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DEVELOPMENT OF RADHARD VLSI ELECTRONICS FOR SSC CALORIMETERS

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ABSTRACT

A new program of development of integrated electronics for liquid argon calorimeters in the SSC detector environment is being started at Argonne National Laboratory. Scientists from Brookhaven National Laboratory and Vanderbilt University together with an industrial participant are expected to collaborate in this work. Interaction rates, segmentation, and the radiation environment dictate that front-end electronics of SSC calorimeters must be implemented in the form of highly integrated, radhard, analog, low-noise, VLSI custom monolithic devices. Important considerations are power dissipation, choice of functions integrated on the front-end chips, and cabling requirements. An extensive level of expertise in radhard electronics exists within the industrial community, and a primary objective of this work is to bring that expertise to bear on the problems of SSC detector design. Radiation hardness measurements and requirements as well as calorimeter design will be primarily the responsibility of Argonne scientists and our Brookhaven and Vanderbilt colleagues. Radhard VLSI design and fabrication will be primarily the industrial participant's responsibility. The rapid-cycling synchrotron at Argonne will be used for radiation damage studies involving response to neutrons and charged particles, while damage from gammas will be investigated at Brookhaven.

INTRODUCTION AND OVERVIEW

At design luminosity the beam-beam interactions in the SSC will create a radiation environment which may damage electronics associated with the detectors. The very large number of readout segments required by the physics in conjunction with the geometrical constraints of the detectors, will require that the electronics be situated close to the interaction region. It is important, therefore, that the nature of this radiation environment be accurately projected and the effects on the detector electronics be simulated in test measurements. The constraints that the radiation fields place on the detectors can then be taken into account in the design.

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The Central Design Group has undertaken studies of radiation levels in the SSC interaction regions and the results of these studies are summarized in a detailed report[1]. The predicted radiation levels require that detector electronics be radiation hard in order that it may operated satisfactorily for a reasonable lifetime. In general, builders of previous high energy physics detectors have not been forced to deal with the problems of radiation hardness in the electronics. Accordingly, the difficulties posed by the SSC bring a new dimension to detector design.

Fortunately, there is a segment of the semiconductor industry that has been developing radiation hard electronics for military and space applications for something over 20 years. A wealth of experience, expertise, and understanding of damage mechanisms exists in this sector of the electronics industry. It is essential that these capabilities be brought to bear on the problems associated with detector design for the SSC.

We have undertaken a program of development of radiation-hard integrated electronics for SSC calorimeters. Specifically this electronics is intended to be optimized for a liquid argon or warm liquid drifting calorimeters[2,3]. This work will also provide some information applicable to the electronics for calorimeters of other types and to tracking electronics.

We have made the following assumptions:

a. An adequate level of expertise in radhard electronics exists in the United States at this time so that the development effort does not require fundamental research into radiation damage mechanisms or other basic aspects of radhard VLSI design. Specifically, extensive capabilities have developed over the last twenty years in the industrial community in response to military and space needs. This expertise is available, and accordingly, the work should be approached as an engineering project, with industrial participation as a basic part of the effort.

b. It is important that SSC detector development activities proceed promptly so that there will be confidence in the projections of cost and feasibility at the time when detector construction must begin.

c. Interaction rates, segmentation, and the radiation environment dictate that front-end electronics must be implemented in the form of highly integrated, radhard, low-noise, analog, VLSI custom monolithic devices. Important engineering considerations come from the power dissipation, the choice of functions integrated on the front-end chips, and the cabling requirements.

The guidelines for this development effort are as follows:

a. The development efforts will be focused on the calorimeter electronics. Argonne has long experience in calorimeter design, construction, and use as evidenced by the calorimeters for the HRS, CDF, ZEUS, and other detectors.

b. The work will focus upon the electronics needed for liquid argon or warm liquid drifting calorimeters as stated above.

c. This project will include extensive radiation damage studies as well as VLSI device and process development. The two areas of work will proceed jointly, in close coordination. Radiation damage exposures and evaluation will be primarily Argonne's responsibility, while radhard device design and fabrication will be primarily the industrial participant's responsibility.

d. No effort will be expended on developing non-radhard devices or designs. An adequate level of radhard expertise exists so that radhard devices will be used at the outset.

e. We will proceed by characterizing the radiation environment in which the electronics must operate, selecting a currently operating radhard process capable of yielding devices which are adequately radhard, and proceeding with a radhard design in that process.

f. The rapid-cycling synchrotron of the Intense Pulsed Neutron Source (IPNS) at Argonne produces 400 MeV protons and a neutron fluence of 10^{12}/sec/sq-cm from the spallation target. This Argonne facility together with a gamma source such as the source at Brookhaven will be used for the radiation damage studies. These studies will be done both at 25C and at liquid argon temperatures. Small prototype calorimeter sections will be operated in the radiation environment.

g. A senior participant or consultant who is an expert in radiation damage will be brought into the project.

OBJECTIVES AND GOALS

The objective of this development effort is to design a prototype VLSI version of the SSC calorimeter electronics using a specific radhard process. A phase 2 follow-on project would involve a prototype production run of a number of wafers. Developing this design will require that radiation damage studies have been conducted on devices from the designated process, that devices from the designated process have been run in prototype calorimeter sections in appropriate radiation environments, and that the radhard electronics design is compatible with the calorimeter physics requirements. As discussed above, technologies exist that meet our radiation hardness requirements for neutron and charged particle total dose. The calculations indicate that the gamma-ray levels experienced by the electronics in very forward locations poses a very difficult challenge that cannot be met with current CMOS technology.

a. Goals for Argonne and Brookhaven

Argonne's contribution will be to provide calorimeter expertise, to conduct radiation damage tests relating to neutrons and charged particles, to conduct the radiation damage tests relating to the prototype calorimeter section, to provide structure and guidance to the development effort, and to provide the interface to the CDG and DOE. The goal for Brookhaven personnel is to produce a detailed set of specifications for the analog calorimeter electronics, participate in the testing, and then to work in conjunction with the industrial participant to design and develop this analog electronics for the VLSI implementation.

b. Goals for Industrial Participant

The Industrial Participant must bring expertise in the design and production of radhard electronics. It is essential that the Industrial Participant have a radhard process that is capable of producing VLSI devices that can operate in the SSC calorimeter environment. We believe that a successful program requires that radiation damage studies begin immediately with existing devices produced in the radhard process that we envision ultimately being used for the final production of radhard VLSI devices. It will be convenient if the Industrial Participant has a gamma source suitable for the gamma radiation damage studies.

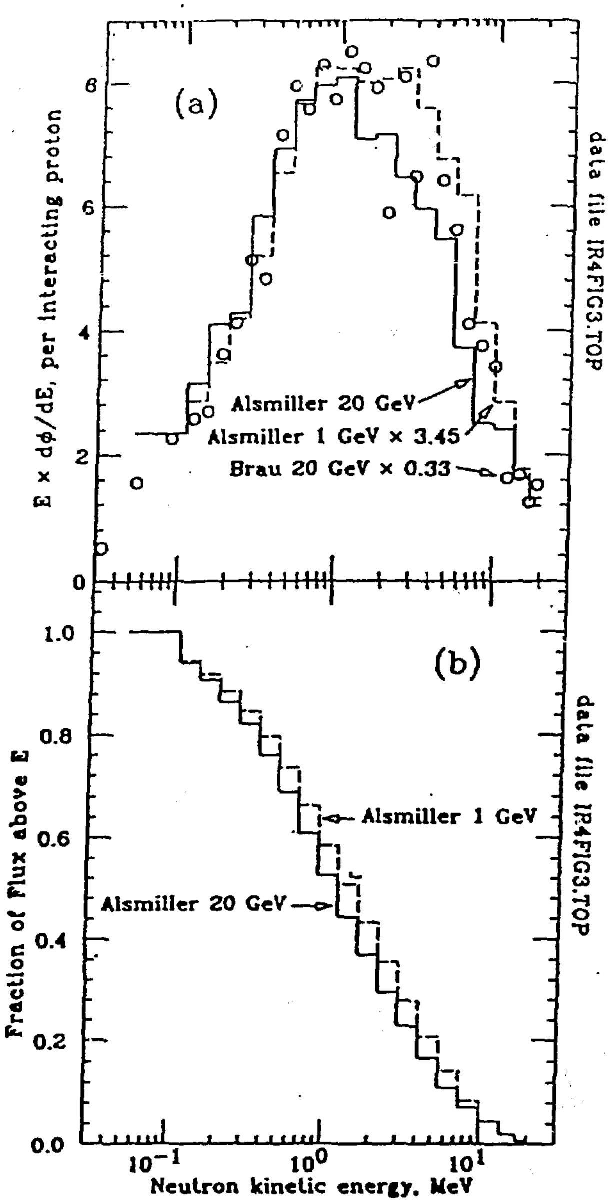

Fig. 1. The spectra of albedo neutrons from a uranium/scintillator calorimeter. Figure taken from SSC Report SSC-SR-1033, "Radiation Levels in the SSC Interaction Region," Task Force Report, D. E. *Groom*, Editor (June 10, 1988).

c. **Goals for Consultant**

As described above, we will have at least one senior participant/-consultant who is an expert in radiation damage to electronic devices involved with the development effort from the beginning. This consultant will provide direction to the research effort and participate in evaluating progress.

RADIATION ENVIRONMENT IN THE SSC CALORIMETER

The radiation levels in a typical SSC detector have been examined by a task force convened by the Central Design Group and the results are summarized in a report SSC-SR-1033, edited by D. E. Groom. The major damage results from the electromagnetic and hadronic cascades that are initiated in the detector calorimeters by secondary particles produced in the 40-TeV pp collisions.

For a typical detector in which a central magnetic field volume containing tracking chambers is surrounded by dense calorimeter, the neutron gas created in the calorimeter leaks back into the tracking volume. The calculated neutron spectrum of this albedo, shown in Fig. 1, peaks near 1 MeV and is similar to the neutron spectrum at IPNS, the neutron facility at Argonne, which is discussed in detail below.

The number of albedo neutrons, as well as the total number of neutrons at cascade maximum in a uranium-scintillator calorimeter stack, are reasonably represented by

$$2.5\left(\frac{p}{1\ \mathrm{GeV/c}}\right)^{0.5}\ \text{n/hadron} \quad \text{and} \quad 18\left(\frac{p}{1\ \mathrm{GeV/c}}\right)^{0.67}\ \text{n/hadrons} .$$

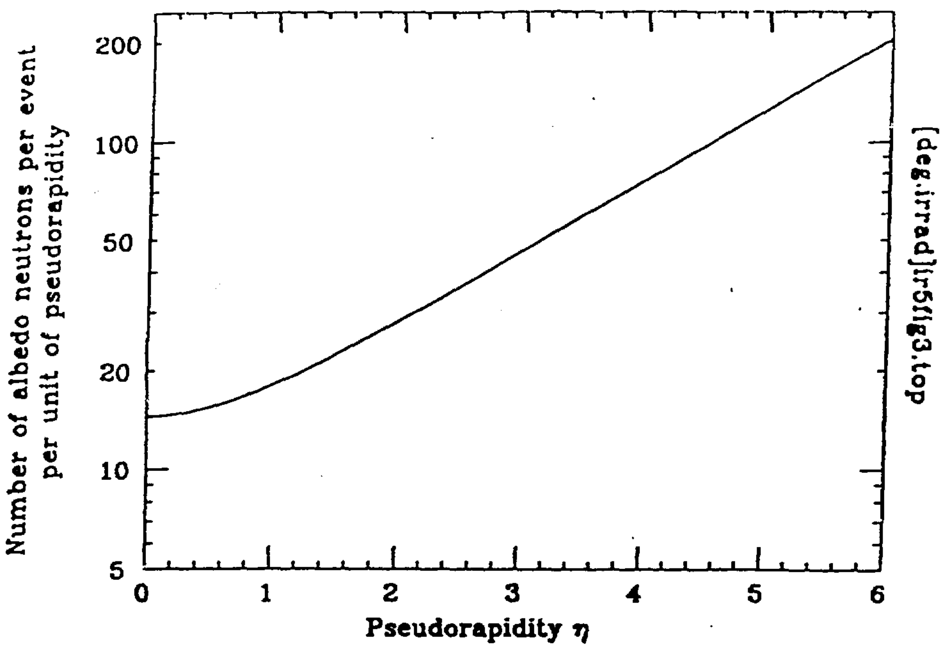

Fig. 2. The number of albedo neutrons per event per unit pseudo-rapidity as a function of pseudorapidity for a fine-sampling U-scintillator calorimeter. Normal incidence is assumed.

respectively, for an incident hadron of momentum p. Folding these expressions with reasonable assumptions about the rapidity distribution of secondary particles from the 40-TeV pp collisions gives the number of neutrons to be expected in different parts of the detector. The results are shown in Fig. 2 for the albedo neutrons and in Fig. 3 for a uranium-scintillator calorimeter. The assumptions used for the latter correspond to 10^8 events/sec for 10^7 operating sec per year or 10^{15} events per year. For a central calorimeter in which the neutron flux maximum is assumed to be at a radius of 2 m, the flux varies from 4×10^{11} to 10^{14} neutrons/cm^2/yr. For a forward detector, the flux can approach 10^{16} neutrons/cm^2/yr. Taking into account the reflections, the albedo neutrons inside a spherical cavity of 2 m radius have a fluence of 2 - 4^{12}/cm^2/yr. This value will scale inversely as the square of the cavity radius.

One concludes that, if implemented at very forward angles, the calorimeter electronics must be able to withstand a total neutron flux, over the lifetime of the experiment, of up to 10^{17} neutrons/cm^2. The neutron flux has a typical energy of 1 MeV.

Similar estimates have been made for the gamma-ray dose with the result shown in Fig. 4. The dose over a 10-year detector life will be about 10 mrad for a 2m radius central calorimeter at (eta) = 2.5 and can get as high as 100 Mrad at very forward angles. The dose from charged hadrons is more an order of magnitude less as shown in Fig. 5.

We do not presently have data relating to the effect of beam loss on the radiation environment. This effect may require an additional safety margin. For the purposes of this work we will address only the radiation environment resulting from beam-beam interactions.

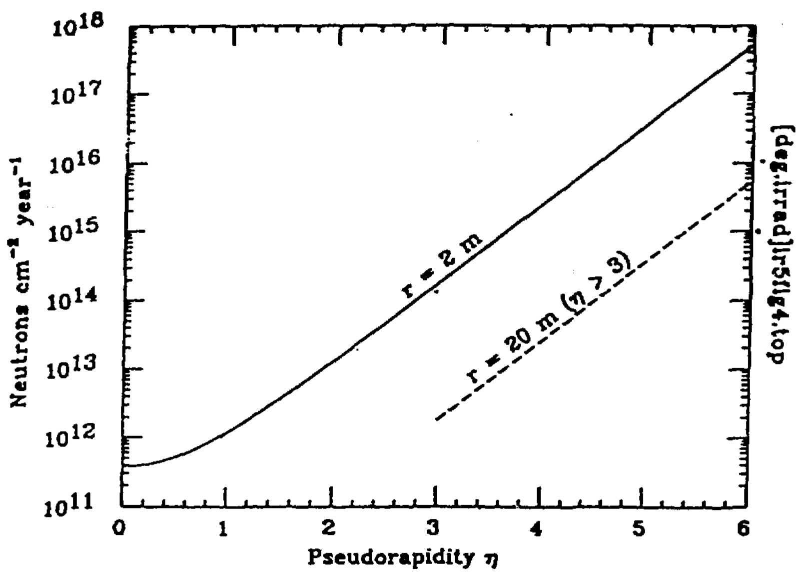

Fig. 3. The maximum neutron fluence for a uranium/scintillator calorimeter. The full curve shows the result assuming the maximum occurs at a radius of 200 cm. Also shown is the result for a radius of 20 m, typical of forward detectors, for rapidity > 3.

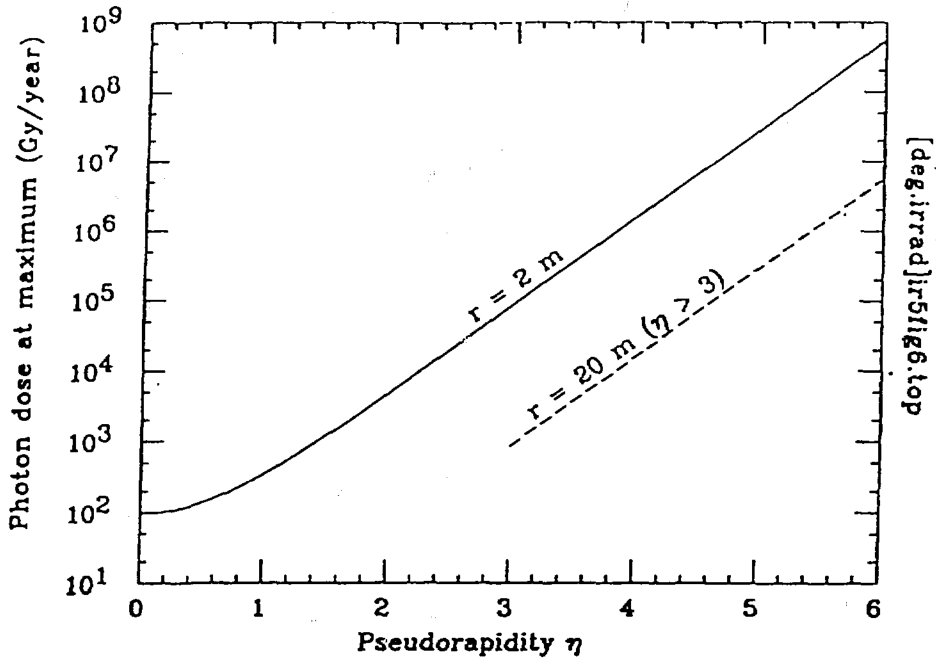

Fig. 4. The maximum dose from incident photons. The full curve assumes the maximum occurs at 200 cm. The other curve is calculated for 20 m, typical of forward detectors.

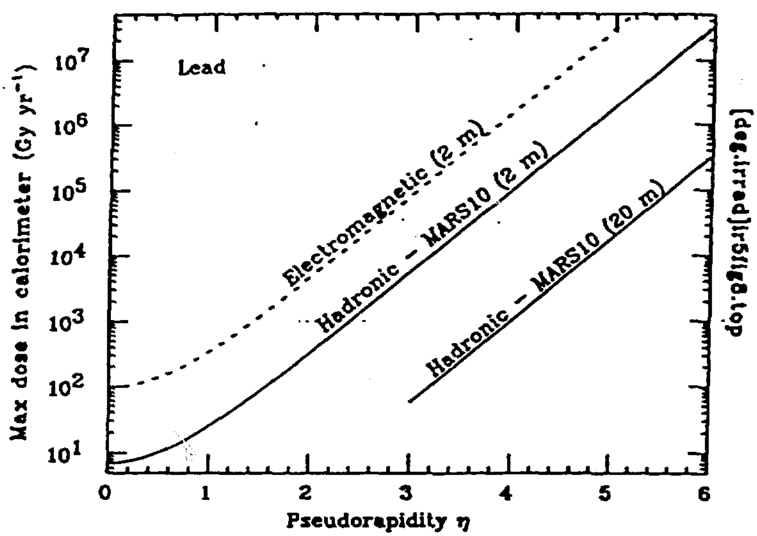

Fig. 5. The maximum hadronic dose as a function of pseudorapidity for a lead sphere, assuming that the maximum dose occurs at the indicated radius. The electromagnetic maximum dose is copied from Fig. G for comparison purposes.

a. **Assumptions Relating to Calorimeter Geometry**

We assume that the calorimeter is configured as a barrel calorimeter and forward calorimeters with dimensions set forth in Fig. 1 of Ref. 4. For this calorimeter geometry, shown in Fig. 6, the barrel calorimeter will experience doses from a pseudorapidity of 0 to 3, and the forward calorimeters will experience doses from a pseudorapidity of 3 to some maximum. We will assume the forward calorimeter covers a pseudorapidity range of 3 to 4. The radiation environment can be easily scaled to other dimensions and configurations.

b. **Neutron, Gamma, and Charged Particle Fluences**

Given the pseudorapidity coverage of the barrel and forward calorimeters, one can then use the data given in SSC-SR-1033 to determine the nature of the radiation environment. Some of the data has been tabulated for lead and some for uranium, and of course the geometrical assumptions are oversimplified. This process allows one to determine values for the doses that will be experienced by the calorimeter. If one assumes an exposure of 10 years, and uses the data given in Figs. 5-4, 5-6, and 5-8 of SSC-SR-1033, one obtains the following approximate maximum total doses.

Table 1. Approximate Maximum Total Doses

	Hadronic	Gamma	Neutrons
Barrel Cal.	2.0 Mrad	20 Mrad	$5e^{14}$/sq-cm
Forward Cal.(3-4)	1.4 Mrad	14 Mrad	$5e^{14}$/sq-cm

(Although the calculations above refer to values at shower maximum, we use the inside radius of the calorimeter to be conservative.)

These total doses are growing very rapidly with increasing pseudorapidity in the forward calorimeters as one would expect. In the barrel calorimeter, the high dose occurs at the inner radius just past the central tracking where the radius is 4 meters and pseudorapidity is 3.0. This geometry must be modified to reduce the dose.

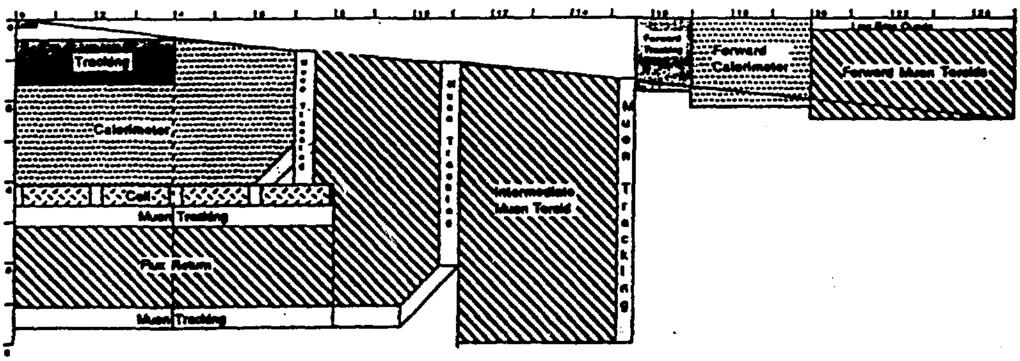

Fig. 6. The large solenoid detector.

RADIATION HARDNESS REQUIREMENTS FOR CALORIMETER ELECTRONICS

The time, segmentation, and hermeticity constraints placed upon the SSC calorimeter will require that the electronics be dispersed throughout the volume of the calorimeter[5]. Accordingly, this work is based on the assumption that the electronics is more or less uniformly distributed throughout the volume of the calorimeter. Therefore, the radiation environment of the calorimeter volume is the radiation environment within which the electronics must function.

An early goal of this project will be to determine, together with the radiation consultant, detailed radiation hardness requirements for the calorimeter electronics and to assess the ability of potential industrial participants to meet these requirements.

Due to the nature of the buried channel, JFETS are insensitive to total dose effects. JFETS have been successfully tested to 10 Mrads with almost insignificant changes to pinchoff voltages and Idss. Gate leakage (Igs) increases by an order of magnitude from less than 10 pA typical to approximately 100 pA. For neutron levels above 10^{14} neutrons/cm^2, N-channel JFETS are a must in order to minimize performance degradation.

Radiation effects on noise performance of JFETS have not been very well researched. After gamma exposures to a total dose of 10 Mrad, device noise for NJFETS typically increases from 10 nV/root hertz to 50 nV/root hertz at f = 10 Hz. While JFETS show promise for the SSC environment, JFET integration into a CMOS technology is not straightforward. In addition, pre-rad noise levels for a JFET in a CMOS technology will be significantly higher than those in a bipolar technology due to side effects of the processing steps.

This problem of gamma total dose in the forward calorimeters is important and must be carefully studied. We intend that in the initial plans for damage studies this problem be given priority because its solution could have profound implications for the solution chosen for the rest of the detector.

TESTS IN RADIATION ENVIRONMENT AT LIQUID ARGON TEMPERATURE AND 25C

Radiation damage studies are an integral part of this work. We propose that all radiation damage studies be undertaken both at liquid argon temperature and at 25C, and that no non-radhard devices be included in this work, except where needed for comparison purposes. The objectives of this damage testing program are to demonstrate that the devices we intend to use for the calorimeter electronics can operate satisfactorily over a reasonable lifetime and to provide confidence that the engineering and physics feasibility of the calorimeter plus the electronics are clearly established in the radiation environment.

Argonne operates the Intense Pulsed Neutron Source (IPNS) for neutron scattering studies[6]. This facility uses a 400-MeV proton beam incident on a heavy metal target. The spallation neutrons are moderated, and the resulting radiation field is viewed by many ports equipped with neutron spectrometers. There is also an alternative IPNS facility for doing radiation damage studies in which the sample is placed close to a high Z moderator.

There are few other particles accompanying the neutrons. The secondary proton flux is 0.4% of the neutron flux with E > 0.1 MeV. An upper limit to the gamma-ray flux is 15% of the total dose in rads.

The proton synchrotron typically operates at 30 Hz with an average beam current of 15 ua so that the neutron flux at the peak of the spectrum is about 10^{12} per cm^2 per sec.

There are several beam holes that can be used for irradiating samples with diameters between 5 cm and 10 cm. The integral neutron fluxes in three such tubes are given in Table 2.

Table 2. Integral Neutron Fluxes per Incident Proton

	REF		NSF
Neutron Energy	Vertical Tube	Horizontal Tube	Horizontal Tube
Total	311	203	194
Thermal	2.4	1.7	44
> 0.1 MeV	199	122	55
> 1 MeV	66	36	13

The neutron flux with energy > 0.1 MeV for the REF vertical tube. The flux varies by less than a factor of two over a cylindrical volume of 10 cm diameter by 10 cm high. This vertical tube is equipped with a cryostat so that experiments can be done at low temperature.

In summary, the facility provides a good capability of studying neutron irradiation of small samples, as well as 450 MeV protons for investigating damage by charged particles. The neutron spectrum peaks near 1 MeV but by choice of irradiation site, some control over the spectrum is possible. Peak irradiation levels up to 10^{12} neutrons/cm^2/sec can be achieved, and long-term lower level irradiations can also be done on a parasitic basis.

Gamma irradiation facilities are not available at Argonne. Brookhaven has gamma sources that are suitable for these damage studies. We assume that the dependence on dose rate will be negligible, but of course this must be clearly understood before the damage studies begin.

The specific goals of the damage studies and the specific initial program to be undertaken will be specified in a planning meeting between personnel from Argonne, Brookhaven, and the industrial participant with the participation of the consultant. It is important that there be periodic reviews of the results of the damage testing program, and that these results are available to the VLSI design program, which we envision as taking place concurrently.

a. **Device Damage Studies**

We plan that, as soon as the details of the damage testing program can be decided damage studies on discrete devices will begin. These damage tests would be conducted at liquid argon temperature and 25C, would measure noise, threshold voltage, transconductance, etc., and would be carried out separately for charged particle, neutron, and gamma fluences. A large enough selection of devices would be subjected to these test to give confidence in the statistics and in wafer-to-wafer variation in the process.

We intend to include in these tests, representative JFET devices which would reasonably allow us to extrapolate radiation damage results to the use of JFET's in appropriate processes.

b. **Prototype Calorimeter Operation in Radiation Environment**

We will operate and take data from a small prototype calorimeter section operating with radhard electronics in a radiation environment. This prototype calorimeter section would be uranium/liquid argon, and can operate with discrete devices created in the radhard process operating in the cryogenic volume. Naturally, it will not be possible to implement this prototype with the final VLSI device which results from the design phase of this work, but it should be possible to implement several channels with discrete devices from the process, or with radhard devices where the results can reasonably be extrapolated.

Our objectives in this part of the study are to examine noise levels of the electronics in the real calorimeter environment, and to examine degradation of the data as a function of dose. Every effort will be made to simulate the SSC calorimeter. For example, the front-end capacitance will be padded to appropriate values. Naturally, it is difficult to make hard statements about such things as calorimeter resolution from tests of this sort, but we intend to provide an experimental basis for confidence in the overall performance of the radhard VLSI design.

VLSI ELECTRONICS DEVELOPMENT

a. **Assumptions on Calorimeter Readout, Architecture, and Layout**

We assume in this work that the calorimeter is organized as a barrel calorimeter and forward calorimeters, and that the electronics is dispersed throughout the volume of the calorimeter. The electronics is implemented in the form of radhard VLSI chips, produced in a radhard low noise CMOS process, probably in a CMOS technology, and is bonded to the electrodes using an advanced technology. At the minimum, each VLSI chip must have a multiplicity of charge sensitive amplifiers, circuitry to store the output of the charge sensitive amplifiers, the ability to multiplex the stored analog voltages on an output bus, calibration capability, and a fast clear[7]. In addition, the VLSI devices must provide an output that is a representation of the sum of the outputs of all the charge sensitive amplifiers to be used in formulating the first level trigger[8].

b. **Specifications of VLSI Device**

In this work, we prefer to think of the VLSI radhard device specs in a very general sense. One of the first milestones is the completion and approval of conceptual specifications for the VLSI device. These conceptual specifications must be generated by a team consisting of Argonne and Brookhaven electronics and calorimeter people, radhard electronics experts from the industrial participant, and the consultant who has been retained for this work. These conceptual specifications would form the basis for the radhard design which could be begun by the industrial participant at that time, subject to review as the radiation damage studies progressed.

c. Proposed Radhard Process

The considerations driving process selection are primarily analog device performance and packing density. Devices should have the lowest noise levels and highest transconductances possible per microwatt of power consumption. This implies leading edge device technology is required with the thinnest and highest quality gate oxides attainable. The requirement also exists for a floating (2 terminal) capacitor with maximum capacitance density (thin dielectric). This is driven by the potential need for large operational amplifier compensation capacitors. Lastly, the tightest interconnect and device isolation photolithography is required to maximize the area available for device gates and capacitors.

The major effects of a total ionizing dose on MOS devices are positive charge buildup in the oxide layer and interface state generation at the oxide-silicon interface[9,10]. Positive charge buildup and interface state generation both give rise to unwanted threshold voltage shifts. Interface state generation also reduces the carrier channel mobility. The generation of interface states is generally believed to be completely suppressed at 75K, however, positive charge buildup is worsened. Recent investigations have concluded that interface states may be generated at cryogenic temperatures, however, they are in effect "frozen out" at the low temperature and thus cause no device degradation. The frozen states become active upon warming to room temperature. A large percentage of the holes created by ionizing radiation in an oxide are trapped at low temperatures, leading to larger threshold voltage shifts. This situation is in contrast to room temperature irradiations where only a small fraction of the generated holes actually become trapped. The holes which escape initial recombination with generated electrons (which are quickly swept out of the oxide even at low temperatures) are trapped very near their point of origin due to the extremely small low temperature hole mobility in oxide. Hole movement is thought to be significant at low temperatures only when under the influence of an electric field greater than around two megavolts/cm.

Threshold voltage shift at liquid argon temperatures is a strong function of device biasing during irradiation due to two field-dependent effects. First, at low fields a portion of the electron-hole pairs generated by radiation in the oxide recombine by geminate recombination (recombination which occurs before the generated electron-hole pairs are thermalized and become mobile in the oxide) and thus neutralize a portion of the trapped holes. Electrons escaping recombination are swept out while remaining holes are "frozen in". As the field is increased, a larger fraction of electrons escape recombination because they are swept out more quickly and have a smaller probability of recombining, leaving an increasingly larger amount of uniformly distributed positive charge. Therefore, the threshold voltage shift at a given dose increases with increasing applied voltage. When the applied voltage is increased to a point where an oxide field of around two megavolts/cm is achieved, holes become mobile in the oxide and a fraction of them will be transported out of the oxide. This gives rise to less positive charge in the oxide and a decrease in threshold voltage shift with increasing applied bias.

To summarize, the combined result of these two effects is that the threshold voltage shift first increases with increasing bias due to an increasing geminate recombination escape probability, and then the threshold voltage shift eventually starts to decrease with further increases in bias due to the initiation of hole transport out of the oxide.

CMOS processes hardened to total dose at room temperature are usually not hard at liquid argon temperatures. Any room temperature hardening technique which depends on the contribution of negative charge due to interface state generation to compensate positive trapped hole charge will be ineffective at low temperatures. Hardening of the gate oxide consists primarily of using the thinnest high quality oxide allowable to minimize the charge generation volume. Room temperature hardened oxide processes do not seem to display increased hardness over non-hardened oxides at liquid argon temperatures. In addition, the pre-radiation interface state density can be minimized for low noise performance since interface state generation is not relied on for negative compensating charge during low temperature radiations.

d. **Proposed Radhard Design**

The design of a radiation hardened circuit requires a radhard technology. Then circuit techniques are used to compensate the parametric degradations of devices and elements, or to avoid them completely. There are three items to be concerned with. The first is burn-out/survival, second is device/element degradation, and the third is radiation-induced ac/transient behavioral errors.

Burn-out is possible if the incident transient ionizing dose rate is very high, which is probably not applicable to the SSC with the possible exception of a beam spill. All the devices then become shorted, and the only resistance between power supplies is bulk silicon. The major cause of burn-out is the interconnect fused open. Survival is achieved through the use of resistors in series with supplies, either on chip or off chip, to limit the short circuit current. Internal resistors must be able to absorb the energy and the interconnect must be designed with this in mind.

Circuit designs must avoid dependence on those device/element parameters that degrade by radiation. Techniques such as using device/element ratio matching, cascoding, and threshold voltage tolerant circuits are the prevalent design methods. Parametric magnitude dependent circuit should be avoided if possible.

Transient radiation induced errors can be minimized if PN junctions are photocurrent compensated. Closed-loop design should be preferred over open-loop system. Closed-loop circuit tends to suppress the induced errors by the loop-gain. Differential mode amplification is more tolerant to this induced aberrations mainly due to common mode rejection.

In some cases, circuits can use self-calibration techniques to adjust to the effects of radiation. The penalties are complexity and real estate.

PLAN OF RESEARCH

a. **Milestones of This Research and Development Work**

1. Appointment of outside consultant.

2. Agreement on radiation hardness requirements and preliminary determination of suitability of potential industrial participant's radhard process.

3. Specification of program for initial radiation damage studies.

4. Completion of administrative procedures necessary to secure participation of an Industrial Participant.

5. Completion and approval of conceptual specifications for VLSI device.

6. Damage testing program activities, with progress reviews.

7. Radhard VLSI design work, with progress reviews.

8. Completion of damage testing program.

9. Completion of radhard VLSI design.

Accomplishment of the above set of milestones is expected to require approximately one year and bring us to readiness to begin producing wafers. Actual production and testing of such wafers would be carried out as a follow-on phase 2 project.

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