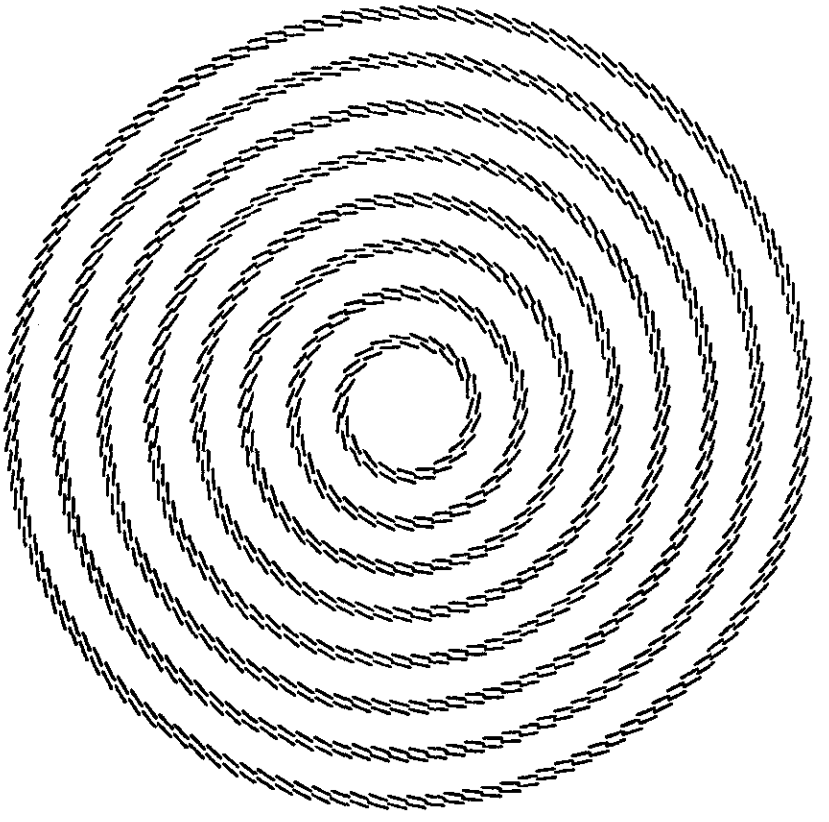
We show in Fig. 4 the tracks with $P_\perp$ >500 MeV for the decay of a 1 TeV Higgs to $\underset{\hookrightarrow \ell\nu}{W} + W \rightarrow$ 2 Jets and a typical mixed electroweak-QCD event. These are generated using the PYTHIA simulation program. The signal and background events look quite different and, in general, do not look too difficult to track provided the detector can handle the SSC occupancy. We will carefully study the tracking efficiency in such events and in the even more difficult case of 1 TeV QCD jets to quantify the capabilities of the detector.

Finally, we plan to look at mixed systems consisting of silicon inside of 50 cm and another tracker at a larger radius $\sim$ 150 cm. We want to understand the possible benefits of such a mixed system, since it is likely that such a system will provide a better optimization for overall tracking in a realistic experiment. Taking a 2 Tesla magnetic field, we can parametrize the momentum resolution in the central region of rapidity as a function which depends on the position resolution in both systems and the geometrical arrangement

$$\frac{\sigma_{P_\perp}}{P_\perp} = \left(\frac{\sigma_{\text{silicon}}}{\sigma_0}\right) f\left(\frac{\sigma_{\text{outer}}}{\sigma_{\text{silicon}}}\right) \; P_\perp(TeV),$$

where σ_{silicon} = position resolution achieved, σ_0=design goal for position resolution, x = $\frac{\sigma_{\text{outer}}}{\sigma_{\text{silicon}}}$ = resolution of the outer tracker relative to the silicon. Since, for the outer tracker, it is the outer radius measurements which matter most, for simplicity we treat the outer tracker measurement as effectively one average measurement at a radius of 1.5 m. For the detector in Fig. 1, we show in Fig. 5, f(x) as a function of x= $\frac{\sigma_{\text{outer}}}{\sigma_{\text{silicon}}}$. We have taken for the figure a value of $\sigma_0 = 6\mu$m. For 25 μm strips, the geometry gives a resolution of, at worst, 7 μm, while signal spreading should allow an improvement which could be as good as 3.5 μm. From the figure, we can get the following momentum resolutions for a mixed system:

σ_{silicon}	x = $\frac{\sigma_{\text{outer}}}{\sigma_{\text{silicon}}}$	$\frac{\sigma_{P_\perp}}{P_\perp}$ (at 1 TeV)
6 μm	x $\gg$ 10	10.9%
6 μm	5	5.3%
30 μm	1	7.8%



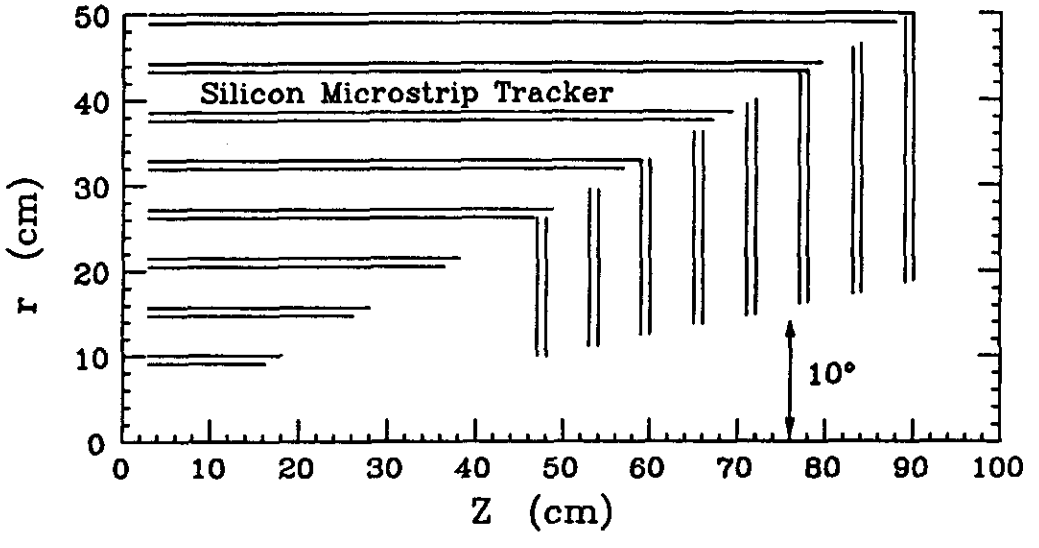


Fig. 1. Silicon Tracking System.

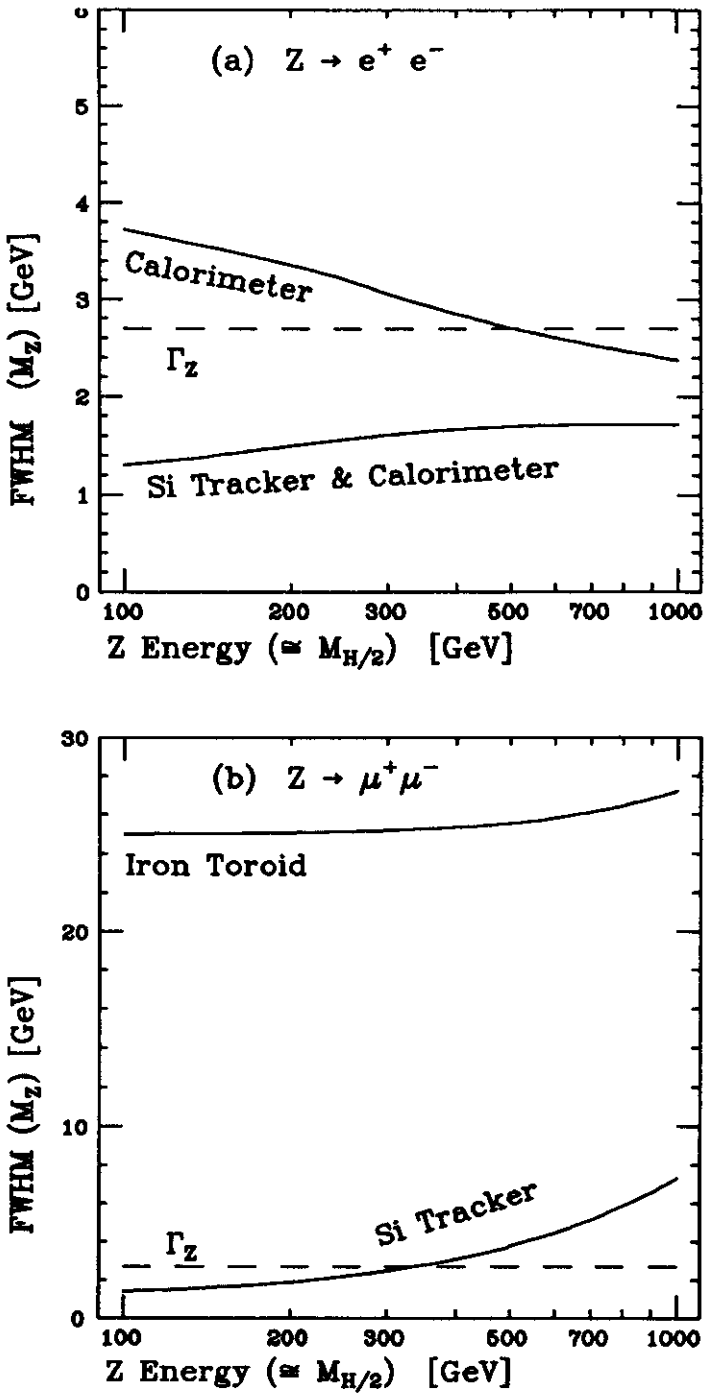
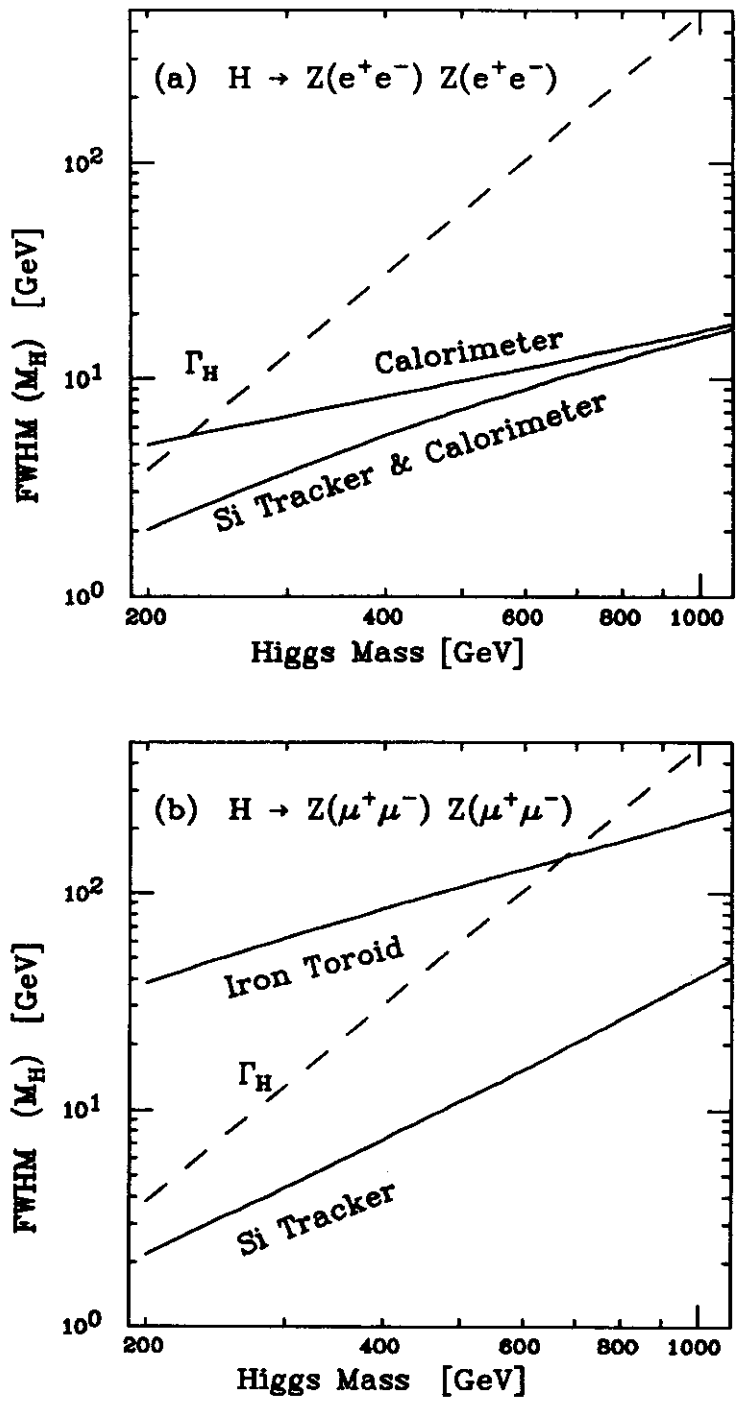


Fig. 2. FWHM resolution of the Z^0 mass as a function of Z^0 energy for a detector with calorimetry and iron toroids only, and for a detector including precision Si tracking. a) $Z^0 \to e^+e^-$. b) $Z^0 \to \mu^+\mu^-$.



ig. 3. Z^oZ^o invariant mass resolution for different detector configurations, compared with the expected Higgs width Γ_H (dashed line). a) $Z^o \to e^+e^-$. b) $Z^o \to \mu^+\mu^-$.

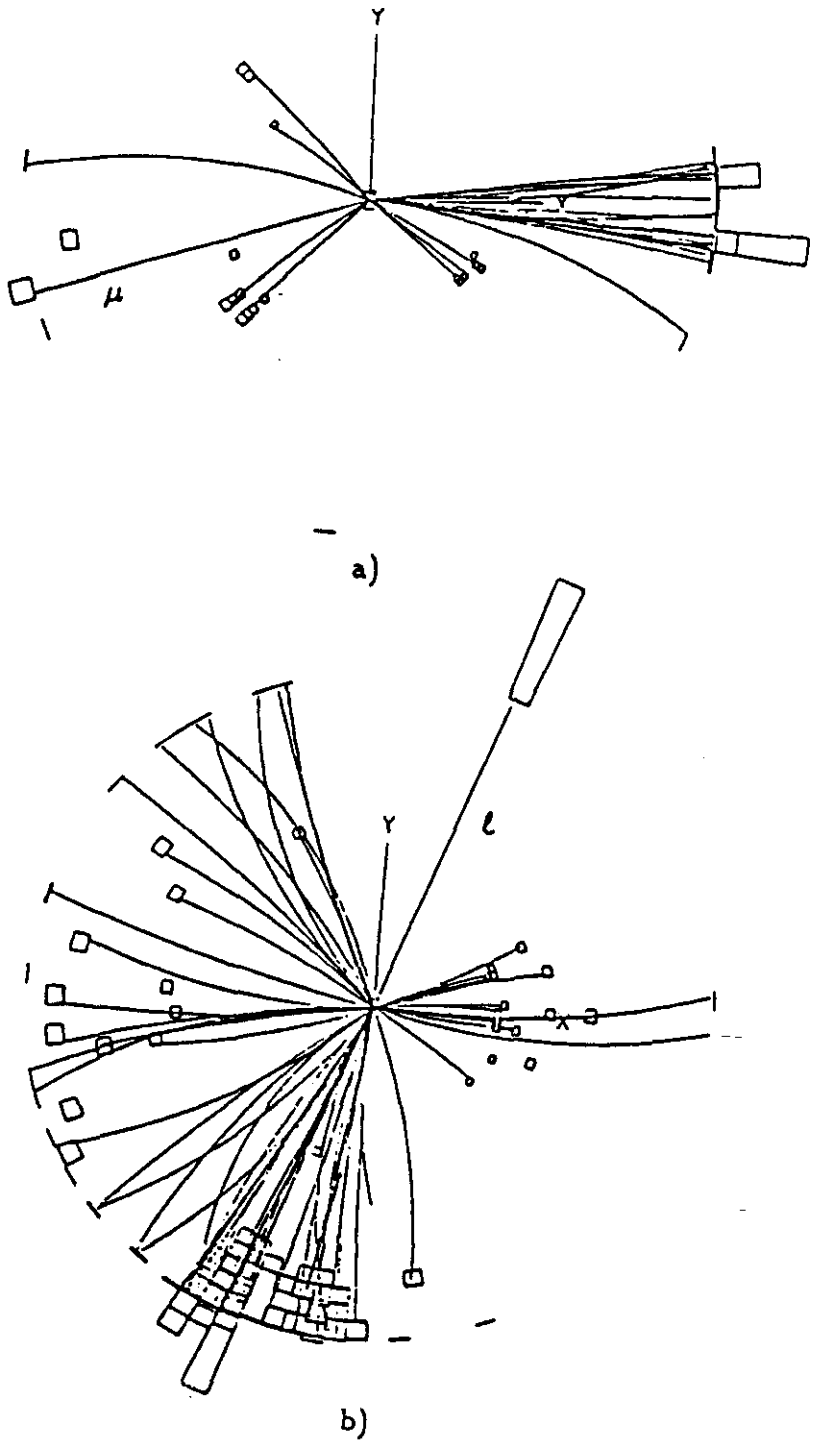


Fig. 4. Event Display which shows charged tracks with $p_t \geq 0.5$ GeV and calorimeter cells with $E_t > 0.5$ GeV in $|Y| < 2.5$ together with the isolated lepton from the W decay. a) Higgs $\rightarrow W^+W^+$ event with $M_{WW} = 1230$ GeV, $N_{ch} = 33$ $m_{\rm jet} = 73$ GeV. b) Mixed EW-QCD event with invariant mass $M_{W_{\rm jet}} = 1280$ GeV, $N_{ch} = 73$ and $m_{\rm jet} = 82$ GeV.

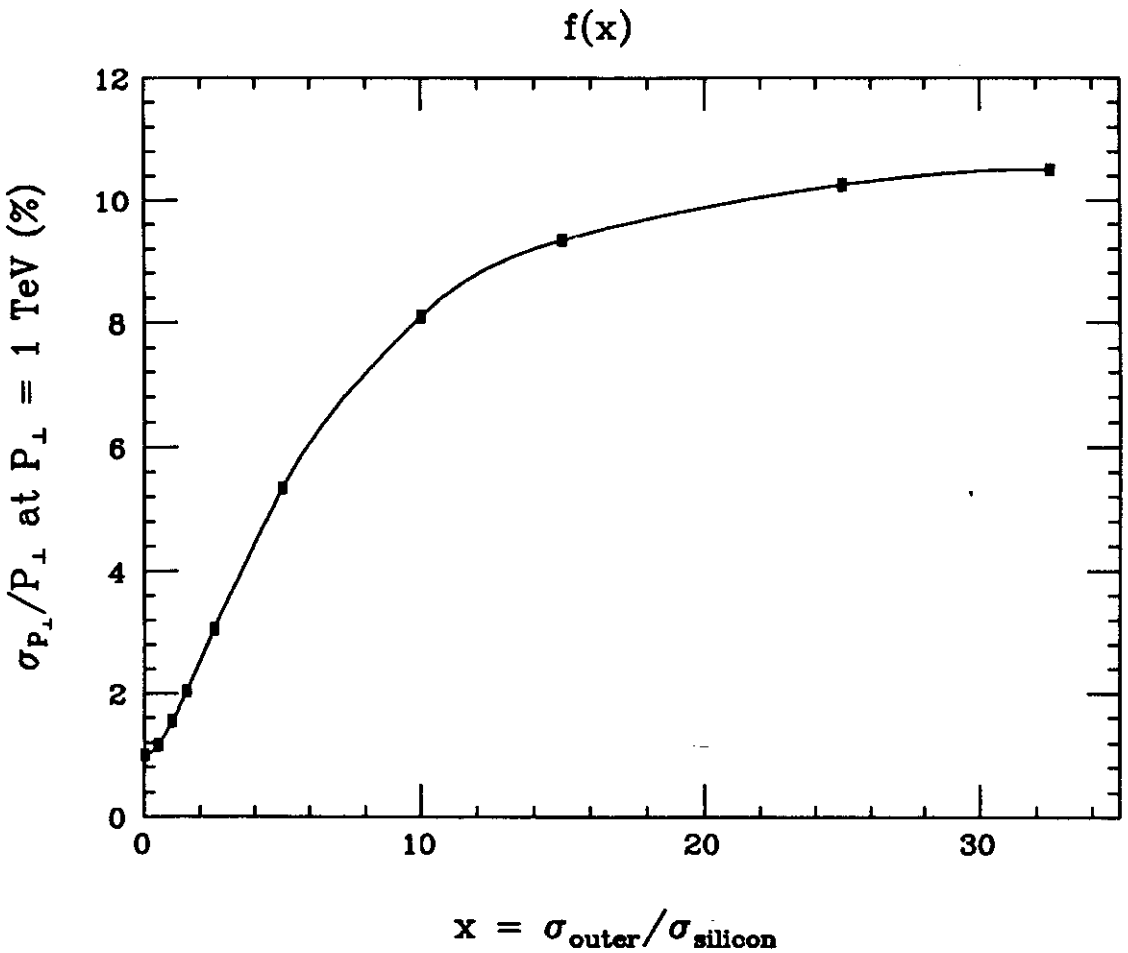


Fig. 5. Resolution for $\sigma_{silicon} = 6\mu m$, as a function of resolution of outer measuring device.

We can already conclude from this that a mixed system can improve the resolution relative to the Si tracker alone by a factor 2, provided the outer measurement is good, $\sim 30\mu$m, which could be achieved by 25 drift tube measurements, each 150 μm in accuracy. Note that such a mixed system provides a more robust arrangement in that a degradation of resolution for the silicon (for example, due to alignment limitations or fewer layers) produces much smaller changes in the overall resolution as shown in the third row in the table above, than for a silicon system alone. This could allow simplification of the silicon part of a tracking system where the ultimate configuration is determined by pattern recognition requirements.

Figure 6 shows the arrangement discussed above, including a detector arrangement for the forward direction. The use of silicon in the forward direction allows a reasonably compact detector with excellent resolution. In general, if a radius r_0 is sufficient to provide adequate momentum resolution at 90°, the detector arrangement with equivalent resolution at a track production angle θ, has to have a length $z_0 = r_0/\tan\theta$. Thus if we want to measure tracks at 10° we need $z_0 = 6r_0$. Thus for silicon, where $r_0 = 0.5$ m gives good resolution, we need $z_0 \simeq 3$ m, which is still a reasonable number. For a detector which requires $r_0 = 1.5$ m, z_0 would have to be 9 m, which makes for a prohibitively long device. To get the good resolution in the forward direction requires that high-resolution devices extend out to 3 m in z. This is shown in Fig. 6, which represents an improvement on our earlier design shown in Fig. 1. Note that charged particle detection is critical over this full rapidity range if we want to maintain a reasonable number of events from Higgs decay into four charged leptons!

Figure 7 shows the resolution $\sigma_{P_\perp}/P_\perp$ at 1 TeV in % as a function of pseudorapidity for the configuration in Fig. 6. Again, for simplicity, the drift chambers are treated as measurements of one point, with $\sigma_{\text{outer}} = 30\mu$m, at $r = 1.5$ m as before, or $z = 2.9$ m for the end region. Curves are shown for $\sigma_{\text{silicon}} = 6\mu$m, 10μm and 30μm to indicate a range of possible results. The results are quite good over the full range of rapidities. Very good resolution, $\sigma_{\text{silicon}} < 15\mu$m, is only needed in the forward direction.

From these considerations we expect that an optimized system will allow us to relax the silicon requirements in the barrel region and would emphasize highest resolution in the end regions. Assuming all detectors are double-sided, we estimate that such a system would have 28 m^2 of silicon and about 11 million electronics channels in total. Based on the MARK II silicon detector cost, the detectors for this system would cost \$28 million. We expect a mimimum cost reduction by a factor of two, to \$14 million, based on discussions with vendors.

Issues that need more study are the optimum angle at which to make the transition from barrel to end geometry and how many layers suffice to get the

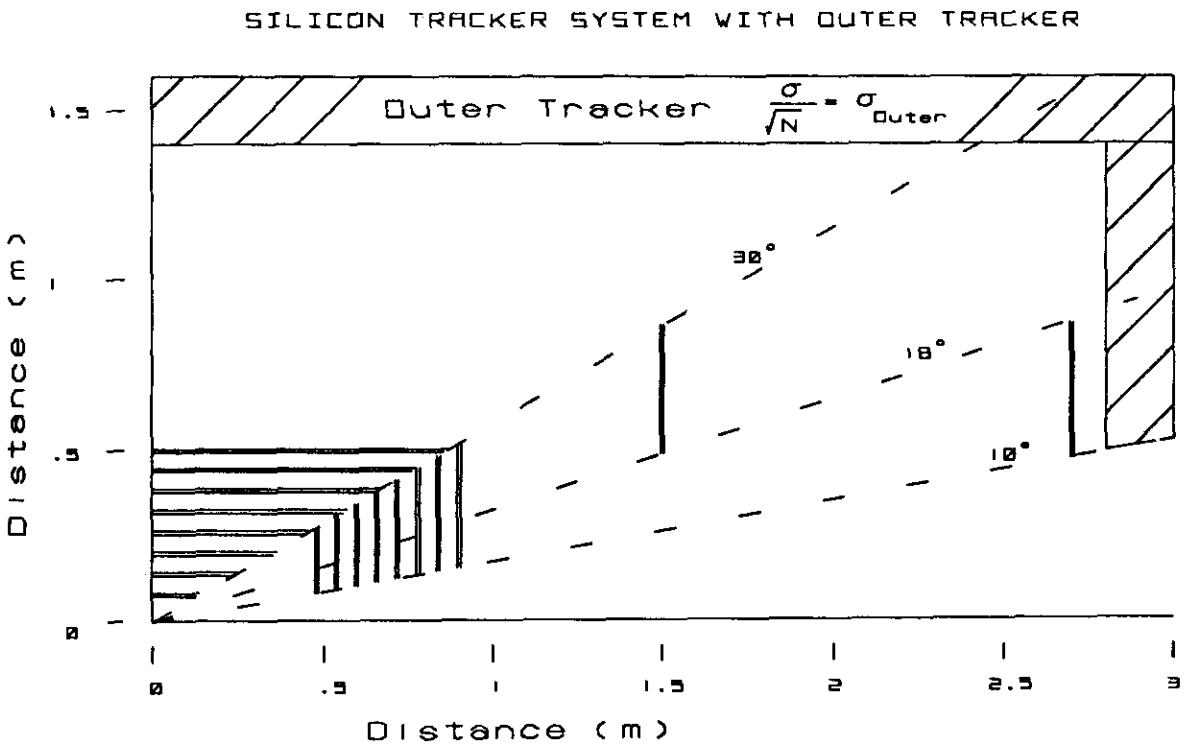


Fig. 6. Tracking arrangement including the forward direction.

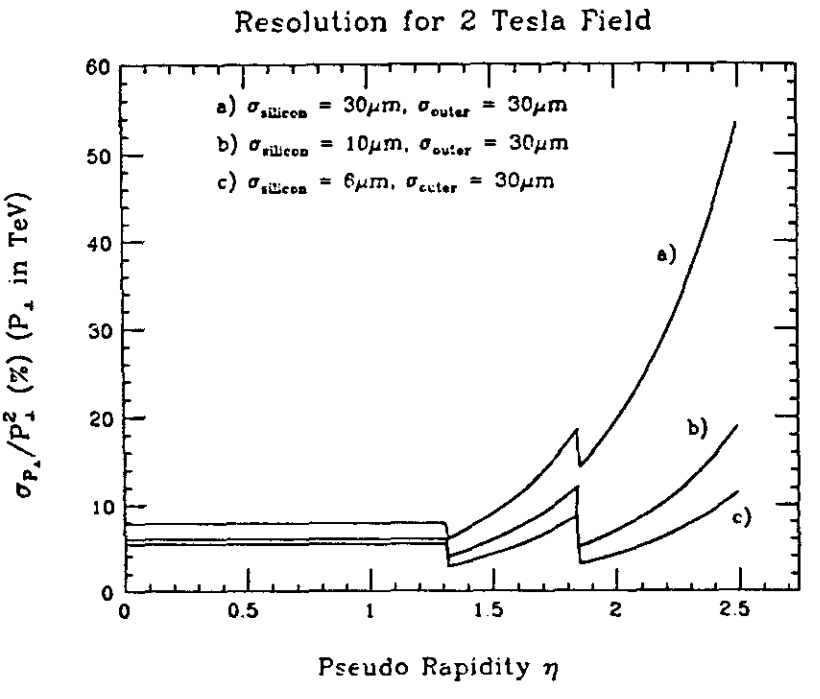


Fig. 7. Momentum resolution $\frac{\sigma_{P_\perp}}{P_\perp^2}$ as function of pseudo-rapidity η for the configuration of Fig. 6 for different resolution in the $\sigma_{silicon}$ silicon tracker.

powerful pattern recognition capabilities of the silicon tracking. We also plan to study the optimum magnetic field strength for the tracker. A high-magnetic field will reduce the size of the tracker and, therefore, the total size and cost of the detector.

B. Engineering Study of the Mechanical Structure

The projected excellent momentum resolution of the silicon tracking device is based on the very good position resolution offered by strip detectors with 25 μm pitch. The accuracy of $\sim 5\mu$m per measurement is about a factor of 20 to 30 times better than the one in modern drift chambers–the tracking devices developed for physics at the 100 GeV mass scale at the SLC, LEP, Tevatron Collider. As a consequence, the requirements for alignment tolerances and rigidity of the silicon tracker are much more stringent than those for drift chambers. Noting that the drift chambers were organized in super cells of n wires, the location of these super cells had to be controlled to about 200 $\mu\text{m}/\sqrt{n}$ or better than 50 μm, which is about a factor of 5 to 10 times larger than the required accuracy in the silicon tracker. Although the radius of the silicon tracker is a factor three smaller than in the drift chambers, the question of controlling the alignment to such a high degree of accuracy is a task new to high energy physics. Very successful existence proofs of high precision can be found. Silicon-strip systems (fixed-target experiments, MARK II, CDF) achieved spatial resolution close to the theoretical limit but on a much smaller scale. We will start an engineering study for a full-scale model of the support structure including cooling and power distribution. At the same time, for the mechanical system, we need to keep the amount of material to a minimum. As mentioned before, such precision (microns) on large-scale (meters) and in a high-radiation environment requires expertise one finds typically in specialized R&D groups in industry and some national laboratories. Therefore, we will contract this work out and have contacted R&D groups at Westinghouse Science and Technology Center in Pittsburgh, PA and at Los Alamos National Laboratory to undertake this project. In both places we have resident collaborators who will act as liaison and provide continuous and frequent contact. We include the proposals of the Westinghouse Science and Technology Center and LANL as Appendices 2 and 3. Note the goal is to have a final system with $\sim 5\%$ of a radiation length material at normal incidence. Heat loads of up to 20 kW have to be handled, with final numbers dependent on the conclusion of the simulation studies and detector development. The support structure envisioned would be made of low Z, low density material. Its behavior (strength and volume) versus radiation dose would be investigated. Part of the study requires a system to ascertain the rigidity of the support structure. One way to measure this is to use the system of the MARK II silicon detectors where collimated x-ray beams are recorded in silicon-strip detectors attached to

the structure to survey the position of the elements. The cooling system has to be integrated into the design. One possible candidate for this is the commercially available micro-refrigerator system which we are presently evaluating as part of our generic SSC R&D.

The goal of the engineering study is a full conceptual design of the silicon tracking support system. This will include details of the fabrication procedure, cost schedules, and time lines for building the detector. Wherever possible, critical engineering features will be identified and prototype components assembled and tested to establish the correctness of the approach. For example, we would expect to fabricate a full scale prototype of the mechanical structure for one super layer.

It is our intention to form a coherent effort utilizing the resources at both LANL and Westinghouse. In view of the extremely challenging problems involving thermal management, accurate and stable alignment to a few microns, coupled with the requirements of a low-mass/low-Z detector, we are anxious to get a broad based input on the mechanical engineering questions. For instance, it is already clear that the organic foam support structure for use in the CDF vertex detector will not be able to maintain the required positional stability of the silicon detectors in a radiation environment as harsh as that expected at the SSC. The Material Science and Technology (MST) Division at LANL has extensive knowledge of low-Z, radiation-tolerant materials such as boron carbide, silicon carbide, and beryllium. This includes experience in the production of very thin precision structures from these materials and low density foams based on carbon.

Westinghouse engineers are very experienced in the design, management, and fabrication of electro-mechanical systems on both a large and small scale. The intention is to overlap the efforts of the two groups rather than to duplicate the efforts. Although we plan to explore more than one detector geometry, the cylindrical geometry will be used in our initial discussions with both groups in order to generate a broad spectrum of ideas to meet the engineering challenges. Based on these discussions, an initial division of responsibilities will be made. Tentatively the engineering responsibilities will be divided between LANL and Westinghouse as follows: LANL will concentrate on the materials survey and thermal management problems associated with individual detector modules. Prototype work on a module will be started. Westinghouse will concentrate on the large scale support structures and the interface with the rest of the detector and the accelerator. Both groups will participate in the overall mechanical design and its analysis. Frequent periodic meetings involving both engineers and physicists will be held to assure that promising answers are not overlooked and that poor ideas are not wastefully pursued.

IV. Electronics R&D

We discuss below the electronics needed for a tracking system based on strip detectors with strip length $\sim$ 10–20 cm (long strips). These detectors are used as the model for our later discussion on trigger schemes. In the subsequent section on detectors alternative schemes based on short strips are described.

A. Bipolar Front-end for Strips

Because of the desire to read out the strip information every time bucket, and, in order to minimize the effect of the leakage current from the strip detectors, we are planning to use fast amplification and discrimination on the strip signals. Information will then be stored digitally. For such a scheme, noise and speed considerations indicate bipolar as the preferred front-end technology. We are working presently on two different amplifier designs and their completion will be of highest priority. Both amplifiers are presently matched to 100μm pitch detectors and use a few milliwatts per channel. These numbers are close to the design goal we would like to set at 25 μm pitch and 1 milliwatt per channel.

The first amplifier has been designed by H. Ikeda and is produced using a 0.8μm bipolar process by NTT in Japan. The circuit diagram is shown in Fig. 8. This amplifier has been successfully made and radiation tested in a neutron beam and with ionizing radiation. This is a very important milestone since bipolar technology is mainly vulnerable to neutron damage. The use of small, fast-transistors, however, minimizes these problems. The transistor h_{fe}, as a function of irradiation, is shown in Fig. 9. The performance is good enough for the SSC. The second amplifier has been designed by D. Dorfan and will be produced using Dielectric Isolated Bipolar. We have purchased wafers for production from ATT and will be producing these chips this year. The circuit diagram for this amplifier is shown in Fig. 10. The individual transistors are located in their own isolated tubs on the silicon, minimizing failure modes due to radiation. We expect to radiation test these circuits this year, after fabrication.

Based on the experience with these two amplifiers, and projections about the performance available in the future, we hope to map out a strategy on how to proceed on an SSC construction time scale. The most knowledgeable members within the group will be responsible for assessing the best direction for the future based on conservative performance projections. In this regard Silicon Dynamics, Inc. will be acting as an industrial consultant in the area of bipolar electrics. Important issues are the appropriate amplifier configuration given speed and transistor capacitance expectations, the detector capacitance that can be accommodated per channel given signal-to-noise specifications, and the expectations for power dissi-

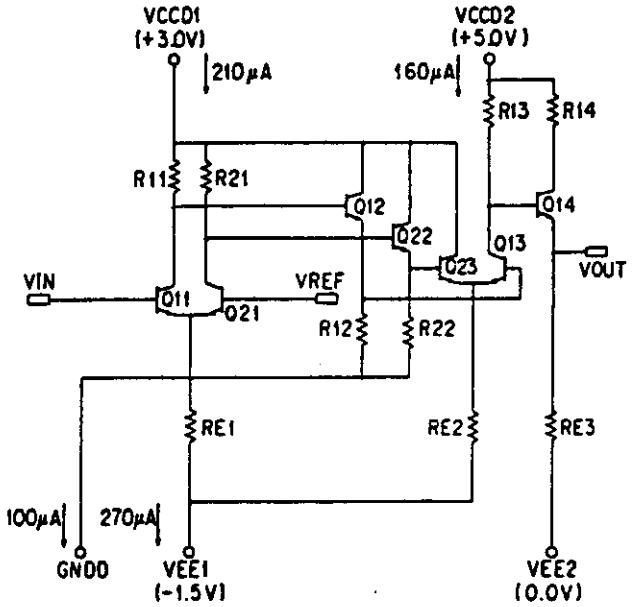


Fig. 8. Circuit diagram of the amplifier designed by H. Ikeda.

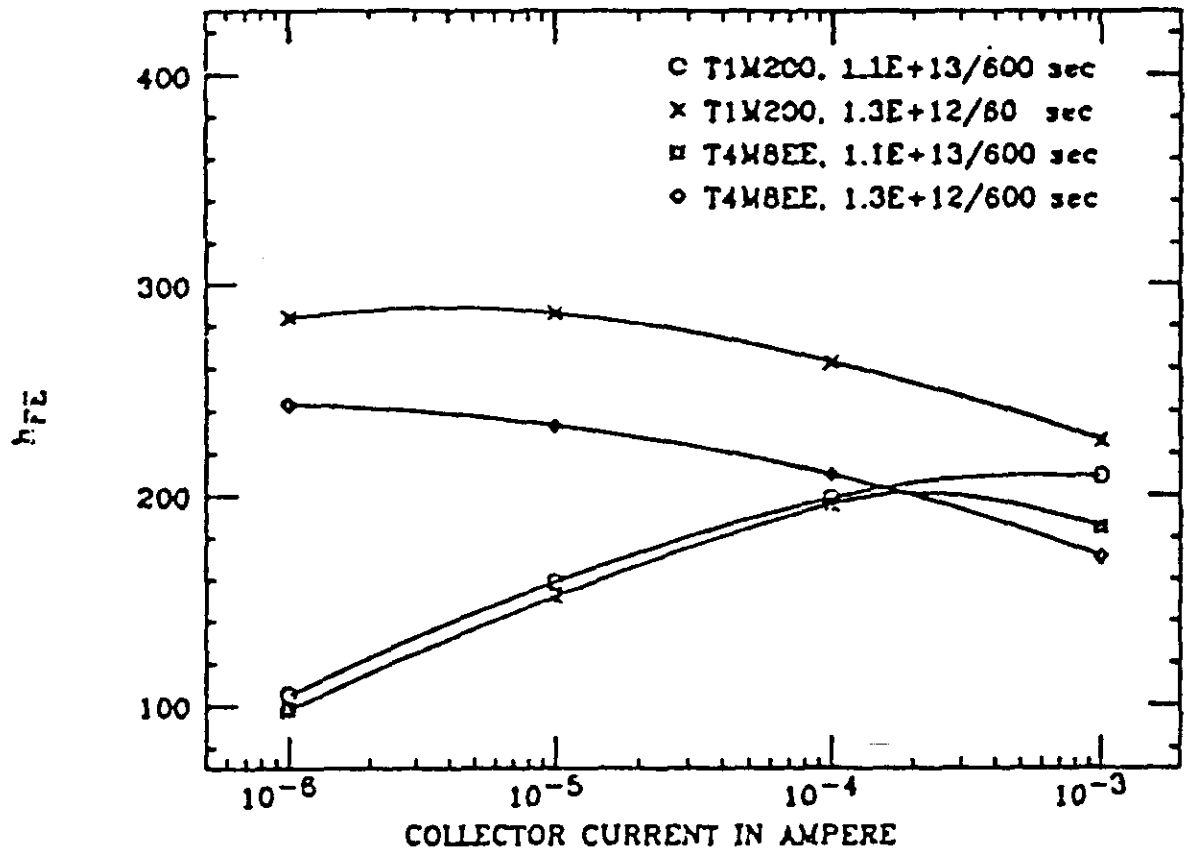


Fig. 9. The h_{fe} of the NTT transistors after different amounts of irradiation.

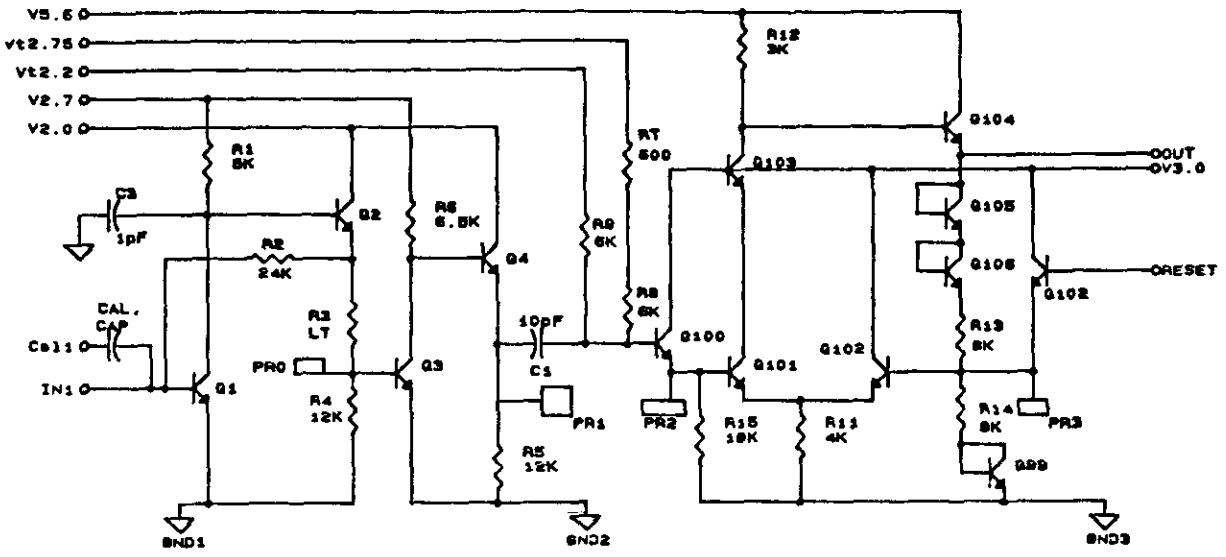


Fig. 10. The amplifier–comparator circuit designed by D. Dorfan.

pation per channel. Conclusions on these issues will provide important input to the group working on detector layout and engineering of support systems.

B. Digital Storage Chip

The information discriminated by the analog front-end will be stored digitally. We are in the process of producing a radiation hardened storage chip using 1.2μm CMOS at UTMC. This chip has 64 channels of storage for a first-level trigger, 32 channels for a second-level trigger, and a shift register for readout. It is the simplest scheme suitable to an SSC storage and readout scheme. The layout is shown in Fig. 11. It can match the 25 μm pitch of the silicon-strip detectors.

This past year we have spent a considerable effort radiation testing the UTMC process at Los Alamos. Tests have been conducted in neutron and proton beams and the process appears to be radiation-hard to a level of 10 MRad. Data are shown in Fig. 12 which shows a comparison of the damage due to neutrons for a non-rad hard chip (by ORBIT) with a rad-hard chip (made by UTMC). At 2×10^{14} neutrons/cm^2, the UTMC transistor shows less than 20 mV threshold shift.

In our recent proton runs we found that the voltage shifts in the rad-hard UTMC chips are about 200 mV for p transistors and about 100 mV for n transistors after irradiation with 10^{14} protons/cm^2 (800 MeV protons). Again, this corresponds to about 10 years of running at the SSC at a 10 cm radius.

This coming year we will radiation test our digital time slice chip to assess the functionality of the full chip. We also will measure speed, power consumption, and error rate vs. radiation dosage. After completion of these tests, we expect to work on the design of the chip we want to use at the SSC. This includes a decision on the exact architecture and the relation to a data acquisition scheme. As in the case of the bipolar technology, we want to have a subgroup look carefully at where we can expect the technology to go and what performance we can expect given an SSC construction timetable.

C. Interconnections

A silicon tracking system at the SSC will likely have 10^7 or more individual detector elements. For each element there will be one or more electrical interconnections made to join the element to a readout amplifier. This large number of channels makes interconnections a major quality control issue for the entire system. Furthermore, the time needed to perform and test interconnections could become prohibitively long. For these reasons it is likely that the use of traditional serial single-wire microbonds will not be the best approach for a large silicon tracking system.

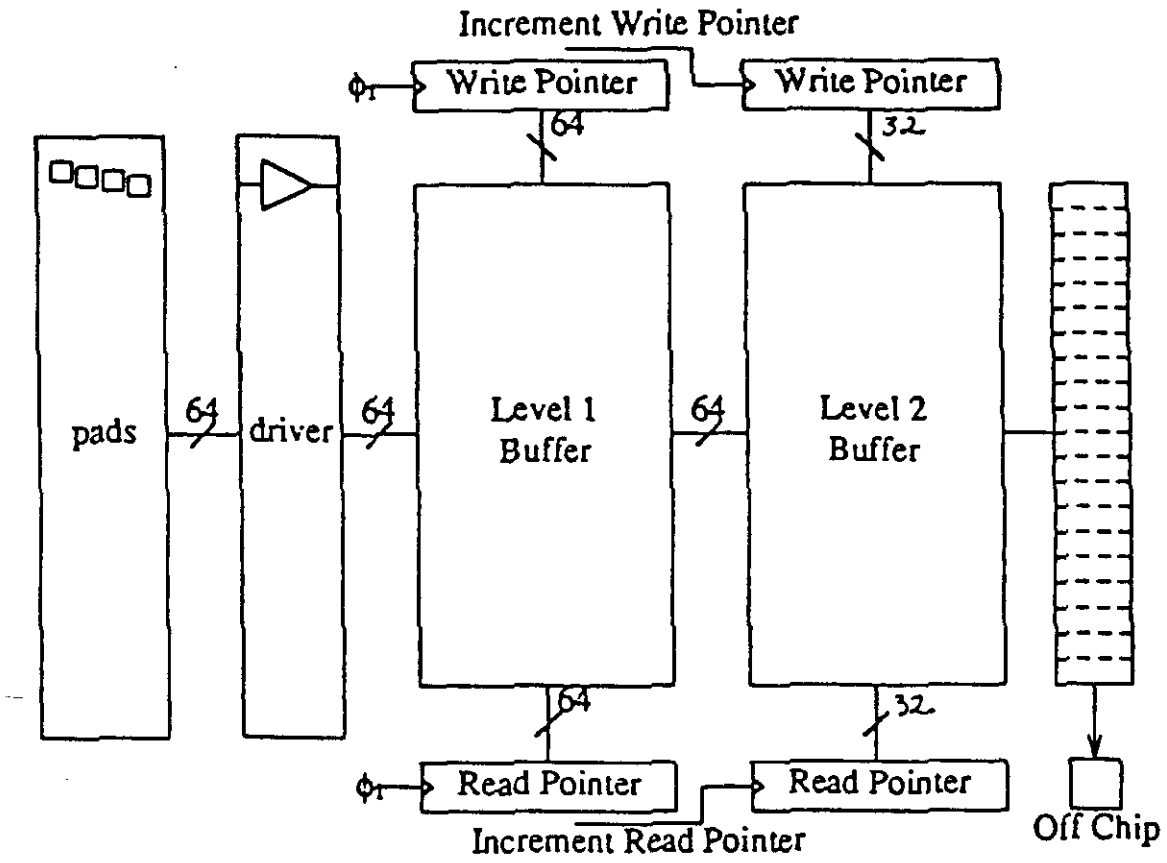


Fig. 11. Layout scheme of the digital-time-slice chip.

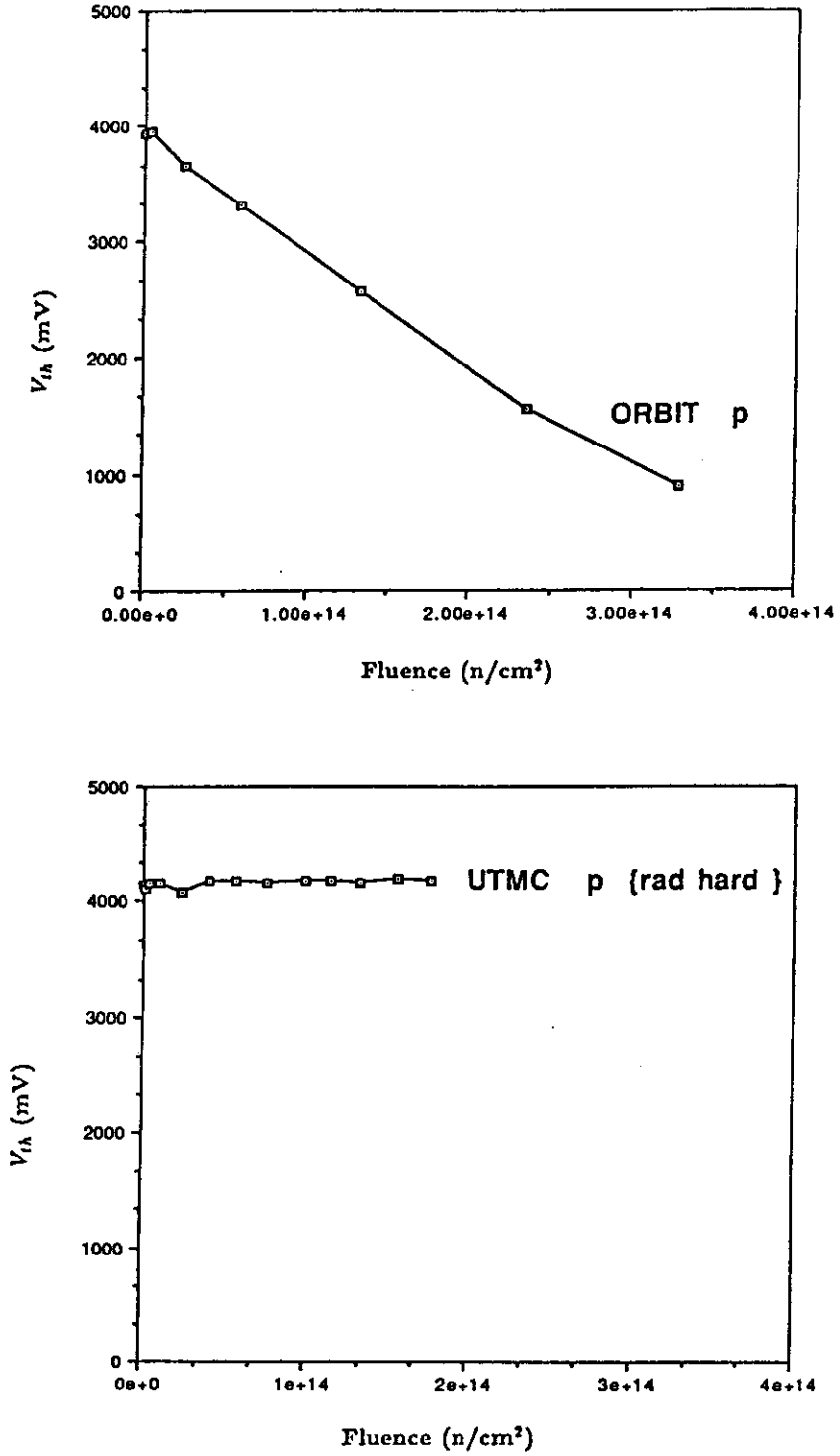


Fig. 12. a) Threshold voltage V_{th} *vs.* neutron fluence for the non-rad hard *p* transistor #2 manufactured by ORBIT. b) Threshold voltage V_{th} *vs.* neutron fluence for the rad hard *p* transistor #7 manufactured by UTMC.

There are a number of new interconnection techniques under study and development in industry which we may hope to apply to the large silicon tracking system. These include high-density variations on tape-automated bonding techniques and high-density polyimide interconnects. Bonds in these approaches may be formed under ultrasonic, thermosonic, or laser irradiation, and may be formed singly or ganged (in parallel at many sites) with special tooling developed for our application. We propose to investigate the applicability of these new techniques to our system. One possibility under study is the development of high-density polyimide interconnection films with an industrial partner. There are a number of questions which need to be addressed here ranging from metallurgy to production procedures. Through our relationship with the CDF Silicon Vertex Detector Group at FNAL, LBL, Johns Hopkins and Pisa/INFN, we plan to apply this technique to a set of spare detector modules being produced for CDF. As part of the CDF production line, these modules will have been well measured and understood mechanically and electronically. This will simplify the evaluation of new interconnection procedures.

We also recognize the need to understand and establish techniques, procedures, and mechanical precedents for bonding to complicated structures such as double-sided detectors, short strips, and detectors on low mass mounts. It is very important to develop a mechanical specification on support structures which respect the requirements of bondability. Naturally these results will be fed directly back into the mechanical design.

V. Detector R&D

A. Double-sided Strip Detectors

The principle of double-sided microstrip detectors has recently been proven[1] and such detectors are planned for the ALEPH microvertex detector.[2] Unlike conventional microstrip detectors, double-sided devices measure two coordinates and, therefore, provide 3-dimensional point of impact information with a single detector, thereby, reducing the amount of scattering material. One problem is that isolation between adjacent n^+ strips (for an n-type silicon bulk) is destroyed by an accumulation layer of electrons induced by the fixed positive charge in the oxide, as shown in Fig. 13(a). This can be solved by interposing a p^+ implant between the n^+ strips as shown in Fig. 13(b).

It is possible to implement capacitive coupling to the readout amplifiers by integration of capacitors on the readout strips. This protects the readout electronics from saturation by strips with large leakage currents. Biasing of the detector can be achieved either by the punch-through effect[1,3] or with polysilicon resistors.[4]

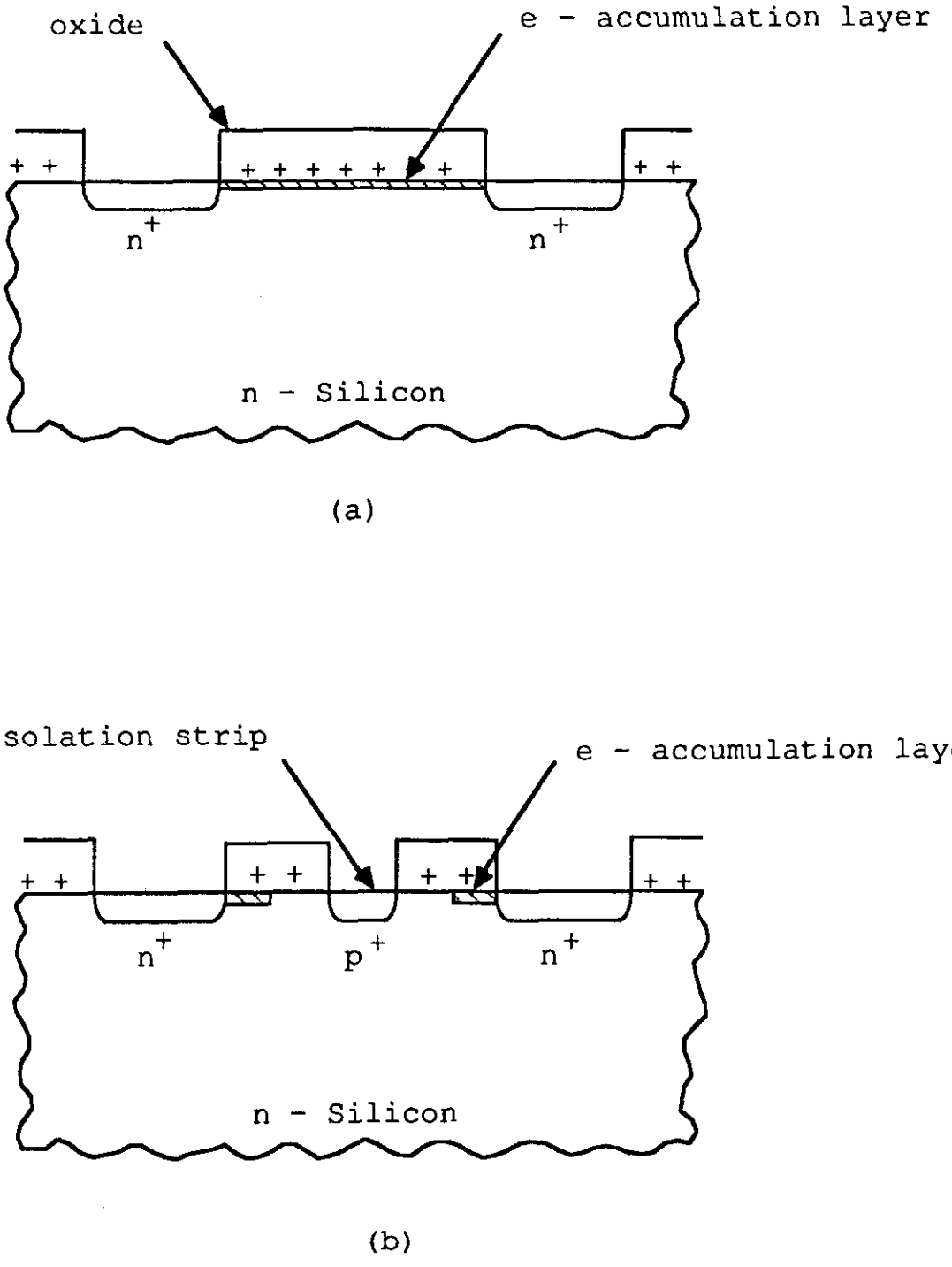


Fig. 13. Cross-section through a double-sided microstrip detector near the n^+ strips side showing the problem associated with the accumulation layer. Adjacent n^+ strips are effectively short-circuited by the electron accumulation layer (a). One solution is to fabricate p^+ strips between the n^+ strips as shown in (b).

The development of the double-sided microstrips will rely heavily on close collaboration with the silicon-detector manufacturers. To this end we have established a close working relation, via our Japanese collaborators, with Hamamatsu Corp. and through our European collaborators with SI in Oslo and MBB in Germany.

Recent advancements in the area of processing at LBL have shown that the use of extrinsic gettering techniques leads to detectors with very low leakage currents.[5] Using the fabrication facilities at LBL we will be able to produce test structures with a rapid turn around time to investigate the various isolation and biasing mechanisms required for the double-sided microstrip detectors. This will provide information in support of the work on double-sided detectors.

The proposed R&D program is divided into three phases as follows :

Phase 1: 1989–Mid-1990

Prototype detectors and test structures will be fabricated at Hamamatsu to develop and test the capacitive coupling and biasing methods, and to evaluate the radiation tolerance of these detectors. We will also carry out a parallel testing and evaluation program with prototype detectors from SI in Oslo and MBB in Germany. The two European manufacturers have agreed to work together on this project. They have already developed excellent double-sided detectors and detectors with capacitive coupling for previous experiments.[6] In addition, SI has shown that 150 μm thick wafers can be processed without significant reduction of yield.[7] We plan to make detailed measurements of the DC characteristics and long-term stability of the test devices that will be made. [All three manufacturers have made extremely high quality detectors for ongoing experiments (MARK II, ALEPH and DELPHI)].

Phase 2: 1990

The goals for this phase are:

(1) Prototype production detectors with stereo-strips will be designed and fabricated.

(2) Investigation of bonding techniques for bonding readout chips to the detectors.

(3) Radiation hardness tests of the prototype detectors.

(4) Readout tests of the prototype detectors. Measurements of the position resolution and efficiency.

(5) Optimization of the detector designs: Charge collection times, interstrip capacitance, stereo angle, detector thickness, etc.

Phase 3: 1991

Development of a final production-type double-sided silicon-microstrip detector. Using these we plan to:

(1) Based on the design of optimal detector layouts for central and forward tracker geometries produce test modules consisting of several readout planes.

(2) Radiation test these modules, measure resolution. The radiation damage to silicon detectors has been measured by many groups in many different radiation environments, which allows one to predict the survivability of silicon strips in SSC detectors.[8] If one restricts the placement of detectors to radii larger than about 10 cm, then the detectors in 10 years of nominal SSC operation will acquire leakage currents which will still contribute a negligible amount of electronics noise. We expect to carefully radiation test the detectors developed. Some aspects of radiation damage need a more detailed and specific investigation, for example self-annealing, trapping, and type inversion. Surface effects are process dependent and must be carefully checked.

B. Detectors with Short Strips

The use of established, proven, strip-detectors allows one to plan a detector design without relying too greatly on technological innovation. On the other hand, the flexibility of silicon technology allows the exploration of some new ideas which we want to pursue.

1. Technical Issues

Conventional schemes for silicon detector modules use rather long strips (up to 20 cm in length) with readout chips mounted at the end of the barrel. This configuration requires rather fast electronics to achieve adequate radiation resistance close to the beam and also obtain adequate time resolution within the constraints of electronic noise. The speed requirement drives up the power dissipation, which, in turn, drives the design towards end-mounted readout chips.

A general analysis of the total dissipation of a strip-detector system as a function of strip length (Appendix 4) indicates an optimum strip length of 5–10 mm. This results in a total power dissipation of 2 kW or less for the detector configuration shown in Fig. 1. This substantial reduction in power for the short strip system has two origins:

(*a.*) The speed of the electronics can be decreased for a given radiation resistance (due to the smaller area of the individual detector elements).

(*b.*) The low occupancy per channel simplifies the circuitry needed for buffering and time tagging.

Furthermore, short strips will provide unambiguous space points with the required resolutions in z and rϕ. This will eliminate the need for double-sided strips, and circumvent the inherent technical difficulties associated with the fabrication and wire-bonding of double-sided detectors. Physics simulations may indicate a strip length that is somewhat shorter than optimum for minimum power; these trade-offs will be considered in detail.

The philosophy of the full event readout follows the basic criteria of the "smart" pixel readout developed at LBL; in addition an "OR"-ed fast signal from these detectors will be provided for triggering. The readout strategy is:

(*a.*) Keep all hit data local as long as possible; read out only after a valid trigger.

(*b.*) Exploit the low occupancy of small detector elements, *e.g.* only 2×10^{-5} per beam crossing at an 8 cm radius ($\times 2$ with loopers).

To implement the read-out logic, there will be a one- or two-word buffer for each short strip. When a strip is hit with a pulse height that exceeds threshold, the number of the beam crossing will be loaded into the buffer for the strip. To read out the detector, the strip buffers will be scanned for strips with the beam crossing number corresponding to the trigger event.

One possible mechanical arrangement, using conventional wire-bonding, is shown in Fig. 14. A drawback of this approach is the large number of bonds required, about 10^8 for the full detector. Hence the arrangement shown in Fig. 14, with simple wire bonds, is useful primarily for prototype testing and a proof-of-principle demonstration. More efficient bonding techniques will be required for the final design. Tape-automated-bonding may be the most practical possibility and will be investigated with an industrial partner.

A second arrangement, which uses bump bonding and allows shorter strips, is shown in Fig. 15. As a conceptual example, we might have a detector with an active length of 9 cm in the z direction, and 2.5 cm in the rϕ direction (similar in size to the long-strip detectors). Each strip would have Δz = 3 mm and $\Delta(r\phi)$ =25 μm. The strips would be placed in a two-dimensional array and provide space points with σ_z = 1 mm (for coarse vertex reconstruction in z) and $\sigma_{r\phi}$ = 7 μm (for the momentum measurement). A mosaic of readout chips would be indium bump bonded to 15 μm diameter bumps at the center of each strip.

The two above schemes share a basic disadvantage, which is the increased thickness of each layer. This may be mitigated by thinning of the detectors and the readout chips.

As an attractive alternative, detectors with monolithic integration of the electronics would solve both the thickness problem and the bonding problem. LBL's high temperature detector process has made this a realistic possibility, and work

to test the viability of this approach will be pursued at LBL, the Stanford Center for Integrated Systems, and the Westinghouse S&T Center.

We note that short strip detectors should be simpler to implement than pixel detectors. The power dissipation per unit area will be lower, there is more area available per channel for the read-out circuitry, and the read-out logic is simpler.

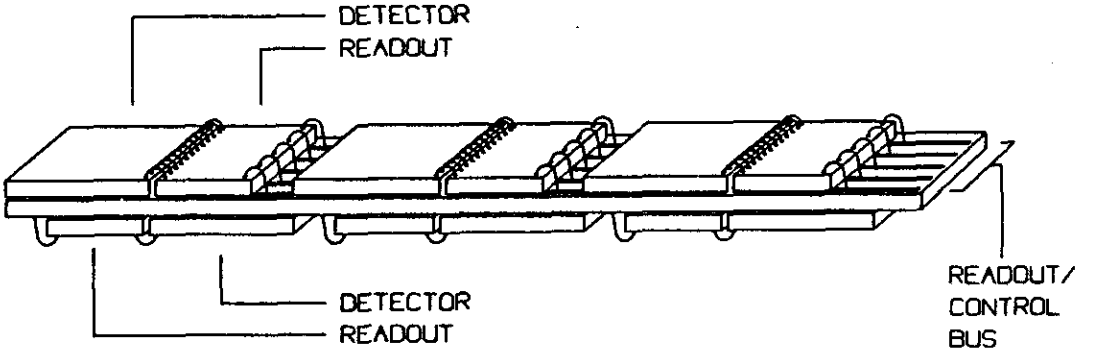


Fig. 14. Schematic arrangement of a short-strip detector ladder using wire bonds.

2. Development Plan

FY90

Detectors—Prototypes fabricated at LBL will be irradiated with neutrons and high-energy protons to establish their radiation resistance. Since a radiation-hard design requires AC-coupled strips, the integration of coupling capacitors and biasing resistors will be investigated using facilities at the LBL Microsystems Laboratory and the UC Berkeley Microelectronics Laboratory. Since the LBL process is quite robust and eliminates many constraints of traditional detector fabrication, we anticipate high fabrication yields suitable for ultimate mass production when transferred to an industrial partner.

Electronics—A detailed circuit design for a suitable preamplifier-shaper-discriminator chain has been completed at LBL for a pixel device. The same circuit can be used with minor modifications in a short-strip system. Layout and fabrication of a prototype device can be completed in early 1990. After thorough testing the circuit will be implemented in a radiation-hard process (*e.g.*, UTMC), building on data taken by UCSC and Los Alamos. Additional key parameters will be measured at LBL; the appropriate non-disclosure agreements with UTMC have already been signed. As small bipolar devices become available they become an attractive alternative to CMOS for very low-power amplifiers. This course will be investigated, closely coordinated with bipolar design efforts directed toward longer strips.

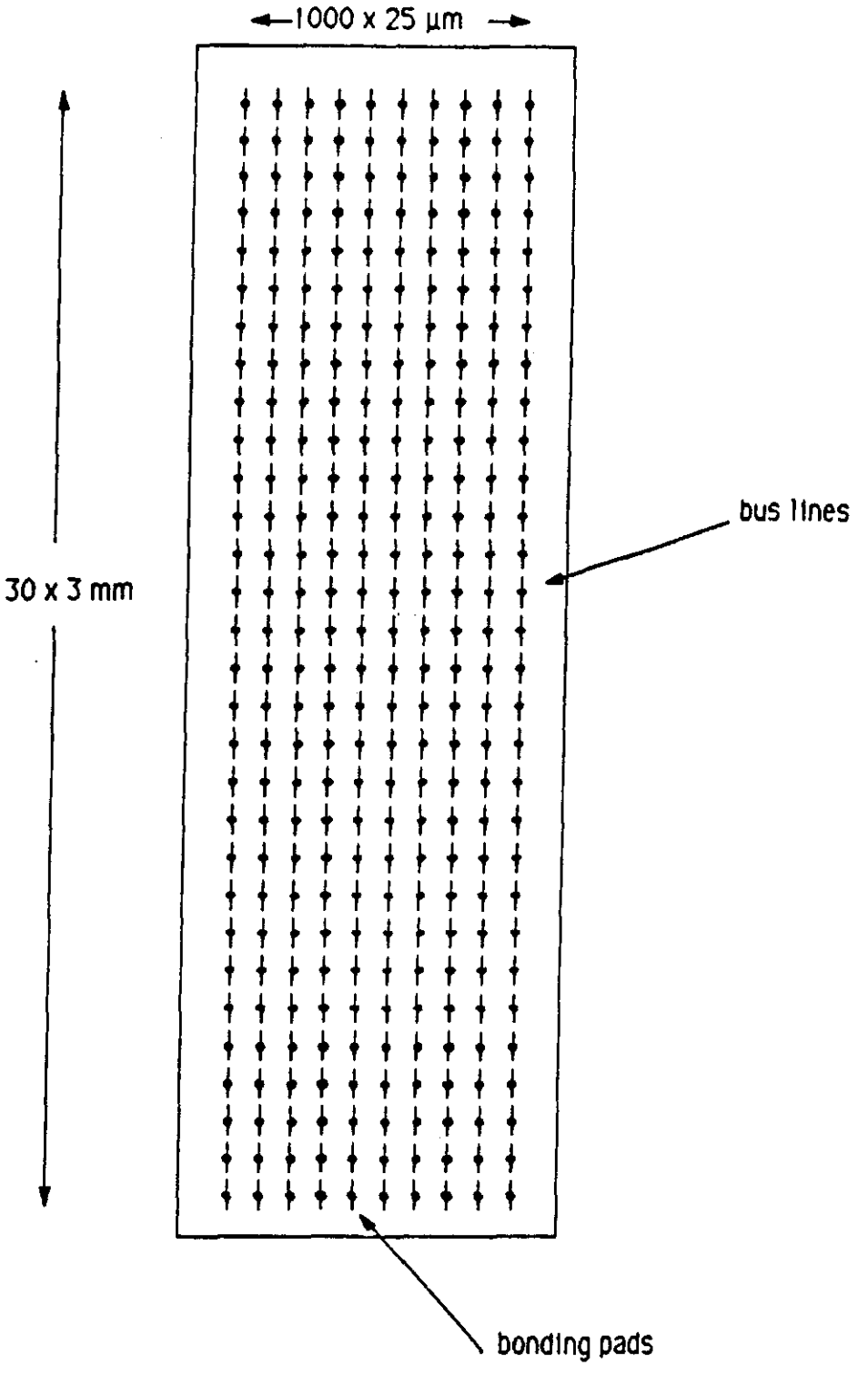


Fig. 15. Short-strip detector using bump bonding.

Bonding—As emphasized above, efficient bonding techniques are of crucial importance in this design. Tape-automated-bonding will be investigated with an industrial partner. In addition, bump bonding will be investigated in collaboration with the Center for Integrated Systems at Stanford University.

Prototype Detector Assembly—At the end of FY90 a prototype detector assembly will be fabricated to verify the performance of this scheme. This will include short-strip detectors bonded to read-out IC's on one of the candidate substrates identified in the mechanical design effort. In order to allow a feasibility test early on, this initial structure will utilize non-hardened electronics and conventional wire-bonding.

FY91

Detectors—We anticipate further refinements in the detector design. In this phase, work on monolithic integration will be intensified. We plan a proof-of-principle device to provide a credible basis for a possible implementation with an industrial partner. It should be possible to run the LBL process on a rad-hard CMOS line; this approach will be investigated.

Electronics—Work on a radiation-hard implementation of the read-out IC will be continued with the goal of fabricating and testing a functional device.

Bonding—Advanced bonding techniques will be implemented on test devices.

Prototype detector assembly—We plan a prototype detector test assembly that includes advanced bonding techniques and radiation-hard electronics.

C. Detectors with Integrated Electronics

Within the group we would like to also pursue the development of a simplified detector-readout scheme which could come about from the integration of the front-end readout electronics on the detector wafer. Two such directions are described below.

1. Detector Development with Westinghouse

It is appropriate during the first year of the R&D program to explore promising avenues in the areas of detector and electronics development. The group at the University of Pittsburgh, together with the Westinghouse S&T Center, will attempt to fabricate a strip detector with an integrated amplifier on the same substrate. The advantage of a fully integrated detector is obvious when one considers the difficulties associated with the 10^7 wire bonds required for a silicon tracker at the SSC. Treating detectors as tiles rather than devices with $\sim 10^3$ channels would be a significant simplification.

The existence of three technical facilities at the Westinghouse S&T Center in Pittsburgh, PA combine synergistically with recent results from LBL (see, for example, S. Holland, LBL-26307) and the flexibility of silicon technology to suggest the exploration of some new approaches which we would like to pursue. The three technical facilities at Westinghouse are the following: The first is SIMOX (Separation by the IMplantation of OXygen), a materials technology which has been developed to serve the needs of the radiation-hard signal processing integrated circuit community. The second is ultra-high resistivity silicon. Westinghouse has a unique float-zone (FZ) silicon-growth facility that supports power device materials development. The Westinghouse S&T Center has the only known fully operational FZ facility in the United States. The third is an operational microlithography capability represented by the Cambridge Microfabricator on line at the S&T Center. Westinghouse is in the process of combining these facilities to develop a new product called SIMOX Microwave Monolithic IC's as a business opportunity emulating other successful ASIC vendors. The process (called MICROX), which can be regarded as a subset of silicon CMOS or CMOS/SOI (Silicon-On-Insulator) technology, is potentially radiation hard and very fast. As such, it is of considerable interest for possible SSC electronic applications. Our interest is that since MICROX will be implemented on high resistivity silicon, it is a natural candidate for integration with silicon-strip devices which also require a high-resistivity substrate. This possibility appears realistic in view of the work of S. Holland, who has demonstrated the processing compatibility of low-leakage current pin diodes with the high temperatures required for MOS devices by the use of appropriate extrinsic gettering techniques. We propose the development of a single-sided strip detector with the integration of the necessary analogue and digital electronics utilizing the MICROX process.

Plan:

(1) The first step is for Westinghouse to make a strip detector. They plan to do this as a cost-sharing contribution using the gettering process developed by Steve Holland at LBL. They will try to accomplish this by January, 1990. We would not proceed with the project until this is accomplished.

(2) The compatibility of the MICROX technology with strip devices would be demonstrated. Some work on this has already started.

(3) Test devices fabricated in (2) would be evaluated for electrical properties and subjected to tests for radiation hardness.

(4) A fast shaping amplifier would be implemented in the MICROX technology coupled to a strip device. The detector/amplifier could be evaluated for performance and radiation hardness.

2. Detector Development at Stanford Center for Integrated Systems

Work is underway, in a collaboration between the Center for Integrated Systems of Stanford University and the University of Hawaii, on the development of a pixel detector with integrated electronics.[9] The basic Pixel structure can also be specialized for additional uses, in particular the detector with short strips mentioned earlier in this proposal could be fabricated in this fashion with substantially fewer interconnects needed. The collaboration had its origin in the CIS-UH-CERN development of the Microplex chip, the first VLSI readout for silicon microstrip detectors, which started in the summer of 1982 and was completed successfully in 1984.[10] At that time UCSC joined the group and work started on the first microstrip vertex detector for colliding beam use, now complete and waiting for installation in the MARK II at SLC in October 1989.[11]

Plans for a wafer integrated device were started in 1985, and an initial specific design was prepared in 1987 and funded in 1988 under the SSC generic research and development program.[12] Unlike the Microplex chip, which used a standard NMOS process, this device, with detectors and transistors on the same silicon substrate, requires the development of a new set of fabrication steps. James Plummer, a Professor of Electrical Engineering at Stanford University and one of his students, W. Snoeys, have now joined the project. Detailed simulations have been completed, a process test chip (one with specialized structures to test the fabrication steps) has been designed, masks have been made, and the first process test wafers are now being fabricated.

We would like to increase the rate of progress by adding a second student. In addition to the fabrication steps, which must be determined before detailed circuit designs are completed, much work will be required in taking the known techniques for radiation hardness and combining them with the steps for high-purity silicon. Detailed circuit design and layout for the on-chip readout, including time-tagging and information storage during the trigger delay, must also be completed.

D. Radiation Damage Studies

One of the major tasks of this proposal is to ascertain the radiation hardness of all the materials, especially the electronics and detectors. This is part of the ongoing R&D in our group and we have established a good collaboration with Los Alamos experts (notably, W. Sommer) on which we can expand. The Los Alamos group has just added a full-time person (from existing funds) to do the dosimetry, which turned out to be very successful in the past proton run, and we expect that Los Alamos personnel will continue to handle the dosimetry. On the other hand, in our past experience the constant attention and monitoring of the runs by physicists is invaluable and we will continue to operate in a mode where the groups working on electronics and detectors will be responsible for the damage testing. In our

past tests, we were able to identify a radiation-hard process in CMOS technology on which will we expand our efforts. We have tested radiation hardness of PIN diodes and detectors. With the development of new electronics and new detector structures, the individual working groups will test more complex properties of the devices than before (noise, voltage off-sets, functionality).

In addition to the test mentioned above, another group at Los Alamos is participating heavily in Fermilab experiment 789. This is a very high-rate fixed-target experiment which is studying B meson decays and uses a series of silicon strip detectors. These silicon strip vertex detectors, for which Los Alamos is primarily responsible, will be exposed to a radiation dose and beam microstructure (19 nanoseconds) very similar to what is expected at the SSC. This experiment will thus serve as an excellent test case for silicon strip detectors. J. Kapustinsky is studying the radiation damage effects for that experiment and will act as a liaison between that experiment and radiation damage studies for this proposal.

Finally, the UCSC group is responsible for the VLSI readout electronics for the forward proton spectrometer for the ZEUS experiment at HERA. This detector is made of silicon strips and bonded electronics which will be submitted to megarad radiation doses. Work on this experiment should also provide important experience for running at the SSC.

VI. Work on a Silicon-Based Second-Level Trigger

The use of silicon detectors in a tracking trigger is very appealing provided that only hits are read out and the very large number of zeros are suppressed. This must be a goal of the architectural design of the digital storage chip. In this case, the silicon detector should generate less data to deal with than most alternative tracking devices since its time response is well matched to the bucket structure at the SSC and the number of layers is modest. In addition, the resolution is inherent in the geometrical hit pattern and does not require any use of timing information. Designing a trigger system which exploits these remarkable qualities of the tracking device is, however, a formidable task.

The speed requirements arising from the SSC luminosity and bunch crossing interval, even assuming a strongly filtering first-level trigger based on calorimetry, impose solutions which rule out the use of standard sequential algorithms for pattern recognition and track fitting, even if executed on very fast processors.

Also, the large quantity of readout channels, imposed by the detector size and coverage, and by the fine granularity of the silicon tracking system, requires a solution which integrates to the greatest extent the track finding machinery with the detector's front-end electronics, in order to minimize cabling and to draw out of the detector itself the most compact information.

We plan to build on the current studies of the Pisa/FNAL group. These studies, aimed at a fast, integrated track-finding system are based on the development of a highly parallel associative memory chip, which should allow performance of the track finding task in a negligible amount of time, once the memory has acquired the digital strip information from the front-end electronics coupled to the detector layers. An associative memory is a device which stores all the possible patterns of strips hit on different layers by all the possible tracks. A track is "found" by the memory if the data coming from the front-end matches one of the patterns stored (which are pre-computed and pre-loaded). It is essentially an upgrade of a CAM (Content Addressable Memory), but the custom design allows optimization of the structure, the speed and the readout mechanism. The chip can find both straight and curved tracks, the only problem being the number of possible patterns to be stored, which grows quadratically with the number of strips in the Silicon detector layers.

Such a chip is now under advanced design at Pisa (INFN), and a first batch will be produced by the end of the year to undergo laboratory tests. It is a full custom, CMOS 1.5 micron technology, 0.7 x 0.7 cm squared chip, which presently houses 128 patterns, each pattern made of 5 hits on 5 Silicon planes, each hit coded on 12 bits (1024 strips/plane). This choice was dictated by the particular arrangement of a set of spare CDF silicon vertex detector modules which will be configured as a telescope and installed by the Pisa group in a CERN beam line, to be used as a prototype test of a complete associative memory based trigger system for future Supercollider applications. The track finding part will be installed by spring next year. The associative memory runs at an overall frequency of 20 MHz, and incorporates a hierarchical readout logic which enormously simplifies the construction of large systems based on many chips (the number of patterns can easily be raised to tens of thousands, depending on the detector geometry). The arrangement for our beam test is shown in Fig. 16.

The associative memory system only performs the track-finding task; the use of this information for the more ambitious task of vertex reconstruction is the object of additional recent studies (note that the track fitting can be done in a table-driven way, once the hit-to-track association has been sorted out by the associative memory). At FNAL we are currently working on some algorithms, which, being designed from the very beginning in a parallel way, are possibly well suited to be run on a "parallel processing" device: these algorithms use the track parameters to determine the number of secondary vertices in a fiducial region between the interaction point and the detector layers, in which heavy flavour decays are expected to take place. Monte Carlo studies have been performed starting from a fixed target environment, and gradually extended to collider configurations. Cuts based on the number and type of secondary vertices seem to be able to discrim-

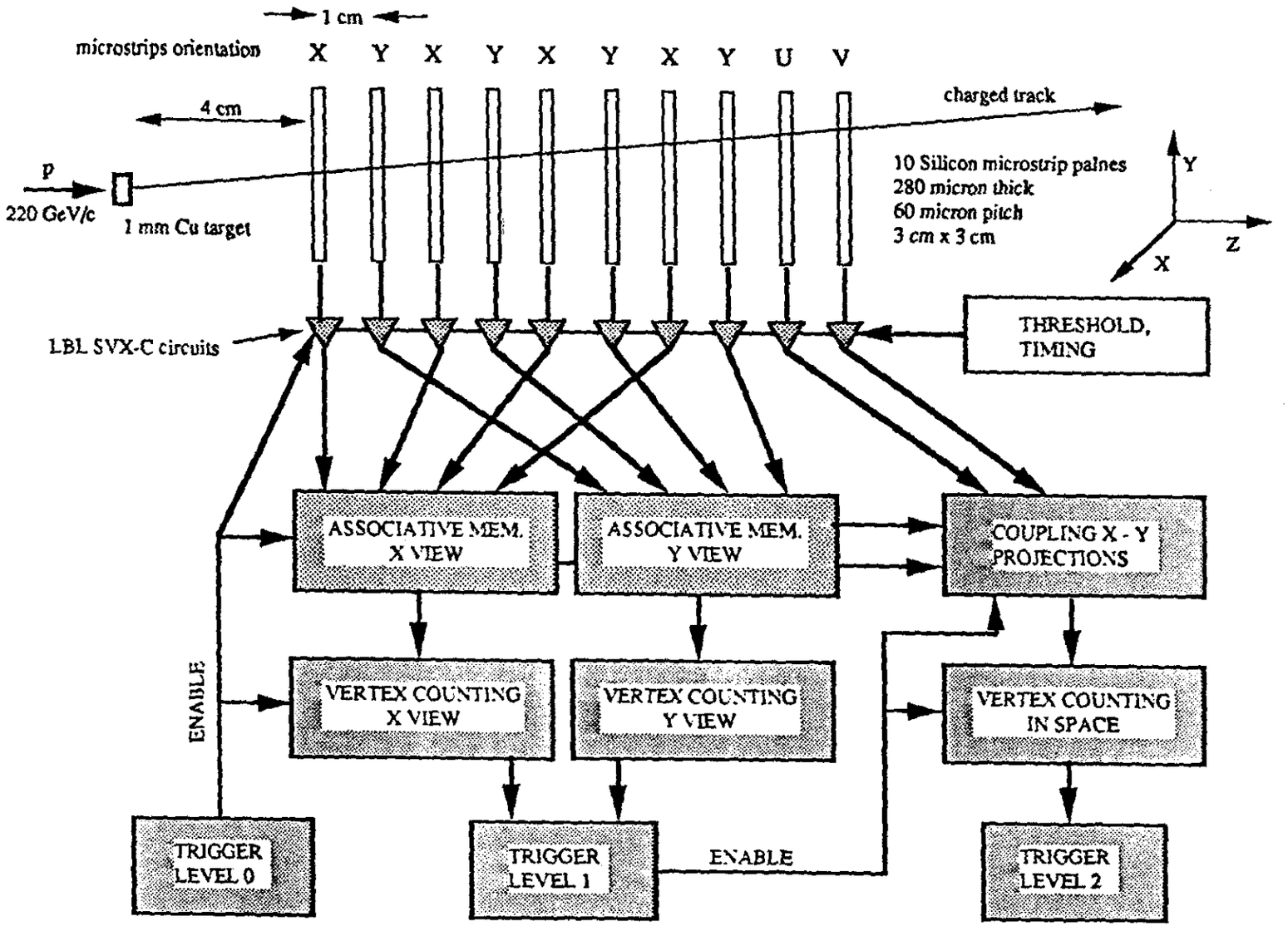


Fig. 16 - Arrangement for beam test.

inate B decays from minimum bias background, with 50% retention of B's while rejecting the background at the level of 1 : 50000 in fixed target, and 1 : 50 in a Collider, both satisfactory when compared with the relative signal to background ratios. We are simulating a neural network which "executes" the algorithm, and preliminary considerations make us think of this as the possible way to implement the "processing" device mentioned above. Neural nets exhibit an intrinsic parallelism and feed-back capabilities (at least in some configurations) which cannot be achieved with conventional sequential approaches. Once implemented as a hardware device, a neural net could sort out the trigger decision in a time of a few tens of nanoseconds.

A test of the silicon tracking-based secondary vertex trigger is under discussion for 1994 CDF upgrade run. More specific studies of such trigger schemes for the SSC will be undertaken as part of this proposal. We want to understand the relation of the trigger to our physics goals and to the first level calorimeter trigger.

VII. Summary of Milestones for Proposal

We summarize below in a concise fashion the goals for our proposal for the first and second year. A more detailed discussion has been given in the text.

Major Milestones: Year One

(A.) *Physics*: (1) Study of $H^0 \to b\bar{b}$; (2) $H^0 \to Z^0 Z^0 \to$ 4 charged leptons–discovery potential versus resolution and coupling; (3) analysis of $H^0 \to Z^0 Z^0 \to$ Jets–signal and background rates vs. Higgs mass.
$\hookrightarrow \ell^+\ell^-$

(B.) *Simulation*: Define small number of detector configurations to look at. Full-tracking simulation for these. Evaluation of tracking efficiency, momentum and mass resolution. Comparison of performance of different styles of detector (double-sided stereo detectors vs. short strip detectors.) Will look at performance for:

(1) $H^0 \to Z^0 Z^0 \to$ 4 charged leptons.

(2) Multiplicity measurement in Higgs decay to jets for a heavy Higgs.

(3) Tracking efficiency in the core of 1 TeV jets.

Want to set limits on allowed material in the detector.

Work on best integration of silicon with outer detectors. Specification of what would be needed in an outer system to complement the silicon tracking for both small and large rapidities.

(*C.*) *Engineering Study*: Study of materials to define direction for support structure. Initial structural design. Investigate cooling techniques for microchips. Prototype of detector element structure.

(*D*.1.) *Double-sided Strip Detectors*: Fabrication of a prototype double-sided microstrip detector in collaboration with the Hamamatsu Corporation and European vendors. Radiation test and characterize performance when bonded to readout.

(*D*.2.) *Short Strip Detectors*: Fabricate and test short strip detectors with integrated coupling capacitors and biasing resistors. Evaluate radiation effects.

Research bonding techniques for *(D.1.)* and *(D.2.)*

(*D*.3.) Development of detectors with wafer integrated electronics.

(*E*.1.) *Bipolar Electronics*: Continue work with NTT and DI amplifiers. Characterize performance on a detector and after radiation. Investigate design tradeoffs involving capacitance, power, and shaping time.

(*E*.2.) *Analog CMOS Electronics*: Fabricate and test prototype CMOS readout for short strips (preamplifier, shaper, discriminator) to verify noise, speed, and power. Initial design and measurements using rad-hard (UTMC) process. (Priority: verify noise characteristics).

(*E*.3) *Interface Storage Electronics*: Investigate buffering schemes for both "long" and "short" strip systems. Continue work with UTMC on a rad-hard digital storage chip. Characterize performance before and after radiation. Investigate ways of prompt signal extraction for triggering.

(*F.*) *DAQ/Triggering*: Beam test of PISA Trigger Chip. Begin to specify what we want for an SSC trigger.

At the end of the first year we expect to put together the information from the above efforts to arrive at a tentative geometrical layout for the silicon tracking detector. This will include a physics justification and technical evaluation. The second year we will work with this design and aim at a more detailed engineering design.

Major Milestones: Year Two

(*A.*) *Physics* and (B.) *Simulation*: Complete analyses with detector geometry chosen in Year 1. Provide guidance on engineering questions such as the effect of material on performance and the importance of position accuracy. More thorough study of vertex detection.

(*C.*) *Engineering Study*: Make a complete design of the support structure, including cooling and cable supports. Prototype of critical elements of the

structure will be made and tested. Design will include fabrication procedure, cost estimate, and time schedule.

(D.) *Detectors*: Develop production-type detectors. Test beam evaluation. Readout electronics will be of the type tested in the first year and will probably not be the final design.

(E.1.) *Bipolar Electronics*: Further evaluate what we can expect in electronics in the future and make amplifier design consistent with expectations.

(E.2.) *Analog CMOS Electronics*: Fabricate and test rad-hard front end circuitry for short strips.

(E.3) *Interface Storage Electronics*: Work out architecture for storage in the final detector and begin production of rad-hard prototypes.

(F.) *DAQ/Triggering*: Work on relationship between data acquisition system and track momentum trigger. Conceptual design of a trigger system.

At the end of the second year we expect to have a detailed engineering and electronics design for the detector layout that had been specified in the first year, as well as a schedule and cost estimate for production of a full-tracking detector.

In addition, a parallel R&D effort on pixels is being pursued under a separate generic R&D proposal. Our physics studies will include a study of the impact of pixels and we expect to share information on technical and engineering issues with the pixel technical proponents.

VIII. Budget and Relation to Milestones

To accomplish the goals outlined above we plan to divide the work among subgroups dedicated to well-defined tasks. Each subgroup will have co-chairmen responsible for organizing the work. The collaboration, as a whole, will meet approximately every three months to pool information and review progress. Groups in related areas (e.g. physics and simulations) will coordinate their efforts and typically share some personnel. Working groups have experts from several institutions to allow a comparison of experiences and maximum exchange of ideas and information. We feel this is particularly useful during the R&D phase of such a project.

For the second year of our project, we have made up the budget assuming all detector development efforts are successful. We plan to assess the progress in each area at the end of the first year and only request funds for those areas that show substantial promise and progress.

The working groups and their co-chairmen are listed below. These are to be supplemented by personnel requested in our budget listed below.

Physics–R. Cashmore, A. Seiden–
M. Asai, B. Barnett, J. Gunion, H. Haber, N. Harnew, J. Hassard, A. Palounek, D. Pellett, D. Pitzl, S. Tkaczyk, H. Sadrozinski, A. Weinstein.

Simulations on Tracking–J. Matthews, A. Weinstein–
D. Amidei, W. Kinnison, W. Ko, W. Lockman, S. Mani, A. Palounek, T. Schalk, A. Seiden, P. Shepard, H. Ziock.

Vertex Detection–D. Pellett–
A. Litke, D. Nygren, S. Parker, A. Weinstein.

Integration of System with Outer Detectors–J. Dainton, D. Saxon–
G. Kalmus, W. Kinnison, W. Ko, J. Matthews, A. Palounek, A. Seiden, H. Ziock.

Mechanical Engineering–P. Shepard, H. Ziock–
D. Amidei, P. Booth, D. Duchane, E. Engels, C. Haber, A. Litke, A. Menzione, W. Nilsson, H. Sadrozinski, A. Seiden.

Interconnects and Cooling–R. Ely, D. Hutchinson–
A. Czermak, C. Haber, A. Litke, T. Ohsugi, K. Pakonski, W. Rowe, M. Turala.

Double-Sided Detectors–T. Ohsugi, J. Ellison–
P. Allport, B. Barnett, F. Bedeschi, L. Bosisio, A. Carter, J. Carter, P. Fisher P. Giubellino, G. Hall, G. Kalmus, J. Kapustinsky, A. Mazari-Chiesa, H. Miyaka, A. Sakaguchi, P. Sharp, M. Turala, S. Wimpinney.

Detectors with Short Strips Including Electronics–A. Litke, H. Spieler–
G. Hall, S. Holland, D. Nygren, M. Wright.

Development of Detectors with Wafer Integrated Electronics–S. Parker, P. Shepard–
E. Engels, T. Humanic, C. Kenney, S. Mani.

Bipolar Electronics–H. Ikeda, E. Spencer–
W. Dabrowski, D. Dorfan, D. Hutchinson, H. Sadrozinski, A. Seiden, H. Spieler, L. Van der Have.

Digital Data Storage–H. Sadrozinski, P. Sharp–
J. DeWitt, R. Ely, A. Litke, P. Giubellino, S. Kleinfelder, H. Spieler, W. Rowe, M. Wilder.

Triggering/DAQ–S.R. Amendolia, W. Kinnison–
F. Bedeschi, B. Denby, J. DeWitt, B. Foster, G. Heath, J. Matthews, R. Nickerson, T. Schalk, P. Sharp, S. Tkaczyk, T. Weidberg.

Our proposal builds on a substantial investment in time and in resources both from generic SSC R&D funds and the Cooperative U.S.–Japanese agreement in high energy physics. The physicists and engineers named on the proposal will be donating their time except where explicitly named in the budget below. In addition, we are requesting the addition of a small number of physicists and engineers for specific areas, as described below. Note, a large amount of equipment (some of it highly specialized, such as wire-bonders and probe stations) is available for use for this project at several institutions. In addition, the Rutherford Laboratory will be able to make masks for detectors and electronics yielding a considerable cost saving.

We outline below our budget request. It is organized in a parallel fashion to the milestone/goals discussed above to allow a clear correlation of goals and costs. The justification of the primary costs is as follows:

(A.) *Physics* and (B.) *Simulation:*

This is the main area in which we are requesting additional support for new physicists because we are anxious to complete this work in a rapid and thorough fashion, in order that clear specifications can be arrived at for the engineering phase of the project.

(C.) *Engineering Study*

This is the most expensive part of the proposal and crucial to the construction of a real detector system. For the price, we will be receiving the efforts of experienced advanced engineering groups, including state-of-the-art analysis techniques and fabrication facilities. This is absolutely essential for a realistic evaluation of the silicon tracking system. In the text we have outlined the division of responsibilities and goals between Los Alamos National Laboratory and Westinghouse. We emphasize that we will get real prototypes to test and work with, and that this will not be just a paper study. The University of Pittsburgh is requesting some additional physicist manpower to work full-time with the Westinghouse engineering staff.

(D.) *Detectors*

The costs here are mainly for engineering and technical personnel and the cost of a significant number of prototype detectors and electronics for a system test. The work on double-sided detectors will be shared between the Japanese members of the collaboration, U.C. Riverside, Johns Hopkins and the U.K. groups. The Japanese groups will work with Hamamatsu. The U.S. and U.K. groups will take responsibility for working with LBL on test structures, will carry out a parallel development program with European vendors, and will radiation test and compare the performance of the various detectors. In addition, they will work on developing

a technique for testing the bulk properties and more subtle behavior of the large number of detectors that will make up a tracking system.

The work on Short Strip Detectors will be shared by LBL and one of the U.C. Santa Cruz tasks. This will include work on all related electronics. The work with Westinghouse will be done by the University of Pittsburgh. Work with the Stanford Center for Integrated Systems will be done by the University of Hawaii.

(E.) *Electronics*

The work on bipolar electronics will be done mainly in Japan and at U.C. Santa Cruz. We are requesting engineering support to help with tests and detailed measurements on cooling at the single detector level. This information will be provided in support of the mechanical engineering effort. Engineering work on integration will be in the area of hybrids for readout and interfacing with the readout system.

Costs for the study of digital storage electronics and trigger electronics is already mostly funded by other sources (SSC generic R&D and INFN). We are, however, requesting funds for a rad-hard run for the second year of a prototype digital storage device.

Finally, we request funds for the travel associated with this work (subgroup meetings and overall group meetings) as well as a small administrative cost for copying, postage, and word-processing time. The group as a whole is expecting to meet every three months to exchange information, assess progress, and review how well we are meeting our goals.

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BUDGET REQUEST	Year 1	Year 2
(A.) Physics and (B.) Simulation		
Domestic Travel	10,000	10,000
International Travel to and from collaborating institutions: (U.K.)	7,000	7,000
UCSC		
1 FTE, Physicist	50,000	50,000
Johns Hopkins		
.6 FTE, Physicist	30,000	30,000
UC Davis		
1 FTE, Physicist, 2nd year. First, to be hired, contribution by U.C. Davis		50,000
(C.) Engineering Study		
Domestic Travel	10,000	10,000
International Travel to and from collaborating institutions: (Poland, Italy)	5,000	5,000
Westinghouse	205,000	482,000
LANL	400,000	400,000
University of Pittsburgh		
.33 FTE, Physicist, first year	17,000	
1 FTE, Physicist, second year		52,000
(D.1.) Double-sided Strip Detectors		
Domestic Travel	8,000	8,000
International Travel to and from collaborating institutions: (Japan, Poland, Italy, U.K.)	19,000	19,000
Detectors--to be shared among collaborators	55,000	50,000
UC Riverside:		
1 FTE, Electronics	60,000	60,000
Probe Station Upgrade	15,000	
Test Equipmennt	15,000	40,000
Mounting & Bonding	15,000	30,000
Electronics & Read-out	40,000	20,000
Johns Hopkins:		
Electronics Engineer	95,000	95,000
.4 FTE, Physicist,	20,000	20,000

Micro Electronics Lab. Equipment:		
Probe Station, Wire Bonder, DAQ System	63,000	23,000
Detector Control/Readout Electronics	20,000	14,000
2 FTE, Engineering Support, U.K. Groups. Equal Matching Funds will Be Provided by U.K.	50,000	50,000
LBL and FNAL:		
Bonding and Cabling R&D	30,000	30,000
(D.2.) Short Strip Detectors		
Lawrence Berkeley Laboratory:		
.5 FTE (Spieler)	75,000	75,000
.5 FTE (Holland)	75,000	75,000
.5 FTE (Wright)	75,000	75,000
Materials	25,000	75,000
UCSC:		
Bump Bonding	25,000	
Read-out Chips		25,000
Detectors		25,000
(D.3.) Detector Development with Westinghouse		
University of Pittsburgh:		
Test Equipment	15,000	25,000
Fabrication	75,000	112,500
(D.4.) Detector Development of University of Hawaii with Stanford CIS		
Mostly funded from generic R&D for first year, second year assumes no generic SSC funds	40,000	170,000
(E.1.) Bipolar Electronics		
Domestic Travel	5,000	5,000
International Travel to and from collaborating institutions: (Poland, Japan)	5,000	5,000
UCSC:		
Probe Station with Laser	55,000	
Test Electronics & Equipment	15,000	15,000
.5 FTE Cooling (Hutchinson)	40,000	40,000
.5 FTE Integration (Spencer)	25,000	25,000

(E.2.) Frontend and Interface CMOS Electronics

Domestic Travel	10,000	10,000
International Travel to and from collaborating institutions: (Italy, Japan)	5,000	5,000
UCSC:		
Commercial Workstation Software	10,000	10,000
Fabrication at UTMC		80,000

(F.) DAQ/Trigger

International Travel to and from collaborating institutions: (Italy, U.K.)	5,000	5,000

Equipment Funding is provided by INFN

Administrative Costs	5,000	5,000
Travel to collaboration meetings	80,000	80,000
TOTAL DIRECT COSTS	$ 1,904,000	$ 2,497,500
INDIRECT COSTS		
Off-campus research rate, 26.5% of modified total direct costs ($85,000)	22,525	22,525
TOTAL PROJECT COSTS	$ 1,926,525	$ 2,520,025

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TRACKING REQUIREMENTS FOR THE SSC AND SILICON STRIP DEVELOPMENT

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ABSTRACT

We quantify the design parameters for a central tracking system capable of good momentum measurements and high reconstruction efficiency for charged particles within 1 TeV jets. We express our results as a set of scaling rules. Based on these rules we outline a silicon strip tracking system which is well matched to the SSC high luminosity environment. Special challenges for the construction of this tracker are in the area of electronics readout. We present initial work we have done in this area.

GENERAL CONSIDERATIONS

In designing a tracking system it is useful to characterize the systems capabilities in terms of a few performance parameters which are determined by the geometry of the device and its detection method. Similarly, one can try to characterize the physics of particle production in terms of a few characteristic parameters, providing a heuristic, simplified picture of the events which have to be reconstructed. The physics and tracker parameters can be combined to yield scaling relations which can guide the choice of tracker technology and geometric layout. Given a design based on these heuristic ideas, a full Monte Carlo can then be performed to quantitatively evaluate the tracker performance and check that it is adequate

In the study presented below, we have chosen tracking within 1 TeV jets in the central rapidity range, $|Y| \leq 2.5$, as the goal for physics at the SSC. We assume that the detector is inside a solenoidal magnetic detector. Using the scaling rules which link the physics and the tracker parameters as a guide, we present a conceptual design of a tracking system made of thin silicon strip detectors. This detector provides the following features:

(1) High efficiency tracking within jets having transverse momentum ≥ 1 TeV in the central rapidity range,
(2) Allows a fast algorithm for usage of measurements and for track finding, which is important given the very large amount of information present,
(3) Allows precision momentum measurement,
(4) Has sufficient angular resolution to allow assignment of tracks to the correct vertex for multiple events in a time bucket and to match muons between the inner tracking detector and an outer muon identifier,
(5) Provides trajectory information for secondary vertex identification,
(6) Allows the measurement of charged energy flow per machine crossing to cross-check the calorimetry measurement which will probably sum over several crossings.

Tracking provides a much more fine grained picture of an event than does calorimetry and could be crucial in identifying new physics signatures. For example, calorimetry, because of tower sizes and shower spreading, will see the event energy in buckets which span a few degrees in angle. The tracking can provide a measurement of the event structure with roughly two orders of magnitude finer angular resolution and within each beam crossing.

Specific physics goals for the tracker are as follows:

(1) Leptons have often been indicative of new physics. The tracker, when combined with the rest of the detector, provides comparable μ and e detection efficiency and momentum resolution. Redundancy is provided for e detection by comparing the measured momentum from the tracker with the energy measured in the calorimeter, while for muons the tracker momentum can be compared to the momentum measured in an external muon identifier such as a toroid.
(2) Tracking provides the ability to search for long-lived particles or jets with unusual topologies.
(3) For the Standard Model Higgs, tracking is important for searches in all mass regions by providing:
   (a) Secondary vertex detection needed in the search for $H^0 \to b\bar{b}$ or $t\bar{t}$, for a Higgs mass less than about 150 GeV,
   (b) Good mass resolution for reconstruction of both the Z^0 and H^0 in the decays $H^0 \to Z^0 Z^0 \to 4$

charged leptons. This provides enough rate for H^0 detection for Higgs masses up to about 600 GeV.

(c) Measurement of multiplicity and event shapes to be used to separate $H^0 \to W^+W^-$ or Z^0Z^0, where one gauge boson decays into hadrons, from the production of a single gauge boson accompanied by quarks and gluons. This is relevant for the Higgs search at masses larger than about 600 GeV.

SCALING RULES FOR TRACKER DESIGN

We take for our heuristic model of a jet a cone of half-angle $\theta_{1/2}$, with particles within the cone spaced by a mean angle $\langle\theta\rangle$, which is the angular spacing in the bend projection which for a solenoidal detector is the azimuthal angle. In addition, we assume the particles in the jet have momenta larger than a minimum, $P_{\min}$, which is determined by the typical transverse momentum relative to the jet axis and the jet angular size. We chose for $\theta_{1/2}$ the angle at which the energy flow drops by a factor of two for 1 TeV jets, according to the PYTHIA Monte Carlo.[1] This number is about 4 mrad for quark jets and 20 mrad for gluon jets. We therefore choose 10 mrad as a typical jet half-angle.

Since the jet core can be expected to contain 10 to 20 particles at these energies, we expect $\langle\theta\rangle$ to be about an order of magnitude smaller than $\theta_{1/2}$. To arrive at a number particularly well suited to tracking, we can use the extensive work done on B reconstruction at the Z^0.[2] For this case the tracker must have a two track resolution in the azimuthal angle of about 5 mrad for efficient B reconstruction. Scaling these jets up in energy to 1 TeV, we can estimate that $\langle\theta\rangle = .5$ mrad for the angular spacing of neighboring particles.

As the third and last parameter characterizing the jet core, we choose as the typical transverse momentum relative to the jet axis 500 MeV, giving $P_{\min} = 500\ \mathrm{MeV}/\theta_{1/2} = 50$ GeV for a 1 TeV jet. Thus in this simple picture the jet core contains all particles with fractional momentum $\geq 5\%$ of the jet momentum.

Because of the very fine segmentation needed to resolve tracks, a tracker will probably have to use infrequent sampling to avoid ending up with an enormous number of channels. It will, in addition, have to go out to a moderately large radius, since it is critical not only to resolve tracks, but also to measure their momentum. Figure 1, below, shows our model of a section of the tracking detector, organized to provide local track samples which can be linked into tracks. The detectors are grouped to provide track segments called vector elements, allowing for efficient pattern recognition. In Fig. 1, the vector elements are two closely-spaced detectors; more generally, these can be several closely-spaced detectors. The parameters describing the detector are:

σ_m = position resolution for each measurement,
ϵ_m = two-track spatial resolving power,
δ = spacing of detector plane pairs forming vector elements,
$\sqrt{2}\sigma_m/\delta$ = error on track tangent,
Δ = spacing of vector elements,
r_m = outer radius,
N = number of layers,
B = magnetic field.

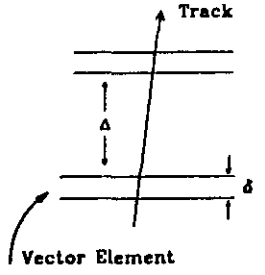

Fig. 1. *Arrangement of detector made up of spaced local track-measuring vector elements.*

We will assume below that measurements are of the azimuthal angle. It is necessary to also measure the z coordinate. We will assume this is done using stereo measurements and return to this question later. For the pattern recognition we require that:

- different tracks give distinct hits in each individual tracking detector of a vector element,
- hits in the vector elements can be locally associated into correct track segments,
- the local track segments have to be correctly linkable into tracks.

Using the three parameters characterizing the jet structure and the tracker characteristics, we quantify the three tracking requirements as follows:

(1) At a radius r, a track will typically have a nearest neighbor spaced by a distance $r\langle\theta\rangle$. The hits will be correctly resolved if the measuring device has a two track resolution $\epsilon_m < r\langle\theta\rangle$. This gives our first scaling rule for efficient tracking

$$\frac{\epsilon_m}{r\langle\theta\rangle} < 1,$$

where r = mean radius of the tracker.

(2) Figure 2 shows a track passing through a vector element. From the measurement in the inner layer, we can predict a hit on the second layer assuming infinite momentum, as shown by the dashed line in Fig. 2. The spatial mismatch between the prediction and the real trajectory is $r\delta/2\rho$, where r = radius of the layer and ρ = radius of curvature of the track. The largest mismatch for tracks in the jet will occur for tracks with the lowest momentum, $P_{\min}$. We will have confusion if a second track leaves a hit between the predicted location and the real hit location. Since a neighboring hit can be expected at a spacing $r\langle\theta\rangle$, this means that we require $r\delta/2\rho < r\langle\theta\rangle$, yielding the second scaling rule, $\delta/(2\rho\langle\theta\rangle) < 1$. Here ρ

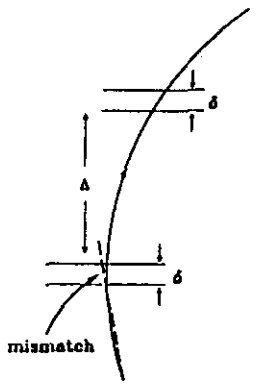

Fig. 2. A Track passing through two adjacent layer pairs.

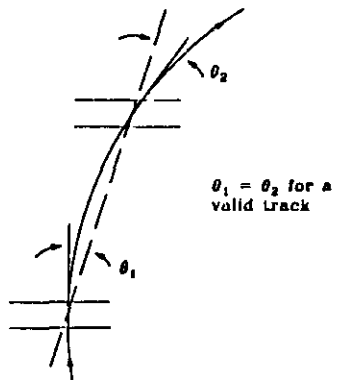

Fig. 3. Relation for vector segments lying on one track.

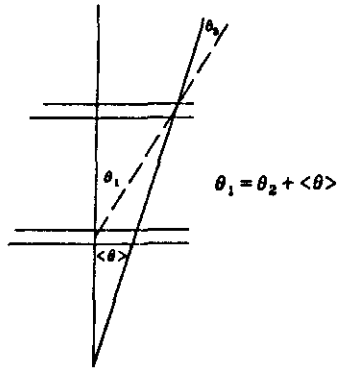

Fig. 4. Two tracks and spurious (dashed) segment linkage.

is calculated from $P_{\min}$ and the B field chosen for the detector.

(3) The basis for linking vector segments is illustrated in Fig. 3. Each angle θ_1 or θ_2 is measured with a precision given by $\sqrt{2}\sigma_m/\delta$. Linking can be done if this accuracy is adequate to exclude wrong combinations. We show in Fig. 4 the trajectories of two very high momentum tracks separated by a production angle $\langle\theta\rangle$. An incorrect link yields the dashed track whose angles don't match by an amount $\langle\theta\rangle$. Thus, a goal for the linking to work is $\sqrt{2}\sigma_m/\delta \lesssim \langle\theta\rangle$, giving the third scaling rule $\sqrt{2}\sigma_m/\delta\,\langle\theta\rangle < 1$.

Note that scaling rules (2) and (3) have an opposite dependence on δ. It has to be carefully chosen, since good matching for segments requires a small δ, whereas a well measured tangent vector in a segment requires a large δ.

The last scaling rule refers to the measurement of z coordinates using stereo tracking elements. We show an arrangement of vector elements in Fig. 5, which will allow full local association of axial and stereo measurements. The stereo layers can be characterized by a stereo angle $\alpha = \alpha_u = -\alpha_v$ and the stereo displacement $s = \ell\alpha$, where ℓ = detector length.

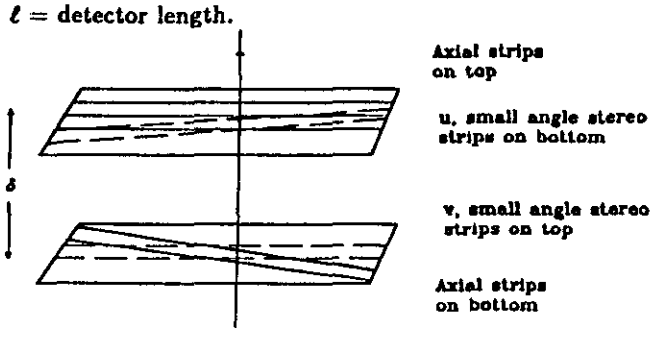

Fig. 5. Orientation of detector elements to allow a local reconstruction of the z coordinate using stereo measurements.

For the two vector elements we measure azimuthal angles ϕ_1, ϕ_2 and stereo measurements $\phi_v = \phi_1 + \alpha z_1/r_1, \phi_u = \phi_2 - \alpha z_2/r_2$. High momentum tracks have a trajectory $z = r\tan\lambda + z_0$, where z_0 is the vertex location in z_0 and $\tan\lambda = P_z/P_T$. For the case $z_0 = 0$, the correct stereo hits are given by the pair satisfying the matching equation $\phi_1 + \phi_2 = \phi_u + \phi_v$.

At the SSC, we expect the length of the interaction region $\sigma_{z_0} \simeq 5$ cm. Assuming complete ignorance of the vertex position in a given event (taking $z_0 = 0$), such a spread in vertex position will produce a mismatch in the angles in the above matching equation of $\sigma_{z_0}\alpha\delta/r^2$. This is smaller than the measurement error in the matching equation$=2\sigma_m/r$, except at small radii, even for a small σ_m. We include the finite beam size in the Monte Carlo studies discussed in the next section.

The confusion from many tracks can be quantified in terms of the detector and physics parameters. If a pair of axial strips have been successfully associated within the jet, all tracks within the stereo displacement region s (defined above) will leave stereo hits which can confuse the z matching. The number of tracks entering this region is $N_s = s/(r\,\langle\theta\rangle)$, since the mean displacement between tracks at a radius r is $r\,\langle\theta\rangle$. All of these tracks will leave stereo hits in the u plane which could accidentally associate with another hit in the v plane falling within a region of full width $2\sigma_m$, which is the resolution characterizing the correct choice. The probability of there being such a hit in the v plane is $P = N_s \cdot 2\sigma_m/s$, and the number of potential incorrect z pairings is $N_{inc-z} = N_s P$. Thus we arrive at the scaling rule for stereo association to work well

$$N_{inc-z} = N_s^2 \frac{2\sigma_m}{s} = \frac{2\sigma_m s}{(r\,\langle\theta\rangle)^2} < 1\ .$$

Note that if we increase s (by increasing the stereo angle α or the detector length l) N_{inc-z} will not necessarily continue to increase. Eventually s will exceed the size of the jet ($\simeq 2r\theta_{1/2}$) and any further increase in s will leave N_{inc-z} unchanged. In this limit, which is characteristic of long drift chamber detectors, the scaling rule is

$$N_{inc-z} = \frac{4\sigma_m r\theta_{1/2}}{(r\,\langle\theta\rangle)^2} = \frac{2\sigma_m}{(r\,\langle\theta\rangle)} \cdot \frac{2\theta_{1/2}}{\langle\theta\rangle} = \frac{4\theta_{1/2}\sigma_m}{r\,\langle\theta\rangle^2} < 1\ .$$

This completes the set of scaling rules, which we will use in the next section to evaluate our silicon strip tracker design.

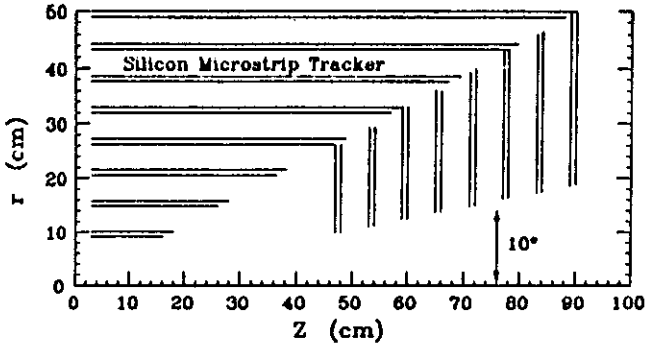

Fig. 6. Silicon tracking system.

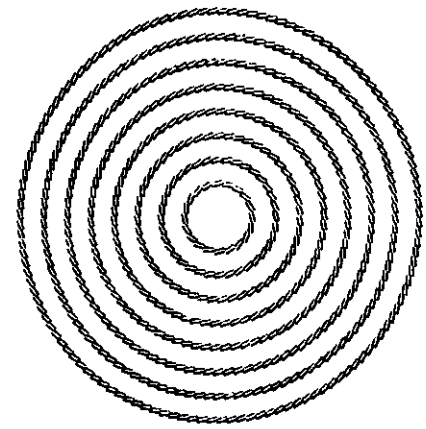

Fig. 7. Central silicon tracker.

SILICON STRIP TRACKING DETECTOR

To meet the very stringent tracking requirements for the SSC, we would like to use a technology offering an order of magnitude improvement in performance over the traditional drift chambers used in present experiments. We feel that silicon strip detectors with 25 μm pitch are a good choice for this problem since they offer:

(1) Intrinsic position resolution of 5 μm and two track resolution of 100 μm, well matched to the scaling rules derived above, thereby allowing efficient tracking,
(2) The time structure of the signal well matched to the SSC machine repetition rate,
(3) Reasonably radiation hard detectors,
(4) VLSI electronics and substantial multiplexing easily incorporated,
(5) A large community working with these types of detectors, yielding substantial technological improvements with time.

Figure 6 shows a proposed design made of 8 pairs of double sided-detectors, providing 32 measurements per track. The pairs yield 8 axial and 8 stereo vector segments for the track reconstruction. This compares, for example, to 6 axial and 6 stereo vector segments for the new MARK II drift chamber. The stereo arrangement is that shown previously in Fig. 5. Figure 7 shows a cross section of the central part of the detector. The individual silicon detectors are tilted to compensate for the Lorentz angle due to the magnetic field. The inner radius of the detector has been taken as 8 cm to limit the maximum radiation damage to less than 0.5 Mrad in an SSC year.[3] The outer radius has been chosen as 50 cm to provide adequate momentum resolution in a 2.5 Tesla field, as discussed below. The maximum occupancy, in the innermost layer, is 2×10^{-3} in a two-hit resolution element, $\epsilon_m = 100$ μm, assuming the detector is read out each beam crossing.

The stereo angle chosen for the detector is $\alpha = 5$ mrad. For a 10 cm long detector this gives a stereo displacement, s, of 500 μm. Tracks separated by a distance greater than s in the axial projection don't interfere with each other at all. The very small stereo angle still yields a $\sigma_z = 1.44$ mm per measurement and a resolution in z at the vertex of 835 μm.

Secondary vertex identification is available in the bend plane where the interaction region is very small. Note, for high momentum tracks, the impact parameter error is still $\sim 5\mu$m, even starting 8cm from the origin, since the long lever arm of the tracking devices provides a very well measured angle and curvature.

Table 1 presents a summary of the scaling rules for this detector. We have chosen $\delta = 1$ cm to provide a reasonably well measured tangent vector. The small stereo angle chosen is motivated by the desire to limit the confusion in the local stereo association, as quantified by the stereo scaling rule. The table indicates that the matching of vector segments into tracks has potentially the greatest confusion. For comparison, we also list the scaling parameters for the new MARK II drift chamber at the SLC, which has been carefully optimized by Monte Carlo studies for jets of 50 GeV.[4]

MONTE CARLO STUDIES

In this section we look in more detail, based on a Monte Carlo simulation, at the ability to do tracking in 1 TeV jets with a silicon tracker. The program ISAJET[5] was used to generate events with two quark or gluon jets, each with $P_T \geq 1$ TeV. The mean multiplicity within $|Y| < 2$ in these events is 330, of which 118 have $P_T \geq 1$ GeV. Figure 8 shows a high P_T event in a 3 Tesla magnetic field. A region near the core of the tight 1.5 TeV jet in the lower left quadrant of the event, at a radius of 26 cm, has been blown up as Fig. 9. The scale is matched to the size of a single strip detector containing 1024 25-μm elements. At this scale, which is the one relevant for the track finding, the stiff tracks are not confusing.

Vector Segment Finding

To quantify this, we have performed the first two steps of the pattern recognition for these Monte Carlo 1 TeV jets. As a first step, we keep only hits with no other hit within 100 μm in space. The detectors are assumed

TABLE 1: DETECTOR PARAMETERS AND SCALING RULES

Physics Parameters for:	1 TeV Jets	50 GeV Jets
Track angular separation $\langle\theta\rangle$	0.5 mrad	10 mrad
Jet angular width $\theta_{1/2}$	10 mrad	40 mrad
Track P_T in jet core	50 GeV	10 GeV
Detector Parameters	**Si Tracker**	**Mark II/SLC**
Magnetic field B	2.5 Tesla	0.5 Tesla
Radius of curvature $\rho = 3.3P_T/B$	66 m	66 m
Radial detector spacing δ	1 cm	0.8 cm
Superlayer thickness δ_{SL}	1 cm	4 cm
Maximum radius r_m	50 cm	150 cm
Mean radius r	29 cm	88 cm
Detector length l	10 cm	230 cm
Double track separation ε_m	100 μm	4 mm
Stereo angle α	5 mrad	74 mrad
Position resolution σ_m	5 μm	100 μm
z position resolution $\sigma_z = \sqrt{2}\sigma_m/\alpha$	1.4 mm	1.9 mm
Scaling Rule Requirements	**Si Tracker**	**Mark II/SLC**
Resolve hits: $\frac{\varepsilon_m}{r(\theta)} < 1$	0.7	0.45
Find vector segments: $\frac{\delta}{2\rho(\theta)} < 1$	0.15	0.006
Link vector segments: $\frac{\sqrt{2}\sigma_m}{\delta_{SL}(\theta)} < 1$	1.4	0.4
Match z hits: $\frac{2\sigma_m l\alpha}{(r(\theta))^2} < 1$, or:	0.24	–
for $l\alpha > 2r\theta_{1/2}$: $\frac{4\sigma_m\theta_{1/2}}{r(\theta)^2} < 1$	–	0.2

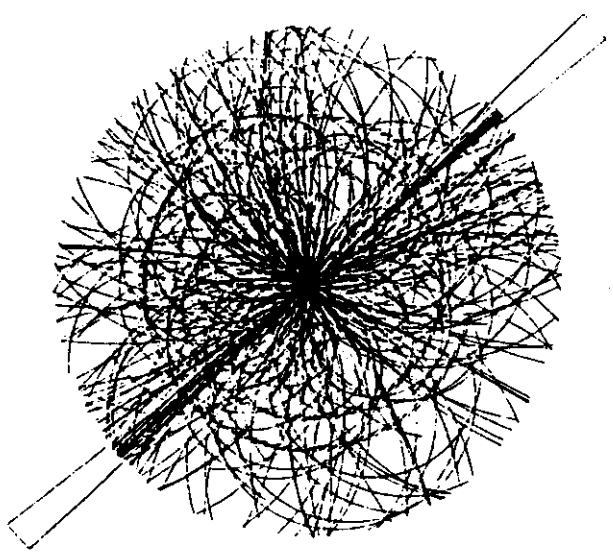

Fig. 8. Typical 1 TeV event from ISAJET.

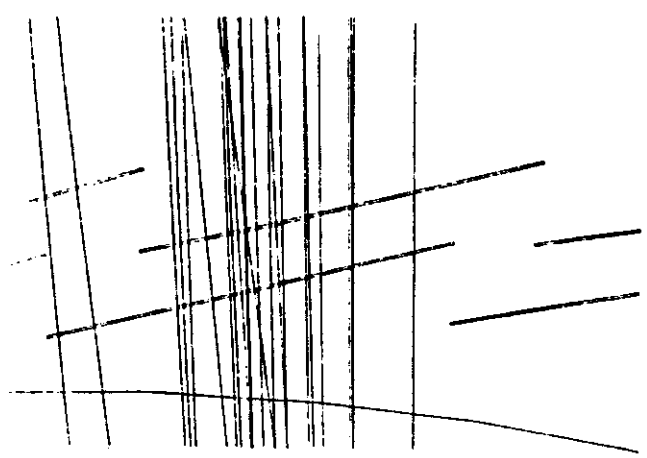

Fig. 9. Blowup of dense jet at mean detector radius.

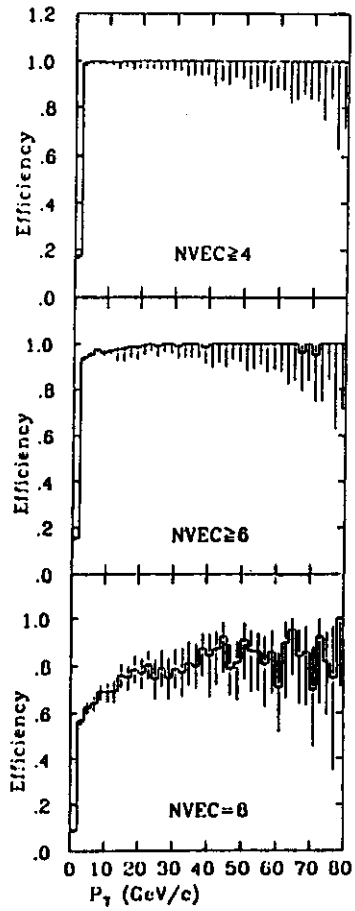

Fig. 10. Vector segment finding efficiency.

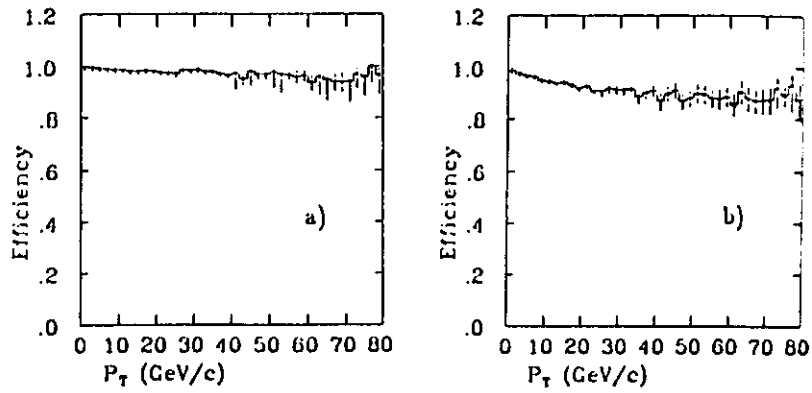

Fig. 11. Stereo association efficiency. a) α = 5 mrad, b) α = 20 mrad.

to be 10 cm in length, with the outer member of a pair staggered by one half of a detector length with respect to the inner layer. Using the simple algorithm presented above to link hits into vector segments, and considering only hits pairs which can come from tracks with $P_T > .5$ GeV, we evaluate the efficiency vs. P_T for finding tracks if we require at least NVEC $\geq$ 4, 6, or 8 correctly found vector segments to call the track found. The results for δ chosen equal to 1 cm for a 2.5 Tesla B field are shown in Fig. 10, where the last bin includes overflows. The efficiency is close to 100% for high momentum tracks, if we require NVEC $\geq$ 6, which corresponds to $\geq$ 12 axial and 12 stereo measurements, assuming the stereo finding is fully efficient.

To test the scaling rule for the stereo z matching, we apply the stereo algorithm discussed above to the vector segments that were found correctly in the axial projection. The efficiency for making the correct local z match, as a function of P_T of the track is shown in Figs. 11a and b for the cases α = 5 mrad and 20 mrad, respectively. The efficiency in the former case is > 95% for all tracks, falling at high P_T where tracks are in the center of jets. It is clear that the efficiency begins to degrade significantly when the stereo angle is increased to 20 mrad, as expected from the scaling rule. We have verified that the effect continues at larger stereo angles.

Dependence of Efficiency on the Magnetic Field

The presence of an axial magnetic field is required for the measurement of the track momentum. However, the magnetic field also has an impact on the pattern recognition efficiency. The field may improve the reconstruction efficiency by separating closely spaced tracks in the outer layers, or degrade the efficiency by causing tracks to cross in the outer layers, leading to confusion.

In order to determine which is the dominant effect for the tracking system discussed here, we evaluated the vector segment finding efficiency for various B fields. We find that this efficiency is degraded with larger magnetic fields, over the entire range of momenta. As an example, the efficiency for finding all 8 vector segments for tracks with P_T > 15 GeV falls from $\simeq$ 80% to about 65% for B = 2.5 and 5.0 Tesla, respectively. For the case we have chosen, B = 2.5 Tesla, the inefficiency for vector segment finding in the inner layers due to the close spacing of tracks is approximately the same as that in the outer layers due to track crossings.

The magnetic field can also degrade the double track resolution by spreading the charge (electrons and holes) over several strips due to the Lorentz drift of the charges in the magnetic field. The Lorentz angle θ_L is defined by $\tan\theta_L = \mu B$, where μ is the Hall mobility of the charge carriers. However, the use of double-sided detectors means that we are collecting both electrons and holes, which have different Hall mobilities.[6] To minimize the problem, we can orient the detectors at an angle which is the average of the Lorentz angles for each charge, and choose a magnetic field which is low enough so that the residual Lorentz drift spreads the charge over a strip width or less. A detector of 150 μm thickness in a 2.5 Tesla field tilted by $\tan\theta_L = (\mu_e + \mu_h)B/2$ will have a charge spread of 22 μm on either side of the detector, just less than one strip width.

Vector Segment Linking

Once vector segments are found, they must be unambiguously linked together to form tracks. For tracks from the origin in the x, y plane, the track trajectory is given by

$$r = 2\rho \sin(\phi - \phi_0)$$
$$z = 2\rho(\phi - \phi_0)\tan\lambda + z_0$$

where the constants characterizing the track are ρ, $\tan\lambda$, ϕ_0 and z_0. A more convenient variable than the radius of curvature ρ is the curvature $\kappa = 1/2\rho$. For high momentum tracks, the above are approximately $\phi - \phi_0 = \kappa r$, $z = z_0 + r\tan\lambda$.

One way to link vector segments, which provides a visual picture of the information quality for a given event, is to use a technique employed successfully with the MARK II jet-cell central drift chamber at the SLC.[7] We describe the method for the barrel section of the silicon tracker. The idea is to calculate, for each vector measurement, the curvature and azimuth at the origin ϕ_0 of a track passing through the origin and tangent to the vector segment. A vector segment provides a measure, at average radius $\bar{r}$, of the track azimuth $\bar{\phi}$ and the rate of change of azimuth $d\phi/dr$. From these we calculate the track constants

$$\kappa = \frac{-d\phi/dr}{\sqrt{1 + (r\,\frac{d\phi}{dr})^2}}, \quad \phi_0 = \bar{\phi} + \arcsin(\kappa\bar{r}) \ .$$

This will produce a mapping in which all vector segments found for a given track lie near a point in the $\kappa - \phi_0$ plane. The vector segments found for the event shown in Fig. 8 have been plotted in Fig. 12a. Up to 8 vector segments are plotted for each track. One can immediately see the two jets in the event. The effect of resolution in curvature is also seen from the spread in points for each track. For this plot we have used $\delta = 5$ mm. Each hit position is chosen as the center of the strip hit, so that the position resolution is $25\ \mu\text{m}/\sqrt{12} \simeq 7\mu\text{m}$.

Figure 12b is a blowup of the region around the jet at $\phi_0 \simeq 3.9$ radians. The effect of resolution is now more obvious, and it is also clear that the error in κ is strongly correlated with the error in ϕ_0. This can be parametrized by a 2×2 error matrix, which can be used to cluster the vector segments into tracks. Even by eye, it can be seen from Fig. 12b that vector segments from nearby tracks in the jet are becoming confused. This can be remedied by making the paired layer separation δ larger. Choosing $\delta = 1$ cm, the value used in Table 1 earlier, results in the measurements displayed in Fig. 12c. Here the individual tracks in the jet are generally separated. Note the spread in these plots of the measured ϕ_0 values for a given track is $\sqrt{2}\sigma_m/\delta$, the parameter introduced earlier to quantify the ability to link vector segments. A study of many such events indicates that $\delta = 1$ cm is a reasonably good choice.

The method outlined above can also be used to cluster vector segments and link them into tracks for tracks

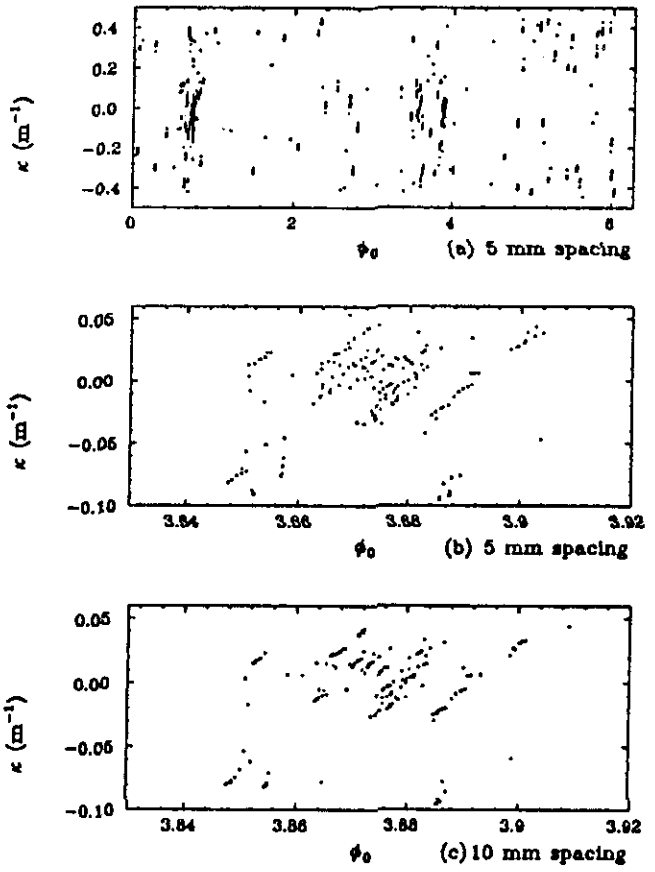

Fig. 12. Clustering for tracks in 1 TeV event.

passing into the forward detectors. Assuming that the strips are organized to measure ϕ at fixed z, the measurement $d\phi/dz$ and $\bar{\phi} - z\ d\phi/dz$ are constant along a track, being equal to $\kappa/\tan\lambda$ and $\phi_0 - (\kappa z_0)/\tan\lambda$, respectively. Thus the two dimensional clustering space is in these two parameters for these detectors.

MOMENTUM RESOLUTION

We look at the expected momentum resolution for the silicon tracker discussed above. We will assume a vertex constrained fit, as would be appropriate for the high momentum leptons from the heavy Higgs decay, which corresponds to an orbit equation at high momentum

$$\phi = \phi_0 + \frac{r}{2\rho}.$$

Measuring the track angle ϕ at m radii $r_1, r_2, \ldots r_m$, the value of ϕ_0 and ρ are extracted by minimizing

$$\chi^2 = \sum_{i=1}^{m} \frac{(r_i\phi_i - d_i)^2}{\sigma_i^2},$$

where d_i is the measured circumferential distance for the ith axial layer. The expected error on d_i is σ_i.

Relating ρ to P_T, and calculating the errors from the χ^2, gives a result:

$$\frac{\sigma_{P_T}}{P_T^2} = \frac{2}{0.3B}\sqrt{\frac{\sum_{i=1}^{m}\frac{r_i^2}{\sigma_i^2}}{\sum_{i=1}^{m}\frac{r_i^2}{\sigma_i^2}\sum_{i=1}^{m}\frac{r_i^4}{\sigma_i^2}-\left(\sum_{i=1}^{m}\frac{r_i^3}{\sigma_i^2}\right)^2}}\ ,$$

where B is in Tesla, P_T in GeV and all distances are in meters.

Assuming that the four measurements in a vector element give an effective measurement with an error σ, that the 8 pairs are approximately equally spaced out to a maximum radius r_m, gives after performing the sums above

$$\sigma_{P_T}/P_T^2 = 5.5\sigma/0.3B\ r_m^2\ .$$

Taking $\sigma = 3\ \mu$m, $r_m = 0.5$m, $B = 2.5$ Tesla, gives:

$$\sigma_{P_T}/P_T = 8.8\% P_T\ (\text{TeV})\ .$$

Figure 13 shows σ_P/P^2, where P is the full momentum, vs. rapidity for the silicon tracking detector, where the error at $Y = 0$ has been taken to be $\sigma_P/P^2 = 0.08$ TeV^{-1}.

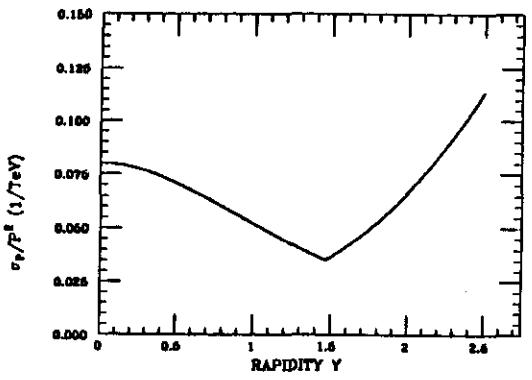

Fig. 13. Momentum resolution vs. rapidity.

MASS RESOLUTION FOR HIGGS DETECTION

The goals for momentum resolution are usually determined by the physics goals of an experiment. For the present case we choose the reconstruction of the Higgs via $H^0 \to Z^0Z^0 \to 4$ leptons, for a mass of the H^0 up to 1 TeV as a suitable goal for the SSC. Since the Z^0 has a finite width, arbitrarily good resolution does not improve background rejection. The width of the Z^0 therefore sets a goal for the resolution. The typical momentum for leptons from the 1 TeV H^0 is 250 GeV. The momentum resolution for these is $\sigma_P/P \simeq 2\%$, using Fig. 13 above.

Using a Monte Carlo for H^0 decay, we have calculated the expected mass resolution for the reconstructed Z^0, for decays into electrons and muons. The results are shown in Fig. 14. Also shown are the electron results for a calorimetric mass reconstruction and the muon results for an iron toroid. We see that the detector resolution is well matched to the limitations of the Z^0 width for Z^0 energies up to nearly 500 GeV. Fig. 15 shows similar quantities for the subsequently reconstructed H^0. The tracking system provides better resolution at all masses than the limitations imposed by the H^0 width. For the simplest Higgs scenario, the detector has about a factor 3 better resolution at about 500 GeV than is necessary. This should provide some safety margin in case the correct theory involves several Higgs particles. In this case each Higgs is narrower and has a smaller production cross section than the Higgs in the simplest model. With sufficiently good resolution, the signal to background will be equally good in this case since the narrower width makes up for the smaller rate in the mass plot.

ELECTRONICS ISSUES

Readout for the tracker must be via high-density (on the detector) fast amplification and discrimination, followed by digital event buffering to store information locally until a valid trigger is asserted.

Figure 16 shows a block diagram of the readout scheme we are working on. It uses two chips with VLSI circuits matched in pitch to the detector strips and wire bonded together. The first chip, to be implemented in bipolar technology, contains a fast amplifier and discriminator. The second chip, to be implemented in CMOS technology, contains level 1 and level 2 buffers and a shift register to readout the hit information. The level 1 buffer is a memory which is clocked at the machine frequency, providing a digital time slice of the detector output. The depth of the buffer, taken to be 64 clock cycles, is matched to the time necessary to make a first level trigger. If a trigger occurs, the information is stored in the second level buffer which can store up to 16 level one triggers. A successful second level trigger causes a readout of the appropriate time slice.

The use of a fast front-end amplifier is well matched to the signal collection time in the silicon as well as the beam crossing rate. It is also necessary since the strip detectors develop leakage current due to radiation damage. The signal expected is 12,000 e$^-$ for 150 μm thick detectors. The equivalent noise charge for the amplifier is expected to be between 700 to 1,000 e$^-$. For a 10 nsec shaping time, the noise from the detector leakage current is $\simeq 250$ e$^-$ $\sqrt{I(\mu\text{amp})}$. We therefore want to keep the leakage current $< 4\mu$amp.

The leakage current for the detectors decreases substantially over a period of several months if not irradiated, therefore an appropriate period for calculating dosage is ≤ 1 year of running. For strips with dimensions 25 μm $\times$ 10 cm $\times$ 150 μm, at the dosage expected,[8] the leakage current will be:

From Charged Particles: 2 μamp/$r_\perp^2$(cm)

From Neutrons: 2.5 $\times 10^{-14}\mu$amp $\times$ Neutron Fluence.[9]

Thus the nearest detector, located at $r_\perp = 8$ cm, for a neutron fluence $\leq 10^{13}$, will develop a leakage current $\ll 4$ μamp, making the noise from the detector current a small contributor to the overall amplifier noise.

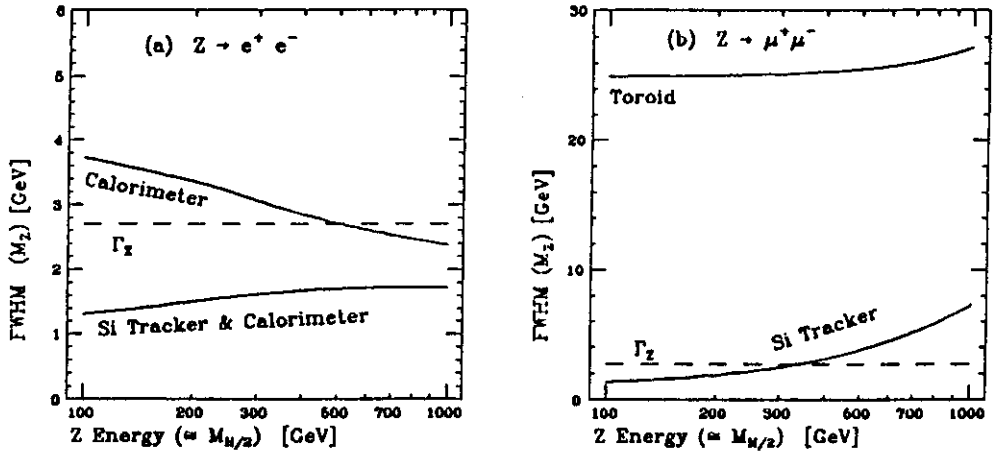

Fig. 14. FWHM resolution of the Z^0 mass as a function of Z^0 energy for a detector with calorimetry only, and for a detector including precision Si tracking. a) $Z^0 \to e^+e^-$. b) $Z^0 \to \mu^+\mu^-$.

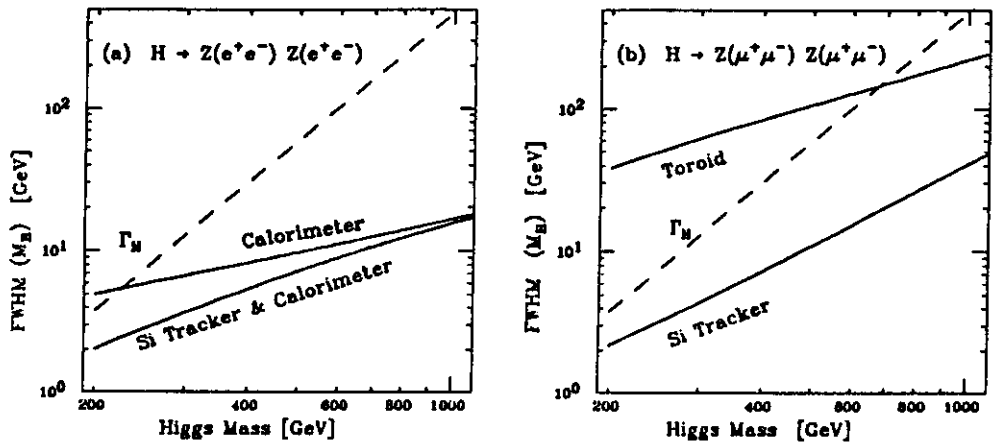

Fig. 15. Z^0Z^0 invariant-mass resolution for different detector configurations, compared with the expected Higgs width Γ_H (dashed line). a) $Z^0 \to e^+e^-$. b) $Z^0 \to \mu^+\mu^-$.

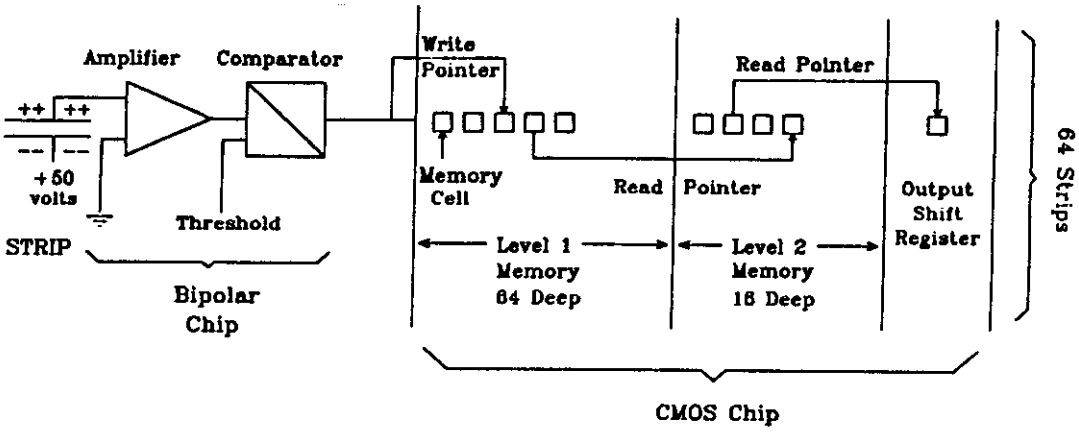

Fig. 16. Readout – VLSI chips.

The memory chip we are presently working on uses 2 μm CMOS feature size, which will not run fast enough to match the SSC requirements. The sub-micron CMOS presently used by some of the large computer companies should be well matched to SSC requirements and is expected to be commonly available well before SSC turn-on. These circuits must be radiation hardened to work after a few megarads of radiation, which is within present capabilities.[10]

The analog circuitry must be carefully radiation tested and is more delicate than the memory which is digital. We are designing this chip using Dielectric Isolated Bipolar, which is expected to be very insensitive to damage from charged particles and neutrons. The latter sensitivity should improve as the speed of the available bipolar circuitry is increased[11] as a result of decreased transistor geometry. It will be very important to minimize the power dissipation within the speed and noise constraints, since cooling of a large system will be a difficult problem.

CONCLUSIONS

A full scale silicon microstrip tracker, capable of resolving tracks in 1 TeV jets with high efficiency and good momentum resolution will provide invaluable information in the search for Higgs production and new physics signatures at the SSC. We present a design which we believe can be built and made to work in the SSC environment given a substantial amount of R&D effort.

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89M844-1

APPENDIX II

Proposal to

Institute for Particle Physics
University of California
Santa Cruz, California

Megatonne Vertex Array
Silicon Strip Central Tracking Subsystem

STATEMENT OF WORK AND COST PROPOSAL

September 1989

Westinghouse Electric Corporation
Science and Technology Center
Pittsburgh, Pennsylvania 15235

89M844-1

Proposal to

Institute for Particle Physics
University of California
Santa Cruz, California

Mechanical Design and Analysis of a Silicon Strip Central Tracking Subsystem

STATEMENT OF WORK AND COST PROPOSAL

September 1989

Approved:

F. T. Thompson

F. T. Thompson, General Manager
Engineering Technology Division
Westinghouse Science and Technology Center

MECHANICAL DESIGN AND ANALYSIS OF A SILICON STRIP CENTRAL TRACKING SUBSYSTEM

— STATEMENT OF WORK —

The Westinghouse Electric Corporation proposes to undertake a 24-month program in cooperation with the University of California at the Los Alamos National Laboratory (LANL) to perform the preliminary mechanical design and analysis of a silicon strip detector array for the superconducting supercollider (SSC) large solenoid detector. The work will be carried out at the Westinghouse Science and Technology Center (STC). Upon completion of the proposed program, the following items will be delivered to the University of California at Santa Cruz: concept drawings and estimated costs and schedule for the procurement, fabrication, assembly, and testing of the proposed silicon strip detector.

The program is divided into four specific areas of performance:

- Mechanical Design
- Material Science
- Thermal Management
- Manufacturability

These four areas will be divided into nine tasks. Each task is described in the following pages, and a task schedule is presented in Figure 1.

Westinghouse will concentrate primarily on the design of the large scale mechanical support structure, the integration with other subsystems in the detector and the collider, interaction with magnetic field, and large scale integration of the support systems, such as power and cooling. LANL will concentrate primarily on the evaluation of

materials, the design of the individual strip detector module (particularly its thermal management), and the building and testing of appropriate prototypes. Both LANL and Westinghouse will participate equally in developing the overall conceptual design of the subsystem.

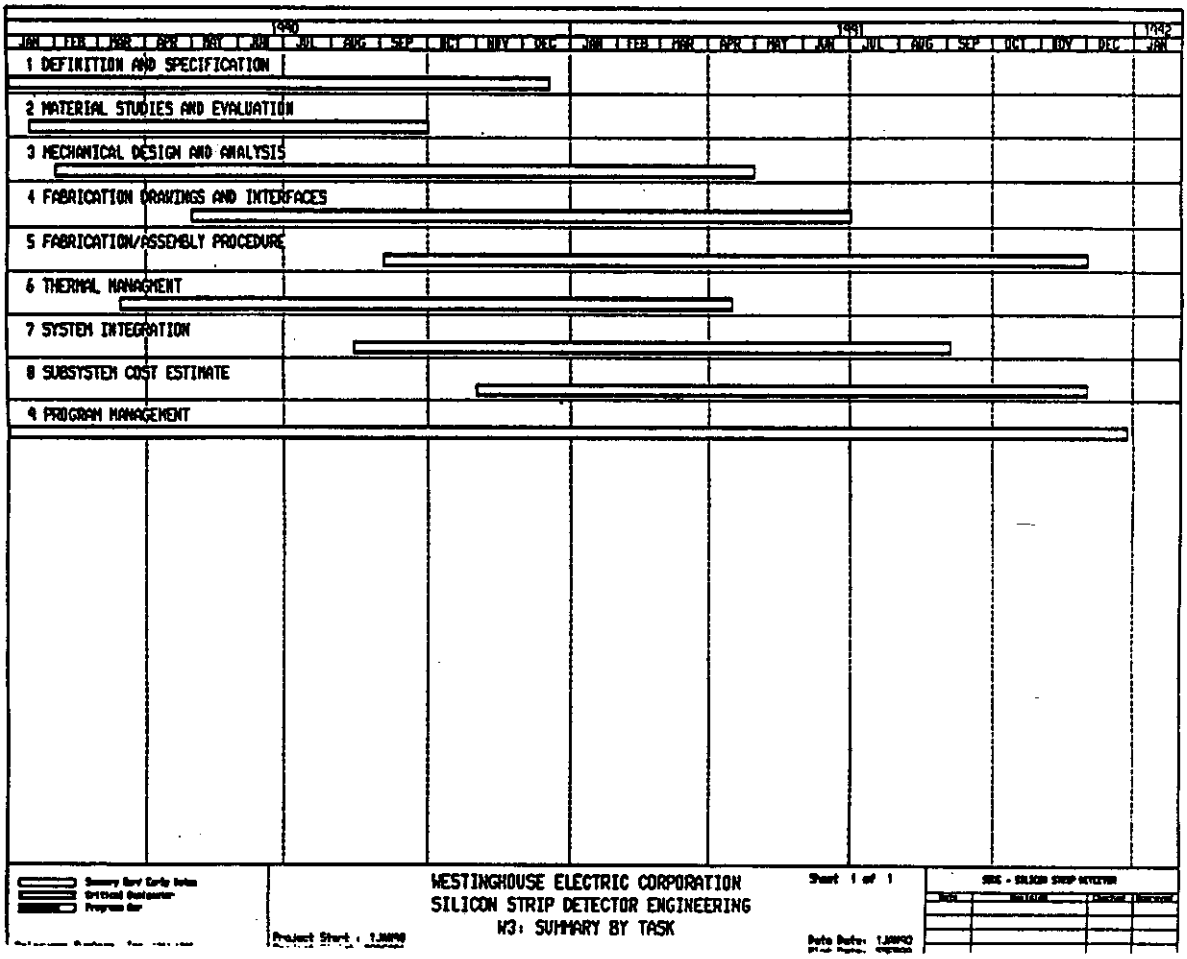

Figure 1 — Schedule for proposed program

TASK 1. SILICON STRIP DETECTOR DEFINITION AND SPECIFICATION

In Task 1, Westinghouse STC will work with the Silicon Strip Detector Group to completely specify the functional design requirements for the detector. Physical constraints, such as size, weight, length, and detector geometry, will be identified as well as electrical leads and cooling requirements. Figure 1 shows this effort lasting most of the first year of the program. This time will be necessary in order to make specification modifications as the concept progresses over the first year.

TASK 2. MATERIAL STUDIES AND EVALUATION

Material property requirements for the support structure and auxiliary system will be specified in this task. Candidate materials will be reviewed for use based on work performed by LANL concerning radiation length and susceptibility to radiation damage. The major effort on materials will be performed by LANL with Westinghouse evaluating the material suitability for a large scale system.

TASK 3. MECHANICAL DESIGN AND ANALYSIS

In this task, the preliminary design of the silicon strip detector assembly will be performed. The detector ladder structure worked out by LANL will form the input to an overall system design. Various concepts proposed by the working group will be reviewed and evaluated. The most promising concepts from the point of view of overall detector operation will be determined. The final selected concept will be analyzed for structural support to ensure sufficient stability and rigidity so that critical alignment requirements can be maintained over the design life of the device. All routing and connections of power, cooling, and instrumentation cabling/hoses will be conceptualized.

In addition to the design and analysis work, general requirements for assembly and alignment will be specified during this task. Whenever possible, appropriate prototype structures that test critical engineering concepts will be suggested and evaluated.

TASK 4. FABRICATION DRAWINGS AND INTERFACES

This task will consist of preparing layout drawings of concepts proposed and studied in Task 3. Concept drawing of the selected silicon strip detector configuration will be prepared in sufficient detail to obtain costing and scheduling information. Assembly drawings will be developed as necessary to assist in the fabrication and assembly procedure as well as for interfaces with adjacent structures.

Three-dimensional solid modeling will be utilized as needed in the design process to verify spatial relationships between components and to ensure proper assembly and system integration.

TASK 5. FABRICATION AND ASSEMBLY PROCEDURES

The purpose of this task is to specify in sufficient detail the fabrication processes and assembly procedures required for the concept selected. These procedures will include such items as the following:

- Silicon strip mounting procedure
- Structural support fabrication method
- Special tooling
- QA/QC testing
- Modular assembly sequence
- Electrical cable routing procedure
- Cooling hoses routing procedures

These procedures will be prepared in a form to match the concept detail and costing estimate requirements for construction of a device. Prior to any device construction, a detailed procedure write-up will be prepared. A full-size mechanical prototype will be constructed at LANL.

TASK 6. THERMAL MANAGEMENT

Thermal management will address cooling methodologies for removing the heat generated within the silicon detector modules. All known sources of heat, both internal and external to the silicon strip detector, will be determined and evaluated as to the effect of the detector concept. A scheme will be proposed for maintaining the

detector modules at a reasonable operating temperature with minimum compromise on the overall performance of the silicon strip detector. LANL will concentrate on the thermal management of the individual detector modules, while Westinghouse will concentrate on the integration of this function with the remainder of the support system. Upon completion of this task, a listing of the cooling system equipment will be identified.

TASK 7. SYSTEM INTEGRATION

In this task, the integration of the silicon strip detector with the surrounding equipment in the overall SSC detector system will be investigated. Included in this effort will be the assembly and disassembly of the silicon strip detector within the system as well as the mounting requirements and constraints of the device. In addition, a survey will be prepared of the known external forces and loading conditions affecting the silicon strip detector. Particular attention will be paid to issues involving the operation of the silicon tracker in a 2 tesla magnetic field.

TASK 8. SUBSYSTEM COST ESTIMATE

The cost and schedule will be estimated for the overall fabrication and delivery of a completed device to the SSC detector location. Included in this task will be the cost and schedule for the following items:

- Materials procurement
- Component fabrication
- Module assembly
- Module QA/QC testing
- Module shipping to SSC site
- System assembly at site
- System testing
- System installation

The effort will require input from all areas within the group in order to establish reasonable and accurate cost estimates.

TASK 9. PROGRAM MANAGEMENT

Program management includes the preparation of reports, design reviews, general meetings, and cost reporting to the program manager. Estimates of the Westinghouse effort are based on the following activities:

- Monthly progress and cost letter reports for 24 months
- Group meeting at Santa Cruz every six weeks
- Two DOE design reviews, one of each at the end of each year
- Yearly reports to DOE describing technical progress

Westinghouse

89M844-1

Westinghouse

D. T. Hackworth, Manager, Electromechanics
Westinghouse R&D Center

B.S., graduate study, mechanical engineering, University of Pittsburgh.

Mr. Hackworth is working in the area of high current systems. This covers all aspects of high current systems: the development, design, analysis, specifications, and testing as well as the development of specialized mechanical equipment. He has lead responsibility for the Westinghouse effort in Superconducting Magnetic Energy Storage (SMES). On this project, he has overall responsibility for all systems of the superconductor and coil cold pack design, analysis, component fabrication and testing as well as the system coil manufacturing plan.

From 1976 to 1981 Mr. Hackworth had responsibility for the design of superconducting apparatus in the design and structural engineering role for the Westinghouse effort on the Large Coil Program with Oak Ridge National Laboratory. On this project, he was responsible for all aspects of the mechanical systems, including design, analysis, drafting, and materials.

Mr. Hackworth had responsibility for the structural design in a DOE-sponsored conceptual study of toroidal field magnets for the Experimental Power Reactor study. In addition, he was Lead Mechanical Engineer on the 400 kJ coil program for LASL. He also completed a conceptual structural design of the toroidal-field coils for the High Field Compact Tokamak Reactor for MIT. This assignment required the integration of a conductor design and a viable structural design based on material and manufacturing capabilities.

From 1973 to 1976, Mr. Hackworth served as a Mechanical Engineer in the Development Group of the Generation Systems Department, where he contributed mechanical development expertise to programs for system design. He has performed stress and dynamic analysis to alleviate vibration and structural problems and has developed testing procedures for structural analysis. Central to his contribution was the development of a Westinghouse computer program to facilitate steady state thermal analysis for internal nonrotating windings of turbine generators.

Mr. Hackworth has nine disclosures in the area of high current systems and robotic systems, and holds two patents dealing with large motor control and robotic vision systems.

Publications:

"Design of Pulsed Power Cryogenic Transformers," Tenth International Conference on Magnet Technology, September 1987.

D. T. Hackworth (Continued)

"Design of Pulsed Power Cryogenic transformers for Electromagnetic Launchers," 1987 Strategic Defense Initiative Technical Achievements Symposium, March 1987.

"Advantages of the Distributed Structure Concept of the Westinghouse LCP Coil Design," Applied S/C Conference, October 1986.

"A 10 MJ Cryogenic Inductor," 3rd Symposium on Electromagnetic Launch Technology, April 1986.

"Advanced Techniques in the Design of Electromagnetic Stirrers for Continuous Casting," 1985 AISE Annual Convention, September 1985.

"Quiet Cooling System Development for a Traction Motor," ASME Vibration Conference, September 1985.

"Manufacturing Plan for the Westinghouse Nb_3Sn Large Coil," 9th Symposium on Engineering Problems of Fusion Research, October 1981.

"Structural Design of the Westinghouse Superconducting Magnet for the Large Coil Program," IEEE Transactions on Magnetics, Volume MAG-15, January 1979.

"Design of a Low-Loss Fast-Pulsed Superconducting Energy Storage Coil," 8th Symposium on Engineering Problems of Fusion Research, 1978.

"Westinghouse Conceptual Design of a Test Coil for the Large Coil Program," Proceedings of the Seventh Symposium on Engineering Problems on Fusion Research, 1977.

Westinghouse

J. A. Hendrickson, Senior Engineer
Westinghouse R&D Center

B.S., mechanical engineering, Pennsylvania State University; M.S., mechanical engineering, University of Pittsburgh; Ph.D., program course credits, University of Pittsburgh.

Registered Professional Engineer (Pennsylvania); Member, American Society of Mechanical Engineers; Society of Automotive Engineers; Society of Manufacturing Engineers; Certified Manufacturing Engineer (Tool Engineering Specialty).

Mr. Hendrickson has over seven years of experience in the field of mechanical tooling systems design and implementation. He joined the Westinghouse Electric Corporation in 1982 as a field service engineer in the Power Generation Service Division. His work history has included maintenance and troubleshooting efforts on steam turbines, electric generators, heat transfer equipment, turbine-generator control systems, and all phases of nondestructive testing and examination of related components. Typical test experience includes rotor bore examinations, fluorescent penetrant inspections of steam turbine components, UT inspection of foundation bolting, and generator thermovision examinations.

In 1983, Mr. Hendrickson transferred into the Nuclear Service Division where he developed an expertise in the area of design and development of remote operated tooling systems to address the needs of the nuclear power industry. The majority of the tooling had special requirements for underwater operation in high radiation fields. Mr. Hendrickson has designed, and fabricated several precision positioning systems to support underwater machining and repair programs as well as various end effectors for remote manipulator applications.

Since joining the R&D Center in 1986, Mr. Hendrickson has been involved with the design of light gas pre-acceleration systems and electromagnetic launchers, "rail-guns," to support various SDI programs. He was responsible for the complete design, erection, and commissioning of the SUVAC II pre-accelerator, the first to be built and operated in the corporation. The SUVAC II pre-accelerator is capable of accelerating a 10 gram projectile to an injection velocity of 1 km/sec.

Most recently, Mr. Hendrickson has been involved in the design of a supercritical hydrogen cooled hyper-conducting alternator stator for the Aero Propulsion Lab at Wright-Patterson Air Force Base. The high voltage stator design incorporates state-of-the-art structural composites technology in order to increase stator power density an order of magnitude over conventional designs. He has also been involved in the design of the plasma accelerator for the space power experiment, SPEAR II.

Mr. Hendrickson has been active in the patent area with over 28 disclosures.

Westinghouse

R. J. Hillenbrand, Senior Engineer
Westinghouse R&D Center

B.S., mechanical engineer, University of Pittsburgh.

Registered Professional Engineer (Pennsylvania).

Mr. Hillenbrand has more than 14 years of experience with Westinghouse: nine years at the Large Rotating Apparatus (LRA) Division, and five years with the Westinghouse R&D Center. Assignment at LRA included positions in Design Assurance Engineering, Reliability and Systems Engineering, and Mechanical Development Engineering. Mr. Hillenbrand was lead engineer on several large programs involving mechanical design and analysis of major machine components on large turbine generators. In 1981 he joined the Product Engineering Department of the Engineering Division at the R&D Center, where he has worked on a variety of product development projects involving equipment for both commercial civilian use and military use.

Areas where Mr. Hillenbrand has had lead design or program responsibility include the design and shock hardening of switchgear related equipment and submarine drive power conditioning equipment, the design of shipboard elevator hoist machinery, development of a brake system for wind turbine machinery, and a water temperature control system for water-cooled electric generators. He recently served as lead mechanical engineer for the design of three major electromagnetic launcher barrels. Additional areas of experience include rotating equipment design, structural analysis, composite insulating material development, and hardware and auxiliary systems for high temperature fuel cell generators.

Westinghouse

[redacted]

89M844-1

COST SUMMARY BY YEAR

WESTINGHOUSE ELECTRIC CORPORATION
SCIENCE AND TECHNOLOGY CENTER
1310 BEULAH ROAD
PITTSBURGH, PA 15235

STC NO: 89M844-1
RFP NO:
AGENCY: UNIV. OF CALIFORNIAQ
DOE-LANL
TITLE: SILICON STRIP DETECTOR

FISCAL YEAR 1990 COSTS

			FY1990
A.	MATERIAL/EQUIPMENT		-
B.	LABOR		
	1. ENGINEERING	HRS	2,104
		($)	66,710
	2. SUPPORT	HRS	240
		($)	5,158
	3. TOTAL LABOR	HRS	2,344
		($)	71,868
C.	OVERHEAD (*)		86,528
D.	OTHER		
	4. CONSULTANTS		-
	5. COMPUTER		3,000
	6. SUBCONTRACTORS		-
	7. OTHER		7,390
E.	IWR		-
F.	TOTAL DIRECT COST		168,786
G.	G&A (16.870%)		28,475
H.	O. T. COSTS		-
I.	COC-STC (9.797%) OF B3		7,039
J.	COC-CORP (0.241%) OF F		405
K.	TOTAL COSTS		204,705
L.	FEE		-
M.	TOTAL COSTS & FEE		204,705

*VARIOUS OVERHEAD RATES USED

THIS IS TO CERTIFY THAT THIS COST DATA IS BASED UPON OR COMPILED FROM THE BOOKS AND RECORDS OF THE COMPANY. TO THE BEST OF OUR KNOWLEDGE AND BELIEF, THE COST DATA PRESENTED IS IN CONFORMANCE WITH PROVISIONAL COSTING RATES.

WESTINGHOUSE PROPRIETARY

Mechanical Design and Analysis
of a Silicon Strip Central
Tracking Subsystem

COSTS BY FISCAL YEAR

Fiscal Year 1990	$204,705
Fiscal Year 1991	481,842
Fiscal Year 1992	51,733
TOTAL . . .	**$738,280**

Mechanical Design and Analysis
of a Silicon Strip Central
Tracking Subsystem

TASK BREAKDOWN

	FY 1990	FY 1991	FY 1992	TOTAL
Task 1	18,049	2,069	---	$ 20,118
Task 2	11,030	---	---	11,030
Task 3	63,644	67,020	---	130,664
Task 4	14,807	30,500	---	45,307
Task 5	7,321	163,753	32,587	203,661
Task 6	42,951	59,904	---	102,855
Task 7	9,022	71,042	---	80,064
Task 8	---	36,719	5,352	42,071
Task 9	37,881	50,835	13,794	102,510
TOTAL . . .	204,705	481,842	51,733	**$738,280**

Los Alamos

Los Alamos National Laboratory
Los Alamos,New Mexico 87545

DATE: September 24, 1989
IN REPLY REFER TO: P-2
MAIL STOP: MS D456
TELEPHONE: 7-4505

DEVELOPMENT OF A CENTRAL TRACKER FOR THE SSC UTILIZING SILICON STRIP DETECTORS

STATEMENT OF WORK

The Los Alamos National Laboratory (LANL) will undertake a 24 month program in cooperation with the Westinghouse Science and Technology Center to perform the preliminary mechanical design and analysis of a silicon strip detector subsystem for the SSC. The effort at LANL will involve a group composed of both physicists and engineers. The physicists are currently heavily involved in simulation of an inner tracking system for an SSC detector in order to understand the impact of the design on its physics capabilities. The Monte Carlo work will be emphasized while the committee is considering the proposal. Upon approval of this subsystem proposal the engineering staff will begin full time work on the project.

The engineering work to be carried out at LANL will concentrate primarily on the evaluation of materials, the design of the individual strip detector module (with emphasis placed on topics of thermal management and the fabricability with the chosen materials), and the building and testing of appropriate prototypes. Westinghouse will concentrate primarily on the design of the large scale mechanical support structure, the integration with other subsystems in the detector and the collider, interaction with the magnetic field, and the large scale integration of support systems such as power and cooling. Both Los Alamos and Westinghouse will participate equally in developing the overall conceptual design of the subsystem.

The mechanical engineering effort will involve:

1) Material studies;

2) Thermal management;

3) Cooperation in the overall design of the subsystem, including 3 dimensional analysis thereof;

4) Production of prototypes to verify the design.

The engineers will work to produce a design which minimizes the material in the system. The design will therefore integrate as many of the other functions (cooling, power supply, cabling, mounting, etc.) with the function of mechanical stability. This will require very close and nearly continuous communications among all those involved.

By the end of the first year of the project a conceptual design of the detector will have been developed. In order to verify critical elements in materials fabrication, integration of the design, and the cooling capabilities LANL will begin production of a prototype of silicon detector module. Testing of the module will follow. Such a module is presently thought to be composed of several strip detectors in a ladder arrangement.

During the second year Los Alamos will work together with Westinghouse on the detailed design of the complete silicon detector subsystem. This will include finite element analysis of the entire structure which will verify the design theoretically and identify the critical parts of the system. LANL will build and test the identified components to assure that the design meets the mechanical specifications and that the structure will achieve the required short and long term mechanical stability under the effects of mechanical loading, thermal gradients, vibrations, and radiation damage.

We request support for 2 FTE engineers in each year of the project at a cost of $200,000 per year per engineer. The work will be distributed among a number of senior engineers whose skills in analysis, design work, and materials science match the state of the art requirements of this project. The $200,000 per year cost for a senior engineer at LANL includes all the salary, burden, fringe benefits, and administration costs in addition to travel expenses, computer time, supplies and materials, and other laboratory resources.

Year 1:

1) Investigation of materials: properties of low Z, low mass materials: radiation tolerance: strength, volume change; thermal properties; manufacturability.

   Required engineering staff: 1/2 FTE

2) Thermal management:

   Required engineering staff: 1/4 FTE

3) Conceptual design: integrate the functions of cooling, support, power, electronics, cabling, and rigidity for the detector ladder structure

   Required engineering staff: 1 FTE

4) Construction and testing: build and test a prototype of one detector module: support structure for several silicon wafers including cabling and cooling, with dummy heat sources and detectors in order to monitor heat transfer, thermal expansion, etc.

   Required engineering staff: 1/4 FTE

Year 2:

1) Detailed design of one full sized mechanical prototype including a finite element analysis thereof and the determination of the critical components needed to verify the mechanical design.

   Required engineering staff: 3/4 FTE

2) Construction and testing: build and test the model of the components specified above, which will be fully instrumented, primarily with dummy detectors and heat sources. Several real detectors will be included to allow an evaluation of stability and precision of measurement for a silicon detector system. The tests will determine the mechanical rigidity and both the short and long term stability under the effects of mechanical loading, thermal gradients, vibrations, and radiation damage.

   Required engineering staff: 5/4 FTE

Appendix 4

The LBL Mini-Strip Detector

The LBL Mini-Strip Detector takes an intermediate ground between traditional strip detectors (strip lengths between 5 and 50 cm) and pixel devices (elements of $(30\ \mathrm{um})^2$ to $(100\ \mathrm{um})^2$). It is driven by the need to reduce power dissipation and the desire to circumvent the technical difficulties inherent to double sided strip detectors. The scheme to be described is an outgrowth of work funded at LBL by the SSC Generic Detector R&D program. The first key aspect of this work was the optimization of overall semiconductor detector systems for minimum power dissipation. The second crucial part developed design procedures for optimizing the speed, noise and power dissipation of front electronics in both CMOS and bipolar devices.

The power dissipation of a semiconductor detector system is given by two terms:

a. the first due to the preamplifier, where, *for optimum scaling*, the power per channel increases with the square of the detector capacitance [1], and

b. the second due to the pulse shaping, discriminator, analog storage (if needed), and readout circuitry. This contribution is fixed for a given response time.

Hence, for a system with n strips

$$P_{tot} = n \cdot P_{preamp} + n \cdot P_{fixed}$$

or

$$P_{tot} = P_o \cdot C_{tot}^2/n + n \cdot P_{fixed}$$

where P_o is a power coefficient characteristic of the preamplifier design for a given set of pulse shaping parameters and noise level (in the range of $1 \ldots 3 \cdot 10^{19}\ W/F^2$) and C_{tot} is the total input capacitance associated with *all* channels in the detector. This expression is constrained by the minimum obtainable noise in bipolar circuits (determined primarily by the detector capacitance) and the limit of capacitive matching in CMOS designs. For a given detector area the resulting power is driven by P_{fixed}, which depends on the required response time. Since the response time is determined by the required radiation resistance [2] and, together with the obtainable signal-to-noise ratio, by the required time resolution, P_{fixed} also depends on strip length. Hence, a practical optimization procedure starts with values of P_{fixed} suitable for a limited range of strip lengths and then determines the corresponding number of strips for minimum power.

Fig. A4.1 shows the results of this analysis for a fast bipolar design ($t_p = 10$ ns) with $P_{fixed} = 500$ uW. The minimum power dissipation is about 16 kW at a strip length of 6.2 cm. This assumes double sided strip detectors with a 25 micron pitch and a total surface area of 25 m^2. Fig. A4.2 shows results for the Mini-Strip design using a CMOS readout developed for LBL's pixel design. Here the peaking time is 100 ns, the fixed power for the shaper/discriminator is 10 uW, and 10 uW/channel have been allocated to the sparse readout logic (similar to the scheme used in the SVX chip). In this design the minimum power dissipation is 2 kW for the whole detector at a strip length of 1 cm. Table A4.I shows a comparison of both CMOS and bipolar designs. It also includes results for $P_{fixed} = 10$ uW, probably a lower limit for current technology. In all cases the achievable noise levels of 200 ... 700 electrons are adequate to preclude an excessive number of noise hits.

The "long" and "short" strip designs provide comparable results, both in position resolution and radiation resistance (lifetime > 10 years for detector shot noise). Beyond the crucial issue of power dissipation, however, the Mini-Strip design offers several advantages:

a. The strips are short (the length could be reduced to 5 or 6 mm) and may provide adequate position resolution in Z. This would remove the need for double-sided strip detectors with all of their attendant problems (fabrication, radiation resistance).

b. The low occupancy simplifies time slicing. At $r_p = 10$ cm the hit rate per channel is $2.5 \cdot 10^{-3}\ s^{-1}$. For a latency time of 100 us (probably an upper limit for a second level trigger) this corresponds to 0.25 hits. Time slicing could be accomplished by recording only the time of a hit, with at most a two-stage buffer.

c. The low hit rate per element allows a system with minimum clock activity. As in the LBL pixel design there is no switching until the strip is struck.

d. This scheme can be implemented with conventional wire bonding, although more efficient techniques (*e.g.* tape-automated-bonding) are necessary for large systems.

e. The uniform distribution of low power (16 mW/cm^2) simplifies cooling.

The Mini-Strip Detector does have one significant disadvantage; it increases the thickness of silicon required, since every detector chip is backed up by a readout IC. To some extent this can be mitigated by thinning the detector and readout chips. Detailed studies are required in both fabrication and physics simulation to find an acceptable compromise.

Prototype strip detectors with 6 mm long strips have been fabricated at LBL with excellent results (Fig. A4.3). These utilize the high temperature fabrication process developed by Steve Holland [3]. Since this process is fully compatible with mainstream IC fabrication, it can also be implemented in conventional IC fabrication facilities, unlike traditional detector processes. This opens up the range of potential industrial partners for the ultimate mass production of the detectors.

References:

1. Helmuth Spieler, *Scaling Rules for CMOS and Bipolar Front Ends*, presented at Task Force Workshop on Front-End Electronic Systems for Silicon and Wire Chamber Tracking at the SSC, SSC Central Design Group, LBL, March 6 - 8, 1989

2. David Nygren and Helmuth Spieler, *Semiconductor Detector Size and Radiation Hardness,* in *Radiation Effects at the SSC*, M.G.D. Gilchriese (*ed.*), SSC Central Design Group, SSC-SR-1035

3. S. Holland, *An IC-Compatible Detector Process*, IEEE Transactions on Nuclear Science, NS-36 (1989) 283

Technology	P_{fixed}	t_p	Opt. Strip Length	Total Area	Total Power
BJT	500 uW	10 ns	6.2 cm	25 m^2	16 kW
BJT	20 uW	70 ns	1.2 cm	12.5 m^2	1.6 kW
CMOS	20 uW	70 ns	1.0 cm	12.5 m^2	2.0 kW
CMOS	10 uW	100 ns	0.7 cm	12.5 m^2	1.4 kW

Table A4.I. Optimum strip length and power dissipation for various configurations. The strip pitch is 25 um in all cases.

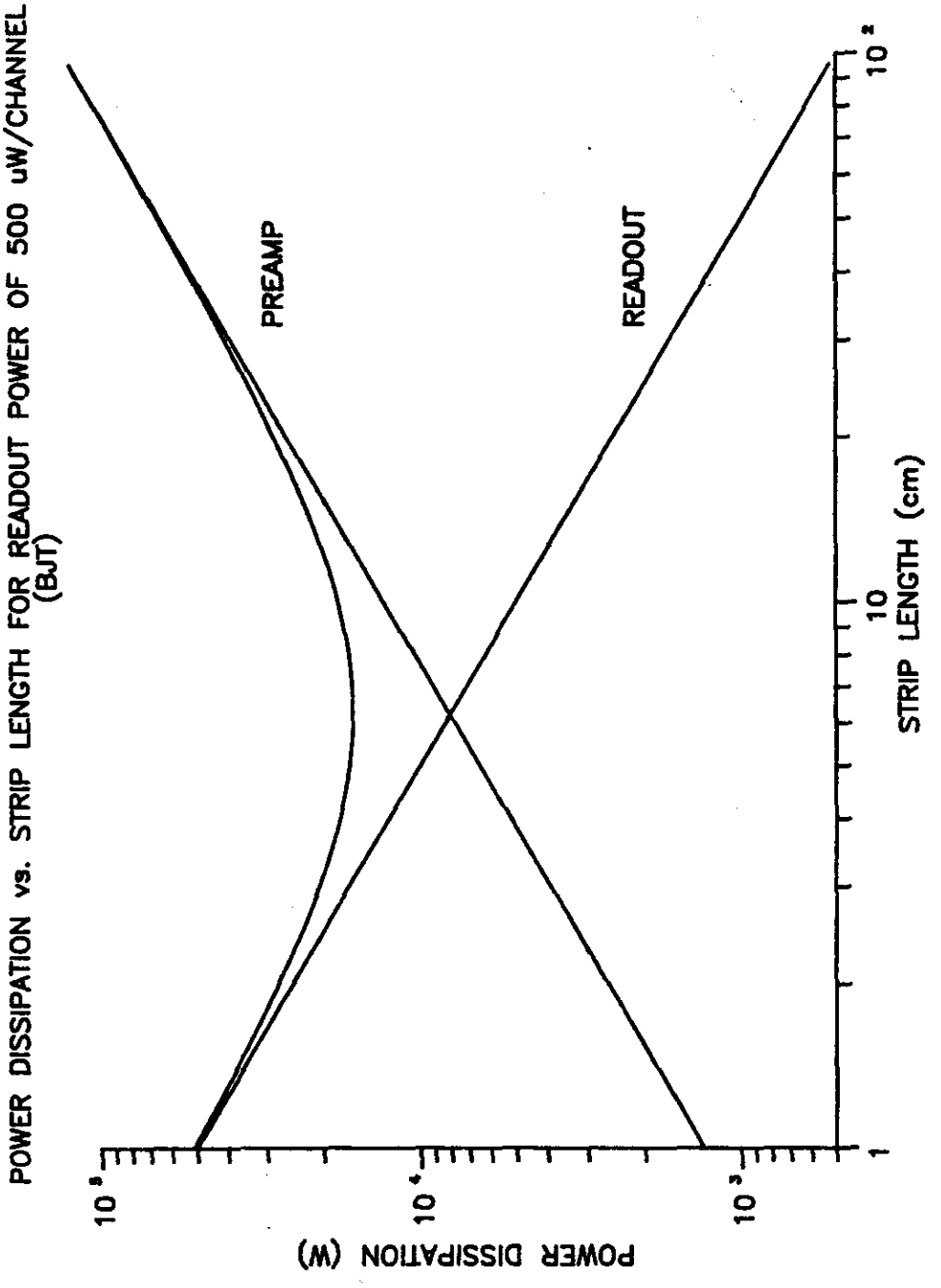
POWER DISSIPATION vs. STRIP LENGTH FOR READOUT POWER OF 500 uW/CHANNEL
(BJT)
PREAMP
READOUT
POWER DISSIPATION (W)
10 ⁻⁵
10 ⁻⁴
10 ⁻³
1
10
10 ²
STRIP LENGTH (cm)

Fig. A4.1.