SSC Detector Subsystem Proposal for Development of an Endcap Electromagnetic Calorimeter Employing Silicon Detector Sampling

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Abstract

Silicon sampling calorimetry holds the promise of providing the fastest, finest grained calorimeter possible at the Superconducting SuperCollider. Present work indicates excellent potential for making a hermetic, radiation- tolerant calorimeter from silicon. However, no working model exists for such a detector. We propose to build an electromagnetic endcap calorimeter quadrant, to illustrate the capabilities of silicon calorimetry in a high-flux, high radiation region. This device will embody all the necessary signal processing and mechanical design considerations to permit extension into a full endcap module and will serve as a test bed both for electromagnetic shower resolution and spatial separation studies and as a model for possible future extension to a hadronic module.

I. Introduction

Jet and lepton measurements will be the fundamental tool in studies of old and new physics at the SSC. Precision calorimetry is one of the principal experimental tools for these studies. In the forward regions ($|y| > 2$) there are severe problems of shower overlap within a single event, due to large multiplicities per unit rapidity interval, as well as pileup problems from previous bunch crossings. In order to minimize these difficulties and give the best access to indications of new physics, an SSC calorimeter should have a short charge collection time, have fine transverse and longitudinal segmentation, require minimal mechanical support and cable penetrations, and be linear and compensated. Silicon sampling calorimetry measures up well to these demands and may be the optimal solution to cover this region of phase space.

In the barrel region the primary pileup concern relates to events from different bunch crossings since the rapidity plateau tends to keep the number of hits per calorimeter cell relatively low. However, a heavy top quark may produce some changes in this thinking. If the $t \rightarrow b + W$ is a major "background" to new physics, then there will be many more leptons associated with W events than has been anticipated. The ability to resolve leptons close to quark or gluon jets is a real strength of a silicon calorimeter, one which makes it especially useful in the barrel system as well as in the forward direction. In this application, good lateral and depth segmentation minimizes confusion between true electrons and possible overlap of hadron and shower from within a jet. This added discrimination is useful both within a single event and in minimizing multiple-bunch pileup.

In the forward region minimum bias event simulations indicate that the angular region from 50-200 milliradians will typically contain 30 charged hadrons and 30 photons per event with energies in the 10-50 GeV range. Most studies of "new physics", e.g., Higgs scalars, new W and/or Z particles, composite particles, etc., show a need for good electron identification and energy measurement throughout this angular zone, which demands minimal shower overlap. Therefore, an electromagnetic calorimeter should be as dense as possible, to minimize the Moliere radius. It should be finely segmented to permit shower shape analysis for separation of overlapping showers and for track matching, e.g., between a TRD electron tracker and the calorimeter. It should also be finely segmented longitudinally to improve discrimination against electron/photon, electron/hadron, or hadron/photon overlaps in this high-flux region. Most SSC studies have agreed that a tower size of $.03 \times .03 dy d\phi$ is the upper limit for good calorimeter performance. The energy resolution should be $0.15\sqrt{E}$ or better and have a minimal constant term. Several groups have constructed and operated silicon electromagnetic calorimeters and have already demonstrated energy resolution of this scale with a negligible constant term for energies in the 1-30 GeV range.[1,2] The inherent linearity of silicon will ensure the persistence of this response throughout the wide energy range of interest at the SSC. At forward angles the pixel sizes needed to give sufficiently small towers are of order 1.5 cm^2 or less. Silicon is probably unique among calorimeter materials in providing pixels of this size with few mechanical constraints and with a graceful match between the endcap device and the barrel structure. The hermiticity thus achieved is especially important in the search for light supersymmetric particles.

Large area coverage with silicon detectors is a maturing technology; several relatively large silicon pad systems, some for calorimetry, have been built or are under construction (See Table 1, Appendix I). Noteworthy among these is the test hadron calorimeter constructed by the SICAPO collaboration.[3] Data from this group is aimed at demonstrating the feasibility of silicon hadron calorimetry and to the understanding of radiation damage and damage annealing.

Thus, silicon calorimetry is advantageous both in the barrel and forward regions to minimize event pileup, by virtue of the very fast charge collection time possible in silicon. It further enhances lepton isolation, and gives stable, well-calibrated gains uniform throughout all parts of a large system. Principal concerns about silicon have centered on its high unit cost and on perceptions of limited radiation tolerance. For this SSC subsystem proposal we plan to dispel both of these concerns by building a silicon electromagnetic endcap module. An endcap will test the performance characteristics of silicon calorimetry and demonstrate all the necessary electrical and mechanical attributes of a silicon calorimeter system. These same electrical and mechanical attributes can then be extrapolated to a full system.

The radiation environment of the endcap calorimeter can be forecast on the basis of presently-available data and simulations.[4] The radiation tolerance of silicon to these conditions has been studied intensively over the last two years by a number of groups.[5] Their results are consistent with each other and lead to the expectation that an endcap unit will handle the dose of an SSC operating year quite comfortably. For damage in the electromagnetic section, recent evidence suggests that the process is self-limiting at an acceptable level of leakage current increase. For hadron damage, recent strides in readout electronics indicate that silicon systems can be made far more neutron-tolerant than had been thought heretofore. Moroever, annealing processes have been studied that allow reactivation of damaged detectors by simple thermal cycling. The good mechanical engineering properties of silicon calorimetry lead us to believe that a modular device could be designed to permit quick exchange of the most susceptible sections of the endcap, if necessary. With a quadrant of an electromagnetic endcap, we will have a test vehicle to show the strengths of silicon calorimetry and to explore its potential weaknesses, all at a level of cost and effort well within the capabilities of the group and the SSC Detector Subsystems funding.

Some designs using other calorimeter techniques for the barrel have not found a good solution for the endcap. Due to its excellent mechanical attributes, silicon calorimetry in the endcap region may prove to have an advantage over other types of calorimetry in the endcap region. In a similar vein, silicon may provide a superior electromagnetic calorimeter for some regions in which another technology would be more cost-effective for hadronic needs. Detector optimization can be done more readily when a set of worked examples exist for all possibilities. The SSC needs are best served by utilizing techniques which offer the fastest response time and best spatial resolution - characteristics that are unique, at this time, to silicon. A more complete discussion of the advantages of silicon calorimetry can be found in the Summary Report of the Silicon Calorimeter Working Group, Workshop on Calorimetry for the Superconducting SuperCollider, Tuscaloosa, Alabama, March 1989, which is included as Appendix I of this proposal. The conclusions of the working group can be summarized as follows:

1. Silicon calorimeters are equal or superior to other techniques of calorimetry with respect to most technical demands of SSC operations, to wit "compactness and flexibility of the overall geometry, single mip resolution, direct charge readout with a non-saturating absolute energy calibration and high speed."

2. The major obstacle to the widespread use of silicon is its high cost. "Presently diodes are available to the high energy physics community at prices in the range of \$6-\$12/cm^2. Reduction to \$2/cm^2 is foreseen and is necessary to permit full scale use of silicon in calorimeters. If the cost is not reduced to or near this level, silicon will likely play a smaller, albeit important role in SSC calorimeters."

3. Annealing studies indicate that the perceived problem of radiation damage to silicon detectors, particularly by neutrons in hadron calorimeters, is either tolerable, or at worst repairable.

II. Proposed Electromagnetic Endcap Calorimeter

The major issues to be addressed by this proposal are related to the construction and operation of a calorimeter which insofar as is possible, meets the requirements for SSC operation. These include compactness, fine segmentation, fast charge collection, and signal processing as well as resistance to radiation damage, particularly to electronic components buried within the calorimeter. While silicon offers an attractive approach in all regions of a detector, we have chosen to construct an endcap electromagnetic calorimeter based on the one specified by the Non-Magnetic Detector Design of the 1987 Berkeley Workshop. This choice results from an analysis of the requirements of the SSC and an identification of the region most able to benefit from the strengths of the silicon. The issues of radiation damage are less of a concern in the electromagnetic calorimeter since the neutron levels are smaller and can be controlled, and silicon is relatively insensitive to electromagnetic radiation. The outstanding transverse segmentation potential of silicon can have a tremendous impact in the endcap region where the density of particles is greatest and the speed of silicon also minimizes the overlap as the number of events is reduced. Answers to key questions necessary to extend the technology to hadron calorimetry are the subject of extensive research by the SICAPO collaboration at CERN. In particular, compensation and linearity of response, and measurement of radiation levels at internal points of a hadron calorimeter are currently being examined in a series of test runs at CERN with participation by members of our group. We plan to continue close cooperation with the SICAPO group throughout the duration of this project. Discussions are underway that eventually may result in this proposed calorimeter being used as an electromagnetic front end to the SICAPO hadron calorimeter.

We propose to construct one quadrant of an endcap module with the dimensions and characteristics shown in Table 1.

Table 1.

Dimensions and Characteristics of the Endcap Module

End Cap beginning:	3.75m
Angular coverage:	50-225 milliradians
Inner radius:	18 cm
Outer radius:	90 cm
Cell thickness:	0.76 cm
Sampling frequency:	1.0 radiation length
Converter:	Pb
Sampling layer:	0.4 mm silicon, 0.8 mm CH_2 coating
Depth:	24 radiation lengths
Total silicon:	14.66 m^2
Mean pixel size:	1.5 cm^2
Readouts/layer:	4070
Total power:	0.6 Kilowatts assuming no radiation damage 10 Kilowatts under maximum leakage current conditions (without any annealing) assuming that 2/3 of the detector is drawing the maximum leakage current
Total weight:	1 ton
Position resolution:	0.5 mm (50 GeV)
Energy resolution:	1.3 GeV (50 GeV)
Ionization sampling:	2%

III. Engineering Design Studies and Division of Responsibilities

In order to carry out this proposal, the group plans to carry out engineering physics studies in the following areas:

A. CALORIMETER ELECTRONIC AND MECHANICAL DESIGN

1) Preamplifiers
2) Summing amplifiers
3) Shaping
4) Analog Storage
5) Bunch Crossing Counter and Tag
6) Packaging
7) Mechanical Design Considerations

B) RADIATION TOLERANCE STUDIES

1) Radiation dose simulation
2) Radiation tolerance experiments
3) Damage annealing studies

C) CALORIMETER PERFORMANCE SIMULATION

1) EGS studies for electron/photon overlap rejection
2) CALOR/FLUKA/EGS studies of hadron/photon overlap rejection
3) Tower structures/triggering studies

D) PRODUCTION AND BEAM TESTING OF ENDCAP QUADRANT MODULE

1) Silicon Detector Production and Testing
2) Cable and connection testing
3) Mechanical construction
4) Test beam operation/Data Acquisition system

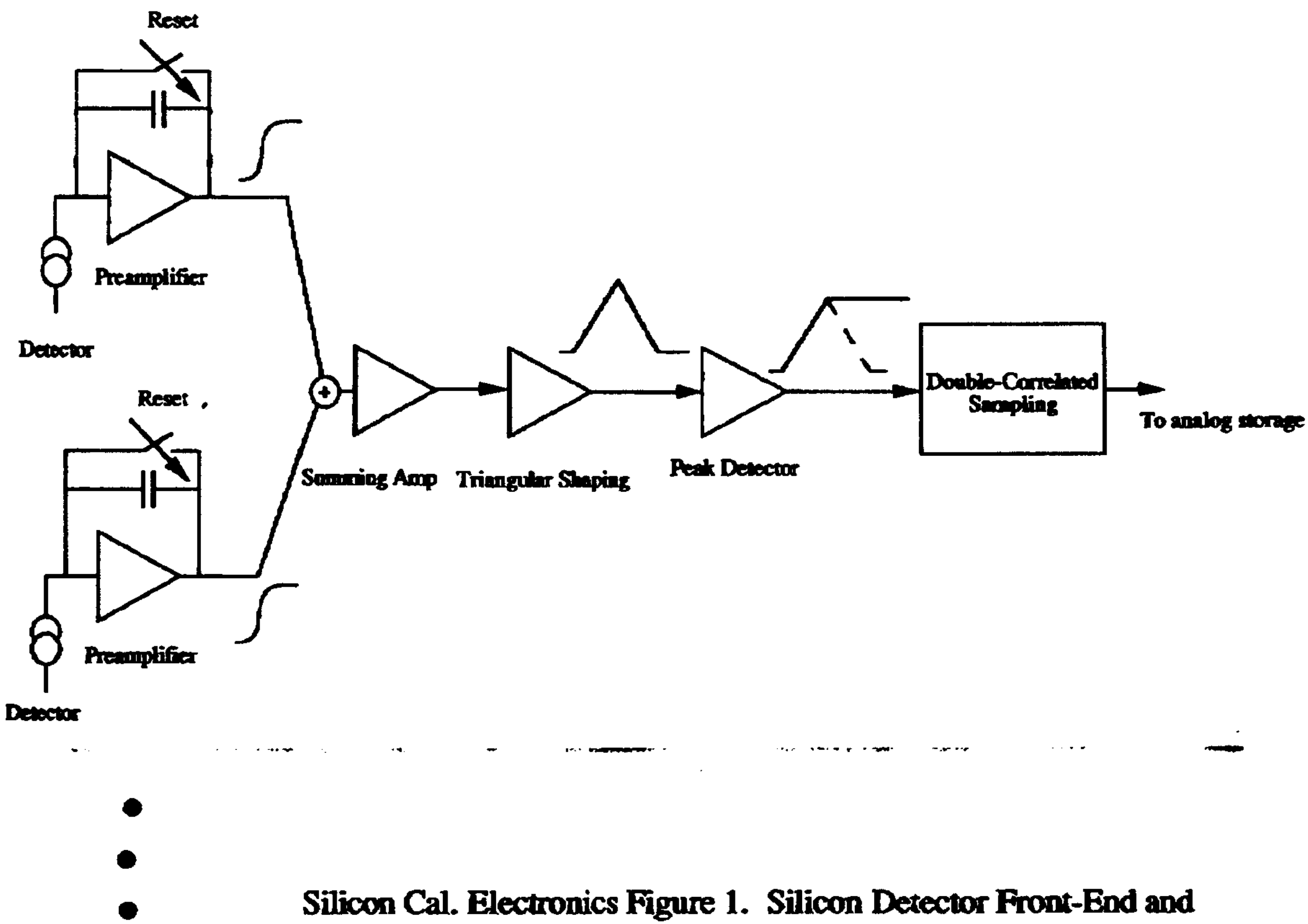
A. ELECTRONICS ISSUES AND DEVELOPMENT

Silicon has long been attractive as a detector for charged particles and the electromagnetic spectra because of its excellent energy to electron-hole pair ratio (3.6 eV per electron-hole pair), low bias voltage required for fast charge collection, and relatively fast electron mobility. The primary problems with silicon have been the traditionally high price for processed detectors and the perception that the signal conditioning electronics are expensive. The cost of the electronics has been high, primarly due to the use of commercially available electronics for small scale detectors. Obviously, for large numbers of integrated circuit preamplifiers, *economy of scale* will reduce the per channel price of electronics to a level similar to that of other detection media. In addition, silicon offers the unique possibility of integrating the electronics directly onto the detector substrate. The electronics development portion of this proposal will address these critical areas in an attempt to be able to take advantage of silicon as a viable measurement media for SSC calorimeter detectors.

The overall goal for this calorimetry electronics development is to design a highly integrated (large number of channels per unit volume) system that will perform the necessary functions of charge-collection, fast signal processing, signal-to-noise enhancement, data storage, and readout in a reliable, radiation-hardened, low-power package. The overall approach will be to DC couple the detector elements to charge sensitive preamplifiers. Investigations will include the option of directly mounting a preamplifier to each silicon detector, then feeding the resultant pulse into a shaping amplifier followed by a peak detecting amplifier. The signal from the peak detecting amplifier will be passed through a double-correlated sampler and into analog storage as shown in Figure 1. Interface for the system clock, circuitry for generating and storing the bunch-crossing/channel ID tag, and an interface for the first-level trigger will be incorporated in this development phase. For purposes of testing, data reduction will be accomplished with conventional electronics.

1. Preamplifier

The charge-sensitive preamplifier design to be used will be a refinement of the mono-



Silicon Cal. Electronics Figure 1. Silicon Detector Front-End and Signal Processing Electronics lithic design already in progress at ORNL under the Generic Detector Funding program. In particular, simulations have shown that the preamplifier has a rise-time of 4 nanoseconds with a noise of approximately 3500 electrons at a shaping time of 100 nanoseconds. The power dissipation is 6 mW for a supply voltage of $\pm$ 3.3V. The preamplifier is being fabricated by VTC, Inc. in a complementary bipolar process with 6 GHz npn and 1 GHz pnp transistors. The topology employed is unique in that the bandwidth is, to an extent, independent of the detector capacitance. In addition, the preamplifier employs a gated servo loop that corrects for the expected increase in detector leakage current due to radiation damage. This *method provides compensation for variations in detector* leakage *current* at regular time intervals (once per second), allowing the preamplifier to be DC coupled, thus eliminating the need for a coupling capacitor. The present method allows for 0 to 15 microamps compensation. A variation of this method could conceivably allow an order of magnitude increase in leakage current with an associated noise penalty due primarily to full shot noise. Our present plans are to fabricate the new version of the preamplifier through the Military and Space Division of Harris Semiconductor. The Harris process is somewhat slower at 1 GHz complementary, but is specified as a rad-hard process. The design environment we will be using should allow for a relatively short development cycle.

2. Summing Amplifier

Since we plan to have one preamplifier per detector element, some number of preamplifiers will need to be summed together depending on the desired granularity of certain sections of the calorimeter. Investigations will need to be performed concerning the granularity requirements before a determination can be made as to how many preamplifiers need to be summed and, therefore, the optimum technology for this summing amplifier. Since we are considering wafer-scale packaging techniques for the preamps, we will also need to determine the physical location of the summing circuitry based on the preceding criteria and on the mechanical constraints of the detector system.

3. Shaping

Simulations indicate at this time that we are primarily series noise limited since we are working at such short shaping times (< 50 nsec peaking time). It has long been known[6] that the desired time-invariant pulse response for series noise limited unipolar nuclear pulse shaping is a triangle. We intend to investigate the application of a time-invariant triangular pulse or, if rise-time and charge collection dictate, some time- variant version such as a variation of the Kandiah [7] pulse processor. The approach of the triangular pulse response will be to generate a delay-line-integrate using an inverting delay amplifier for the delay channel. This should be appropriate since we only need a few nanoseconds delay for the function. The pulse processor will form the filtering for a double correlated sampling baseline restorer. This should come close to being an almost optimum pulse processing system for the speeds of interest, i.e.. 10 nsec to 50 nsec peaking time. Some investigation into the possible scenarios for pulse pileup and how to handle such pileup will be needed.

4. Analog Storage

We will develop a feedback analog memory cell for analog storage. The main area of investigation will be to determine the optimum configuration for maximum signal fidelity. s will include work on the lowest offset input configuration for the small input devices required by a highly arrayable analog memory unit. A block diagram of what such a cell might look like is shown in Figure 2.

5. Bunch Crossing Counter and Tag

The pulse (analog) data that will be stored in the analog memory must be tagged as to which beam crossing produced it and from which channel it came. Circuitry will be developed to generate digital words to represent the crossing number and channel location. These words will be stored in digital memory and linked to the "slice" of analog memory that it labels.

6. Electronics Packaging

The packaging of the electronics will require some new techniques to provide maximum packing density, adequate signal fidelity, and desired hermeticity. In addition, a low cost per channel will be required to allow affordability for the large number of desired channels. We are presently planning to investigate a form of wafer-scale integration[8] in which the active integrated circuits are embedded and bonded into the detector substrate and metallization runs are made to complete the desired connections. This type of packaging holds promise for the type of mixed technology circuits (CMOS & bipolar) that will likely be needed for a successful calorimeter.

7. Mechanical Design Considerations

The mechanical design will be developed from a system point of view and will be strongly influenced by the electronic design. Mechanical design considerations will be extremely rigorous given the size, weight, and compactness of the endcap calorimeter. Special machining and assembly techniques will need to be investigated to provide for the close sampling layer spacing proposed. In particular, to remove heat load from the electronics, paths of conducting material, e.g. copper, may need to be embedded in the radiator. A certain amount of materials research will also be necessary to identify a radiator material of sufficiently high Z value, rigidity and strength which is also machinable, although at present lead seems to be suitable. The total weight of the calorimeter quadrant is projected to be approximately one (1) ton. The constraining mechanical structure which supports this load will be designed so that interference with the detector is minimized. Therefore, the detector radiator plates and mechanical support structure will be fully integrated to reduce extraneous mass as much as possible.

B. RADIATION TOLERANCE STUDIES

1. Radiation Dose Simulation

One crucial issue to calorimetry at the SSC, regardless of the technology, is the radiation environment. As part of this effort we intend to devote considerable attention to simulation of the fluxes, primarily with the Oak Ridge code, CALOR. Investigators in this collaboration have extensive experience in this area, from the code's author (T.A. Gabriel) to others who have used the code for many calorimetric studies, including the official SSC task force study on the radiation environment in the SSC experimental areas. By carefully studying the results of these detailed Monte Carlo calculations, it is possible to engineer detectors more able to survive the radiation environment. An example of such an application is the recent study by Furuno, Brau, and Hwang on the neutron flux reduction in hadron calorimeters possible with additions of polyethylene layers in silicon detectors. Figure 3 shows one result from this work; here the neutron flux is compared at shower maximum for increasing thicknesses of polyethylene. This study finds that in silicon calorimeters the neutron flux can be decreased by more than an order of magnitude with this approach.

In much of this work there is considerable overlap between the needs of silicon calorimetry and other calorimetry schemes. The collaboration intends to capitalize on this other work whenever possible, adapting circuits and/or techniques as needed to fit silicon demands. Also, the Generic Detector Development program has supported a number of important research programs on specific areas of interest, such as radiation damage tolerance studies, preamplifier design considerations, and simulation development. The collaboration will exploit this initial investment to generate a high-performance calorimeter prototype.

2. Radiation Tolerance Experiments

There have been several recent studies on the radiation tolerance of silicon exposed to all types of damaging radiation - neutrons, protons, gammas, and X-rays. The studies agree on the damage constants and on the damage mechanisms. One can categorize the results by noting that hadronic damage mechanisms cause both surface and bulk defects, but that the bulk defects are far more serious in their effects on silicon calorimetry. Some elegant spectroscopic studies of the bulk damage done by the SICAPO collaboration have illustrated the different types of defects that are introduced by hadrons, both point and cluster. These studies have demonstrated that the point defects can be annealed out by relatively low-temperature (180°C) annealing, but that the cluster defects are in fact stablized by this process. The remaining cluster defects result in an increased bulk resistivity of the silicon and could, if sufficiently numerous, actually result in an inversion of the silicon in certain regions from n-type to p-type. This would destroy the reverse bias and quench the operation of the detector. Present studies indicate that radiation levels at the SSC are insufficient to cause the inversion. Furthermore, studies by the University of Hamburg

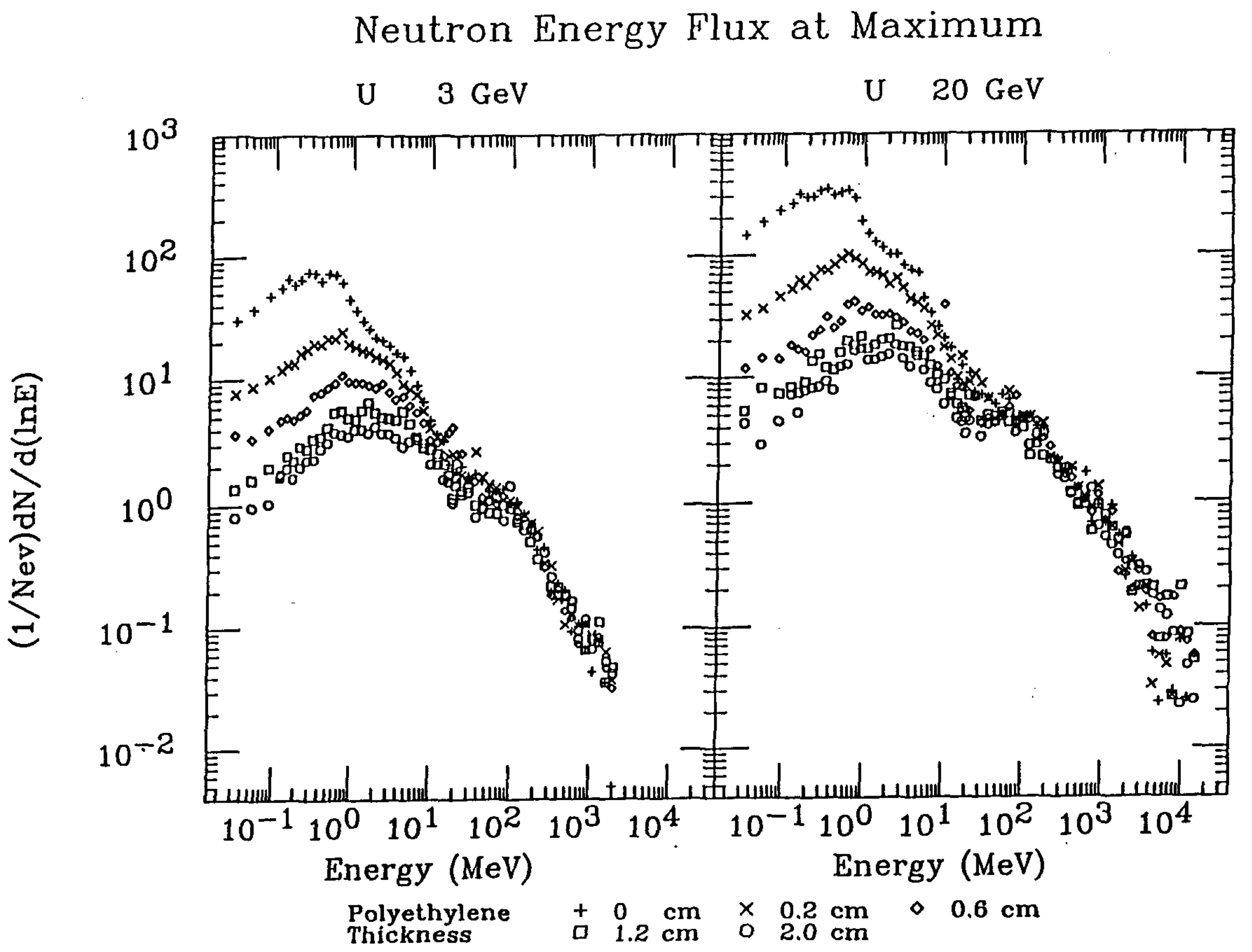

Neutron Energy Flux at Maximum
U 3 GeV
U 20 GeV
(1/Nev)dN/d(lnE)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-1 10^0 10^1 10^2 10^3 10^4
Energy (MeV)
10^-1 10^0 10^1 10^2 10^3 10^4
Energy (MeV)
Polyethylene Thickness
+ 0 cm
× 0.2 cm
◇ 0.6 cm
□ 1.2 cm
○ 2.0 cm

Figure 3.

group have shown that relatively large resistance increases (30%) produced by fluences of order 10^{12} hadrons/cm ^{2} have very little effect on the charge collection efficiency ($< 1\%$).

Furthermore, for electromagnetic radiation doses the effects are mostly surface charge buildup and point defect creation, both of which are amenable to treatment by annealing. The electromagnetic damage coefficient is lower than that due to hadrons, but further work must be done to determine the damage coefficient pertinent to the SSC environment. That type of study is included in the plan of this proposal.

3. Damage Annealing Studies

As the remarks in the preceding sections imply, we expect that the electromagnetic calorimeter described here will operate comfortably in the SSC environment without the need to anneal the detectors. The doses anticipated from present simulation studies are high, but the increases in leakage current appear to be manageable with the electronics that we are studying. However, one must always be concerned about accidents giving a greatly increased dose of either hadronic or electromagnetic radiation to the system. We plan to push the damage studies to doses at least 5 times those expected per year of running in the SSC and then examine the effects of annealing at these elevated doses. One should note that the damage to the silicon detectors around the beam pipe in UA2 during the 1988 run showed that leakage current increases were linearly proportional to the luminosity after the installation of loss monitors around the UA2 intersection region to dump the beam if there was a bad fill. This experience bodes well for the SSC. Scraping and dumping are expected to be handled cleanly in the arcs, with the radiation environment in the intersection regions dominated by the luminosity itself.

The elegant tools introduced by the Milan and Hamburg groups for studying damage can be used to good effect to ensure a detailed understanding of the physics of the damage process. For the purposes of calorimetry one would also like to measure the energy resolution as a function of dose and as a function of annealing treatment. The group will continue the kinds of studies that the Milan, Hamburg, Brookhaven, and KEK groups have been pursuing, with particular focus on the kinds of damage expected in an electromagnetic endcap module at the SSC. We intend to explore the response of silicon detectors to dose levels above 10 MRad.

C. CALORIMETER PERFORMANCE SIMULATIONS

In order to have a strong experimental calorimeter program, a substantial effort must be made in calculational analysis of the detector system. This calculational capability must be fundamentally sound and based on previous interchange between theoretical calculations and experimental test programs. Due to financial and manpower constraints only a few prototype detectors can be built and tested. However, once the calculated results have been shown to agree with the test program data, a much wider variation of the design can be calculationally investigated. This will be the approach followed by this group to minimize effort and cost.

1. EGS Studies for Electron/Photon Overlap Rejection

One of the primary demands on electromagnetic endcap calorimetry will be to identify electrons from t, b, W, Z, and perhaps tau decays, as well as be in position to tag the singular electrons that would arise from the decays of new, massive particles like a Z'. These electrons will be kicked forward via multi-step decays of heavier particles, even though massive parents might be limited to 1.5 units of rapidity. The energy regime of interest for such electrons in the angular range proposed here (50-225 mrad) is 50 GeV-5 TeV. At the high end, events will be unusual, to say the least, and the major job of the calorimeter is to reject the conjunction of low-probability apparatus failures that can mimic a real, ultrahigh energy electron. At the low energy end it is necessary to isolate electrons from nearby jets, to give a clean electron tag in the presence of a high flux of hadrons and photons, and to reject pileup of a real electron with an overlying photon shower which could fake a high-energy electron.

For any assumed electronics and tower structure, these electron purity studies will examine the joint problems of single-bunch confusion and multiple-bunch overlap. They will also look into the question of shower position resolution for comparison to trajectories seen in tracking devices - silicon, drift chamber or TRD systems. It is clear that an important piece of the electron tag will be the *position match* between the calorimeter and the tracker. We will also examine the effects of fine depth segmentation, to improve the separation of electron/photon overlaps by longitudinal shower shape discrimination. The effects of pileup within such a system can also be explored, once the full electronic readout chain is designed. We observe that since the ratio of "interesting" events to all interactions is of the order of 10^{-10}, simulations cannot be expected to predict the tails of distributions correctly, but it is important to demonstrate that there are enough independent tests of the particle identification to have confidence in the result despite the low rates of occurrence of events from "new" physics.

2. CALOR/FLUKA/EGS Studies for Hadron/Photon Overlap Rejection

At the SSC, the forward region of solid angle ($2 < \eta < 4$), will contain, on average, 50 to 60 photons and hadrons from minimum bias events, with energies in the 10-50 GeV range. Careful studies of shower overlaps between electrons, photons, and hadrons are needed and the adverse effect on trigger and reconstruction efficiencies of the overlaps in time and space must be understood. Few if any electromagnetic calorimeters have done well in these circumstances. Detector simulation will play an important role in the initial understanding of these issues.

We plan to study the response of the calorimeter in a twofold simulation effort. Monte Carlo Studes of $e/h/\gamma$ response in the calorimeter will be carried out using the CALOR/FLUKA/EGS simulation packages and compared closely with test beam data. The event generators ISAJET/PYTHIA/DTUJET will be utilized to project physics events into the calorimeter and study $e/h/\gamma$ overlap.

Studies will be done to: (1) develop a flexible method of introducing geometry and materials changes to the Monte Carlo shower codes, (2) tune the simulation packages to test beam and physics results, (3) study e/h and e/γ separation as a function of longitudinal sampling frequency, transverse cell size, and tower structures, (4) study the dependence of hadron rejection and electron efficiency on hadron calorimetry (Some studies indicate that multiple longitudinal sampling reduces the need for hadron calorimeter information in a reconstruction or trigger algorithm. This technique may be important in establishing a fast electron trigger from the silicon electromagnetic calorimeter.) (5) investigate the advantage of a 1-2 radiation length presampling layer to improve electron/photon position measurements and how this might reduce the need for such high tranverse segmentation in this busy region of phase space, (6) include saturation and recombination effects in silicon.

The projects mentioned above will take a great deal of CPU time. We propose to run the Monte Carlo codes on a system of workstations based on RISC CPUs (25MHz R3000 chip). Such systems are currently in use at FNAL (E769), at prices of about $1.5/Mips. These microcomputers are a cost effective method to do large scale computing for high energy phsyics in which single events are processed independently, and can easily equal the power of a mainframe.

Some estimates give that a single SSC event will take about 1 day on a 1 Mips (.9 VAX 11/780) processor. Since 1000 event samples will be needed to establish variation of detector parameters to a few percent, a 100-1000 Mips processor farm could begin to answer some of the questions posed above. We propose to use a small 20 Mips workstation to establish the feasiblity of such a solution for Monte Carlo needs.

3. Tower Structure and Triggering Studies

One of the advantages of a calorimeter medium like silicon is the flexibility in cell structure design. In the forward region fast summed hardware towers might be used in a fast electron trigger, and they could enhance the speed of a shower reconstruction algorithm. On the negative side, hardware tower structures will likely add to the cost of the detector, perhaps complicate the fabrication, and possibly result in some sacrifice in uniform response and hermiticity of the calorimeter.

Since the pad sizes will be small, tower structures may be defined in the software. Definitions of these “software towers” can then be changed in the trigger or reconstruction algorithms, which could represent a distinct advantage.

It remains to be seen from careful study of electron shower development and practical considerations of assembly costs and complexity which option will be taken.

D. PRODUCTION AND BEAM TESTING OF ENDCAP QUADRANT MODULE

1. Silicon Detector Production and Testing

Silicon calorimetry work has provided high energy physics experiments with detectors which have exceptional performance characteristics; for example, low full depletion voltages (<100VDC) and very low leakage currents (typically <10nA/cm^2). Most devices used thus far have been produced using ion implantation techniques. Detector development work is currently under way to implement standard diffusion processing into silicon detector fabrication. The prime objectives of this work are to reduce the unit cost of such detectors, and to cultivate U.S. manufacturing interest for large scale projects such as the SSC. The advantage of ion-implantation may not be worth the cost for large cells such as those employed in silicon.

The devices for this project will be procured from a reliable vender using proven processing technology to insure optimum performance and longevity. Specifications will be developed which are based on the findings from other studies described elsewhere in this proposal (i.e., radiation hardness requirements and annealing treatments, if required). The detectors will be fully tested by the manufacturer and tested by the assembly group prior to system assembly.

2. Cable and Connection Testing

Due to the large number of cells and the large physical area that the end cap will cover, as well as the speed required for operation, the electronics from the preamp through summing stages will have to be located close to the detectors themselves. Several approaches for the implementation of such an electronics package have been conceived and must be studied in detail to select the optimum solution. Interconnection among electronic components and detector elements represents a sizable design challenge. Detailed reliability studies will be conducted prior to the writing of the manufacturing and testing specifications for these components and interconnects. Of course, final assembly test procedures will be created to facilitate system checkout.

3. Mechanical Construction

Mechanical tooling and construction will be developed and performed in such a way as to produce repeatable and dependable structures throughout the endcap. Mechanical tolerances consistent with desired endcap performance will have to be developed in conjunction with tower structure and EGS overlap studies.

4. Test Beam Operation

We plan to test prototypes of the calorimeter in test beam runs at FNAL during the 1990 and 1992 fixed target running periods with the effort culminating in a test of a fully constructed quadrant. It is our intention to perform a complete test, from hardware through the data acquisition and shower reconstruction phase. We feel that the major advantages of a finely segmented and fast silicon based calorimeter may well lie in its capability to reduce pileup in time and to provide superior reconstruction capabilities for confusing events. Only a complete test will establish these qualities.

If possible, we would like to test intermediate versions of the calorimeter at Fermilab during the 1990 fixed target running period. The first version will be a scaled down version of the full quadrant. It will be 20-25 radiation lengths long and 25 cm wide for good lateral and transverse containment. It will be finely segmented in the center (1 cm^2 pads) with coarser segmentation towards the outside.

Given the short time scale, the amplifier/readout electronics will likely be conventional, i.e., similar to that used by the SICAPO group. We would prefer to set up the test in a common user site, but due to the expected high demand for these areas, we are negotiating to run parasitically in an experimental area. We anticipate checking the calorimeter's response for particle fluxes $> 10^7$/sec in an energy range from 50-500 GeV.

The primary goals of the initial tests will be:

(1) to measure electron, photon, and hadron signal to noise response, (2) measure energy resolution as a function of stack parameters, (3) study pileup effects at high rates, (4) study shower reconstruction problems as a function of rate, (5) measure shower profiles as a function of energy, rate, and incident angle, (6) study any hybrid detector/amplifier prototypes which are available, (7) critically compare these studies with EGS and CALOR

simulations.

In a second phase of test beam runs occurring in the 1992 fixed target period at FNAL we will test the full quadrant with all of the same goals in mind. At this time a complete testing of new advances in detector/amplifier hybrids and other associated electronics will be possible.

6. Data Acquisition System

We plan to instrument a few hundred channels of electronics and read them out through a standard data logging system for the early test beam runs. Due to our strong interest in electron triggering, we are particularly interested in a novel DAQ system used by E791 at FNAL. It is a VME based system capable of recording 12 MB/sec of data to 8mm video tape. This high rate capability is accomplished by having fast front- end ADCs, and a high degree of parallel event buffering. The events' fragments are assembled by ACP modules (16 MHz 68020). With the advent of ACPII systems (25MHz R3000), and introduction of massive parallelism, we can envision a third level trigger which reduces the load on earlier trigger decisions. In a parallel proposal to the SSC, the University of Mississippi has displayed interest in developing DAQ and triggering along these lines.

The spatial segmentation is driven by the electron identification objective. Hadron / photon overlaps are reduced by having good shower centroid information. With good longitudinal segmentation, shower development criteria can be used to reduce hadron/electron confusion. For an endcap module, the mean energy of electrons will be high, so the spatial extent of the electromagnetic shower will be limited in the first 10 radiation lengths. Good two-dimensional shower profile information can be used to reduce electron/photon overlap problems. The exact nature of the optimization depends on the electronics design, emphazing the importance of a system approach for the calorimeter electrical and mechanical assembly.

IV. Operation in the SSC

For an electromagnetic endcap module in the SSC the first question to be addressed is the radiation damage. There are two independent approaches to an evaluation of the damage, both of which yield consistent results. First, at the La Thuile Workshop, G. Stevenson did a FLUKA simulation of an endcap calorimeter design very similar to this one, using 1 radiation length sampling with 1 mm silicon. The dose at 50 milliradians, the worst case for this problem, scaled from a distance of 117 cm to our case of 380 cm, is 0.039 MGy at electromagnetic shower maximum. This same simulation has been used to evaluate doses at the SPS in a variety of conditions and agrees with measurements to within a factor of 1.5. Stevenson's numbers at 100 milliradians are almost an order of magnitude lower because of the well-known falloff of particle flux with angle on the rapidity plateau. At the SSC the fluxes at the same angle will be somewhat higher than Stevenson's LHC computation, but the silicon sampling fraction is only half as much. The SSC dose in 0.4 mm silicon is actually lower, about .028 MGy.

One can get an independent estimate of the dose by using a particle production model to estimate the photon flux in this angular region. This will be much cruder than Stevenson's actual simulation, of course, but it gives some confidence in the numbers. From Ranft's model of minimum bias collisions, each interaction produces about 28 photons of mean energy 15 GeV in the angular region from 40-100 mrad. For a Pb converter (E_{crit} = 6.7 MeV) this will make a flux of 63,000 electrons/interaction in the calorimeter. Of these, about 12% cross the layer at shower maximum. Thus, per SSC operating year, the silicon at shower maximum will see 2% of this dose, or 5 $\times 10^{13}$mips/cm^2/yr. This is a dose of .015 MGy/SSC year, comparable to Stevenson's real calculation scaled to our sampling fraction.

For this dose, how will the silicon respond? A series of recent measurements on damage mechanisms in silicon are summarized in the Summary Report of the Silicon Calorimetry Working Group at the Tuscaloosa Calorimetry Workshop. The charged particle dose response is shown in Figure 1 from Lindstroem, et al. For 3 x 10^4 Gy, ignoring annealing effects, the leakage current will increase by about 5 orders of magnitude. However, this changes the current drawn from the 100 volt bias supply from 100 microamps/m^2 to 10 amp/m^2. The maximum power dissipation in the silicon under extreme radiation damage conditions would increase to 1000 watts/m^2 - significantly greater than the preamp power input. Further measurements on charge collection efficiency at these dose levels show very small decreases in the charge collection efficiency. Thus, all present information indicates that even without annealing effects, the annual operating dose from the SSC would not cause serious disruption to the endcap module. Furthermore, we emphasize that the dose decreases by an order of magnitude in going from 50 to 100 milliradians. Only the innermost sectors of the endcap module will experience these highest dose rates. The simple mechanical layout of silicon calorimetry may allow these lightweight, small elements to be handled differently or replaced if required.

The neutron dose for an electromagnetic endcap module will include neutron albedo from the forward hadronic calorimeter and also from the beam collimators protecting the forward quadrupoles. Measurements of neutron albedo agree generally with simulation. The albedo flux is predominantly low energy neutrons, and moderating them with a polyethylene layer (about 10 cm) between the electromagnetic module and the downstream region should make the flux quite tolerable. Again there have been a series of recent measurements on the neutron dose effects. Widely-varying techniques have been used, and all agree on the dose coefficient of leakage current increase and on the existence of annealing effects. Present information suggests that the radiation dose in the electromagnetic endcap module will be dominated by the electromagnetic effects, not the neutron dose. The group will pursue these studies as an early part of the design analysis.

V. Budget

OPERATING

	Year 1	Year 2	Year 3	Total
Oak Ridge National Laboratory (Two man years electronic engineers, year 1 and 2, one man year electronic electronic engineer, year 3 Subcontract to Harris Semiconductor, $50K each year Subcontract to Vanderbilt University, $75K year 1 Subcontract to Intraspec Corp., $20K year 1 and 2 Travel and miscellaneous $26K per year Computer programming $80K per year)	$470K	$395K	$265K	$1,130K
University of Tennessee (1 postdoctoral research associate 1 student, 1 technician, travel .5 man year project engineer 1st year 1 man year years 2 and 3)	$164K	$205K	$215K	$584K
University of Oregon (1 postdoctoral research associate 1 student, 1 technician, travel)	$130K	$136K	$143K	$409K
Carnegie Mellon University (1 postdoctoral research associate 1 student, travel)	$110K	$115K	$150K	$375K

University of Colorado	$50K	$52K	$55K	$157K
(1/2 postdoctoral research associate				
1 student)				
University of Mississippi	$60K	$63K	$66K	$189K
(1/2 postdoctoral research associate				
1 student)				
Brookhaven National Laboratory	$35K	$35K	$0	$70K
Total operating budget	$1019K	$1001K	$894K	$2914K

EQUIPMENT

	Year 1	Year 2	Year 3	Total
Silicon Detectors (includes 10% spares)				
University of Oregon	$107.5K	$215K		$322.5K
University of Tennessee	$107.5K	$215K		$322.5K
Detector Mounting				
University of Oregon	$10.75K	$21.5K		$32.25K
University of Tennessee	$10.75K	$21.5K		$32.25K
Mechanical Construction				
University of Tennessee	$16.7K	$33.4K		$50.1K
Electronics				
included in ORNL operating budget	$ 0	$ 0		$ 0
Total equipment budget	$253.2K	$506.4K		$759.6K
Total Budget	$1272.2K	$1507.4K	$894K	$3673.6K

VI. Project Schedule

Perhaps the most challenging problem in silicon calorimetry is the development of electronics to take full advantage of the superior performance characteristics of silicon detectors. The Instrument and Controls Division of Oak Ridge National Laboratory has assumed the primary responsibility for this development in close cooperation with Brookhaven National Laboratory. The Brookhaven group will provide consulting services and ensure that the project is closely coordinated with SSC subsystem research on general electronics for calorimeters so that major duplications of effort do not occur. In Year 1 fabrication of an improved radiation-hard bipolar preamplifier developed at ORNL for silicon detectors under the generic detector research program will take place. It is planned that this preamplifier will be fabricated using the Harris Space and Military Division process line. Techniques will be developed to incorporate the preamplifier into the detector directly using a silicon on silicon approach, and testing of the detector-preamp combination will be completed. In Year 2 testing of the preamplifier for overall performance will be completed and schemes for routing the preamplifier signals to summing amps will be developed. Non rad-hard CMOS data handling circuits will be designed in a CMOS process that can be translated into radiation hardened CMOS such as the new Harris fabricated lines. Furthermore, the overall electronic design with the silicon detectors will be tested. In Year 3 testing of the data processing VLSI circuits will be completed. Design translation of the data circuity into rad hard CMOS will take place, and the rad-hard CMOS will be fabricated and tested. The electronic installation system testing will be completed.

The mechanical design and construction of the calorimeter will be done by the University of Tennessee. The project engineer will closely coordinate the design with the electronics group at ORNL and with the members of the collaboration engaged in simulation work. Tennessee will have the final responsibility for system integration. Silicon detector procurement, testing and mounting will be done jointly by Tennessee and the University of Oregon. Both institutions have well equipped clean room and laboratory facilities and have experience in acquisition, testing and installation of fairly large quantities of silicon detectors (several square meters). They are also engaged jointly in a generic R&D

project to locate and encourage potential suppliers of low cost detectors. These efforts will continue during the lifetime of this project. Acquisition of detectors will be conducted in such a way as to facilitate and take advantage of continued efforts at price reduction.

Radiation damage studies and tolerance experiments will be conducted by Carnegie Mellon University and Brookhaven National Laboratory in years 1 and 2. Radiation levels at least five times the expected dosage will be explored. Extensive simulations are required for this project. The collaboration has extensive experience with the use of calorimeter codes used in these studies. ORNL will improve CALOR code to describe saturation and recombination effects in silicon more accurately. These codes require large blocks of computer time and will utilize the computing power of several institutions. Simulations will be carried out at Mississippi, Colorado, Oregon, Carnegie Mellon and Tennessee. The University of Mississippi and ORNL will incorporate CALOR89 into the GEANT program describing the calorimeter geometry.

VII. Requests from SSC Management

This proposal represents a significant new technique for calorimetry. We expect that it will succeed and indicate good potential for extension to other SSC proposals. Its demand for detector-grade silicon is modest at the moment, not larger than already planned for Zeus. However, if one combines the plans for silicon calorimetry with plans for silicon tracking devices, strips and pixels, then it is clear that the SSC will make an unprecedented demand on the silicon foundry production of high resistivity silicon. We would hope that the SSC management will join us in discussions with American and foreign silicon suppliers and processors to solicit bids to supply large areas of high resistivity silicon wafers for diodes and strips or pixels. Such a demand will require large industries to be involved, and the support of the SSC directorate will be important in persuading such companies that the scale of the project is large enough to hold their interest.

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Appendix I

See attached copy of Summary Report of the Silicon Calorimeter Working Group, Workshop on Calorimetry for the Superconducting SuperCollider, Tuscaloosa, Alabama, March 1989.

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Silicon Calorimetry for the SSC*

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* Summary Report of the Silicon Calorimetry Working Group, Workshop on Calorimetry for the Superconducting Super Collider, Tuscaloosa, Alabama, March, 1989.

Silicon Calorimetry for the SSC

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ABSTRACT

SSC experiments will rely heavily on their calorimeters. Silicon calorimetry, which has been introduced in recent years as a useful technology, has many attractive characteristics which may make it a viable option for consideration. The many attractive properties of silicon detectors are reviewed. The relevant present day applications of large areas of silicon detectors are summarize to illustrate the emerging use. The troublesome issue of radiation damage in a high luminosity environment like the SSC is considered with a summary of much of the recent new measurements which help clarify this situation. A discussion of the electronics and a possible mechanical configuration is presented, followed by a summary of the outstanding R&D issues.

INTRODUCTION

Experiments at the Superconducting Supercollider (SSC) will place severe demands on the performances of the hadron calorimeter [1]. As the core element of the central detection system,the calorimeter must face the exceptional experimental conditions created by a very high luminosity, high multiplicities, and the large variety of physics phenomena to study. The following features will be asked of the hadron calorimeter: compact construction, flexibility, fine segmentation, fast charge collection, easy calibration, good resistance to radiation damages, good energy resolution and a compensating (e/h=1) response. With respect to these issues of performance, silicon detectors offer an attractive approach for SSC calorimeters. Futhermore, they can be employed as complementary components with other calorimeters [2], for example as the present applications of plug calorimeters and small angle calorimeters described below.

Though the first applications of silicon detectors in high energy experiments were largely motivated by the high resolution possible with microstrip devices in vertex detectors, there is now a growing demand for large area pad detectors. This rather new field has recently become very interesting especially for the instrumentation of calorimeters and other related equipment. In the following discussion, we enumerate the features which make silicon detectors very attractive for calorimetry at the SSC.

The unsurpassed signal to noise ratio results in single mip resolution possible already with an active layer thickness of less than 500 μm. Due to such thin sampling gaps, silicon instrumented calorimeters can be made most compact. In fact they may be the only choice, where limited space does not permit other solutions. On top of this, these detectors can be used in normal laboratory ambients and at room temperature. No special encasement such as a vacuum tank or a cryostat vessel is necessary. Therefore the construction of calorimeters with almost perfect hermiticity is feasible. The technology of silicon detector fabrication enables a tailored geometry with a fine lateral and longitudinal segmentation. Another big advantage is the overall modular design of calorimetric devices possible with this technique. Thus the sampling geometry can easily be changed and optimized in test setups. Dead cells resulting from radiation damage or electronic failures are in principle replaceable. Due to their small thickness of less than 500 μm and the high ohmic resistivity of about 5-10 kohm-cm, silicon detectors can be operated at comparatively low bias voltages. In most cases total depletion, i.e. the extension of the electric field throughout the detector thickness, is already achieved at about 100 V. Like other active media, silicon detectors exhibit a direct charge readout. Since their response is practically nonsaturating, independent of the particle type, and exhibits a perfect charge collection, a direct and absolute calibration of the deposited visible energy is possible and can be readily accomplished using, for example, an alpha source. Especially for large area detectors with a small thickness, the Hall effect is not expected to play a significant role. The signal response is therefore nearly insensitive to magnetic fields. A high value of the average electric field, which in these thin detectors is already established by the low operating voltage, together with the comparatively high mobilities of the charge carriers (electrons and holes) leads to very short charge collection times of less than 20 ns. Finally it should be mentioned that semiconductor detectors are the only active devices which have the potentiality for a direct integration of the front end electronics. In summary, it is the combination of the mentioned outstanding properties like compactness and flexibility of the overall geometry, single mip resolution, direct charge readout with a nonsaturating absolute energy calibration and high speed, which make silicon detectors most promising for future applications.

These attractive features (as they apply to any particular situation) have lead to a growing number of instrumental developments which are summarized in table 1 (see reference 3 for details). Total areas between 0.1 and 50 m^2 are already employed or under design. Except for the SICAPO calorimeter [4], which is the first and up to now only project for a full hadronic test calorimeter, the other installations are either mainly designed for dE/dx-measurements, electron hadron separation, luminosity monitoring or as plug calorimeters. The following examples illustrate the different applications.

The UA2 detector at CERN was the first experiment to employ a large area of pad detectors [5]. For the inner cylindrical layer each detector contains 16 pads of 2x16 mm^2. The detectors of the outer layer have 7 pads of 9x40 mm^2. The total area covered is 0.1 m^2 for the inner and 1 m^2 for the outer layer. The main purpose of the installation is a fast and simple vertex reconstruction as well as a rejection of otherwise not resolved tracks.

The ZEUS experiment at HERA will contain in the forward part of the uranium/scintillator calorimeter 2 planes of 9 cm^2 silicon detectors at 3 and 6 X_0 and 1 layer in the other parts of the calorimeter at 3 X_0. This instrumentation exhibits the largest total area of silicon detectors (about 50 m^2) so far under development. The purpose of the sampling layers is an improved electron/hadron separation.

The small angle electromagnetic calorimeter at SLD [6] will cover an overall 2 m^2 active area and consists of four subcalorimeters with fine granularity. 1-2 cm^2 detectors are being used and the design covers the otherwise not accessible forward region between 23 and 200 mrad. The purpose is to provide a high precision luminosity monitoring via Bhabha scattering and the extension of the electromagnetic coverage to very small angles. The coverage in the small angle region is particularly important for vetoing backgrounds to missing energy events, such as

$$e^+e^- \rightarrow \gamma Z^0(Z^0 \rightarrow \nu\overline{\nu}) \tag{1}$$

This calorimeter is included in the SLD trigger.

The plug calorimeter for the H1 detector at HERA is another example for the possibility of filling the gap between the beam pipe and the main liquid argon calorimeter. But in contrast to SLD, it is devised as a hadronic module installed

experiment	UA2	UA2	NA35	JETSET	ZEUS	SLD	H1	LEP	DELPHI	SICAPO
	outer	inner			HES	LMSAT				
purpose	dE/dx +lr	dE/dx +lr	multipl.	dE/dx	hadr/elec	plug-cal .	plug-cal.	lumin.	plug-cal.	full calor
date of operation	1987	1988	1989	1990	20% 1990	1989	1990	1989	part.89	1988
silicon:										
total active area	1 m^2	0.1 m^2	0.1 m^2	$\approx$ 1 m^2	$\approx$ 50 m^2	1.65 m^2	1.56 m^2	0.3 m^2	$\approx$ 1 m^2	6.5 m^2
# of diodes	3024	3072	800	$\approx$ 10000	$\approx$ 50000	11776	672	848	$\approx$ 60000	$\approx$ 2200
area/diode	3.5 cm^2	0.3 cm^2	1.12 cm^2	$\approx$ 1 cm^2	$\approx$ 10 cm^2	1-2 cm^2	25 cm^2	.4-25 cm^2	$\approx$ 0.2 cm^2	28 cm^2
# of crystals	432	192	25	$\approx$ 2500	$\approx$ 50000	736	672	128	$\approx$ 1300	$\approx$ 2200
# of cr.tested	432	$\approx$ 130	25	0	350	$\approx$ 50	$\approx$ 50	$\approx$ 50	few	
local electr.:										
type	hybrid	ASIC	ASIC	ASIC	hybrid	hybrid	hybrid	hybrid	ASIC	hybrid
# of channels	3024	3072	800	$\approx$ 10000	$\approx$ 50000	1024	336	848	$\approx$ 60000	440
power/channel	70 mW	1.5 mW	12 mW		$\leq$ 100 mW	120 mW		70 mW		$\approx$ 100 mW
multiplexing	64:1	128:1	64:1	$\leq$ 512:1		512:1	128:1*			
performance:										
noise [e rms]	1800 e	1200 e	2500 e	< 2000 e	$\approx$ 5000 e	6-16 ke	$\approx$ 7000 e	5-20 ke		$\approx$ 4000 e
signal/noise	13/1	20/1	$\approx$ 10/1	> 12/1						

Table 1. Summary of large area silicon projects as reported by Gössling in [3]. * indicates addition to Gössling table.

in the proton direction and will serve to complement the liquid argon calorimeter for reducing the missing p_T. It will also be implemented in the overall trigger. About 700 detectors of each 5x5 cm^2 are foreseen.

The SICAPO Collaboration is employing large area silicon detectors in their beam test calorimeters [7,8]. These detectors have a standard area of 28 cm^2 and can assembled to build mosaics with an active area of up to several thousands of cm^2 [8]. The silicon detector thickness (around 300 μm) and its thin support allow sampling gaps of less than 2.5 mm. These detectors naturally allow a very flexible, and very fine, longitudinal and lateral segmentation; this is the essential property to provide precise angle measurements and separation of very close jets and/or photons. The high granularity so achieved is the necessary condition to resolve possible complicated interaction configurations present at the SSC energy [9]. At the same time silicon detectors allow very flexible constructions which can very efficiently cover available space left by the relatively small crossing angle at the SSC. The use of serial coupling of 5 silicon detectors, while reducing the number of electronic channels and the overall detector capacitance, allow the use of fast electronics (about 100 ns base-time signals) with a wide dynamical range. The silicon detectors are also characterized by a fast response; for standard silicon detectors (300 - 400 μm thick) the electron collection time is 2 ns or less whereas the hole collection time is less than 6 ns, although electronics response necessarily limits the collection time to somewhat longer than this. Furthermore, they operate with very low voltages, typically less than 100 V for 200 μm depletion and a resistivity between 1 and 5 $k\Omega cm$.

At the same time that these applications of high resistivity detectors are growing, amorphous silicon shows potential for future applications [10]. Research and development is being pursued to make large area amorphous detectors available. Presently, these are not suitable for systems applications, but the R&D should and will be pursued.

COMPENSATION IN SILICON

Reaching a good electromagnetic and hadronic energy resolution is certainly the most crucial goal to be achieved for any SSC calorimeter.

Electromagnetic calorimeters using silicon as active medium have been demonstrated to have a good energy resolution. Measurements performed by the SICAPO (SIlicon CAlorimeter and POlarimeter) Collaboration (Florence, Hamburg, McGill, Messine, Milan, Oregon, Tel - Aviv, Tennessee, Trieste, Turin) with an electromagnetic calorimeter (24 radiation lengths deep) using silicon as active material (each detector had an area of 5x5 cm^2) and tungsten and uranium as passive material, have shown an energy response which is linear and stable to better than 1%, and an energy resolution of $\sigma(E)/E = (17.6 \pm 0.3)\% \sqrt{\tau / E[GeV]}$ where τ is the thickness of each absorber layer in radiation lengths (i.e. the sampling frequency)[7]. Other groups have reported similar results [11].

Obtaining a good hadron energy resolution necessitates the achievement of the compensation condition. Contrary to the electromagnetic cascading, which is fully described [12] by Quantum Electro-Dynamics (QED) and depends essentially on the density of electrons in the absorber medium, the hadronic cascading is propagated by a variety of complex hadronic processes [13]. Decays of hadronic resonances created during the degradation of the energy of the incident hadrons, and charge exchange reactions in these processes, yield an electromagnetic component for any hadronic shower; this component is largely determined by the production of π and μ in the first interaction, and therefore event-by-event fluctuations are important. In the hadronic interactions of a cascade, a sizeable amount of the available energy is converted into excitation or break-up of the absorber nuclei, of which only a fraction would result in visible energy. Therefore, the signal per unit of incident energy will be different for electromagnetic and hadronic cascades. The performance of hadron calorimeters is determined by the relative response to the electromagnetic and non-electromagnetic shower component, the e/h signal ratio. Equalizing the response of the calorimeter to electrons and hadrons (that is, achieving the compensation condition of e/h = 1) is the requirement for reaching optimal performances of the calorimeter. It has been shown [14,15,16] that the e/h signal ratio is in fact determined by the processes that occur at the nuclear and atomic levels during the last stages of shower development. In hadron calorimeters employing hydrogenous material as active devices, the compensation condition can be achieved by increasing the relative contribution of the pure hadronic signal; this is obtained by neutrons (generated in the last stages of the hadronic shower development, where processes at the nuclear level occur) interacting on the protons of the readout material. The relative contribution of neutrons can be modified by varying the sampling fraction in order to achieve the compensation condition [15,16]. Silicon, being hydrogen free, is less effective in absorbing neutron energy than a hydrogenous material. However, recent work reported in these proceedings [17] finds that a polyethylene layer around a silicon detector gives an enhanced detection sensitivity to neutrons via the knock-in protons. This effect is most pronounced for the higher energy neutrons which carry most of the neutron energy in the hadronic cascade. This enhancement may be used to tune the e/h response over a significant range and aid in compensation. Other means of compensation, besides neutron detection, can be considered, and will have implications on the choice of the absorber.

In order to explore the expectations for compensation in silicon (since experimental work is incomplete) a understanding of the theory of compensation is required [18]. The original motivation of the technique of compensation was the understanding that hadronic cascades with large amounts of electromagnetic energy have less losses of energy due to nuclear break-up than those which contain little electromagnetic energy and therefore a large number of hadronic interactions [19]. Showers with a large fraction of the incident hadron energy converted to π^0s and other forms of electromagnetic energy yield an observed signal comparable to the response of the calorimeter to incident electrons of the same energy with little energy lost to the breakup of nuclei; the e/h ratio for such events is nearly one. On the other hand, showers with large amounts of lost energy in the nuclear break up resulting from many hadronic nuclear interactions (including nuclear binding energy losses, as well as losses from heavy fragment production, neutrino production, and low energy nucleon generation) may result in a reduced detectable energy in the calorimeter. In the absence of compensation, these showers have a minimal amount of generated electromagnetic energy and the resulting e/h ratio is much greater than one. Combining all types of hadronic cascades leads to a very broad distribution of responses, and a resulting poor resolution for the measured energy deposition.

In compensating calorimeters, the nuclear breakup energy has been *compensated for*, by designing the calorimeter to preferentially respond to the low energy loss. While the intrinsic saturation in liquid argon is less than in scintillator, the kinematic constraint on the energy transfers in neutron-nucleus collisions leads to a greater suppression of the transfer of neutron energy to observable signal. In liquid argon the highly ionizing recoil nuclei receive only one-tenth the relative energy of the less highly ionizing recoil protons in scintillator.

This understanding that now exists concerning compensating calorimeters can be applied to the silicon detector calorimeters. The fundamental question that needs to be addressed is what the e/h ratio for these silicon based calorimeters will be. One property of silicon that plays an important role in this study is the extreme linearity of silicon up to very large stopping power. That is, silicon exhibits very little saturation. It has been demonstrated that saturation prevents full compensation in currently designed uranium-liquid argon calorimeters, so this could be a very important factor in silicon calorimeters. Naively it is expected that very good results can be obtained for silicon calorimeters.

It is pedagogically useful to consider the differences between the response of silicon and liquid argon, since except for the saturation in liquid argon, full compensation could possibly be achieved. The three critical factors above which determine the difference in neutron response in scintillator and liquid argon are useful to compare again for silicon. First the neutron cross section in argon falls for energies below a few MeV, while the cross section in silicon remains large and even rises below 500 keV. This will result in a larger energy deposition by low energy neutrons in silicon than is observed in liquid argon. Secondly, the effect of the kinematic limitation on neutron energy transfer can be considered. Equation 2 shows that while only one-tenth of the neutron energy can be transferred in liquid argon collisions, the restriction on energy transfer is somewhat less in silicon. This should lead to an additional increase in the energy transferred to the silicon. Thirdly and finally, the very limited saturation which occurs in silicon will enable these increased neutron depositions to be more observable.

The potential for compensation with silicon certainly seems better than for liquid argon. To make quantitative predictions it is necessary to make use of a Monte Carlo code system which takes into account all of the basic processes and examines the details of the shower development. The Oak Ridge system CALOR has been applied to this problem [18]. Figure 1 shows the calculated

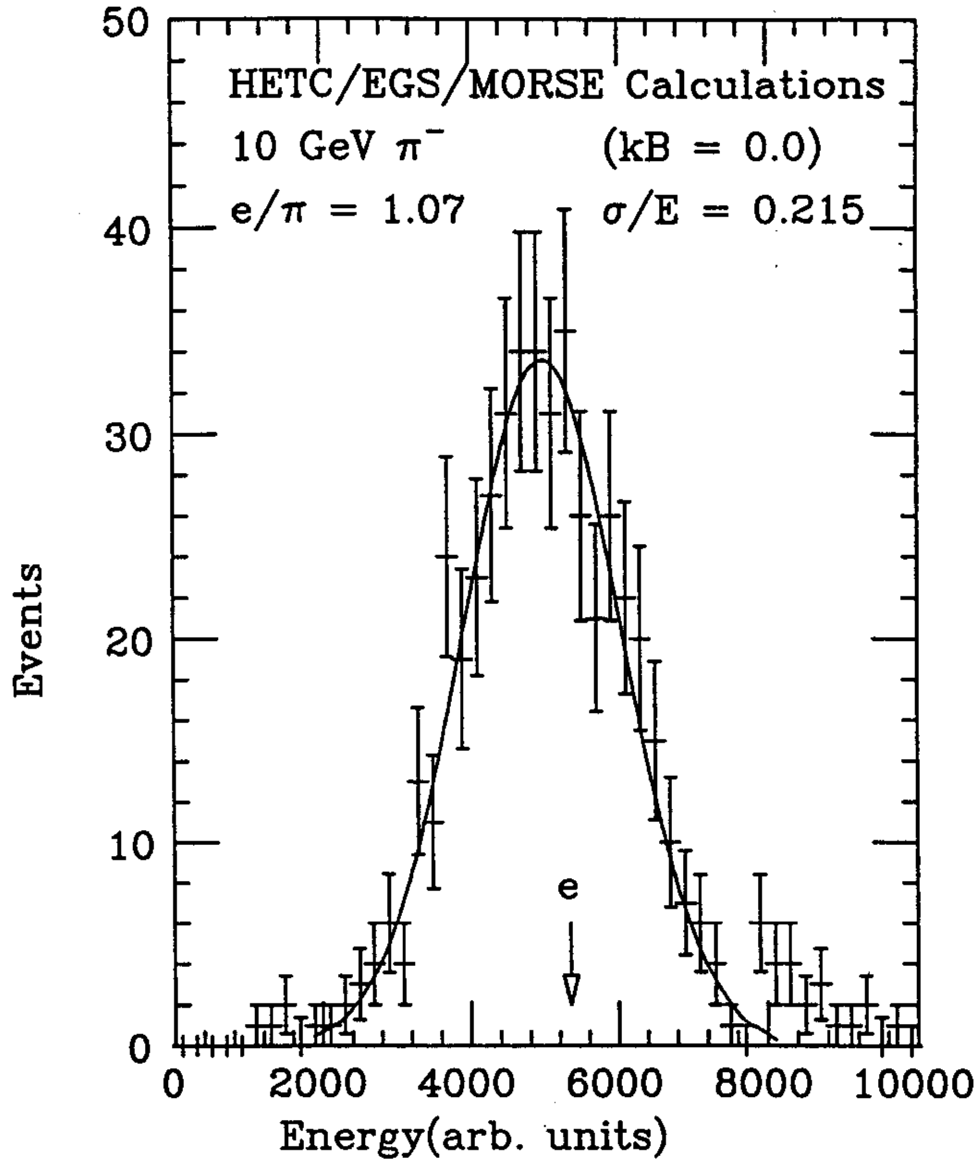

Fig. 1: The calculation of the measured hadron energy distribution for 10 GeV π^{-}s incident on a uranium-silicon calorimeter with 5 mm thick uranium radiators and 400 μm fully depleted detectors imbedded in 5mm thick G10 supports.

response distribution for 10 GeV π^-s incident on a silicon calorimeter with 5 millimeter thick uranium radiators and 400 μm fully depleted silicon detectors sandwich between two layers of 5 millimeter thick G10. Therefore, the total layer thickness is 15.4 millimeters and the depth of the stack extends for 150 readout and radiator layers. The transverse dimensions of the stack have been taken to be 100 × 100 cm^2. The charge collection is cut off after 50 nanoseconds. The resulting energy resolution (σ/E) is 21.5% and the e/h ratio is 1.07, close to compensation. In fact the two layers of G10 in this stack are increasing the value of e/h as the neutron energy from the uranium is being deposited in the G10 through the large energy transfers via hydrogen. Additionally, significant transfers occur to the carbon and oxygen in the G10.

The energy resolution of a sampling calorimeter can naively be written as

$$\sigma/E = C/\sqrt{E} + f(\frac{e}{\pi} - 1) \tag{3}$$

where $\sigma = (\sigma_{bind}^2 + \sigma_{samp}^2)^{1/2}$, contains the contribution from the intrinsic fluctuations due to nuclear binding energy losses (σ_{bind}) and that from the sampling fluctuations (σ_{samp}). $f(\frac{e}{\pi} - 1)$ is energy dependent as a result of the logarithmic increase of $< n >$ ($\sim 5lnE(GeV) - 4.6$) [13] with energy and is vanishing only if $\frac{e}{\pi} = 1$.

For a given absorber the sampling fluctuations can be modified by changing the frequency of the sampling (i.e. changing the number of active planes per interaction length (λ)) and/or by changing the ratio between the relative thicknesses of the readout and the absorber. The value of σ_{bind} correlates with the number of neutrons released by the absorber per GeV of incident energy and can be minimized by an adequate choice of the absorber. For instance at 5 GeV, $\sigma_{bind}/E_{dep} \approx 35\%/\sqrt{E}$ for uranium absorber and $15\%/\sqrt{E}$ for iron absorber [18]. Therefore the aim to reach a resolution of $\sigma/E = 50\%/\sqrt{E}$ lead to the concept of a calorimeter with a Fe dominated absorber [23]. In fact for a calorimeter with silicon readout, the compensation condition is realized with a combination of Fe (low-Z) and Pb (high-Z) as the passive media [23]. Such a combination leads to an electromagnetic shower energy transformation effect, generated by a sharp transition from small to large value of the critical energy.

Therefore the lower the critical energy of the absorber, the softer is the energy spectrum of the electromagnetic shower when entering a low-Z (Fe) absorber and exiting from a high-Z (Pb) absorber. As a result, the energy distribution of the shower is transformed and the response of the calorimeter to the incoming shower is dramatically modified. The degree of the effect obviously depends on the fraction of Pb in an absorber made of a combination of Fe and Pb. A complete study has been performed by the SICAPO Collaboration and we summarize here the results they have obtained [23, 24].

The sensitivity of the visible energy (ϵ_{vis}) to the sampling frequency and configuration is shown in fig. 2 where $\epsilon_{vis}.\tau$ is given as a function of the sampling frequency τ. In absorber material configurations such as FePb-Si-FePb and PbFePb-Si-PbFePb, where the forward-generated electrons in Pb can enter the silicon detectors directly, a substantial increase of $\epsilon_{vis}.\tau$ is measured (as expected). However for the configuration PbFe-Si-PbFe (where the forward-generated electrons in Pb enter the Fe absorber) the measured values of $\epsilon_{vis}.\tau$ increase only slightly. In fig. 3, the values of e/mip are given as a function of the Pb fraction f in the passive absorber ($f = L_{Pb}/[L_{Pb} + L_{Fe}]$) and show that when low-Z Fe and high-Z Pb absorbers are joined there is a deep modification of the absorption properties of the electromagnetic shower.

These data have to be compared with the e/mip values for Pb and Fe absorbers [23]: 0.78 $\pm$ 0.02 (at τ = 1.99) and 0.74 $\pm$ 0.04 (at τ = 3.98) for Fe, and 0.69 $\pm$ 0.04 (at τ = 1.96) and 0.66 $\pm$ 0.04 (at τ = 3.39) for Pb. The data, in particular those for the PbFe-Si-PbFe configuration, suggest that the electromagnetic shower generated in the Pb sampler (with ϵ= 7.4 MeV) is filtered by the Fe sampler (ϵ= 21.0 MeV). In fact, the mean energy of the electrons of the electromagnetic shower generated in the Pb material is lower than the critical energy of the Fe absorber. Consequently, these electrons undergo mainly collision losses in Fe, where they are easily absorbed. An appropriate use of this filtering effect on electromagnetic showers allows the modification of $(e/mip)_{Fe+Pb}$ with the fraction of Pb in the absorber and leads to the possibility of tuning the ratio $e/\pi = (e/mip)/[(e/mip)f_{em} + (h/mip)(1 - f_{em})]$, where (1 - f_{em}).h is the visible hadronic energy (see ref. [4] and references therein) and f_{em} is the

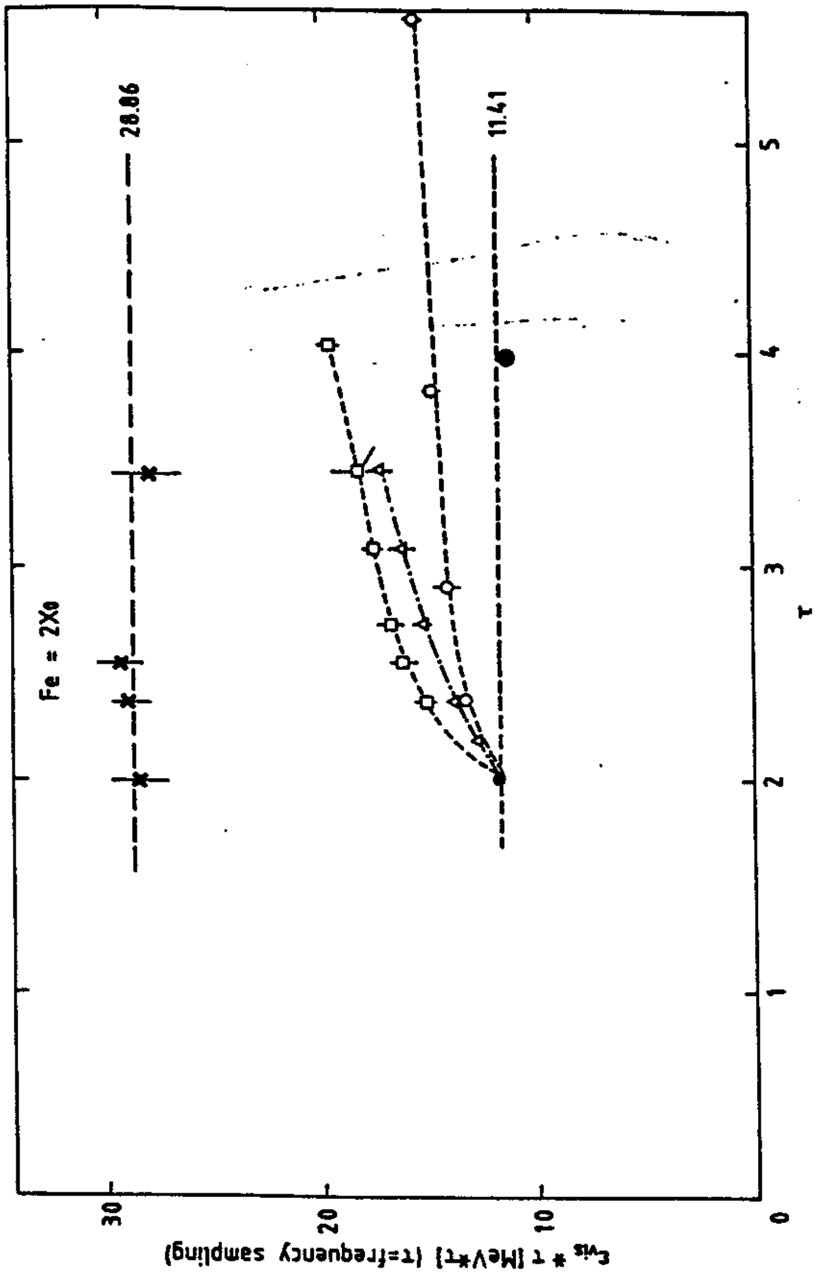

Fig. 2: $\epsilon_{vis}.\tau$ as a function of the sampling frequency τ for incoming electrons of 4 GeV for Si/Fe, Si/Pb, and various configurations with Fe ($1.99X_0$= thick) and Pb as absorbers: (▫) PbFePb-Si-PbFePb, (Δ) FePb-Si-FePb, (∘) PbFe-Si-PbFe, ($\times$) Si-Pb, and (•) Si-Fe.

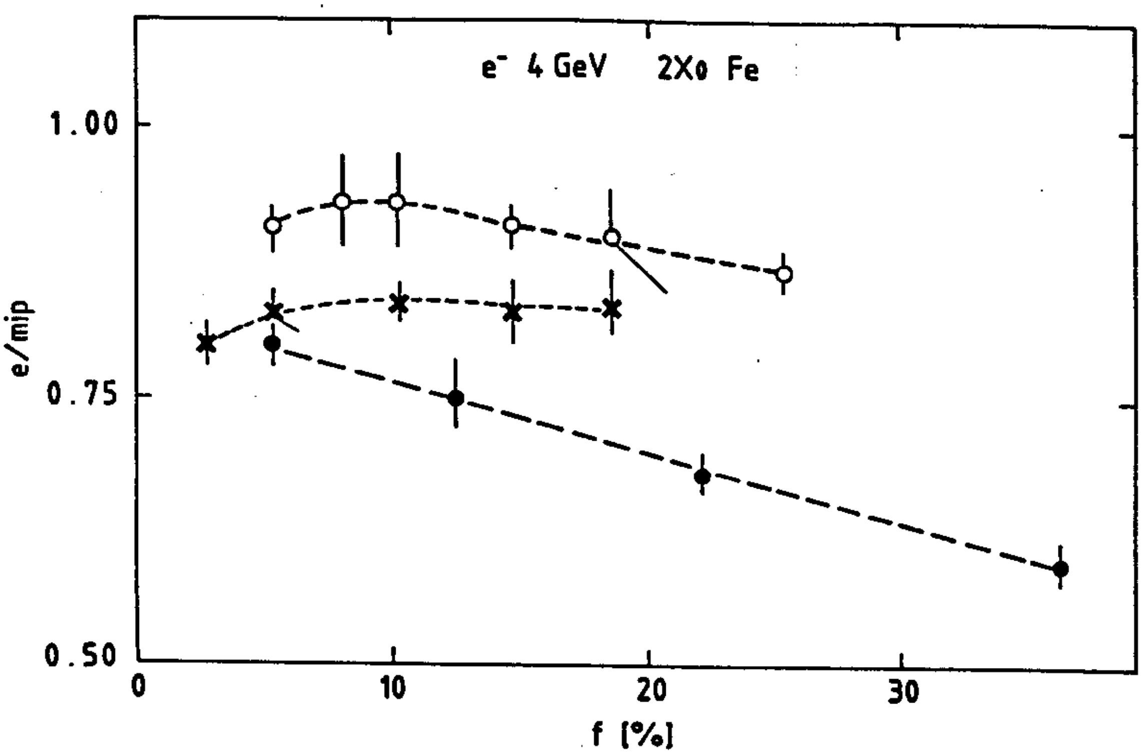

Fig. 3: e/mip as a function of the Pb fraction, f, in the passive absorber ($f = L_{Pb}/[L_{Pb} + L_{Fe}]$; L_i is the thickness of absorber i) for various calorimeter configurations (Fe is $1.99X_0$= thick) and for 4 GeV incoming electron energy: (•) PbFe-Si-PbFe, (×) FePb-Si-FePb, and (∘) PbFePb-Si-PbFePb.

average fraction of hadron energy deposited by the electromagnetic shower in the calorimeter.

At 4 GeV the comparison of $\epsilon_{vis} = (e/\pi)[(h/mip)E_s.(1 - f_{em})/(1 - (e/\pi)f_{em})]$ (E_s is the energy shared by the minimum-ionizing particle in the silicon detectors) when $e/\pi = 1$, with ϵ_{vis} measured for the PbFe-Si-PbFe configuration will provide, at the crossing point of the two lines (see fig. 4), the exact fraction ($\sim$ 25%) of Pb needed in the absorber to achieve the compensation condition. Insertion of G10 will change the position of the crossing point as a consequence (mainly) of the absorption by G10 of soft backward-scattered electrons thus not entering the Si detectors. Furthermore the h-signal has to take into account the neutrons (generated in the hadronic cascade shower) interacting on the protons inside the G10 material. This results in a smaller fraction of Pb being needed in the absorber to achieve the compensation condition. In fig. 5 we show the reduction of the electromagnetic shower energy (which is due to the local hardening effect [24].)

A recent systematic study on the influence of relevant parameters in the EGS4 code has led to an improved understanding concerning the properties of silicon instrumented calorimeters including the G10 effect [25]. The results may be summarized as follows. Thin active media pose a special problem to any reliable Monte Carlo study since they are much more sensitive to the low energy part of the particle spectrum than thick detectors. In an EM sampling calorimeter instrumented e.g. with 400 μm detectors, electrons with an average energy of about 0.5 MeV are still completely absorbed while 10 MeV particles traversing the detectors at the same average incidence of 45 degree lead to an energy deposition of only 200 keV. For a Cu/Si sandwich calorimeter with one X_0 sampling, 20 percent of all particles traversing a detector plane have an energy of less than 1 MeV, but 40 percent of the total visible energy is caused by these crossings. This illustrates the predominant role played by low energy electrons in such devices. For a reliable simulation of the calorimeter response it is therefore essential to ensure a correct reproduction of the energy deposition for low energy electrons. Fig. 1 of ref. 25 shows how well this can be achieved, provided the step size parameter (ESTEPE) is kept below 1 percent and the energy cut (ECUT) below 100

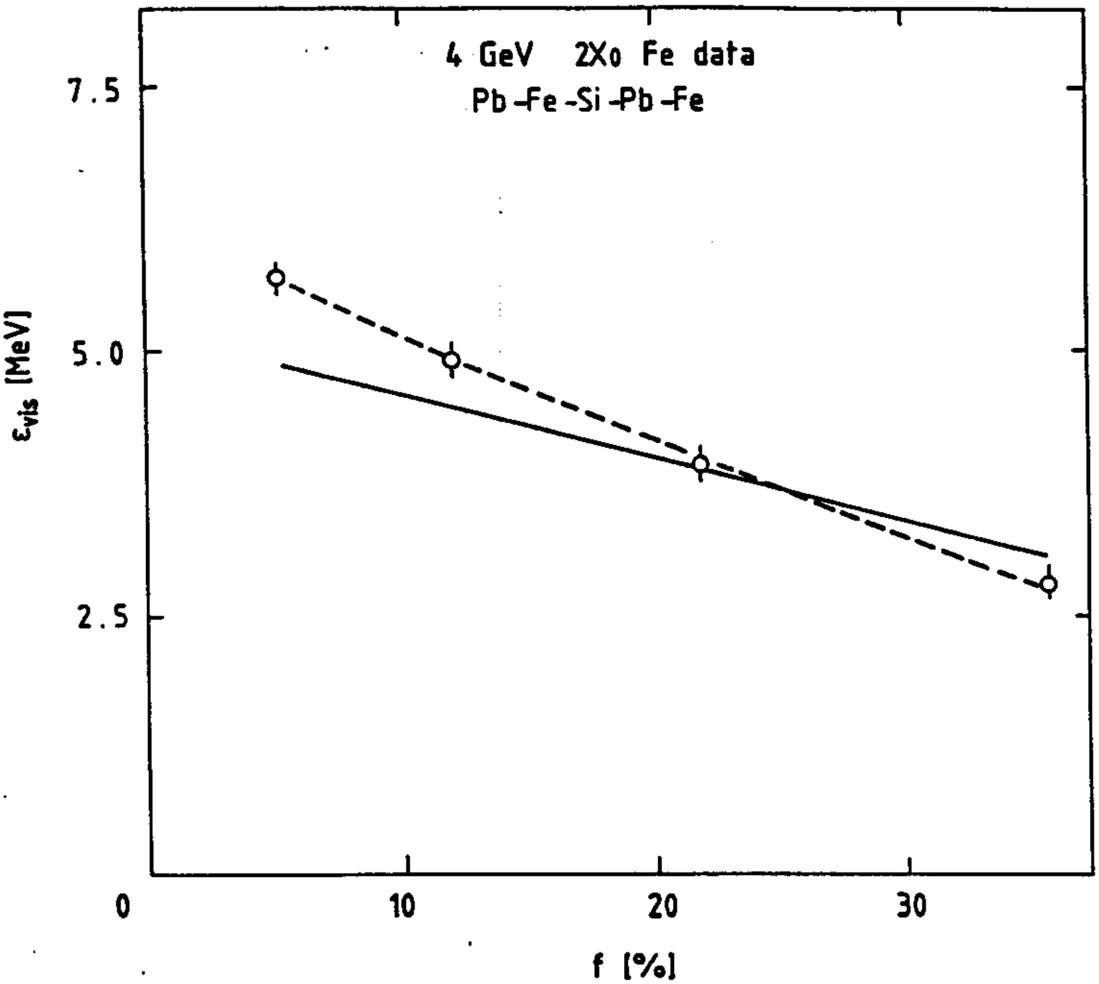

Fig. 4: ϵ_{vis} obtained from (h/mip).E_s ($e/\pi = 1$) (continuous line) compared with ϵ_{vis} measured for the PbFe-Si-PbFe configuration (dashed line). The exact fraction of Pb ($\sim$ 25%) needed to achieve the compensation is indicated at the crossing point of the two lines. The incoming electron energy is 4 GeV and the thickness of Fe is $1.99X_0$.

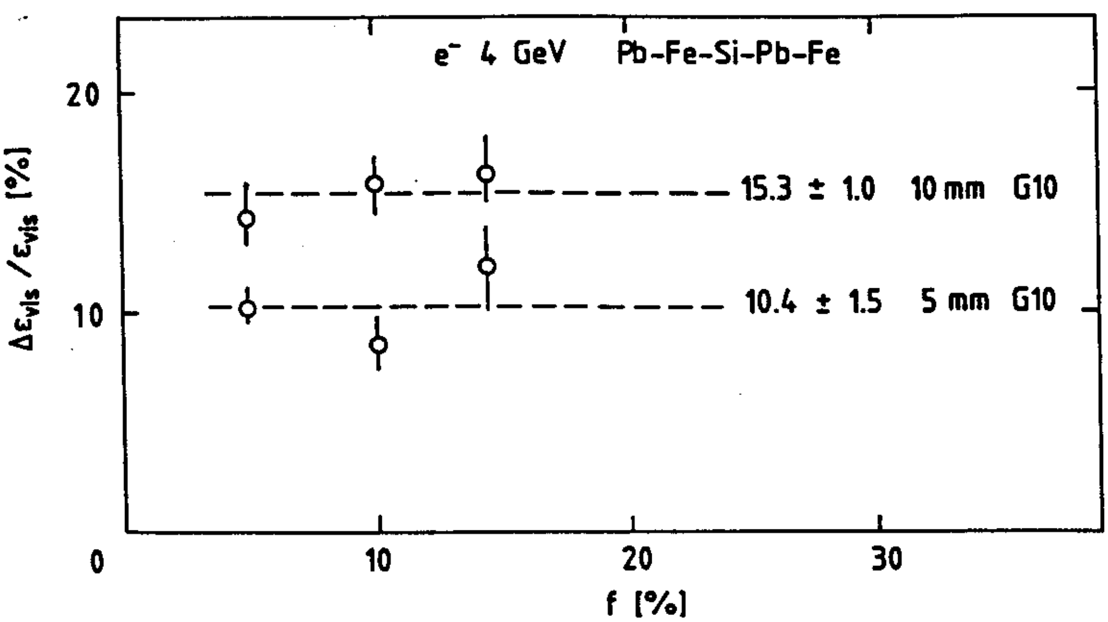

Fig. 5: Reduction of the electromagnetic shower energy due to the local hardening effect, $\Delta\epsilon_{vis}/\epsilon_{vis}$, as a function of the Pb fraction in the absorber at 4 GeV for the PbFe-Si-PbFe configuration when low-Z G10 absorbers 5 or 10 mm thick are inserted at the rear side of the Si detectors (i.e. in front of the high-Z Pb absorbers).

keV. Only for such small step sizes does the EGS4 multiscattering algorithm lead to correct results, while larger values overestimate the incorporated step length correction. The energy cut should be chosen such that the corresponding range is small compared to the detector thickness. The range of 100 keV electrons is 50 μm, i.e. about 10 percent of the detector thickness in this case. A further reduction to 10 keV was shown to affect the deposited energy by less than 1 percent. With the same precautions for the choice of ESTEPE and ECUT the well known energy range relations have also been very nicely reproduced (fig. 2 of ref 25). Based on these findings the response of different silicon sandwich calorimeters, for which experimental results were available, were then investigated. In this case the parameter choice not only in the active medium but also in the absorbers will influence the visible energy. If e.g. too much energy is deposited in the absorbers due to inadequate parameters, the active layers will see less. In order to reduce CPU time consumption without losing accuracy it was shown to be sufficient to subdivide the absorbers in a bulk part with a high energy cut while maintaining low cuts in appropriate interface layers adjoining the detectors. A quite low ESTEPE value had to be chosen throughout the absorber and it was shown that this value has even to be smaller for higher Z material (ESTEPE = 0.5 percent for copper but for lead even 0.4 percent seems not to be sufficient). Following this recipe the visible energy and the energy resolution of EM Cu/Si and Pb/Si calorimeters could be very well reproduced (table 3 of ref 25). This includes also several configurations with G10 layers in front or rear of the detectors. The reduction of the visible energy by such G10 layers or other low Z material has so far been described qualitatively as a local hardening of the electron energy spectrum and this is of course the main effect. Low Z layers lead to energy absorption with much less particle production by photo or Compton effect than in the comparatively high Z absorbers. Thus the intensity of low energy electrons traversing the detector planes is reduced, an effect which is clearly reproduced by the Monte Carlos. This absorption is more pronounced for high Z absorbers since in this case the soft electron component is more intense due to energy focusing via the energy shift of the minimum attenuation cross section for photons. Also more elaborate Monte Carlos which concentrate on the particle tracking through the different media in the forward and backward direction has been performed meanwhile by the same group. These calculations result in an understanding of the additional effect that the visible energy reduction is much larger if the G10 plates are placed at the rear of the detectors than in front. In summary one can conclude that the EGS4 code if used properly represents a very reliable tool for calculating the properties of electromagnetic silicon sampling calorimeters and that we have learned to understand effects being produced by the incorporation of other material.

As a conclusion, we find experimental evidence for a filtering effect on the soft-electron component in electromagnetic showers when combinations of low-Z and high-Z materials are used as absorbers. This effect can produce the compensation condition ($e/\pi = 1$).

RADIATION DAMAGE STUDIES - ANNEALING

Very high neutron fluences of several 10^{13} n/cm^2 per year are foreseen in the SSC calorimeter at very forward angles. These exceptional experimental conditions [26] require a detailed understanding of the defect formation processes and of the electrical behavior of irradiated silicon detectors. It is therefore important to perform measurements on silicon samples in order to correlate the damages caused by neutrons with the degradation of detectors. During irradiation the incident particles collide with silicon atoms, thus transferring part of their energy and producing primary knock -on atoms (PKA). The spectrum of energies and directions of PKA depends on the nature and energy of the incident particles. The primary defects (vacancies and interstitials in equal number) may move around independently and join up with impurity atoms or other vacancies and interstitials, forming vacancies-impurity pairs and aggregates such as multi-vacancies, string of interstitials, etc. These defects are deep in general since they introduce tightly bound localized states, in contrast with the well known shallow hydrogenic donor and acceptor impurities. Information about many of the properties of the radiation induced deep defects have been obtained in recent years principally by means of Thermally Stimulated Current (TSC) [27] and Deep Level Transient Spectroscopy (DLTS) [28] methods, and variants thereof. However, as far as the effects of high energy particles on silicon diodes are concerned, there is no large data base available. Fast neutrons essentially interact by elastic scattering with silicon atoms, imparting at most 1/7.5 of their elastic energy (see equation 2). Such direct collisions result in up 10^3 displacements per event. Within the very short range of silicon recoils, a vacancy rich and somewhat disordered zone (cluster) is formed which may produce, in the silicon band gap, defect levels different from those of isolated point defects. There is experimental evidence that the formation of point defects (vacancy-oxygen complex or A center, vacancy-phosphorus complex or E center, di-vacancy complex) may be attributed to a large extent, to the vacancy release from defect clusters. Some preliminary results on point defects produced in n-type silicon detectors by neutron irradiation have been presented previously [29] using DLTS technique. A more complete set of measurements by the SICAPO Collaboration, both with DLTS and TSC methods, was completed recently on n-type silicon detectors with different doses of neutrons. Results are presented here on the annealing behavior of the defects. From these measurements a coherent picture emerges which generally agrees with experimental data obtained by other experimental groups [30,31]. In particular, a comparison is carried out with the results by Brotherton and Bradley [32] on defect production and lifetime control in electron and gamma irradiated silicon.

The effects of radiation damage on the detector performance may be enumerated as follows. The leakage current is strongly dependent on the accumulated dose. Very high values of the current and the related electronic noise impose a limit on the operability of the detectors and hence the lifetime of the calorimeter. Though this is certainly the most severe implication, there are other effects which may be important too: radiation induced trapping centers lead to a charge collection deficiency. If this effect would be strong it would result in a degradation of the calorimetric response and hence influence the absolute energy calibration. The change of the effective impurity concentration is also a consequence of radiation damage. This effect tends to increase the material resistivity and hence changes the depletion thickness of the detector at a given bias voltage. Finally all or at least some of these effects may be dependent on the operating parameters of the detector under irradiation. On top of these issues it is of course of utmost importance to study the possibility of damage annealing. Room temperature self annealing and short term heat treatments seem to be likewise important and have been investigated carefully. Following this outline we will describe the major findings of the several contributions given in this conference [33,34,35] and compare the results with a recent damage study by Kraner [36]. The SICAPO work is described in some more detail since the work by Lindström et al [34] as well as that by Ohsugi et al [35] is covered by individual reports.

Defect formation and characterization. In the following, the work being reported by the SICAPO group is summarized [33]. Samples were irradiated using a ^{252}Cf neutron source. Fluxes were varied from 3.3×10^3 to 9.1×10^4 [neutrons/cm^{2}sec] with exposure times between 1.6×10^6 and 1.0×10^7 [sec]. The point defects formed by neutron irradiation were electrically characterized using DLTS [28]. The DLTS analysis of the silicon sample was carried out using a Boonton DLTS system, DL 4600, manufactured by Bio-Rad UK. The details of the methods of measurements are reported in [29]. A typical DLTS spectrum after irradiation is shown in fig. 6. Thermal emission rate measurements made on the first peak, called E_1, give an activation energy of (0.16±0.02) [eV] below the conduction band edge E_c. This is the activation energy reported for the A center [30]. The second peak, E_2 corresponds to the energy E_c-(0.25±0.03) [eV] and can be associated with the double charge state of di-vacancy, while the third peak, E_3, with energy of E_c-(0.40±0.02) [eV], is interpreted as a sum of the two contributions of the single-minus charge state of the di-vacancy and the E center [30] . These experimental values are compared with the DLTS results obtained in electron and gamma irradiated n-type silicon by Brotherton and Bradley [32]. This comparison shows a substantial agreement in the behavior of the point defect energies. This indicates that damage is quite independent from the various conditions of irradiation as well as of material parameters for what concerns the point defects generated into the irradiated detector lattice. The N_t/N_d fraction (where N_t is the trap concentration of the deepest E_3 point defect and N_d is the donor concentration) obtained from irradiation of 10 samples is shown in fig. 7. The plot shows the linear dependence of N_t/N_d on the fluence. Table 2 shows the energy of the three defects E_1, E_2,E_3 together with the electron-capture cross sections for E_1 and E_3 obtained with DLTS technique .

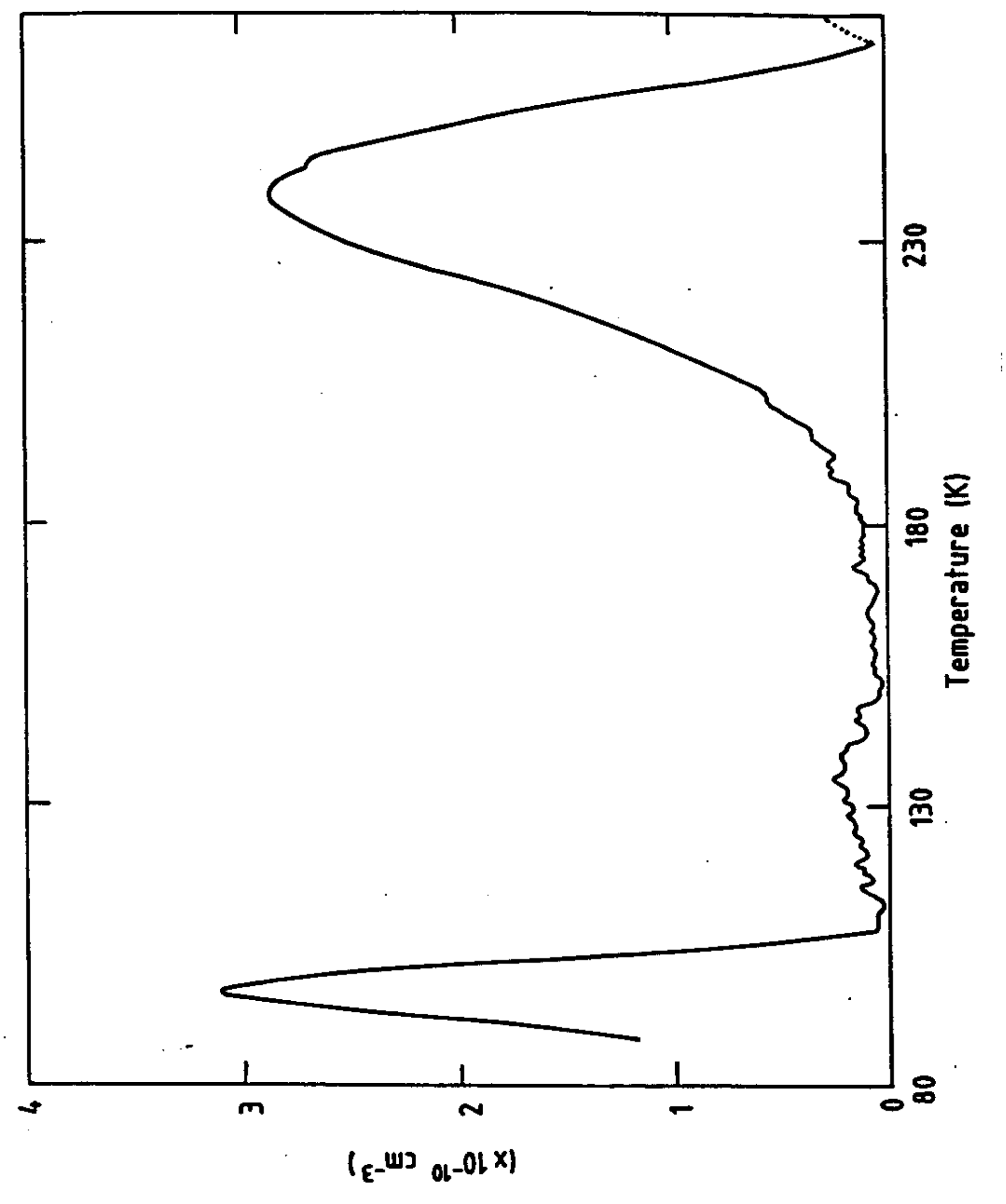

Fig. 6: DLTS spectrum after neutron irradiation.

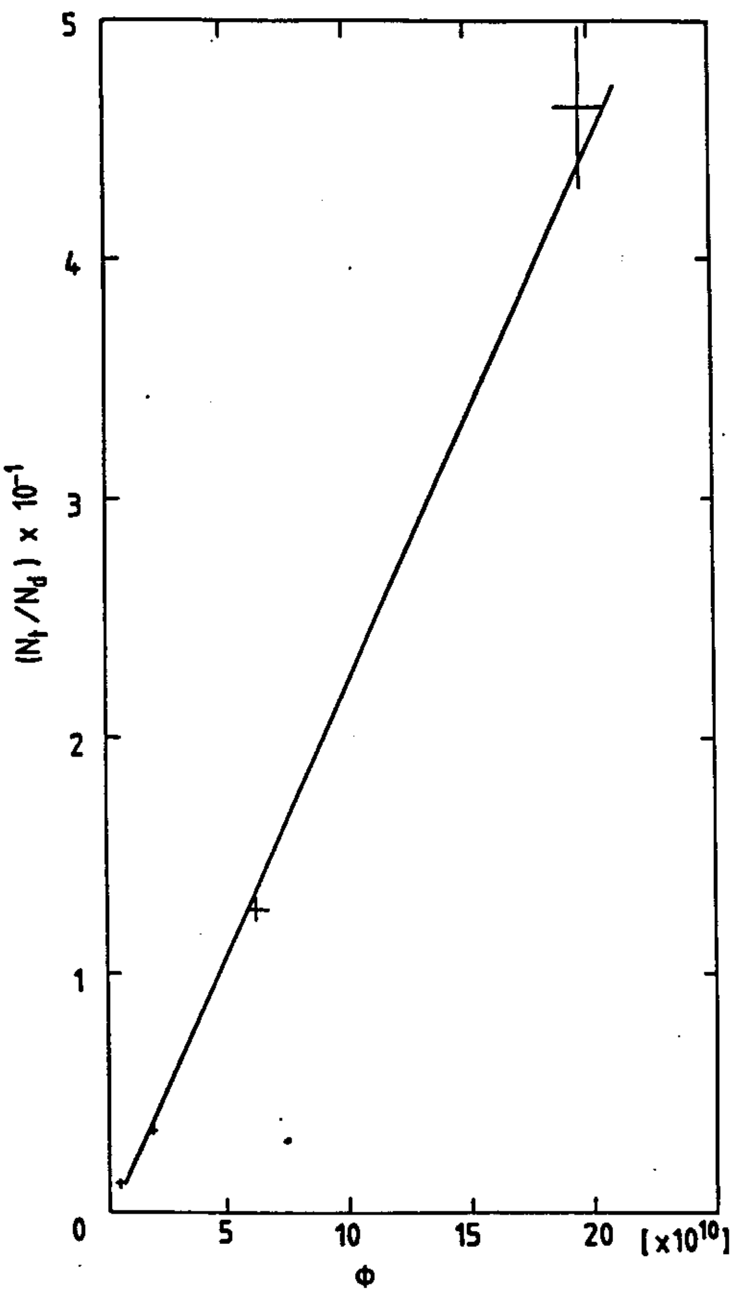

Fig. 7: Fraction N_t/N_d obtained from irradiation of 10 samples as a function of the neutron fluence. The dependence is linear.

In the TSC method the silicon sample, maintained to a certain reverse voltage, is cooled to liquid nitrogen or liquid helium temperature. . Then the energy levels associated to the defects are filled giving a small forward bias. Coming back to the reverse voltage, the sample is now heated with a known rate β while the reverse current is measured. The de-trapping of carriers from a defect level causes a peak in the measured current; the temperature, at which the peak occurs, is related to the energy level of the defect [27]. Typical TSC spectra are shown in fig. 8 and for two peaks with energies of (0.39±0.010) [eV] (fig. 8a) and (0.25±0.03) [eV] (fig. 8b) respectively. Note that two similar TSC peaks have been found by Heijne et al. [37] at (0.29±0.02) eV and (0.4±0.02) eV below the conduction band edge in silicon detectors irradiated with high energy muons. The region of temperature where the A center is presumably located has not been analyzed yet. By using the delayed heating method [38] or the thermal cleaning method [39] it is possible to resolve the different contributions that give rise to the peak at energy 0.39 [eV]. The details of this study will be reported in a forthcoming paper.

Defect code	energy level	cross section
E_1	E_c-(0.16±0.01)	(1.40±0.15)x10^{-14}
E_2	E_c-(0.25±0.02)	
E_3	E_c-(0.40±0.02)	(1.70±0.40)x10^{-15}

Table 2. Energy levels (in eV) and electron-capture cross sections (in cm^2) obtained with DLTS measurements on neutron irradiated silicon detectors.

Effects on Detector Performance. By far the most important effect is the increase of the leakage current. If ΔI is the difference of the detector current before and after irradiation, V is the depleted volume, and f is the irradiation

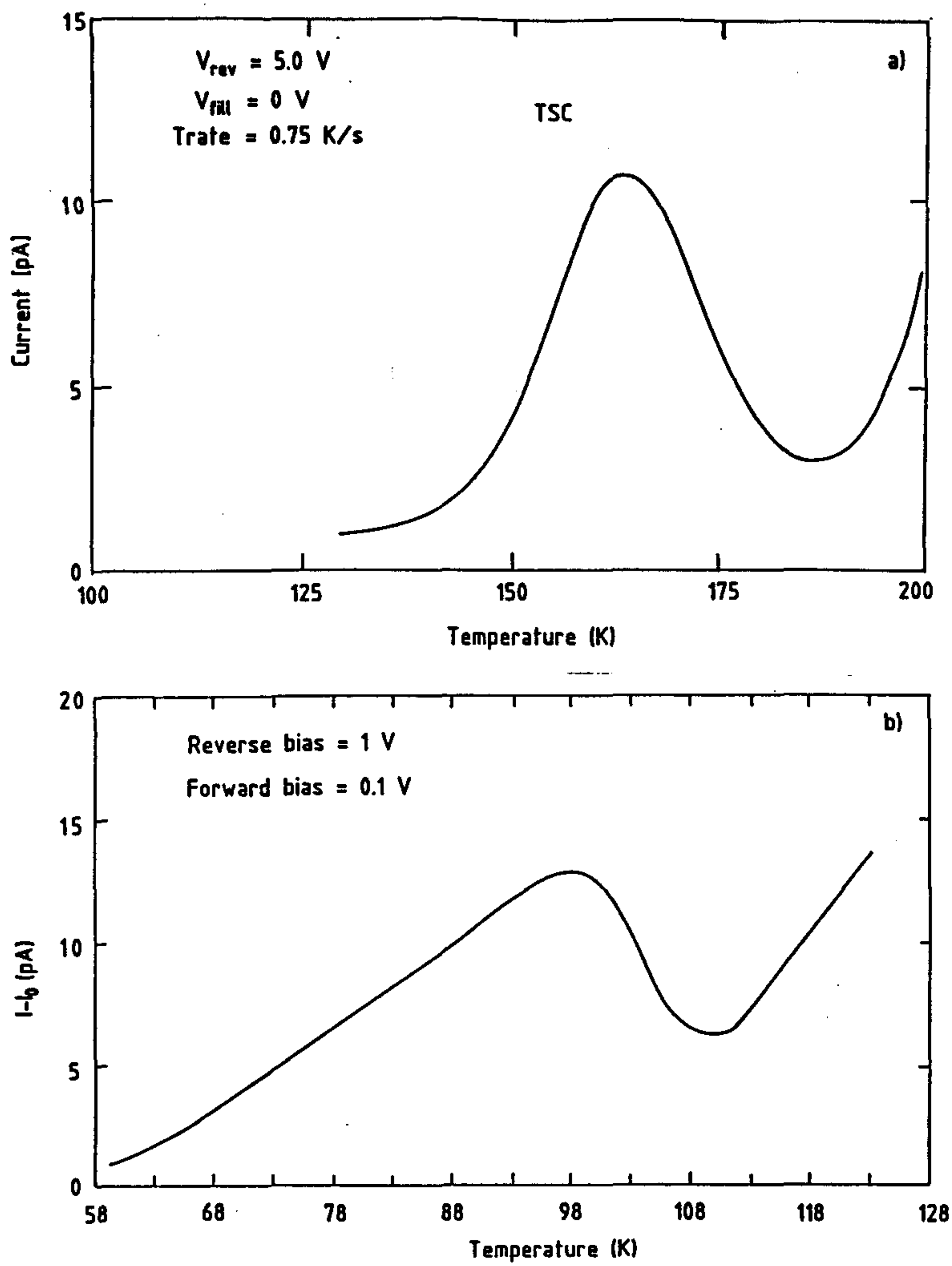

Fig. 8: a) and b): TSC spectrum of neutron irradiated detector showing the presence of defects E_2 and E_3.

fluence, the leakage current constant α is defined by:

$$\Delta I/V = \alpha f \tag{4}$$

Though a number of different investigations have been performed recently from which the damage rate α can be extracted [33,34,35,36], the comparison of these results is complicated by the situations under which the irradiations and measurements have been done. Various neutron sources have been used, roughly between average energies of about 1 and 14 MeV. The value of α depends, however slowly, on the neutron energy. It is therefore necessary to normalize all values to that for a standard energy, which may be done following a recipe by Kraner[36]. As will be described later, an appreciable self annealing effect is already visible at room temperature. This leads to a reduction of the visible damage during a long exposure as compared to that seen in a short irradiation with the same fluence. Also the measured current increase depends on the time at which the measurement has been undertaken after the irradiation. Both effects can also be corrected for using the data on self annealing reported in this conference [34,35]. The bulk generation current given in eq. (4) is proportional to the intrinsic charge carrier density which depends very much on the detector temperature. It is therefore advisable to normalize the different data to the same temperature. Within this scope all available data on the damage constant were normalized to a standard situation (see Table 1 of [34].) This leads to an average damage rate for 1 MeV neutrons, corrected for self annealing and normalized to 20° C of $\alpha = (6.8 \pm 0.2) \times 10^{-17}$ [A/cm]. It should be emphasized that a possible dose rate effect has not been observed [35]. The dependence of α on the material resistivity and on the operating conditions seems not to be very pronounced [34,35]. Other effects concerning the influence on the material resistivity and the charge collection efficiency have been reported by [33,34]. In general the observed donor removal leads to an increase of the resistivity by about 35% for a fluence of $10^{12} n/cm^2$. On the other hand, the charge collection efficiency was shown to remain stable within 1% even after irradiation by the same high fluence [34]. This is important since it guarantees the calibration stability of a silicon instrumented calorimeter.

Annealing procedures. The SICAPO results are reported as follows

[33]: Mixed isothermal and isochronal annealings were carried out on these silicon samples with temperature from 100° C to 300° C and annealing times from 1 up to 50 hours. Fig. 9 presents the decrease of the leakage current caused by annealing with the temperature range from 100 to 250° C as a function of the annealing temperature. ΔI is the difference of the leakage current before and after annealing and ΔI_o is the same difference before and after neutron irradiation. Each annealing step was carried out for 50 hours. The plot shows that recoveries of 80% and 85% of the neutron irradiated detector leakage current is obtained with a 50 hours annealing at 150° C and 250° C respectively. Fig. 10 shows the ratio of the concentration of E_3 trap after annealing N_t and the concentration of the same trap after neutron irradiation N_{t_o} of the sample versus the annealing temperature. An 80% decrease of the concentration of the E_3 trap occurred with a temperature annealing of 200° C. The differences between leakage current and concentration of E_3 trap annealings should be associated to the contribution of A center on electrical behavior of the irradiated samples. Anyway, it seems that a 200° C annealing for 50 hours should be a good experimental compromise for the recovery of both electrical and lattice characteristics of the sample. DLTS measurements after annealings with higher temperatures (up to 350° C) revealed the presence of two annealing induced defects E_4 and E_5 with corresponding energy levels of E_c-(0.35±0.04) [eV] and E_c-(0.48±0.05) [eV] respectively, values in a relative good agreement with those estimated by Tokuda and Usami (E_c-0.31 [eV] and E_c-0.45 [eV]) [30]. Re-irradiation of the annealed samples with neutron fluences of about 2.3x10^{11} [neutrons/cm^2] gave approximately the same results concerning the leakage current measurements and confirmed a leakage current constant of $\sim$ 6.0x10^{-17} [A/cm]. Re-irradiated samples annealed at 200° C during 50 hours showed a leakage current recovery of $\sim$ 80%, in agreement with the value obtained with a similar annealing after the first irradiation. Hence, it seems that the detectors behavior after irradiation and annealing is independent from previous irradiation-annealing cycles, if during those cycles a good recovery of the detector was obtained. A similar study is carried out with DLTS and TSC techniques on re-irradiated detectors and the results will be reported in a forthcoming publication.

These SICAPO findings are consistent with the results of Lindström et al

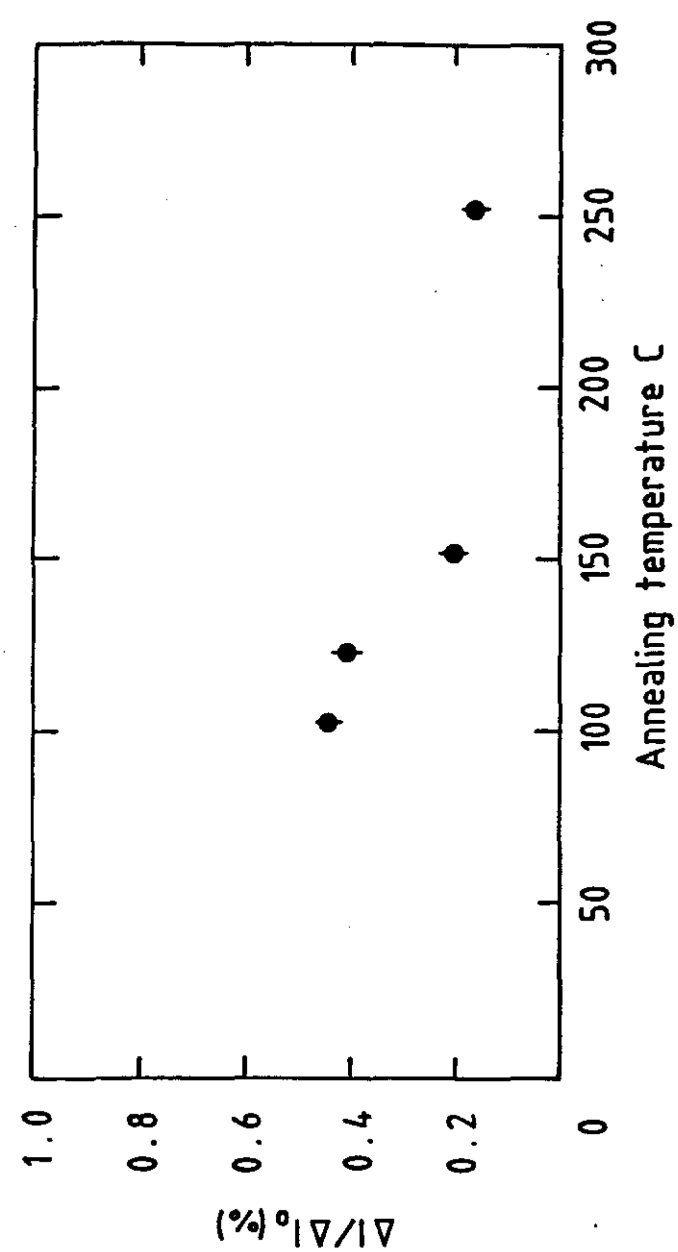

Fig. 9: Percentage leakage current recovery $\Delta I/\Delta I_o$ versus annealing temperature. Each step refers to a 50 hours annealing.

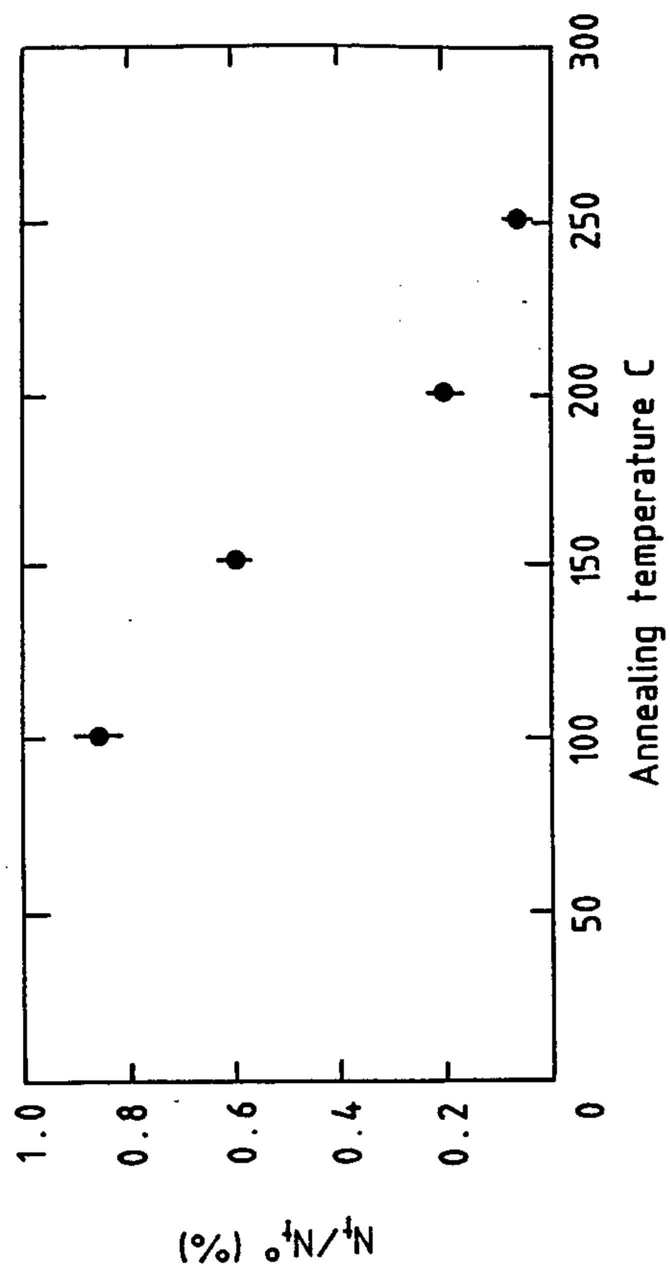

Fig. 10: Percentage trap concentration recovery N_t/N_{to} for E_3 defect versus annealing temperature. Annealing times range from 2 to 50 hours.

[34] reported to the workshop in which the dependence of annealing to previous irradiation/annealing cycles was examined. In both this report and that of Ohsugi et al [35] the room temperature annealing was studied. Their results are compared in Table 4 of [34] showing very good agreement. The time constants for self annealing reported by Lindström et al [34] would lead to an effective damage reduction in a long time exposure of, for example, one year with a constant flux factor of 3. In [34] it was also reported that a short heat treatment of 1 hour at 200° C seems to be enough to guarantee a current recovery of 90%.

Radiation damage summary. Experimental studies of the electrical behavior of n-type silicon detectors irradiated with fluences up to $\sim 10^{12}$ [neutrons/cm^2] showed a linear increase of leakage current vs the fluence of irradiation with a proportionality constant $\alpha = (6.8 \pm 0.2) \mathrm{x} 10^{-17}$ [A/cm] for 1 MeV neutrons. It has been recognized from DLTS and TSC analysis that the main effect of neutron irradiation on detectors lattice is the formation of three point defects at (0.16±0.2), (0.25±0.02) and (0.40±0.01) [eV] below the conduction band edge, to be associated to A center, double-minus charge state center and to the sum of single-minus charge state center and E center respectively. It has to be noted that neutron irradiation also causes formation of defect clusters that are invisible with these techniques [40] and which participate in defining the electrical characteristics of irradiated samples. A correct study of clusters could be done with Hall effect measurements [41]. Studies on electron-capture cross sections showed that the shallow A center could give an important contribution together with the deeper level at 0.40 [eV] to the leakage current. Electrical and lattice characteristics recovery of ~ 80% occur with a 200° C annealing during 50 hours. Re-irradiation and re-annealing of the previously annealed samples give approximately the same result concerning leakage current measurements, so that it seems that detectors behavior after irradiation and annealing is not affected by previous irradiation-annealing cycles, if these cycles have brought to a good electrical and lattice recovery of the samples. Neutron damage results reported previously by Kraner and collaborators [36] are consistent with our findings [33,34,35].

ELECTRONICS

In silicon calorimetry the large unit capacitance of the individual silicon sampling elements precludes the assembly of many units into a tower with a single amplifier. On the other hand the high response speed of silicon readout (< 15 ns shaping time) permits one to consider electronics which handles individual bunch crossings at the SSC in real time. These two considerations suggest an electronics scheme in which each detector element has a preamplifier, limiting the capacitive noise to the noise per element (≈ 100 pF) added in quadrature for the NTOWER elements in a given tower. There will be a very large number of amplifiers needed, $\approx 7 \times 10^6$, and they will be embedded in the calorimeter. However, the reliability of these circuits can be made extremely high. Recent data on radiation hardness of digital CMOS circuitry indicates that circuits will tolerate neutron fluxes of 10^{15} neutrons/cm^2 and electromagnetic doses of 0.1-10 Mrad without loss of function [42].

The Milan group [43] have studied a CMOS preamplifier that demonstrates the performance level needed for silicon calorimetry. Their circuit had a risetime (10-90%) of 30 ns and a power consumption of 35 mW. One would hope to improve both these numbers by a factor of 2 with later technologies, but this indicates a satisfactory level of performance already has been attained. For reference, 35 mW/detector implies an overall power consumption of 70W/m^2 and for 60 layers in a depth of 1.5 m, a volume power generation of 2.8 kW/m^3. These devices will be in good thermal contact with the absorber, so one expects to transfer heat along the absorber layers to heat wicks at the ends of the structure, interleaved with the data cables. The noise characteristics of the present-generation circuits look good, compared to any other calorimeter technology. The measured noise per pad in a model calorimeter structure being tested by the SICAPO collaboration at CERN is 30 keV noise. The sampling fraction for electromagnetic energy with 1 radiation length sampling is measured to be 0.3%. The hadronic sampling fraction is estimated at 1.2% and will be at least as large as the 0.3% in the electromagnetic section. A jet region defined by $R = 0.4$, typical of jets measured at hadron colliders, will include about 500 silicon detector pixels per sampling layer. Thus, the noise expected for 60 measuring layers (30,000 total pads) will be:

$$Noise < \sqrt{3 \times 10^4} \times 30\ keV/pad/.003 = 1.8\ GeV/jet \quad (5)$$

This will be increased by the effects of shot noise in the detector bias current to about 2.5 GeV noise/jet. However, there will not be any added contribution from the pileup effects that plague media with longer readout and shaping times. The estimates of pileup noise for 75 ns shaping times in liquid argon detectors are two or three times worse than these noise figures according to studies made for high luminosity operation at the LHC at CERN.

The electromagnetic energy resolution for silicon-W or silicon-Pb calorimeters has been measured by several groups [7,11]. Energy resolutions of about $0.15/\sqrt{E}$ have been attained with one radiation length absorbers, i.e. sampling-dominated resolution. The constant term has been shown to be very small, as expected for a linear medium like silicon. If one estimates the dynamic range required to handle the extraordinary case of a 5 TeV electron, then it becomes very awkward to measure the expected soft electrons and photons from conventional but interesting sources like heavy-flavor decays with the same electronics. For the silicon calorimeter, we propose to add parallel, lower-gain electronics on specific sampling layers and process these signals differently from the conventional tower sums. For dramatic electromagnetic energy deposits like those from 5 TeV showers, the energy resolution possible by shower shape analysis on 5 samples should give excellent energy measurement without skewing all remaining measurements of low energy electrons or photons.

The question of grouping signals into towers remains an open issue. One of the major advantages of silicon calorimetry is that longitudinal AND lateral segmentation can be very fine at little additional expense in the electronics. This advantage stems from having placed preamplifiers on each pixel in each layer. Therefore, the grouping of signals for trigger purposes and for readout may be handled differently in silicon calorimeters than in other devices. The study of separation of electrons from nearby quark or gluon jets and the question of jet-jet separation from W decays done at La Thuile [44] indicated that there were substantial advantages to having longitudinal segmentation of 0.5 λ. Silicon electronics can be adapted easily to such requirements, but there is appreciable systems engineering that must be done before the optimal readout structure can be defined. However, one clear advantage of silicon calorimetry should be emphasized - mechanical and electrical connections present the minimum possible difficulty. All power is low-voltage ($< 100V$). There are no edge considerations; detectors can be located within a few hundred microns of each other. Mechanical structure can be used for electrical power and/or signal transmission. Silicon calorimetry offers the prospect of the most nearly hermetic structure of any of the candidates, along with the potential benefit of very fine tower segmentation to facilitate jet separation and lepton isolation.

COST OF DETECTORS

The cost of silicon detectors is a major issue for any interest in using large areas of silicon in an SSC experiment. Presently, diodes are available to the high energy physics community for prices in the range of 6 to 12 dollars per square centimeter. It is possible to foresee a reduction of this price to around 2 dollars [45]. Such a price would appear necessary for silicon detectors to reach their full potential as active components of large calorimeters [1]. If the cost is not reduced to or near this level, silicon will likely continue to play a smaller, albeit important, role in SSC calorimeters.

CONCEPTUAL DESIGN

A conceptual design has been developed following the constraints discussed above. The guiding principle is to employ mainly iron as the radiator material. This should minimize the radiation damage from neutrons. Furthermore, we attempt to equalize, as best we can, the response of different shower components in the electromagnetic and the hadronic sections of the calorimeter. This is accomplished by mixing in some lead (high-Z material) in order to tailor the electromagnetic response, as described above. In order to achieve a survivable design, we find it is necessary to insert sheets or an hydrogenous medium (such as polyethylene) in the stack. This moderates the neutrons, leaving a large fraction of their energy in the sheets, not in the silicon. These expectations are based on simple extrapolations from the neutron flux calculations for silicon and scintillator calorimeters, in which the effect of hydrogenous layers (scintillator) are clear in suppressing neutrons [46], and in recent follow on calculations with CALOR [47].

With these concepts in mind, one arrives at the cell configuration shown in table 3. The 36 cells of the electromagnetic section constitute 24 radiation lengths, and when combined with the 48 cells of the hadronic section, we have 7.4 interaction lengths. This will require 3700 m^2 of silicon. One would plan to have 8 longitudinal readouts. Extra silicon planes would be inserted a several depths in the electromagnetic calorimeter (say 4, 8, and 12 radiation lengths) with low gain preamps to reduce the dynamic range demands on the regular preamps, but still achieve good resolution for the highest energy electromagnetic showers.

electromagnetic cell	hadronic cell
6 mm Fe	15 mm Fe
2 mm Pb	5 mm Pb
0.4 mm Si	0.4 mm Si
polyethylene	polyethylene
(24 cells)	(48 cells)

Table 3. Cell structure

It is necessary to keep the inner radius reasonably small to ensure acceptable total silicon area and cost. Figure 11 shows the schematic layout of the calorimeter. The chosen inner radius is 0.7 m.

The estimated power consumption of this design is about 300 kilowatts. Roughly half of this will come from the seven million preamps and roughly half from the remaining electronics. Leakage current heating will account for only a percent or so of the thermal budget.

We expect this calorimeter to achieve excellent performance, with an electromagnetic energy resolution of $15\%/\sqrt{E}$ plus a very small constant term and

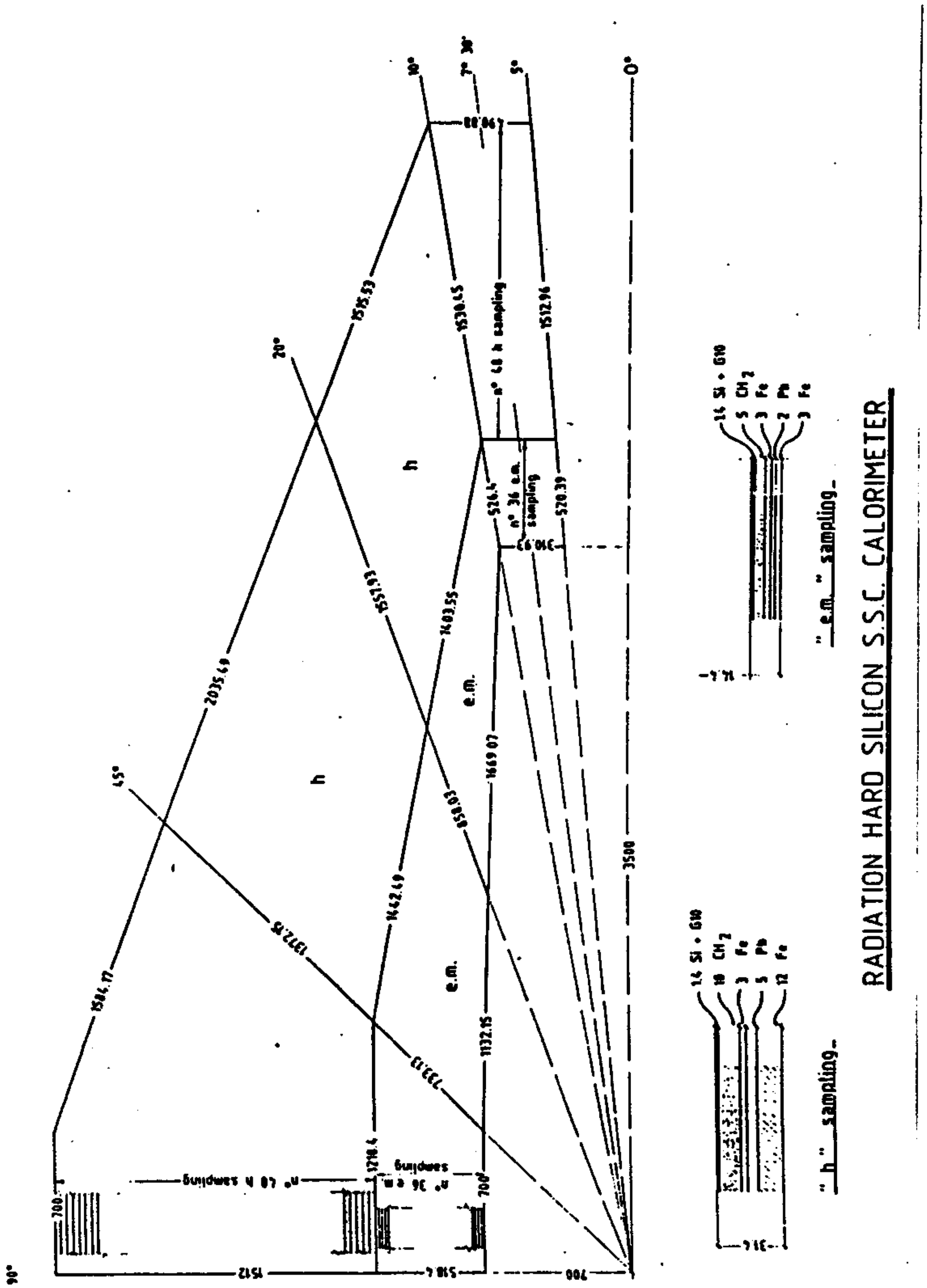

Fig. 11: Schematic of an SSC silicon calorimeter.

an hadronic resolution of $60\%/\sqrt{E}$ or better with a small constant term. The equalization of electromagnetic and hadronic response will be achieved through the mixing of some lead with the dominant radiator, iron. Timing better than a beam crossing will easily be achieved due to the very fast intrinsic response of silicon. The jet noise will be less than two GeV/jet.

It must be emphasized that this design has been developed largely to provide a radiation resistant calorimeter. First, the dominant material of the calorimeter is iron, leading to a small number of generated neutrons, and a minimal neutron damage condition. Secondly, the addition of polyethylene will significantly moderate these neutrons and further minimize their impact on the silicon detectors. Finally, the installation of heater in the high radiation regions will provide for an annealing capability to extend the life of those detectors (in the small angle regions) that are significantly exposed to the neutron radiation. Given this design, the expected lifetime of the devices outside of the ten degree region will be seven years, an adequate period of a successful physics program. In the five to ten degree we would expect to have to replace calorimeter modules yearly. However, this represents only two percent of the total system, so this is a tolerable fraction. There will be a fraction of the calorimeter (just outside ten degrees, representing another two percent of the system) that will need to be replaced every three years. In summary, the neutron damage is manageable; the frequency of replacement represents about a fifteen percent increase in the cost of the calorimeter modules.

RESEARCH AND DEVELOPMENT REQUIREMENTS FOR SILICON CALORIMETERS

Technically it is clear that silicon devices are potentially superior with respect to many of the required characteristics for a SSC calorimeter. In flexibility, compactness, hermiticity, fine segmentation, fast charge collection, ease of calibration and potential for direct integration with electronics, silicon is unmatched by any other system. On the other hand certain disadvantages, most importantly cost, could severely limit the utility of silicon calorimetry at the SSC. Research and development are needed not only to reduce cost but to ensure that, through proper calorimeter design, maximum advantage is taken of the unique properties of silicon. It is also important that further attention be given to such important issues as compensation, radiation hardness, power dissipation in compact systems, and optimal utilization of the unique properties of silicon detectors in data acquisition and buffering, triggering, preprocessing, multiplexing and system design.

Specifically the following items are among those important for future R and D on silicon calorimetry.

(1) Research on reduction of price of silicon, including new refining techniques and wafer processing. While $\$2/cm^2$ (not yet achieved) is an acceptable price [1] for a compact calorimeter, price reductions below this level would markedly improve the attractiveness of silicon. Cooperation with industry is essential for this effort.

(2) Additional research on radiation hardness, annealing effects and on reduction of neutron flux within calorimeters with moderators of hydrogenous material. Improvements in these areas will eventually determine minimum angles for which silicon calorimetry can be used at the SSC.

(3) Development of components capable of in situ annealing would greatly simplify the use of the calorimeter and could even permit tolerance of the high radiation levels in the extreme forward region of an SSC detector.

(4) Development and design studies are needed on systems for removal of the heat generated by the high speed electronics necessary to take full advantage of silicon's outstanding speed and compactness. In so far as possible this system should be integrated with the annealing system described above. One could, for example, envision a thermal system which could protect sensitive electronics while at the same time heating radiatively damaged silicon detectors to temperatures necessary for annealing.

(5) Although Monte Carlo results are most promising, tests must be completed to establish experimentally that a fully compensating hadron calorimeter with good resolution can be built with e/h = 1 and that techniques for reduction of internal radiation levels with the calorimeter proper are effective. These test can only be made conclusively with a fully hadron test calorimeter module. Construction of such a calorimeter module for

SSC research is desirable also from the view point of testing electronics packaging schemes.

(6) Perhaps the most important area for research and development is in the area of electronics for silicon calorimeters. While there are special requirements for front end electronics in silicon detectors, many of the electronics problems are common to all SSC detectors. However, if one is to take advantage of the high speed of silicon to provide trigger information at the earliest possible time it is necessary to carefully design an integrated calorimeter/electronics system. While it is generally accepted that front end amplifiers should be located immediately at the detector proper, the question of the location and type of pipeline storage, multiplexing, digitization equipment, trigger sum networks, etc., remain open questions. Prototypes must be built to test schemes of "gluing" amplifiers to silicon and perhaps to investigate the more ambitious question of direct integration of front end electronics with the high resistivity silicon wafers themselves.

SUMMARY

Silicon detectors show promise for applications in SSC calorimeters due to their many attractive properties. Unsolved problems still limit the plans than one can presently make for their application. Research and development on these is being conducted and one can expect the situation to mature in the next few years. Independent of the resolution of the problems limiting large calorimeters, silicon layers will likely be included even in the experiments which deploy primarily another technology for the calorimeter, due to silicon's outstanding adaptability and usefulness in covering regions of extremely limited space.

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