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# Single Event Effects and Laser Simulation Studies

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16. Abstract


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# ABSTRACT

The single event upset (SEU) linear energy transfer threshold ($LET_{TH}$) of radiation hardened 64K Static Random Access Memories (SRAMs) has been measured with a picosecond pulsed dye laser system. These results were compared with standard heavy ion accelerator (Brookhaven National Laboratory (BNL)) measurements of the same SRAMs. With heavy ions, the $LET_{TH}$ of the Honeywell HC6364 was 27 MeV-cm$^2$/mg at 125$^o$C compared with a value of 24 MeV-cm$^2$/mg obtained with the laser. In the case of the second type of 64K SRAM, the IBM6401CRH, no upsets were observed at 125$^o$C with the highest LET ions used at BNL. In contrast, the pulsed dye laser tests indicated a value of 90 MeV-cm$^2$/mg at room temperature for the SEU-hardened IBM SRAM. No latchups or multiple SEUs were observed on any of the SRAMs even under worst case conditions. The results of this study suggest that the laser can be used as an inexpensive laboratory SEU prescreen tool in certain cases.


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# SUMMARY

In this study, a focused, pulsed dye laser was employed to predict the single event upset (SEU) threshold of radiation hardened 64K SRAMs by comparing laser results with heavy ion SEU data. These results suggest that the MicroElectronic Advanced Laser Scanner (MEALS) can, in certain cases, be used as an inexpensive laboratory pre-screening tool.

Pulsed laser and heavy ion SEU tests were performed on radiation hardened 64K SRAMs from two manufacturers participating in the Advanced Spaceborne Computer Module Program funded by the Air Force Phillips Laboratory. IBM6401CRH 64K SRAMs were supplied by IBM and HC6364 devices were provided by Honeywell.

The heavy ion tests were performed in the usual manner at the Brookhaven National Laboratory (BNL) accelerator. SEU data were taken between room temperature and 125°C over an LET range accessible using some or all of the ions, 316 MeV iodine, 240 MeV bromine, 121 MeV chlorine and 123 MeV nickel at various angles. The available LET range was restricted because the DUT test board socket geometry limited the beam angle of incidence to less than 30° for the HC6364 and less than 45° for the IBM6401CRH. Two samples of each SRAM type were tested at various temperatures (room temperature, 80°C, and 125°C), $V_{DD}$ values (4.5, 5.0, and 5.5 V), and test vector patterns (all 0's, all 1's, and checkerboard). The remainder of the samples were tested only under worst case conditions (T = 125°C, $V_{DD}$ = 4.5V for SEU). Latchup was also monitored at $V_{DD}$ = 5.5 V, although device latchup was not expected nor was it observed. For the HC6364 at 4.5 V, $LET_{TH}$ varied from 38 MeV-cm$^2$/mg to 27 MeV-cm$^2$/mg over the temperature range, room temperature to 125°C, while the "saturation" cross section at high LET varied from $2.2\times10^{-2}$ cm$^2$/device to $3.9\times10^{-2}$ cm$^2$/device over the same temperature range. Essentially no pattern dependence was observed in the LET vs. cross-section data. As expected, the cross-section was strongly dependent on $V_{DD}$ exhibiting a strong decrease in going from 4.5 V to 5.5 V at an LET of 35 MeV-cm$^2$/mg. For the harder IBM6401CRH, no SEU events were observed up to the maximum available LET of 79 MeV-cm$^2$/mg, even at the worst case temperature of 125°C. Therefore, in the case of the IBM SRAM, only laser data was obtained. As one would expect for hardened SRAMs, no multiple SEU hits were observed for either SRAM type.

In order to determine the SEU properties when measured with the focused, pulsed laser, the devices were scanned by the MicroElectronic Advanced Laser Scanner (MEALS). The most sensitive portion of the SRAMs to SEU was the area between the common gate and the common drain. The SEU sensitivity was also dependent upon the laser energy, device operating temperature, and drain voltage. The higher the operating temperature was, and the lower the drain bias voltage, the lower the SEU $LET_{TH}$, in agreement with the heavy ion results. Also in agreement with the heavy ion data, there was no evidence of test pattern or operating frequency dependence.



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When tested by the MEALS laser scanner, numerous single event upsets were recorded for the Honeywell HC6463 64K SRAMs at all three laser wavelengths (652, 668, and 724 nm), even at room temperature. The threshold laser energies for upset of the devices under worst case conditions ($V_{DD}$ =4.5 V, 125°C) were found to be 3.9, 6.6, and 10.1 picojoules, equivalent to $LET_{TH}$s of 17, 22, and 24 MeV-cm$^2$/mg, respectively. Recall that the measured heavy ion LET of this device at 125°C was 27 MeV-cm$^2$/mg indicating good agreement with the laser data, especially for a wavelength of 724 nm. The threshold laser energies at a wavelength of 652 nm and a $V_{DD}$ of 4.5 V were found to be 3.9, 5.1 and 7.0 picojoules at 125, 80, and 28°C, respectively. These are equivalent to $LET_{TH}$s of 17, 22, and 30 MeV-cm$^2$/mg, respectively. The actual measured values of heavy ion $LET_{TH}$s at BNL were 27, 30 and 38 MeV-cm$^2$/mg at 125, 80, and 28°C.

The IBM6401 was also examined with the laser scanner at a wavelength of 652 nm at room temperature, in spite of the fact that no heavy ion-induced SEUs or latchups were observed at BNL. With the laser, SEUs were observed even at room temperature, but no latchups were found. These laser test results indicated that the estimated $LET_{TH}$ of the IBM device would be 90 MeV-cm$^2$/mg at room temperature compared with an IBM-reported heavy ion measured value at 125°C of 75 MeV-cm$^2$/mg.

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# SINGLE EVENT EFFECTS AND LASER SIMULATION STUDIES

## A. Introduction

Space applications of microelectronic integrated circuits (ICs) are very attractive because ICs provide increased performance, and result in lower spacecraft power consumption and mass. However, IC reliability must be achieved prior to use in a space environment. Common concerns of IC quality assurance in space include single event effects (SEE) caused by cosmic rays and protons, and total ionizing dose (TID) effects due to electrons and protons.

Single event effects are the result of the interaction of a high energy, heavy ion with the semiconductor device active region. The density of electron-hole pairs generated by the ion is proportional to the linear energy transfer (LET) between the heavy charged particle and the semiconductor (or oxide) material. The ion LET depends on the mass of the ion and its energy. If the collected charge in the depletion layer (plus "funneling") of a transistor in a memory cell exceeds a minimum "critical charge", a single event upset (SEU) of the data stored in the memory cell will occur. The critical charge depends on the effective sensitive volume, device topological layout (including cross-coupled resistors), doping densities and the carrier transport mechanism. Static random access memories (SRAMs) are often hardened to SEU by inserting cross coupled resistors in the memory cell so that the transfer of the ion-induced pulse to other portions of the cell, necessary for upset, is slowed down enough for recovery to take place before upset can occur. Other SEE can take place that are catastrophic such as single event latchup (SEL), single event burnout (SEB) in power transistors and single event gate rupture (SEGR).

The reliability of spacecraft electronic systems requires that device susceptibility to SEE be determined prior to use in a system. Traditionally, SEE vulnerability is established through testing with a series of different energetic, heavy ions at large accelerator facilities, which is time consuming and expensive. In addition, because the entire chip is exposed to the ion beam, particularly sensitive circuit regions of the chip cannot be identified and studied.

Alternative SEE test techniques have been developed that overcome to some degree the negative aspects of heavy ion testing at accelerators. Cf-252 sources provide fission fragments that allow SEE tests to be conducted in the laboratory in a relatively simple experimental setup. However, the available ions are restricted to LETs in the range 30 to 40 MeV-cm$^2$/mg and the range of these ions is often too short because of their relatively low energies. Ion microbeam testing allows selective probing of device components, but requires a complex experimental apparatus that usually must be installed at a large accelerator facility rather than in the standard laboratory. In addition, the concentrated ion microbeam can introduce lattice damage in the device material [1].

The above comments suggest that an alternative technique for the simulation of the effects of cosmic rays on microelectronic devices would be very beneficial if it were inexpensive to use and able to selectively probe isolated regions on the device. Recently,

various pulsed laser techniques have been developed to simulate ion single event effects [2,3]. It has been shown [2-5] that these laser techniques are an effective alternative to heavy ion testing in certain limited cases. In our laboratory, we have developed a laser scanning system that is based on a focused, pulsed picosecond dye laser [6,7]. Although such a system cannot replace accelerator testing, primarily due to the fundamental difference in energy transfer between high energy, heavy ions and the pulsed laser, the present study suggests that a dye laser can be an effective pre-screening tool for SEU, provided that the metallization does not restrict exposure of critical regions of the device to the laser beam. In this Report, we describe both the heavy ion and laser test techniques as applied to radiation hardened 64K SRAMs from two vendors, Honeywell and IBM, and then compare the results for these devices.

## B. Ion Test System

In the conventional SEU test, the device is exposed to a series of highly energetic, heavy ions, each at various angles to the device surface, in order to construct a plot of LET vs. SEU device cross section. A "well behaved" device is characterized by a threshold LET, $LET_{TH}$, and a saturation cross section at high LET. As shown in Figs. 1 and 2, the SEE test system used by JPL at Brookhaven National Laboratory (BNL), consists of a logic analysis system and programmable power supplies, controllable by computer via the GPIB (General Purpose Instrumentation Bus) interface. The controller computer runs a JPL software application program, called single event effects system (SEES), which provides integrated control of the test instruments, and collects and processes test data.

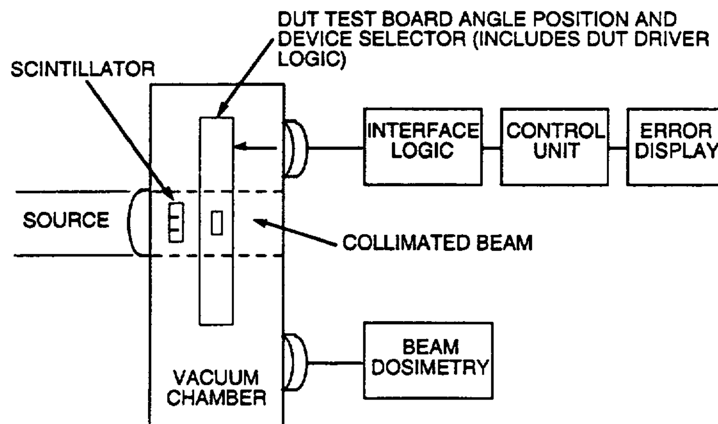


*Figure 1. Schematic diagram of the high energy, heavy ion SEE test system at BNL.*

As shown in Fig. 2, for testing digital devices like the SRAMs examined in this study, the test system is configured with a logic analysis system containing pattern generation and data acquisition modules. The system is cabled to the Device Under Test (DUT), located on a card mounted in the accelerator vacuum chamber. Test vectors are written by the pattern generator which operates the DUT as if it were in a complete system, and provides the acquisition module with control signals telling it when to look for valid data. The acquisition module

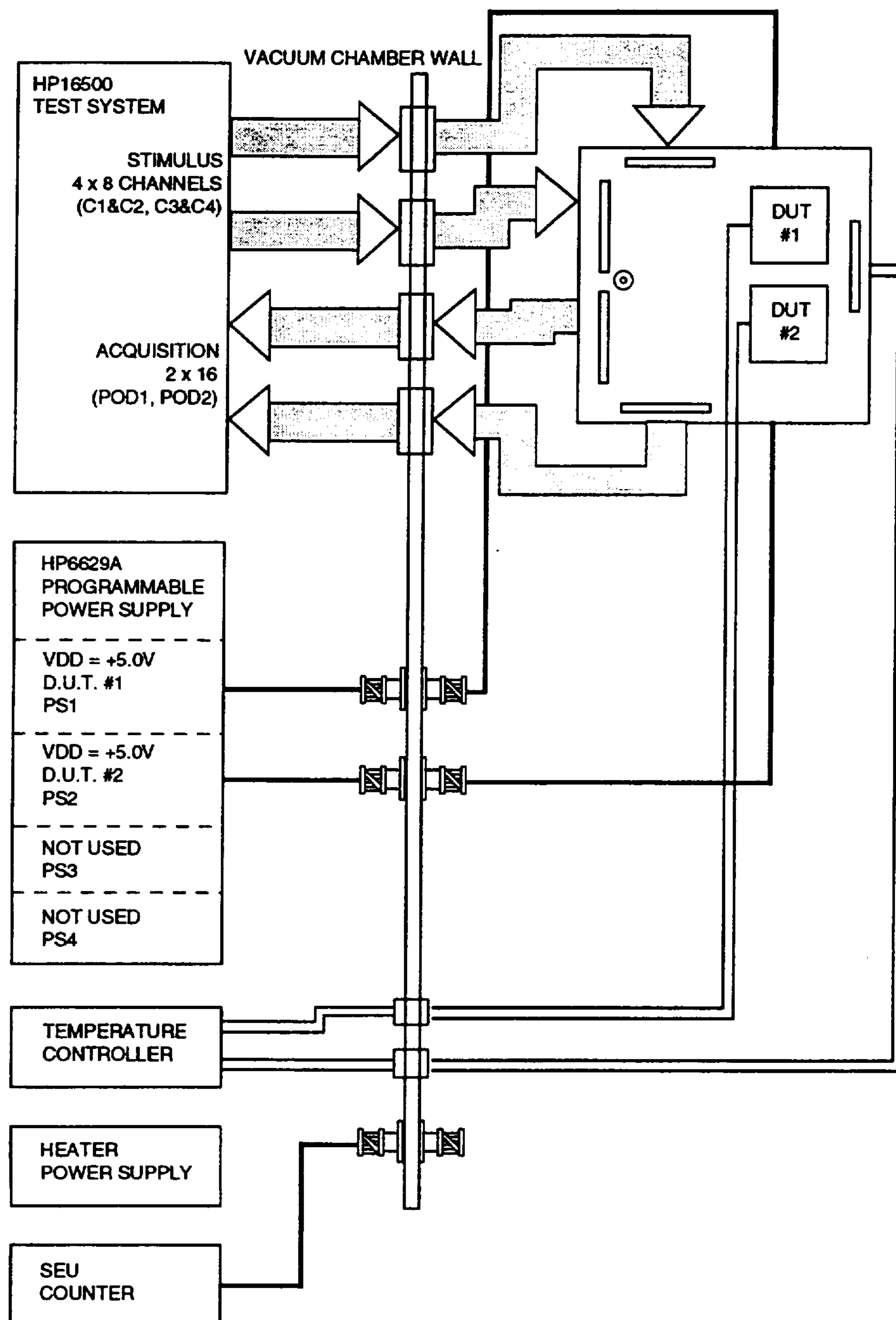


*Figure 2. SEE test setup and data acquisition system with latchup detection.*

compares actual DUT data with expected data during the valid data period, and flags any difference as an error, while simultaneously recording all data pertinent to the error condition. For a typical SRAM, this includes run number, setup file name, all bit data, address, and control lines, as well as power supply voltages and currents. The error data is stored to disk on the controller computer at the conclusion of each run, and may be used to provide a bit map of the physical cell locations affected by errors.

The SEES software provides the capability of displaying error data as an SRAM bit map on the computer display. Error data from each run may be "played back" with the bit map

display enabled. This allows the experimenter to observe such phenomena as multiple cell upsets from a single ion hit, and unusual peripheral circuitry sensitivities. The logical to physical address conversion of the specific device being tested, as well as its physical layout, must be known and reduced to an algorithm which is programmed into the bit mapping module of the software. Currently, the display accommodates 8192x8 pixels at 1:1 resolution, but assigning multiple cells per pixel allows larger arrays to be displayed. At larger magnifications, individual cells become visible, the display of which is limited only by the hardware configuration of the test system and DUT card.

The software program has a latchup detection feature which accomplishes latchup testing by comparing the measured DUT current to a user-settable latchup threshold, and incrementing a software latchup counter if the threshold is exceeded. Simultaneously, the software shuts off the DUT power for a user-settable period of time, and then restores power. The power-off period allows the DUT to recover from the latchup condition, while providing protection against thermal self-destruction. The present system polls the programmable power supply, which provides voltage and current readings, in a continuous asynchronous loop during testing. Because the instrument readings are asynchronous to a latchup event, the system reaction time to a latchup can vary from 20 - 200 milliseconds, including instrumentation and software overhead. The reported latchup current is only a rough indicator of actual latchup current vs. time, and represents a reading taken anywhere from 0 - 180 milliseconds after the latchup event occurs. Depending on DUT latchup propagation, current, and power supply characteristics, the reported latchup current reading with respect to time may be inaccurate by a factor of 100 or more. For those tests where it is important to measure the latchup current, the system is easily modified to provide this additional feature.

The latchup protection period is user-settable in 55 millisecond steps, and must be determined empirically for each device type. If the period is too short, the DUT will not fully recover from the latchup, and will still draw excessive current when power is restored. Under this condition, the DUT is still protected, because DUT power will continue to cycle indefinitely until the operator shuts down the test. Increasing the protection period allows the DUT to recover from the latchup and resume normal operation when power is restored after the protection period.

The JPL heavy ion SEE Test System is a highly flexible automated system designed to measure and record the effects of simulated cosmic radiation on electronic devices. The system as described above is capable of testing devices of any complexity from simple gates through 32-bit microprocessors.

## C. MicroElectronic Advanced Laser Scanner (MEALS)

The microelectronic advanced laser scanner (MEALS) is an opto/electro/mechanical apparatus for nondestructive testing of integrated logic circuits, memory circuits, and other microelectronic devices such as CCDs. The MEALS is a multipurpose diagnostic system that can be used to determine ultrafast time response, latchup, and electrical overstress in

integrated circuits. Most notably, under certain conditions it can be used to simulate in the laboratory single event effects caused by heavy ions in the cosmic ray spectrum.

The MEALS is designed to overcome the main disadvantages of heavy ion testing, which are that such testing is expensive and time-consuming because the devices must be tested off-site at a large accelerator facility, and that the ions cannot be directed to specific locations on the devices. By focusing a laser down to a spot size of 1 to 2 μm and restricting the laser pulse width to the range 10 to 20 picoseconds, a single heavy ion interaction can be simulated closely enough to provide results that are comparable to single particle effects.

As shown in Fig. 3, after passing through beam splitters necessary to allow monitoring of the laser pulse characteristics including total power output, the laser light impinges on the DUT mounted on a test board that is mounted in turn on a micromanipulator. The laser is a cascade pumped picosecond multimode organic dye laser that can be tuned to several wavelengths. Ability to select the wavelength and hence the depth of penetration of the laser beam, allows one to perform a rough vertical separation of SEE effects [6,7]. For the simulation of SEE interactions, the laser pulse width is set at 10 to 20 ps and the laser spot size at the sample surface is focused by a microscope objective to approximately 1.5 μm at selected locations on the chip. The chip can then be scanned in a precise manner by the computer controlled micromanipulator. The computer also correlates the micromanipulator setting with processing of a video image of the chip so that the laser can be located and placed at specific sites such as access transistors or memory cells. For SRAMs and DRAMs where the correlation is known between the address location of a particular memory cell and the physical location of that cell, the necessary algorithm is fed into the computer so that the memory cell where the laser is located can be identified. This function is shown in Fig. 3 as

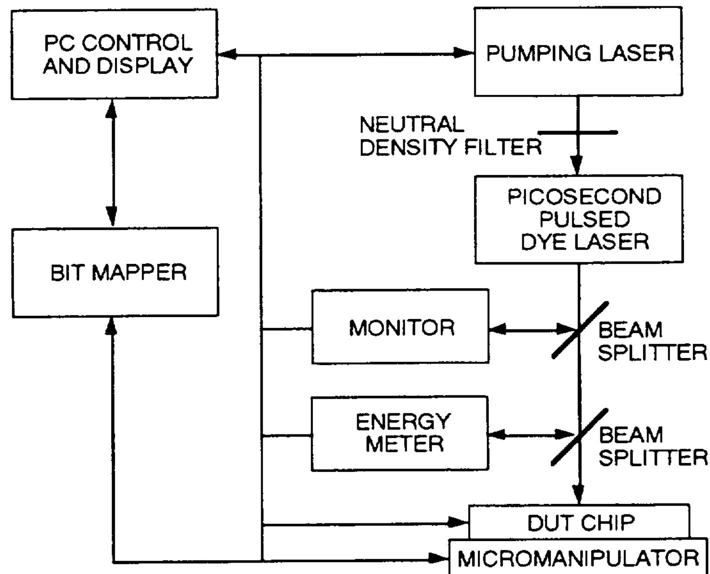


*Figure 3. Experimental setup for MEALS laser scanner simulation of single event effects. The beam diagnostics and power outputs are monitored when the bit mapper interrogates the memory status.*

the optical bit mapper. Thus, particular regions of the device that are sensitive to SEE can be identified and plotted on an optical "bit" map. The computer system also performs additional housekeeping functions such as synchronization of the laser pulse time with the monitoring time of the optical mapper, and tracking and storing of SEE events.

Because of important differences between the interaction of the laser with the device and the interaction of a single charged particle with the device, one must exercise caution in interpreting the results of the laser tests and comparing them with heavy ion-induced SEE. One difference is that the track of electron-hole pairs produced by an ion is only about 0.05 μm in diameter; much smaller than the laser beam and its track of electron-hole pairs. In addition, as the laser beam passes through the device material it tends to spread so that further into the material this difference is accentuated.

Another important difference is that the density of charge carriers produced by the laser beam decreases approximately exponentially with depth of penetration because of the variation of light absorption with depth, dictated by the absorption coefficient of the material. In contrast, electron-hole pair generation by a heavy, highly energetic ion is relatively constant through the device active region. In other words, the ion LET is essentially constant while the equivalent LET of the laser light can vary strongly with depth. In the next Section we explore these issues in more detail.

## D. Calculation of Laser-Induced Equivalent LET

To facilitate the direct comparison of laser data with ion data, the definition of the mass stopping power of the high energy, heavy ions is used to define and calculate the laser Effective Linear Energy Transfer (ELET). Mass stopping power of a material is defined as mean rate of energy loss of a charged particle along the track per unit distance traveled, divided by the target material density, usually expressed in MeV-cm$^2$/mg:

$$\text{Ion LET} = \frac{1}{\rho}\frac{dE_{ion}}{dz} \qquad (1)$$

where $\rho$ is the material density (for Si, $\rho$ = 2.33 gm/cm$^3$), $E_{ion}$ is the particle energy and z is the vertical distance into the chip with z = 0 at the surface.

In the case of the laser, electron-hole pairs are created by absorption of the laser light which is governed by the absorption coefficient, $\alpha(\lambda)$, in cm$^{-1}$ that depends, in turn, on the wavelength of the laser light, $\lambda$. For light wavelengths significantly greater than the wavelength corresponding to the energy gap (for Si, the energy gap, $E_g$, is 1.12 eV at 300 K or 903 nm), light penetration is deep and the absorption and consequent creation of electron-hole pairs is relatively weak. Because the energy gap, and hence the absorption coefficient, depend on temperature the effectiveness of the laser beam in creating a dense track of electron-hole pairs will depend on temperature. Note however, that in the case of an indirect band gap semiconductor like Si, the variation of the absorption coefficient with wavelength

is more gradual than in the case of a direct gap material like GaAs. We express the laser ELET, which is analogous to the ion LET, as

$$\text{Laser ELET} = \frac{T}{\rho}\frac{dE_{las}}{dz} = -\frac{T}{\rho}\frac{d}{dz}\left[P_o t_o e^{-\alpha(\lambda)z}\right] \tag{2}$$

$$\text{Laser ELET} = \frac{TP_o t_o \alpha}{\rho} e^{-\alpha(\lambda)z} = \frac{T\alpha}{\rho} E_{las}(z) \tag{3}$$

where T is a transmissivity factor governing the fraction of incident laser light that enters the device, $E_{las}$ is the laser energy as a function of distance, z, into the material, $P_o$ is the average power during the pulse of width $t_o$ so that $P_o t_o$ is the incident laser energy propagating into the device surface from an approximately 2 μm diameter illuminated area during pulse widths of $t_o = 15, 14, 20$ ps for each pulse at wavelengths of 724, 688, and 652 nm, respectively, and $\alpha(\lambda)$ is $6.5\text{x}10^2$, $9.2\text{x}10^2$, and $1.2\text{x}10^3$ $\text{cm}^{-1}$ at room temperature for the three respective wavelengths used in these tests. Using Equation (3), the laser ELET can be calculated from the measured energy output of each laser pulse for a given wavelength at an appropriate depth, z.

While Equations (1) and (3) are in the usual format for LETs used in assessing SEE events, they cannot be used as a basis for comparison between the laser and heavy ions because the energy required to create electron-hole pairs is different in the two cases. Since the total charge required to cause an SEU is directly proportional to the number of electron-hole pairs created in the active region of the device whether by the ion or by the laser, the threshold LETs should be the same for either type of electron-hole pair creation mechanism when normalized to the energy required for pair creation:

$$\frac{LET_{TH}}{\varepsilon_{ion}} = \frac{ELET_{TH}}{\varepsilon_{las}} \tag{4}$$

where $\varepsilon_{ion} = 3.6$ eV is the energy required to generate an electron-hole pair by a heavy ion, and $\varepsilon_{las} = 1.1$ eV is the energy required to generate a pair by the laser light.

Unfortunately, Equation (4) cannot be used in this simple form to estimate the ion LET threshold from laser data because, as indicated in Equation (3), ELET varies with vertical distance, z, into the chip. Therefore, we must integrate over the active region of the device to calculate the total minimum charge (number of electron-hole pairs) that will cause upset in order to estimate the ion $LET_{TH}$ from the minimum incident laser energy, $(P_o t_o)_{TH}$, that will cause an upset. We then divide by the active region thickness, d, to obtain an average value of ELET through the active region. Using Equations (3) and (4), we can write

$$LET_{TH} = \frac{\varepsilon_{ion}}{\varepsilon_{las}}\frac{1}{d}\int_{\substack{\text{active}\\\text{region}}} ELET_{TH}\,dz = \frac{\varepsilon_{ion}}{\varepsilon_{las}}\,\alpha\int_0^{1/\alpha} ELET_{TH}\,dz \tag{5}$$

and

$$\mathrm{LET}_{TH} = 0.632 \frac{\varepsilon_{ion}}{\varepsilon_{las}} \frac{T\alpha}{\rho} (P_o t_o)_{TH} \qquad (6)$$

where, for illustrative purposes, we have integrated over the region from the surface ($z = 0$) down to one absorption length into the material. At 652 nm, $1/\alpha \approx 8$ µm which is an appropriate penetration depth for creation of charge contributing to upset. Using Equation (6), one can show that at $\lambda = 652$ nm, an ion $\mathrm{LET}_{TH}$ of 10 MeV-cm$^2$/mg is equivalent to an initial laser energy of $(P_o t_o)_{TH} \approx 2.3$ picojoule.

Note that $(P_o t_o)_{TH}$ will depend upon the absorption and transmission coefficients of the laser and the optical elements in the MEALS system, resulting in variations in the incident laser power that actually enters the device. In addition, it is often difficult to determine the actual active region depths for use in Equation (5). Also, we have not taken into account the differing roles that diffusion can play between the very small diameter ion track and the much broader laser beam. Finally, we have not accounted for any differences in charge separation and yield between the ion and laser cases. Thus, the optical system should be calibrated to find $P_o t_o$ prior to an absolute measurement in joule/cm$^2$. The MEALS system with a 4 nanojoule capability at 652 nm, can cover a range up to an ion LET of approximately $1.7\times10^4$ MeV-cm$^2$/mg.

## E. Experimental Conditions

Using the test setup described earlier, heavy ion tests were performed at the BNL accelerator. SEU data were taken between room temperature and 125°C over an LET range accessible using some or all of the ions, 316 MeV iodine, 240 MeV bromine, 121 MeV chlorine and 123 MeV nickel at various angles. The range of all ions in Si was more than sufficient to penetrate well beyond the active regions of the SRAMs. The available LET range was restricted because the DUT test board socket geometry limited the beam angle of incidence to less than 30° for the HC6364 and less than 45° for the IBM6401CRH. Two samples of each SRAM type were tested at various temperatures (room temperature, 80°C, and 125°C), $V_{DD}$ values (4.5, 5.0, and 5.5 V), and test vector patterns (all 0's, all 1's, and checkerboard). The remainder of the samples were tested only under worst case conditions ($T = 125$°C, $V_{DD} = 4.5$V for SEU). Latchup was also monitored at $V_{DD} = 5.5$ V, although device latchup was not expected nor was it observed.

Prior to high energy heavy ion tests, the two SRAM types were tested with the MEALS system at the three different wavelengths noted above (652, 688 and 724 nm) in order to estimate device SEU sensitivity at various temperatures.

The results measured both by heavy ions and the MEALS laser system were compared with data provided by each manufacturer. In order to establish credibility of a data base for the qualified manufacturing list of the Advanced Spaceborne Computer Module, it is necessary to perform SEE tests on contractor standard evaluation chips as an independent verification and validation.

## 1. Honeywell HC6364 64K SRAM

The Honeywell HC6364 8Kx8 radiation-hardened Static RAM, shown in Figures 4 and 5, is a high performance 8192x8-bit SRAM with industry-standard functionality. It is fabricated with the Honeywell radiation hardened CMOS (RICMOS) technology, and is designed for use in systems operating in radiation environments. The RAM operates over the full military temperature range and requires only a single 5 V power supply. Power consumption is typically 40 mW/MHz in operation, and 5 mW/MHz in the low power, disabled mode. The RAM read operation is fully asynchronous, with an associated typical access time of 25 nsec. The SEU sensitive volume depth of these devices was reported as a nominal value of 7.1 μm.

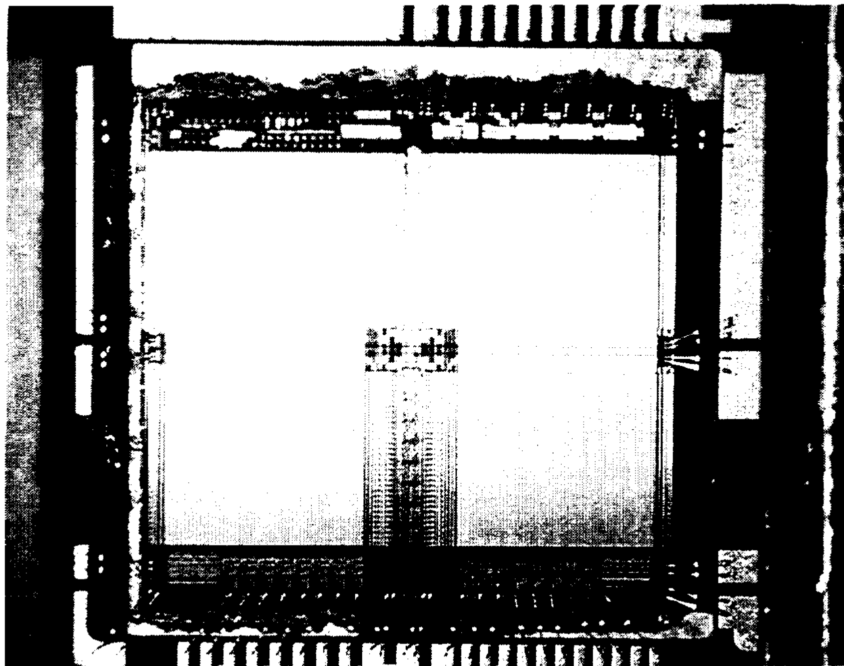

*Figure 4. Overall optical view of the packaged Honeywell HC6364 64K SRAM.*

The Honeywell RICMOS technology is radiation hardened through the use of advanced design, layout, and process hardening techniques. The RICMOS process is a 5-volt, n-well CMOS technology with a 259 angstrom gate oxide and minimum feature size of 1.2 μm. Additional features include two layers of interconnect metallization, a lightly doped drain structure for improved short channel reliability, and an epitaxial starting material for latchup-free operation.

High resistivity cross-coupled polysilicon resistors (150 - 700 kΩ) have been incorporated for single event upset hardening. The predicted threshold LET of this device at 125$^{o}$C is 5 to 40 MeV-cm$^{2}$/mg depending upon the resistivity of the cross-coupled resistors. Ten of the fifteen devices (HC6364) delivered to JPL by Honeywell through Aerospace Corporation with cross coupled resistor values of 181 kΩ were fabricated from the same wafer lot. Since the feedback resistors increase the write time, especially at low temperature, a compromise

Package body has VDD & VSS power planes
VDD pins: 2, 17, 20, 35
VSS pins: 1, 18, 19, 36
No Connect pins: 3, 16
Cavity size: 412 mils x 432 mils

Bonding wires to VDD and VSS can be repositioned to minimize length.

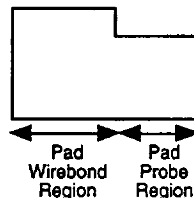


*Figure 5. A 36-lead flat pack wire diagram of Honeywell HC6364 64K SRAM.*

between write time performance and SEU hardness must be made. Increasing the resistor size increases the SEU resistance, but it also increases the write time. Because polysilicon resistors have negative temperature coefficients, the susceptibility to SEU increases with temperature. Thus, the design space is limited by poor write time characteristics at low temperature and SEU vulnerability at high temperature. This is why Honeywell offers a series of SRAM products with varying SEU hardness.

### 2. IBM IBM6401CRH 64K SRAM

The IBM 64Kx1 IBM6401CRH, shown in Figure 6, is a relatively fast access time (36 nsec/cycle at 25$^{o}$C, VDD = 5 V), radiation hardened (Total dose ≈ 106 rads(Si), survivability ≈ $10^{12}$ rads(Si)/sec) CMOS static random access memory. This SRAM features separate data I/O and fully asynchronous operation requiring no external clock. Address transition detectors initiate bit line pre-charging, resulting in improved performance. The chip enable feature of the device places the device in a low power (11 mW) standby mode reducing supply current to less than 2 mA. The cells of this device incorporate a six transistor CMOS design with polysilicon cross coupling resistors that provides SEU hardness of approximately $10^{-10}$ errors/bit-day). An optimum balance between radiation-hardening, low power, fast access and short write time was developed for these static random access memories by utilizing unique cross-coupled resistors, retrograde well design and an ultra-thin epitaxial layer. According to IBM data, the nominal threshold LET of these devices at 125$^{o}$C is about 70 MeV-cm$^2$/mg depending upon the cross coupled sheet resistivity. The average sheet resistivity of the samples that IBM shipped to JPL was 27.9 ohms/cm$^2$. The SEU-sensitive volume depth of these devices is approximately 2 μm according to IBM.

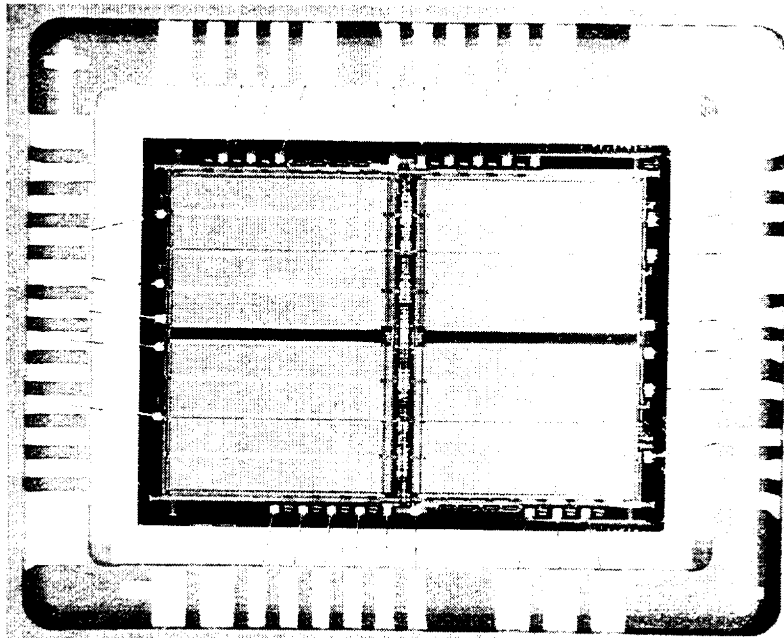

*Figure 6. Overall optical view of the IBM IBM6401CRH 64K SRAM.*

## F. Experimental Results and Discussion

### 1. Honeywell HC6364 SRAM

Typical results of the heavy ion tests at BNL of the Honeywell HC6364 64K SRAMs biased at VDD = 4.5 V are shown in Figure 7. As expected, the $LET_{TH}$ and the SEU cross section below saturation strongly depend upon the operating temperature because of the negative temperature coefficient of the feedback resistors. The $LET_{TH}$ values (defined as the

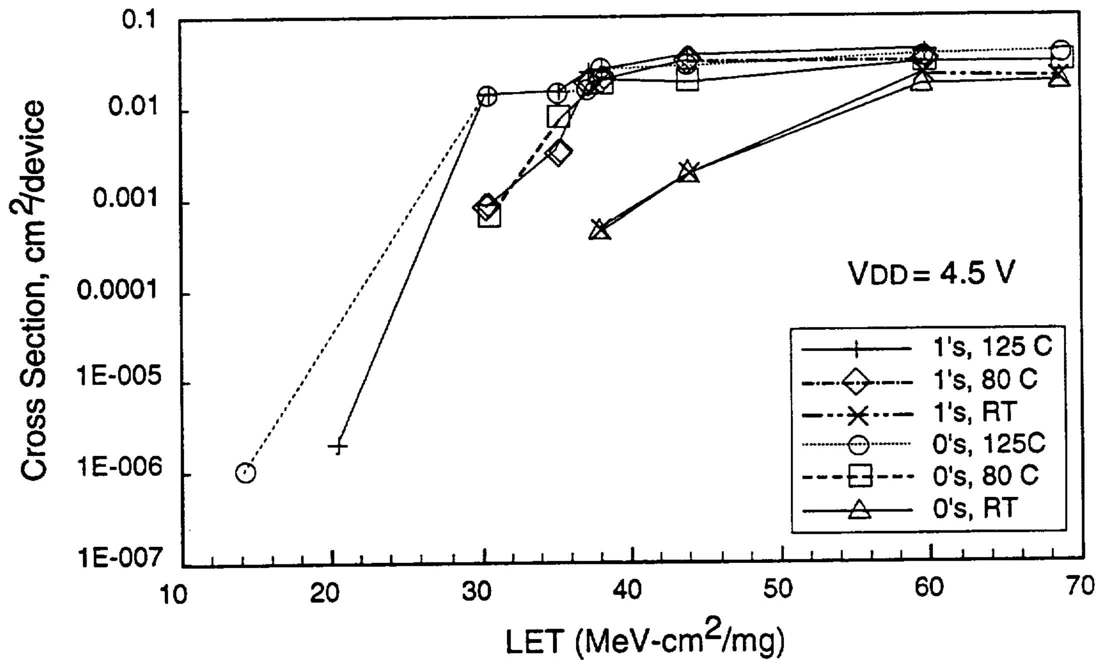


*Figure 7. SEU cross section data obtained at BNL on the Honeywell HC6364 64K SRAM.*

value of LET at 10% of the saturated cross section) at each temperature are approximately 27, 30 and 38 MeV-cm$^2$/mg at 125°C, 80°C and room temperature. In contrast, there is no measurable dependence of $LET_{TH}$ or cross section on the "all 1's" or "all 0's" patterns loaded into the SRAMs. As shown in Figure 7, the SEU saturation cross section at large LET (> 60 MeV-cm$^2$/mg) of approximately $5 \times 10^{-7}$ cm$^2$/bit is essentially independent of temperature over the measured range of room temperature to 125°C. No multiple upsets or latchups were observed even under worst case conditions. Results essentially the same as those in Figure 7 were observed for the other Honeywell SRAM samples.

The variation of the SEU cross section at 125°C with SRAM operating voltage is shown in Figure 8 at two LET values, 30.4 and 35.2 MeV-cm$^2$/mg. As expected, the cross section at these LET values near the threshold, decreases as the operating voltage increases indicating that the devices are less susceptible to SEU when they are operated at higher bias levels. Note that there is essentially no pattern dependence of the SEU cross section at the higher voltages, as was the case at 4.5 V. While the cross sections are the same at the two LET values at 4.5 V, they differ significantly at 5.5 V. This indicates, as one would expect, that the $LET_{TH}$ has shifted to a higher value at 5.5 V so it is closer to the LET values used for the data in Figure 8.

The Honeywell 64K SRAMs were tested with the MEALS system after calibrating it with a silicon sensor (Molectron Model No. J35-10) at a wavelength of 652 nm using various objective lens systems. MEALS scans revealed that the most SEU-sensitive portion of the device was the area between the common gate and the common drain. Numerous single event upsets were recorded for the HC6364 memories at all three wavelengths (652, 668, and 724

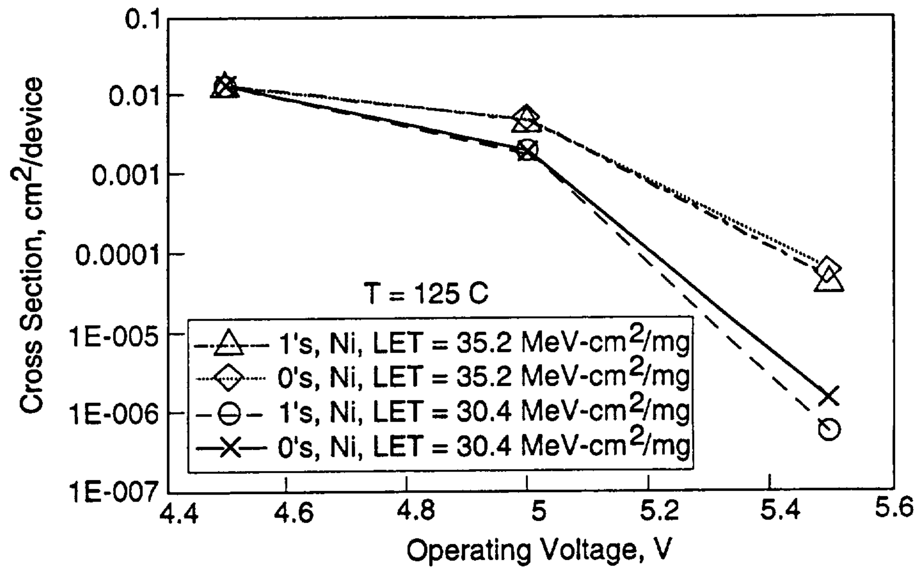


*Figure 8. Dependence of SEU cross section on operating voltage for Honeywell HC6364 64K SRAMs.*

nm), even at room temperature. As one would expect, the SEU sensitivity was also dependent upon the laser energy (intensity), device temperature, and operating voltage, in agreement with the heavy ion results. The threshold laser energies of the devices under worst case conditions (125°C, 4.5 V) at the three wavelengths were found to be 3.9, 6.6, and 10.1 picojoules, which were equivalent to ion $LET_{TH}$s of 17, 22, and 24 MeV-cm$^2$/mg, respectively. Recall that the $LET_{TH}$ of this device measured by iodine ions at 125°C and 4.5 V was 27 MeV-cm$^2$/mg. At a wavelength of 652 nm, the threshold laser energies of the devices at 4.5 V were found to be 3.9, 5.1, and 7.0 picojoules at 125, 80, and 28°C, which were equivalent to ion $LET_{TH}$s of 17, 22, and 30 MeV-cm$^2$/mg, respectively. These values are compared in Figure 9 to the measured ion $LET_{TH}$s at Brookhaven National Laboratory that were found to be 27, 30, and 38 MeV-cm$^2$/mg. Finally, also in agreement with the heavy ion data, there was no pattern dependence in the MEALS laser scan data, nor were any latchups observed.

It may be worth noting that the numerical cross section of the device can be calculated in principle once the MEALS scanner has identified which component of the device is most sensitive to laser-induced SEU, because the SEU saturation cross section should be equal to the total sensitive area. For the case of the HC6364, the most sensitive areas for SEU were found to be the n- and p-channel drain areas of the memory cell, having an approximate area of $2.6 \times 10^{-8}$ cm$^2$. The measured saturation cross section of the device was $60.8 \times 10^{-8}$ cm$^2$ at 125°C, which is a factor of 30 larger. The difference in these values may suggest that additional devices become sensitive as the LET is increased. If all of the most sensitive devices, the n- and p-channel drain areas, were to respond equally, one might approximate their response with the threshold LET and its cross section. We note that 10% of the saturation cross section ($6 \times 10^{-8}$ cm$^2$) is roughly equal to the calculated drain area. Further study should be done to understand these discrepancies.

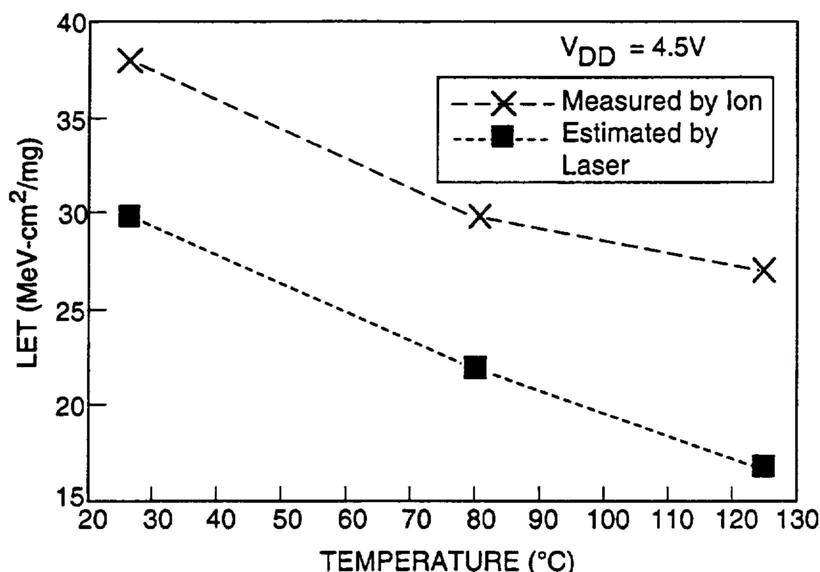


*Figure 9. Comparison of threshold ion LET with threshold LET predicted by the MEALS system for Honeywell HC6364 64K SRAMs.*

**2. IBM IBM6401CRH SRAMs**

Samples of the IBM IBM6401CRH 64K SRAMs from different stages of the fabrication process were tested at BNL to a maximum ion LET of 79 MeV-cm$^2$/mg. However, no SEUs were observed in any of the eight tested samples, even for the worst case conditions of 4.5 V and 125°C. Thus, $LET_{TH}$ is greater than 79 MeV-cm$^2$/mg at 125°C and 4.5 V. This result agrees with the fact that the saturation cross section of the HC6364 at 125°C ($5 \times 10^{-7}$ cm$^2$/bit) is much larger than that ($1.7 \times 10^{-8}$ cm$^2$/bit) reported by IBM for the IBM6401CRH.

Similar tests were performed for the same devices using the MEALS at a wavelength of 652 nm (penetration depth of about 8.4 μm) at room temperature. These laser test results predicted that the threshold laser energy was 21 picojoules for both test patterns of "all 0's" and "all 1's". This indicates that the predicted ion $LET_{TH}$ for the IBM SRAM should be 90 MeV-cm$^2$/mg. This value is to be compared with the nominal $LET_{TH}$ reported by IBM for this device as 75 MeV-cm$^2$/mg at 125°C. Because of the use of cross coupled resistors, one would expect a larger value of $LET_{TH}$ at room temperature than at 125°C. Thus, the comparison between the laser at room temperature (90 MeV-cm$^2$/mg) and the IBM ion test result at 125°C (75 MeV-cm$^2$/mg) exhibits the proper trend. SEUs were also observed with the laser at 125°C but neither latchups nor multiple SEUs were found.

The fact that SEUs were difficult to observe during the heavy ion test at BNL, but were easily produced at room temperature with the MEALS system indicates that the laser can produce higher energy deposition compared with the BNL accelerator. Similar results were reported on non-rad hard SRAMs [3-4]. It would be beneficial to find the threshold ion LET by testing with higher LET ions. Our results suggest that a simple test by pulsed lasers could be used for screening highly radiation resistant devices from different vendors without costly

high-LET ion tests at off-site accelerators.

## G. Conclusions

Radiation-hardened 64K SRAMs from two of the Government Furnished Equipment Contractors, the HC6364 from Honeywell and the IBM6401CRH from IBM, were tested by both high energy heavy ions and the pulsed dye laser MEALS system in order to assist in the independent validation and verification of the SEU threshold LET as a part of Qualified Manufacturer List (QML) qualification efforts for them for the Advanced Spaceborne Computer Module Program sponsored by the Air Force Phillips Laboratory.

The heavy ion SEU $LET_{TH}$ of the HC6364 at 125°C and $V_{DD}$ = 4.5 V (worst case conditions) was found to be 27 MeV-cm$^2$/mg. Good agreement was found between this ion $LET_{TH}$ and the value of 24 MeV-cm$^2$/mg predicted by the minimum laser energy at a wavelength of 724 nm that induced upset at 125°C. In contrast, the IBM6401CRH did not exhibit upset even at 125 °C with ion LETs up to 79 MeV-cm$^2$/mg. A picosecond pulsed dye laser beam of 652 nm wavelength was able to upset the IBM memory at room temperature, and predicted the SEU ion $LET_{TH}$ to be 90 MeV-cm$^2$/mg, in approximate agreement with the IBM-reported ion $LET_{TH}$ at 125°C of 75 MeV-cm$^2$/mg.

No significant variations among the samples selected from the same fabrication processes were observed either by heavy ions or the MEALS laser system. Neither latchups nor multiple SEUs were observed with heavy ions or the MEALS laser system in any of the devices from both vendors even under worst case conditions.

The agreement between heavy ion and MEALS laser system results obtained in this study suggests that for certain cases, the pulsed laser system is an effective SEU pre-screen tool that is quicker and much less expensive to use than heavy ion testing at large accelerators. For example, for very stringent SEU requirements, the laser could have been used to select the most SEU-hardened SRAM of the two examined in this study without resorting to accelerator testing.

## H. References

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