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Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Test Guideline for Proton and Heavy Ion Single-Event Effects

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Abstract

This document gives detailed test guidelines for single-event upset (SEU), single-event latchup (SEL), single-event burnout (SEB), and single-event gate rupture (SEGR) hardness assurance testing. It includes guidelines for both heavy-ion and proton environments. The guidelines are based on many years of testing at remote site facilities and our present understanding of the mechanisms for single-event effects.

I. Introduction

The following detailed test guidelines for single-event effects (SEE) proton and heavy-ion testing are meant to be a practical step-by-step guideline for performing hardness assurance testing. Although the test guideline is applicable to all radiation sources, to highlight some specific details, test conditions at the TRIUMF proton cyclotron, Texas A&M's heavy-ion cyclotron, and Brookhaven's heavy-ion Tandem van de Graaff are given. Testing at other test facilities will follow the same basic procedures, but possibly with small differences in details. The procedures cover proton-induced single-event upset and latchup testing and heavy-ion induced single-event upset and latchup testing. These guidelines assume that all personnel have taken the required safety training required by DOE and the radiation facility. These procedures are valid for earth-based satellite orbits and for devices that do not exhibit proton-induced upsets caused by the direct ionization of protons. For other space systems, e.g., space systems flying in Jupiter's radiation belts, the test guidelines may need to be adjusted. For example, in other environments the flux of protons at high proton energies (i.e., 180 to 400 MeV) may be considerably higher than in earth-based orbits, requiring proton testing to be performed only at proton facilities that can generate protons with very high energies ($>$400 MeV). The radiation test facilities most frequently used by Sandia personnel and their key features are listed. Test planning and data analysis are briefly discussed.

II. Definitions

Flux is the rate at which particles impinge upon a unit surface area. It is normally given in units of particles/cm^2-s. The time integral of flux is fluence.

Fluence is equal to the total number of particles that impinge upon a unit surface area and is normally given in units of particles/cm^2.

Linear energy transfer (LET) describes the energy loss per unit path length of a particle as it passes through a material. LET has units of MeV-cm^2/mg. Because the energy loss per unit path length (in MeV/cm) is normalized by the density of the target material (in mg/cm^3), LET may be quoted roughly independent of the target. We can easily relate the LET of a particle to its charge deposition per unit path length. In silicon, an LET of 97 MeV-cm^2/mg corresponds to a charge deposition of 1 pC/μm. This conversion factor of about 100 is handy to keep in mind to convert between LET and charge deposition.

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TABLE I

SINGLE-EVENT EFFECTS TEST MATRIX FOR VARIOUS COMPONENTS.

Component	SEU Proton	SEU Heavy Ion	SEL Proton	SEL Heavy Ion	SEGR Heavy Ion	SEB Heavy Ion	SE Microdose
discrete MOS	no	no	no	no	yes	yes	yes
CMOS ICs	yes	yes	yes	yes	yes	yes	yes
discrete power MOS	no	no	no	no	yes	yes	yes
discrete bipolar	no	no	no	no	no	yes	yes
bipolar linear ICs	yes	yes	yes	yes	yes	yes	yes
discrete MEMS	no	no	no	no	no	no	no
MEMS ICs	yes	yes	yes	yes	yes	yes	yes
discrete III-V	no	no	no	no	no	yes	no
III-V ICs	yes	yes	no	no	no	yes	no
discrete optoelectronics	no	no	no	no	no	no	no
optoelectronic ICs	yes	yes	yes	yes	yes	yes	yes

A **rad** is defined as radiation absorbed dose. It is a measure of the amount of energy deposited in a material and is equal to 100 ergs of energy deposited per gram of material. The energy deposited in a device must be specified for the material of interest. Thus, for a MOS transistor, total dose is measured in units of rad(Si) or rad(SiO_2).

SEE **cross sections,** σ, are a measure of the SEE-sensitive cross-sectional area of a microelectronic device. They provide a measure of the sensitivity of the device and are used to calculate error rates for a given radiation environment. They are calculated from experimental measurements by dividing the number of events observed (SEU, SEL, etc.) by the particle fluence. SEE cross sections are generally reported in units of cm^2, or sometimes for memories in cm^2/bit.

III. RECOMMENDED TEST MATRIX

The effects of radiation on components can vary significantly depending on the type of component and the type of radiation. In space, although the fluxes of particles and their energies can vary significantly depending on the orbit, most orbits can be exposed to all radiation particles of interest. For example, for a GPS or GEO orbit, the number of trapped protons is negligible. However, satellites can still be exposed to protons from solar flares. As a result, it is often best to assume that components will be exposed to all types of energetic particles. Whether or not a given type of radiation will cause radiation-induced degradation will depend on the type of component. Table I lists a number of different types of components and which types of tests should be performed for each component type. Note that this is meant to be a general guide based on our current knowledge of radiation effects. In space, the amount of radiation-induced degradation each component is sensitive to can be impacted by many factors, including the fluence (total dose) and dose rate to which devices are exposed. The final column of Table I, single-event microdose (SEM), refers to total ionizing dose effects that are caused by single particle strikes. These effects have been observed in several device types, most notably in memories and power MOSFETs [1]–[5]. Because they are due to total dose effects, they are not discussed further in this document. However, the reader should be aware that testing for SEM would be performed using the same particle sources as for other single-event effects.

Notes on Table I: Almost all devices which are sensitive to at least one type of single-event effect, in general, may be susceptible to other types of single-event effects. For example, even advanced SOI ICs, which do not contain four layer n-p-n-p paths and therefore will not exhibit traditional latchup, are susceptible to single-event snapback, which is very similar to SEL and which can have similar effects. Discrete III-V includes MESFET, HEMT, JFET, and other types of III-V devices. III-V ICs include MMIC and other types of microwave ICs fabricated using active III-V components. Discrete optoelectronic devices include light emitters (e.g., LEDs and lasers) and detectors (e.g., photodiodes). Optoelectronic ICs include discrete optoelectronic devices, associated circuitry, and fibers. MEMS ICs include associated circuitry fabricated using MOS devices.

IV. Proton Single-Event Effects Hardness Assurance Testing

The optimum sequence of tests (e.g., SEL first, SEU second, etc.) can be application dependent. For example, if a system application dictates that devices cannot latchup in space but can tolerate relatively high upset rates, then SEL testing should precede SEU testing. In this test order, if a latchup is detected, no further testing is required because the device is not usable in the intended application, and considerable test time can be saved. However, if some latchups can be tolerated, it may be preferable (but not absolutely necessary) to perform proton-induced upset testing prior to proton-induced latchup testing. Latchup testing requires elevated temperature irradiations while upset testing often does not require elevated temperature testing. It is simpler to first perform room temperature irradiations and then elevated temperature irradiations because of the time required to cool devices back down to room temperature. Also, latchup testing can potentially be destructive.

A. Pre-Test Setup

1) Radiation Source: The radiation source must be capable of providing protons with energies over a range from at least 20 to 180 MeV. Ideally, the radiation source should be capable of producing protons with energies as high as that of the maximum energy of protons in the system environment. For trapped protons in space, this is 400 MeV [6]. At any given energy, the full-width half maximum (FWHM) of the beam straggle (variation in beam energy) should be less than 25% of the target energy. Beam straggle primarily occurs due to the intentional degrading of the proton energy using materials in the beam line. For most high-energy proton facilities, this is the only practical method for varying proton energy. For facilities that can provide monoenergetic protons at multiple proton energies and degrade the proton beam using materials in the beam line to obtain intermediate proton energies, one should tune to the lowest proton energy that is above the target proton energy and then degrade the proton beam using materials. For example, the TRIUMF proton cyclotron can provide monoenergetic protons with energies of 70, 116, 220, 350, and 498 MeV [7], [8]. If a test calls for a proton energy of 85 MeV, one should degrade the 116 MeV proton beam using the plastic degraders provided by TRIUMF. Figure 1 is a photograph of the exit port at TRIUMF. The plastic degrader used for varying the proton energy is in the center of the photograph.

Note: Proton energy can be decreased either by degrading the beam by placing materials in the beam line or tuning the beam to a different proton energy. The time required to tune to different proton energies can often be excessive. Hence, frequently changing the proton energy by tuning the beam is impractical. If other devices or device types require testing, it is prudent to perform all testing at a given proton energy before tuning the beam to a different proton energy. This includes latchup testing. However, as described below, latchup testing should start at the highest proton energy available at the facility (up to 500 MeV). If this is not the case, latchup testing will still need to be performed at higher proton energies, even if no latchups are detected at lower proton energies. Also, if latchup testing is performed, it must be taken into account that the devices will be exposed to more total dose. If total dose impacts the SEU cross section, multiple devices should be used. If the proton energy is to be degraded by placing materials in the beam line, this can often be done more quickly than devices can be changed. (Some facilities degrade the beam line by placing metals in the beam line that can become highly radioactive. In these cases, to minimize radiation exposure to personnel, it may be prudent to change devices before changing proton energy.)

2) Personnel: Many remote test sites operate 24 hours per day, 7 days per week. Bringing a limited number of people to a remote test can result in very long days and nights for each individual and may result in inefficient use of the test facility. Having sufficient people to take data and perform preliminary data analysis during the test is essential for optimum use of the facility and for ensuring the quality of the data. Not having the right people at a remote test site that charges hundreds of dollars per hour for beam time is usually a poor economy.

3) Dosimetry: Dosimetry must be provided by the facility. Understanding the method used for dosimetry measurements can be very helpful. However, to verify the accuracy of the dosimetry, one should provide a secondary method. Fluence (total dose) can be measured using thermoluminescent detectors (TLDs). Another approach is to measure the SEU cross section on previously characterized devices that are not sensitive to total dose effects. As long as the SEU or SEL cross section is not impacted by total dose, for a given LET in the saturation region, the SEU or SEL cross section should not vary significantly for different ion conditions (i.e., specie or energy). As a result, if significant differences are observed, this is a strong indication that either the dosimetry is incorrect or there are problems associated with the measurement system. In either case, the cause of the differences should

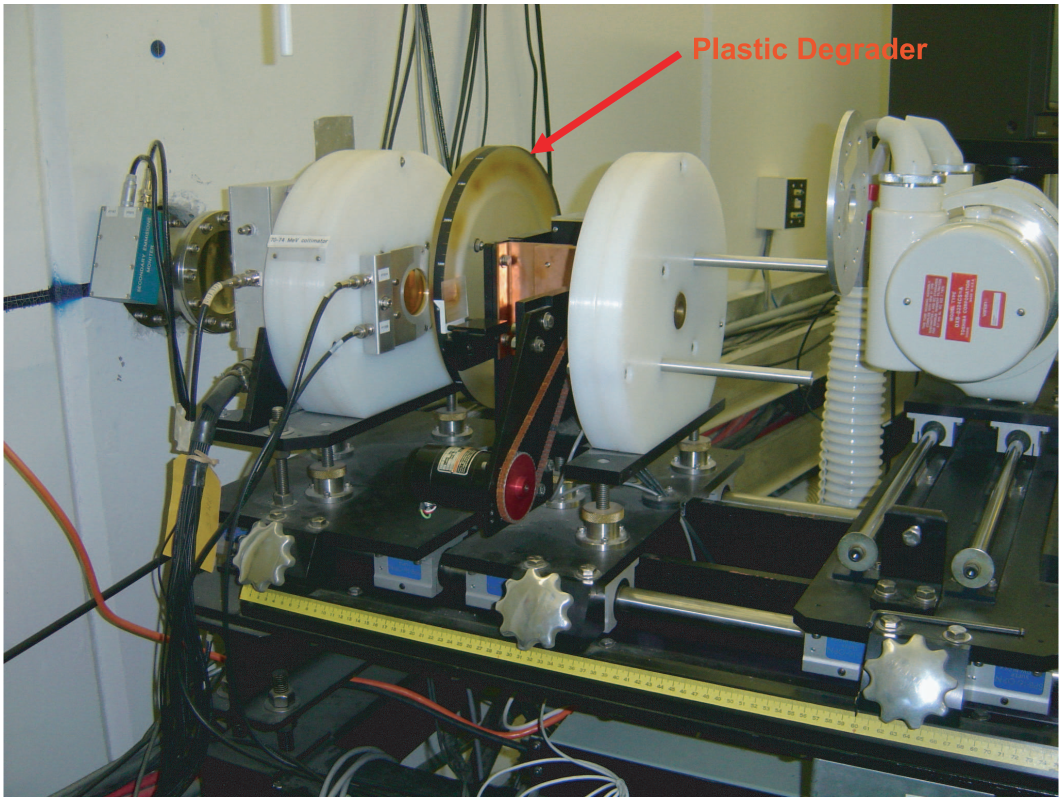

Fig. 1. Exit port of the low-energy beam line at TRIUMF. The proton energy is varied by degrading the proton beam using a plastic degrader (center).

be resolved before testing is continued. For SEU and SEL testing, the dosimetry must be sufficient to ensure that the fluence is known with an accuracy of ±10%. In addition, the flux must be high enough to achieve the target fluence within a reasonable time period. For both SEU and SEL testing, a typical proton flux range is 10^7 to 10^9 protons/cm^{2}s.

4) Test Circuit Boards: Devices to be irradiated should either be mounted on or connected to circuit boards together with any associated circuitry necessary for device biasing during irradiation or for in-situ measurements. Unless otherwise specified, all device input terminals and any others which may affect the radiation response should be electronically connected during irradiation, i.e., not floating. The geometry and materials of the completed board should allow uniform irradiation of the device under test (DUT). Good design and construction practices should be used to prevent oscillations, minimize leakage currents, prevent electrical damage, and obtain accurate measurements. Only sockets that are radiation resistant and do not exhibit significant leakages (relative to the device under test) should be used to mount devices and associated circuitry to the test board(s). All apparatus repeatedly used in radiation fields should be checked periodically for physical or electrical degradation. Components which are placed on the test circuit boards, other than DUT, should be insensitive to accumulated proton total dose. Unless it is absolutely necessary that test circuitry be located immediately adjacent to the DUT, the test circuitry should be located a distance that is at least twice the diameter of the proton beam from the DUT to minimize the possibility of proton-induced total-dose degradation. This diameter of the proton beam will vary from facility to facility. For example, at TRIUMF the diameter of the beam can vary anywhere from 2 to 10 cm. For many tests, test circuitry does not have to be located on the same board as the board used for the devices under test. Because of secondary particles (e.g., neutrons and gammas) that can be produced by protons striking materials in the beam line, all test equipment (including bias supplies) should be located as far from the beam line as possible. Equipment located too close to the beam line can be degraded and potentially become malfunctional by exposure to the secondary particles. Equipment can also become activated if located too close to the beam line. Shielding using concrete (neutrons) and/or lead (gammas) can be used to minimize the exposure of equipment to secondary particles. However, the equipment must not be located too far from the DUT such that the integrity of the test system is compromised. The

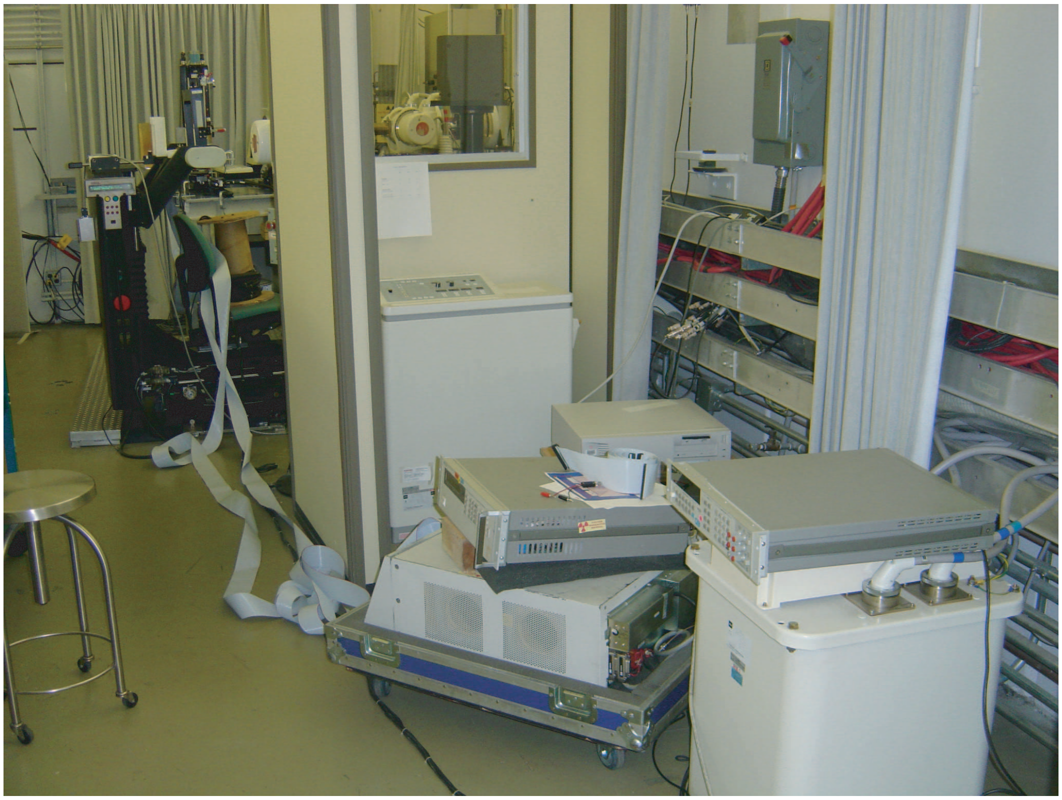

Fig. 2. Positioning of test equipment at TRIUMF. The DUT is in the far left top corner of the photograph.

impedance associated with long cables can potentially affect bias levels to the DUT, high frequency measurements, etc. Bias levels should always be verified at the DUT using a voltmeter prior to irradiation. At TRIUMF, distances of 5 to 15 feet are typical. Figure 2 is an example of the positioning of test equipment at the low-energy beam line at TRIUMF. Whenever possible, board and package designs should minimize the use of materials that have long radioactive half lives. The use of high-Z materials (e.g., tungsten) and hazardous materials (e.g., lead) should be avoided. In general, it is good practice to always minimize the amount of material in the beam line. Note that cables and other components in the beam line can become activated and, in some instances, may not be shippable for extended time periods. As a result, for very long cable runs that terminate at the DUT or test board in the beam line, it is often prudent to use short extender cables at the end of the long cable runs in the beam line that are easier and less costly to replace for future tests. If temperature testing is required, the test circuit boards, sockets, etc. must be capable of withstanding the temperatures to be used.

5) Cabling: Good cabling is extremely important and should be verified for proper operation before conducting remote site tests. Often, problems encountered during testing are related to faulty cabling, i.e., shorted, open, or intermittently shorted or open cables. Proper handling of cables is essential. Cables connecting the test measurement equipment to the test circuit boards must be as short as possible. The cables should have low capacitance and low leakage between wires. Longer cables can be used to connect the test measurement equipment to computer systems used to control the test equipment, and to collect and analyze data. Cable lengths of greater than 50 feet to connect test equipment to computer systems used to control the test equipment are not uncommon at many remote test facilities. Users must contact test facility operators prior to the test to determine the minimum lengths of cables required at the facility. Note that for all proton test facilities, the experimenters themselves are located in a separate room shielded from the beam room (normally by extremely large concrete blocks).

6) Environmental Chamber: For most proton facilities, tests are conducted in the open air (i.e., not in a vacuum chamber). If environmental chambers are used for controlling device temperature, they must be capable of withstanding the maximum temperature required. If the proton beam must pass through the walls of the chamber to reach the DUT, the materials used to fabricate the walls of the chamber and their thicknesses must be minimized to reduce the degradation in proton energy. This is especially important for low-energy protons.

Fig. 3. Portable environmental chamber for testing devices at elevated temperature. The DUT is located inside the heated chamber.

7) Temperature Control: Temperature can be controlled in several different ways. For example, resistive heater strips can be used between the device under test and the device socket. By controlling the power to the heater strip the temperature can be varied. Another method for controlling temperature is to use an environmental chamber, as shown in Figure 3. In this example, hot air is forced into the environmental chamber using a heated air gun. By controlling the temperature and air flow of the heat gun, the temperature can be easily varied remotely. This type of heating is especially useful for cases where heater strips cannot be readily placed between the device socket/board and DUT, or where it is desired to heat a larger subsystem.

Accurate temperature measurements are key to repeatable SEE testing at elevated temperatures. For either method of heating, a thermocouple must be connected to the device package to monitor the temperature. Temperature can be controlled automatically by using the measured temperature to control the output of a bias supply. Placement of the thermocouple close to the DUT and maintaining good thermal contact to the DUT are critical for accurate temperature measurements. Ideally, thermocouples should be connected at multiple locations to determine temperature variations across the package. An alternate method for monitoring the temperature is to characterize input diode forward voltage for a given current as a function of temperature. This technique can be used to give accurate measurements of temperature on the test die. Diodes are available on many devices (e.g, input protection diodes, drain-to-substrate diodes, etc.) These diodes can be calibrated in advance using well-controlled thermal environmental chambers, for example by placing the device in a well-characterized oven and measuring the diode forward voltage as the oven temperature is varied. Since the diode voltage is strongly dependent on the die temperature, this method gives a sensitive measurement of the actual die temperature and can be performed prior to the test, with plenty of time allotted for the device to stabilize at the oven temperature. Figure 4 shows an example of using input diodes as a temperatature monitor. Regardless of the method used for monitoring temperature, the temperature is typically not known within an accuracy better than $\pm$5%. As a result, to ensure that the temperature meets system requirements, the temperature should be set for a value that is 5% higher than the maximum system or device operation temperature (as appropriate).

8) Test Circuit Board Alignment: The DUT must be aligned in the center of the beam at the required angle. The size of the beam will limit the number of devices that can be tested in a single test run. The area to be irradiated must be smaller than the beam diameter. The variation in beam flux can vary considerably across the beam. The beam flux should not vary by more than 20% across the area to be irradiated. At most facilities, lasers are used to align the devices under test in the beam, as shown in Figure 5. At TRIUMF, a laser behind the DUT can be used to center the x-y position of the beam onto the DUT. A laser parallel to the DUT can be used to precisely locate the DUT the required distance from the exit port of the beam. It can also be used to ensure that the device surface is located normal to the beam. Once the DUT is aligned normal to the beam, the angle of incidence can

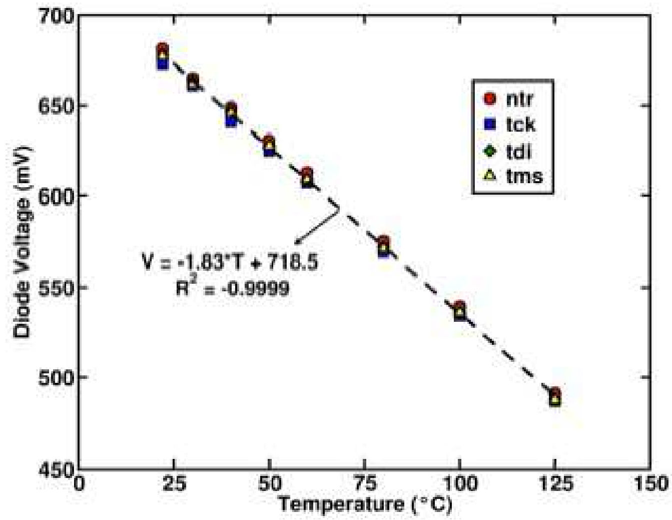

Fig. 4. Example of using input diode voltage as an indicator of DUT die voltage. The diode voltage is calibrated pre-test in an oven.

be changed using electrically controlled positioning equipment or manually using simple protractors or other test equipment. Care must be taken to ensure that when the angle of incidence is changed, the device under test's x-y position remains centered in the beam.

9) Upset Characterization: The upset cross section should be characterized using multiple test conditions (e.g., static and dynamic tests if possible) and test patterns. For example, the proton SEU cross section of SRAMs can be characterized in a static mode. In a static mode, devices are written with a specific pattern to the memory array, irradiated to a given fluence, and after the beam is turned off the parts are read and errors are counted. For this type of test, multiple test patterns can be used for characterization. One typical pattern is a checkerboard pattern (a logical series of 1's and 0's), however, since all 0's and all 1's patterns are usually easy to implement, it is recommended to compare the SEU sensitivity using all three patterns (checkerboard, 1's, and 0's) first to determine if there is any SEU pattern dependence before choosing a pattern for complete characterization. If the logical to physical mapping for an SRAM is known, vector maps should be generated to distinguish between single and multiple bit upsets, and to verify that the upsets are not due to single-event latchup. Of course, to fully characterize ICs in all the different possible test conditions is not possible because of budgets and time constraints. For example, synchronous DRAMs and microprocessors may have many distinctly different modes of operation. Thus, it is important to work with the end users to develop test conditions that closely match actual system use conditions. SEU cross sections are normally specified in units of either SEU-sensitive area per device (e.g., cm^2/device) or SEU-sensitive area per bit (in memories).

10) Latchup Characterization: Ideally, a latchup test should allow for both functional testing and current monitoring. Some parts are known to show only small increases in currents and without functional testing it may be difficult to detect such "microlatchups." Functional tests could also be used to detect single-event snapback in SOI devices where the increase in static power supply current can be very small. By examining vector maps and by recycling the power supply, single-event latchups (and single-event snapback) can be distinguished from single-event upsets, single-event functional interrupts, etc. For cases where functional testing is not practical, devices can be characterized in their preferred power-up logic state, i.e., they do not have to be written with a specific pattern prior to exposure. For this case, the power supply current must be continuously monitored during irradiation. When the power supply current increases to above a preset limit a latchup is recorded. To measure a latchup cross section, multiple latchups must be recorded as a function of proton fluence. To measure multiple latchups, after a latchup is first recorded, the power supply voltage must be quickly removed for a short period of time (e.g., 0.5 s) to clear the latchup state, the power supply voltage must be reapplied, and the latchup test can be continued. (Note that one must account for this dead time when determining the effective SEL cross section at a given proton energy. Also, to keep the dead time correction small the time between latchups should be much longer than the time period chosen for removing the bias.) The preset limit should be set to a current 10% above the static current for the device. Note that this current can change with temperature and total dose. As a result, it may have to be adjusted as

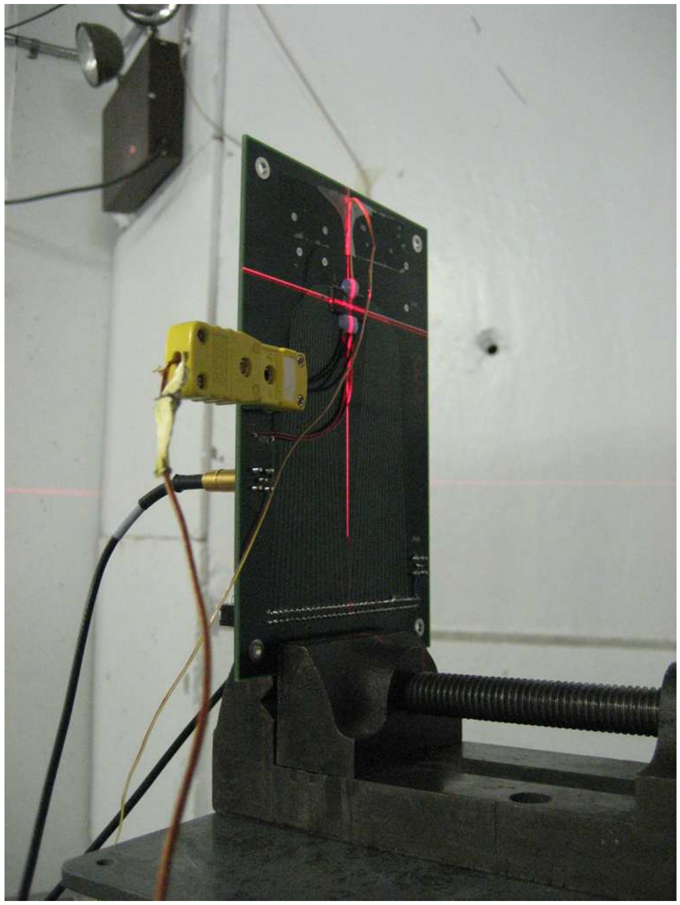

Fig. 5. Board alignment is typically performed using laser cross-hairs to center the DUT in the beam.

testing continues. To avoid catastrophic device failure caused by repeated latchup testing, the device current should be limited to a safe operating value.

11) Impact of Total Dose on SEU Cross Section Characterization: Because the single-event upset cross section of some devices is sensitive to total dose effects (to date this has been shown only for SRAMs), unless known otherwise, it should be assumed that the SEU cross section will be sensitive to proton total dose effects. Note that whether or not a device will be sensitive to total dose effects can depend on details of both fabrication steps used to make the device and circuit design. As a result, devices built in the same technology by the same manufacturer may have different sensitivities to total dose. If testing is to be performed for satellite systems, devices can be irradiated prior to the tests using standard Co-60 gamma sources because of the long times associated with satellite system operation. Devices should be irradiated using worst-case total dose test conditions. For most devices, this is maximum power supply voltage. To determine if devices are sensitive to total dose effects a set of devices should be irradiated to 80% of the total dose level of the system requirement. Devices must be fully functional immediately after irradiation. Devices can be annealed under bias at room temperature as long as the anneal time is short compared to the duration the devices will be in the system. This actually provides for more realistic simulation of device radiation-induced degradation in satellite environments than if devices are not annealed. Note that devices can also be total dose irradiated during proton testing. However, because devices will not have time to anneal, this is normally a more conservative test. On the other hand, if devices are total dose irradiated with protons, devices can be total dose irradiated on an as needed basis, minimizing the number of required test devices. The measured upset cross sections on total dose irradiated devices should be compared to the upset cross sections measured on non-total dose irradiated devices. If the maximum cross section for the total dose irradiated devices is more than 10 times the maximum cross section for the non-irradiated devices, the devices should be considered as total dose sensitive. Note that this difference of 10 times is somewhat arbitrary and larger or smaller values may be used depending on the sensitivity of the system to single-event upsets. If the device is determined to be total dose sensitive, all testing

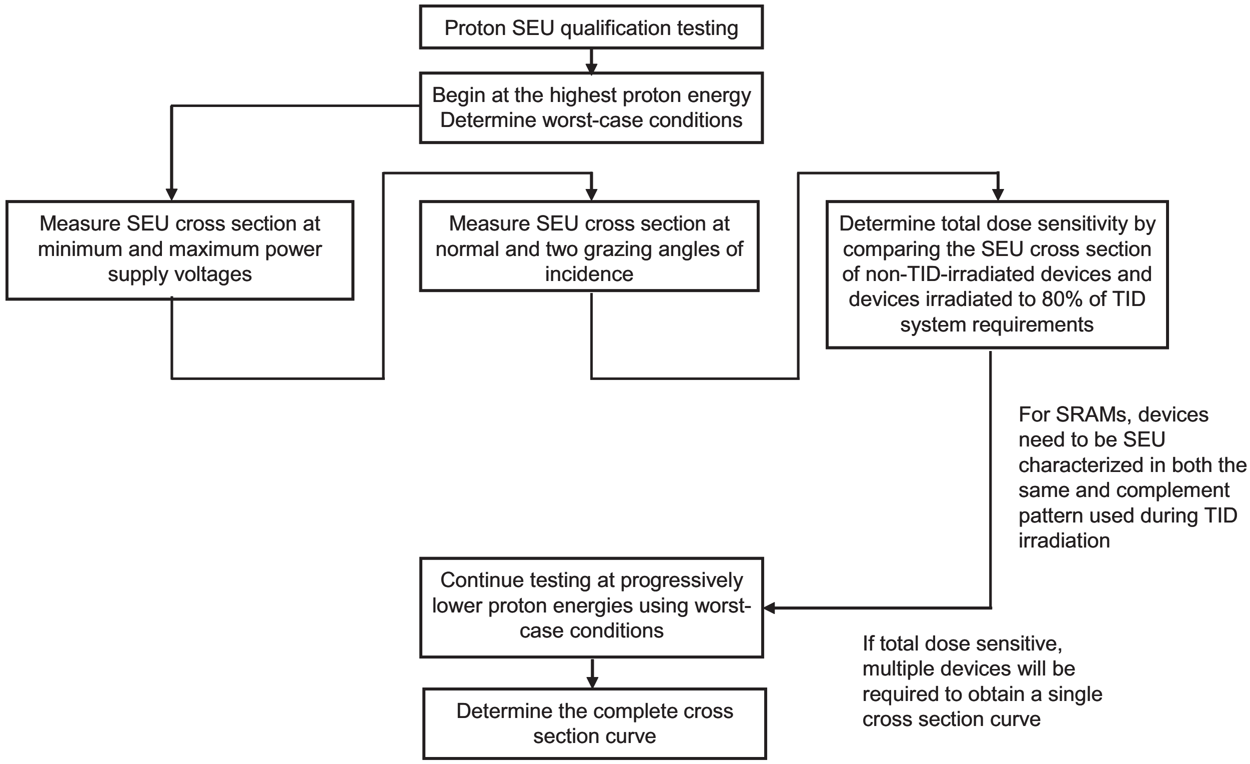

Fig. 6. Test flow for proton-induced SEU hardness assurance.

needs to be performed at a minimum on total dose irradiated devices. If time permits and sufficient devices are available, tests should also be performed on non-total dose irradiated devices to determine differences in upset rates during space flight. Note that experimental data taken on present-day SRAMs have shown that only devices that exhibit an increase in static supply leakage current with total dose exhibit a total dose sensitivity on the upset cross section. Hence, if the static supply leakage current does not increase with total dose, it is probably not necessary to compare the upset cross section of total dose irradiated and non total dose irradiated devices and all testing can be performed on non total dose irradiated devices.

B. Proton-Induced Single-Event Upset Test Flow

A general test flow for proton-induced single-event upset testing is given in Figure 6. The first step is to tell the facility operators to tune the beam to the highest proton energy of the facility and to the approximate flux required for the first test. To determine the facility conditions required to give a desired flux, consultation with a person experienced in operating the beam may be required.

Connect cables from the test equipment to the DUT and to the system used to control the tests (normally a computer controlled system). Apply bias to the DUT and verify the bias levels at the DUT using a voltmeter. Test the device using at a minimum the test patterns and bias levels that will be used during the tests. Make sure that it is fully operational (this should have also been performed at some point prior to arriving at the remote site). Align the DUT in the center of the beam and at the required distance from the exit port of the beam. Once the beam is aligned onto the DUT, enclose the DUT in an environmental chamber (if required). Heat the device if required. Allow time for the temperature to stabilize (normally 5 to 10 minutes after reaching the desired temperature). Note that all of this should be performed prior to closing the doors to the beam room. Once the DUT is determined to be fully functional and the temperature is correctly set, testing can begin.

Close the doors to the beam room using the procedure given by the test facility. Request beam. At some facilities a facility operator must be called and at other facilities this can be done using computer systems provided by the facility.

Bias the device using the minimum bias supply voltage and program the device using the same test pattern as was used for the total dose irradiations (if applicable and if previously performed). Set the fluence as required.

Because this may not be known in advance, initially set the fluence for 100 times lower than the maximum test fluence if a static test is being performed. (This value is system dependent.) If a dynamic test is being performed and the number of upsets can be determined during irradiation, the fluence can be set at the maximum fluence level and the irradiation sequence terminated when a statistically appropriate number of errors has been accrued.

1) General Characterization Test: Irradiate the device. For dynamic tests, stop the irradiation when the desired number of upsets is obtained or irradiate to the maximum fluence, whichever comes first. For maximum statistical confidence in the data, the number of upsets should be as high as feasible (>100), but not more than 1% of the total memory if an SRAM or similar device is being tested. For static tests, once the fluence has been reached, read the device and record the number of upsets. If the number of upsets is greater than the desired number of upsets, the test can be stopped. Otherwise, the test should be continued. Estimates of the required fluence may be obtainable from the first measurements. If an SRAM or similar device is being tested and the number of upsets is a significant fraction of the total memory of the device (greater than 1%), tests should be started over to a smaller fluence level (as appropriate to yield the desired number of upsets). Note that after each test, the DUT should be reprogrammed using the same pattern used during irradiation. If no errors are measured, testing can proceed as needed. If errors are measured after reprogramming the DUT, the bias supply should be removed for 0.5 s, the bias should be reapplied, and the device should be reprogrammed. If errors are still detected the device is no longer functional and testing must be continued on a new device. If the device is fully functional after cycling power, this is a possible indication that the device latched up during the test. If the device did latchup, the number of upsets is erroneous and cannot be used to calculate the soft error rate. For the number of errors to be valid, the DUT cannot latchup during testing. If latchups continually occur during testing at a high rate, it may not be possible to measure the upset cross section for the device. Whether or not the device is usable will depend on system application and the proton energies at which the latchups occur. Note that the bias supply voltage that normally corresponds to worst-case conditions for SEU testing is normally the least sensitive bias conditions for SEL testing.

2) Determine Total Dose Sensitivity: Compare the upset cross sections on devices total dose irradiated to 80% of the maximum total dose of the system to the upset cross section on non total dose irradiated devices. If an SRAM or similar device is being tested, the upset cross sections must be determined at a minimum on devices characterized in the same and complement memory patterns as used for the total dose irradiated devices. If the upset cross section is determined to be sensitive to total dose, then all further testing must be performed on total dose irradiated devices (at a minimum). Also, the fluence levels that each device is exposed to will have to be kept at a minimum. For example, during a single SEU characterization a device may be exposed to a total dose of 2 krad(Si). As testing is continued, the total dose level the device is exposed to will continue to increase. Once this total dose level reaches an appreciable fraction (e.g., 10%) of the total dose level of the system, testing must be continued using new devices.

3) Determine Angular Sensitivity: The next test should determine whether or not the upset cross section depends on the proton angle of incidence. Note that this test does not have to be performed if it has been previously determined that devices built by the same manufacture in the same technology do not have an angular dependence. Adjust the angle of incidence to 90 degrees (grazing angle). Bias the device using the minimum bias supply voltage and if applicable program the device using the worst-case test pattern as determined above. Set the fluence as required to obtain approximately the desired number of upsets (based on the above tests). Irradiate the device and measure the number of upsets as described above on separate devices at angles of incidence of 0, 90, and 180 degrees. If the upset cross section at either 90 or 180 degrees is greater than two times the upset cross section at 0 degrees, all further testing needs to be performed at the angle of incidence that gave the highest upset cross section and at normal angle of incidence until the upset cross section at normal angle of incidence becomes larger than the upset cross section at the worst-case angle of incidence. Note that as the proton energy is decreased as described below, the thicker materials in the beam that are usually present at 90 and 180 degrees will degrade the proton beam more rapidly than at normal angle of incidence and will eventually attenuate the proton beam.

4) Determine Worst-Case Bias: In most cases, the worst-case bias for SEU is the minimum supply voltage. However, the worst-case bias for some device types could be the maximum supply voltage (e.g., floating body effects in silicon-on-insulator devices can be worse at high supply voltages potentially leading to higher SEU cross sections at the maximum supply voltage). The worst-case bias can be easily determined by characterizing the SEU cross section at the minimum and maximum supply voltages. Bias the device using the maximum bias supply voltage and if applicable program the device using the worst-case test pattern as determined above. Adjust the angle of incidence for worst-case conditions. Set the fluence as required to obtain the approximate number of desired upsets (based on the above tests). Irradiate the device and measure the number of upsets as described above. Compare the cross sections for minimum and maximum bias supply voltages. Henceforth, use the worst-case bias supply voltage. If there is no appreciable difference in the cross sections, use the minimum bias supply voltage.

5) Upset Cross Section Versus Proton Energy: Using the results from the above tests, the worst-case conditions are now known. The next step is to measure the upset cross section versus proton energy. This is required to determine the soft error rate in space environments. Decrease the proton energy. If the total dose cross section varies with total dose, mount a device total-dose irradiated to 80% of the total dose expected for the system level. If the total dose cross section does not vary with total dose, mount either a device previously total dose irradiated or a device not total dose irradiated. Bias the device using the worst-case bias supply voltage and if applicable program the device using the worst-case test pattern as determined above. Adjust the angle of incidence for worst-case conditions. For static tests, set the fluence as required to obtain the desired number of upsets (based on the above tests). Irradiate the device. For static tests, once the fluence has been reached, stop the test and record the number of upsets. If the number of upsets is close or greater than the desired number of upsets, the test can be stopped. Otherwise, the test should be continued up to the maximum fluence level. (Note that as the proton energy is decreased the cross section tends to decrease, thus, progressively higher fluence levels will be required to obtain the desired number of upsets. In fact, near the threshold energy for upsets, only a few upsets will likely be observed for reasonable test fluences). If a dynamic test is being performed, the number of upsets can be determined during irradiation and the fluence can be set at the maximum fluence level. The test can be stopped when the desired number of upsets are recorded. Repeat the above tests to determine the complete SEU cross section vs. proton energy curve until no further upsets are measured at the maximum fluence level or until the FWHM straggle in beam energy is greater than 25% of the target energy, whichever occurs first.

C. Proton Single-Event Latchup Test Flow

A general test flow for proton-induced single-event latchup testing is given in Figure 7.

1) Test Flow (Facilities with proton energies $>$400 MeV): The first step is to tell the facility operators to tune the beam to the highest proton energy of the facility and to the approximate flux required for the first test. To determine the facility conditions required to give a desired flux, consultation with a person experienced in operating the beam may be required. The flux can normally be as high as possible, unless a latchup cross section curve is being determined. In this case, the flux must be low enough to ensure that the time between latchups is significantly longer than the length of time required to reset power and clear a latchup. For example, if power is removed for 0.5 s when a latchup is detected, the flux should be low enough to prevent latchups occurring more often than every $\sim$10 s. On the other hand, the flux must be high enough to complete the tests in a reasonable time period. Note that for many test facilities, the flux cannot be sufficiently lowered to meet this requirement for some commercial technologies. If this is the case, the real SEL cross section will be much higher than the measured cross section. To account for this, the dead time associated with removing the bias must be subtracted from the irradiation time to determine the effective flux (fluence) to the device while it is in a biased state.

Connect cables from the test equipment to the DUT and to the system used to control the tests (normally a computer controlled system). Apply bias to the DUT and verify the bias levels at the DUT using a voltmeter. Make sure that the device is fully operational (this should have also been performed at some point prior to arriving at the remote site). Align the DUT in the center of the beam at normal angle of incidence and at the required distance from the exit port of the beam. Once the beam is aligned onto the DUT, enclose the DUT in an environmental chamber (if required). Heat the device to the maximum system operating temperature specification. Allow time for the temperature to stabilize (normally 5 to 10 minutes after reaching the desired temperature). Note that device operating current is often temperature dependent. Because of this and the fact that higher operating currents may lead to larger voltage drops in the test cabling, the DUT bias level should be re-verified once the temperature has stabilized. These steps should be performed prior to closing the doors to the beam room. Once the DUT is determined to be fully functional and the temperature is correctly set, testing can begin.

Close the doors to the beam room using the procedure given by the test facility. Request beam. At some facilities a facility operator must be called and at other facilities this can be done using computer systems provided by the facility.

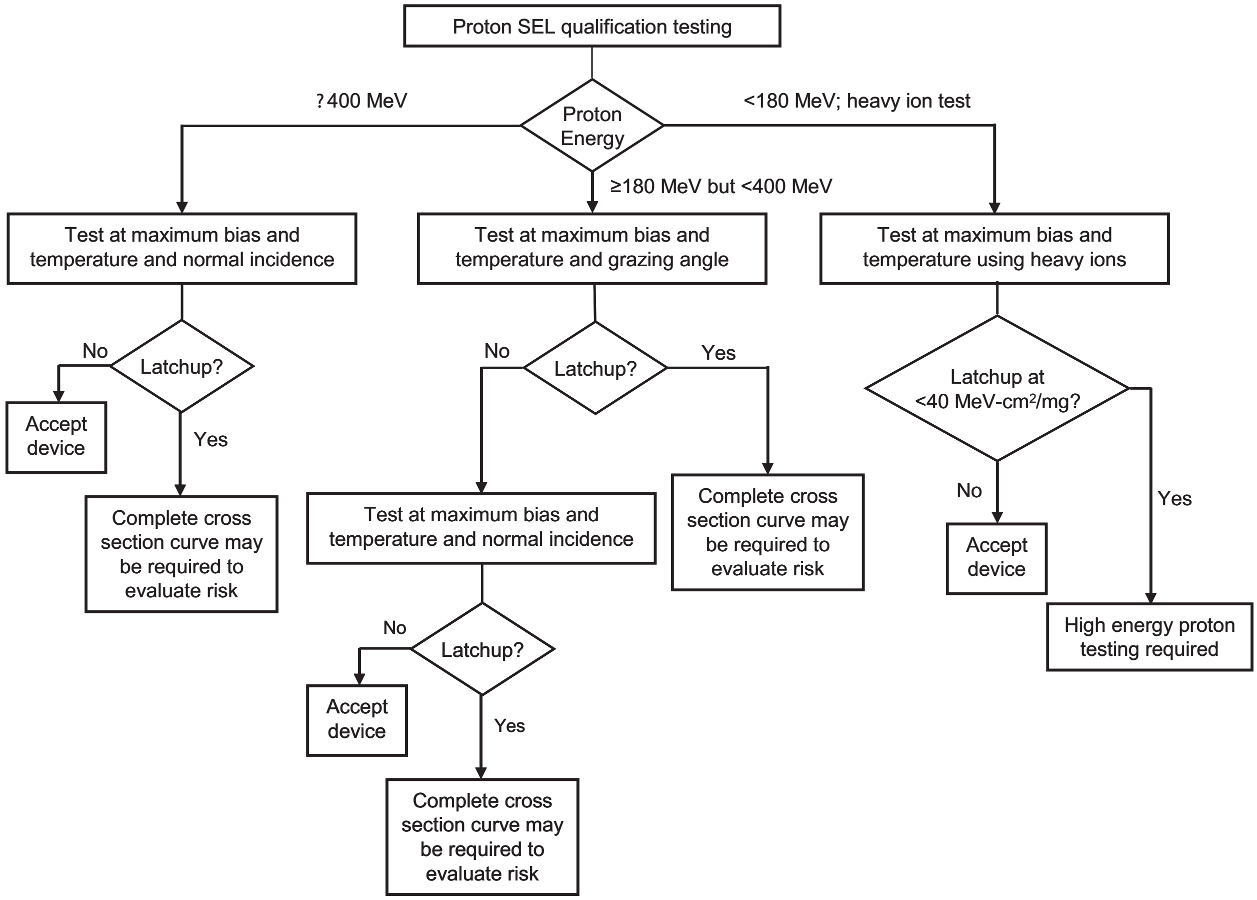

Fig. 7. Test flow for proton-induced SEL hardness assurance.

Bias the device using the maximum bias supply voltage and program the device if functional testing is to be performed. Set the fluence to the maximum fluence level. (This value is system dependent and should take into account the aggregate fluence if multiple devices of the same part type are used in the system.) Set the current level for recording a latchup to a value ten percent higher than the static bias supply current.

Irradiate the device. If a single latchup cannot be tolerated in system application, stop the irradiation if a latchup is recorded. The device has the failed the test. If no latchups are recorded at the maximum fluence level, the device passed the test and no further testing is required.

If some probability of latchup is acceptable, then a complete SEL cross section curve will be required to evaluate the risk of using the device in the system. If the latchup cross section is being determined, stop the irradiation if more than 100 latchups are recorded or irradiate to the maximum fluence, whichever comes first. Note that after each recorded latchup, the bias supply voltage must be removed for 0.5 s, and then the bias supply voltage must be reapplied and the device reprogrammed (if functional testing is being performed). If the number of latchups is greater than 100, the test can be stopped. If functional testing is being performed and at some point the device is no longer fully functional, latchup testing has caused permanent failure in the device and testing needs to be stopped. If no latchups are measured, the device should be retested for functionality. If functional testing is not possible at the facility, functional tests should be performed after return from the facility.

Decrease the proton energy. Repeat the tests above to determine the latchup cross section at the new proton energy. Continue decreasing the proton energy until no further latchups are measured at the maximum fluence level or until the FWHM straggle in beam energy is greater than 25% of the target energy, whichever occurs first.

2) Test Flow (Facilities with proton energies <400 MeV but >180 MeV): The first step is to tell the facility operators to tune the beam to the highest proton energy of the facility and to the approximate flux required for the first test. Setup the DUT as described above. Irradiate the device at angles of incidence of 0 and then at 85 degrees. (The choice of 85 degrees rather than 90 degrees is a practical choice that takes into account some possible misalignment of the device in the beam. If an angle of 90 degrees is chosen and the device is slightly misaligned resulting in an angle greater than 90 degrees, the sides of the test boards may become positioned in the beam line which may severely degrade the proton beam.) If a single latchup cannot be tolerated in the system application irradiate to the maximum fluence level (regardless of whether dynamic or static functional testing is being performed or if the device is allowed to power up in its preferred logic state). Stop the irradiation if a latchup is recorded. The device has the failed the test. If no latchups are recorded at the maximum fluence level at both 0 and 85 degrees, the device passed the test and no further testing is required.

If the latchup cross section is being determined, stop the irradiation if more than 100 latchups are recorded or irradiate to the maximum fluence, whichever comes first. Note that after each recorded latchup, the bias supply voltage must be removed for 0.5 s, and then the bias supply voltage must be reapplied and the device reprogrammed (if functional testing is being performed). If the number of latchups is greater than 100, the test can be stopped. If functional testing is being performed and at some point the device is no longer fully functional, latchup testing has caused permanent failure in the device and testing needs to be stopped. If no latchups are measured, the device should be retested for functionality. If functional testing is not possible at the facility, functional tests should be performed after return from the facility. Perform the tests for angles of incidence of both 0 and 85 degrees.

Decrease the proton energy. Repeat the tests above to determine the latchup cross section at the new proton energy at both 0 and 85 degrees. Continue decreasing the proton energy until no further latchups are measured at the maximum fluence level or until the FWHM straggle in beam energy is greater than 25% of the target energy, which ever occurs first.

3) Test Flow (Facilities with proton energies <180 MeV): Proton testing at facilities with maximum proton energies less than 180 MeV should not be performed. The SEL probability can be significantly underestimated using low proton energy facilities. If proton facilities capable of producing protons with energies above 180 MeV are not available, testing should be performed using a heavy-ion source. If test results using a heavy-ion source show that the SEL threshold is above an LET of 40 MeV-cm^2/mg, it is very unlikely the device will latch up due to proton exposure. If the SEL threshold is below an LET of 40 MeV-cm^2/mg, the device may latch up due to proton exposure. If this occurs the user may want to take a complete SEL cross section curve versus ion LET to evaluate the risk of using the device in the system. A detailed test guideline for performing heavy-ion SEL testing is given elsewhere in this document.

V. Heavy-Ion-Induced Single-Event Effects Hardness Assurance Testing

It is normally best (but not necessary) that heavy-ion-induced upset testing be performed prior to heavy-ion-induced latchup testing. Latchup testing requires elevated temperature irradiations while upset testing often does not require elevated temperature testing. It is simpler to perform room temperature irradiations first and then elevated temperature irradiations because of the time required to cool devices back down to room temperature. Also, latchup testing can potentially be destructive.

A. Pre-Test Setup

1) Radiation Source: The radiation source must be capable of providing a range of monoenergetic ions with high energies. The ion energy must be high enough such that the ion can penetrate deep enough into the active region of the semiconductor with sufficient LET to capture all mechanisms that can lead to SEU or SEL. Failure to do so can lead to erroneous results. Note that if the mechanisms for SEU or SEL are not captured, even significant overtests will not ensure part functionality in space. For some devices with moderate to high SEU or SEL thresholds, high energy ions can also cause nuclear interactions creating secondary particles that can trigger SEU or SEL for incident ions with LETs below the apparent LET threshold; whereas, lower energy ions may not trigger SEU or SEL. Because of these effects, for any given LET, the worst-case ion energy is the highest ion energy. All heavy-ion radiation sources will provide users with the range of ions in materials. The simplest method for determining the depth of active regions, overlayer thicknesses, etc. is to contact the manufacturer. However, because manufacturers are reluctant to give specifics of device fabrication, determination of depths of active regions, overlayer thicknesses must often be found from destructive physical analysis of sample devices. This should be done before selecting the radiation facility used for hardness assurance testing. The ranges of ions obtainable from some radiation facilities are not sufficient for ensuring that all failure mechanisms are captured. This is especially true for advanced IC technologies which can have very thick overlayers of oxides and metals.

Note that at some heavy-ion ion facilities, ions can be changed almost as rapidly as it takes to change devices. Because repeated device changes increase the risk of damaging devices, test fixtures, and cabling, for these facilities it is best to measure the entire upset or latchup cross section curve versus LET on a single device (or set of devices on a single test board) than to change devices. For other facilities, ions cannot be readily changed and for these facilities it is best to characterize multiple devices before changing ions.

2) Personnel: Many remote test sites operate 24 hours per day, 7 days per week. Bringing a limited number of people to a remote test can result in very long days and nights for each individual and may result in the inefficient use of the test facility. Having sufficient people to take data and perform preliminary data analysis during the test is essential for optimum use of the facility and for ensuring the quality of the data.

3) Dosimetry: Dosimetry must be provided by the facility. Understanding the method used for dosimetry measurements can be very helpful. However, to verify the accuracy of the dosimetry, one should provide a secondary method. Another approach is to measure the SEU cross section on previously characterized devices that are not sensitive to total dose effects. As long as the SEU or SEL cross section is not impacted by total dose, for a given LET in the saturation region, the SEU or SEL cross section should not vary significantly for different ion conditions (i.e., specie or energy). As a result, if significant differences are observed, this is a strong indication that either the dosimetry is incorrect or there are problems associated with the measurement system. In either case, the cause of the differences should be resolved before testing is continued. For SEU and SEL testing, the dosimetry must be sufficient to ensure that the fluence is known with an accuracy of $\pm$10%. The flux must be high enough to achieve the target fluence within a reasonable time period. For both SEU and SEL testing, a typical heavy-ion flux range is 10^4 to 10^6 ions/cm^{2}s.

Users should consult with facility operators to determine the facility procedures for specifying device passivation overlayers and for determining the LET of ions at the active device surface. Heavy ion LET in the sensitive volume depends on the type and thickness of overlayers in the device and the depth of the sensitive volume in the material. The effects of passing through various materials on LET can be readily calculated, and most automated heavy-ion SEE test facilities provide for this calculation as a part of their dosimetry. However, if the device overlayers' composition and thicknesses are not precisely known, it is best not to enter overlayer materials and thicknesses when performing the heavy-ion characterizations, but rather to simply record the incident LET at the outer device surface. Deconvolving the LET at the surface from the LET calculated assuming different overlayers and thicknesses can be extremely difficult.

4) Test Circuit Boards: Devices to be irradiated should either be mounted on or connected to circuit boards together with any associated circuitry necessary for device biasing during irradiation or for in-situ measurements. Figure 8 is a photograph of a typical test board used at Brookhaven National Laboratory's tandem van de Graaff. Unless otherwise specified, all device input terminals and any others which may affect the radiation response should be electronically connected during irradiation, i.e., not floating. The geometry and materials of the completed board should allow uniform irradiation of the device under test (DUT). Good design and construction practices should be used to prevent oscillations, minimize leakage currents, prevent electrical damage, and obtain accurate measurements. Only sockets that are radiation resistant and do not exhibit significant leakages (relative to the device under test) should be used to mount devices and associated circuitry to the test board(s). All apparatus repeatedly used in radiation fields should be checked periodically for physical or electrical degradation. Components which are placed on the test circuit boards, other than DUT, should be insensitive to accumulated heavy-ion total dose or shielding must be used. Note that for most heavy-ion sources, the energies of the ions are low enough such that moderately thick materials can completely attenuate the ion beam. Unless it is absolutely necessary that test circuitry be located immediately adjacent to the DUT, the test circuitry should be located a distant that is at least twice the diameter of the heavy-ion beam from the DUT. The diameter of the heavy-ion beam will vary from facility to facility and often can be controlled by the user. Typical values can vary from 2 to 5 cm. For many tests, test circuitry does not have to be located on the same board as the board used for the devices under test. For these cases, all test equipment (including bias supplies) can be located farther away from the DUT. However, the equipment must not be located too far from the DUT such that the integrity of the test system is compromised. Whenever possible, board and package designs should minimize the use of materials that have long radioactive half lives. The use of high-Z materials (e.g., tungsten) and hazardous materials (e.g., lead) should be avoided (although radioactivity issues are less of a problem at most heavy-ion facilities than at proton facilities). If temperature testing is required, the test circuit boards, sockets, etc. must be capable of withstanding the temperatures to be used.

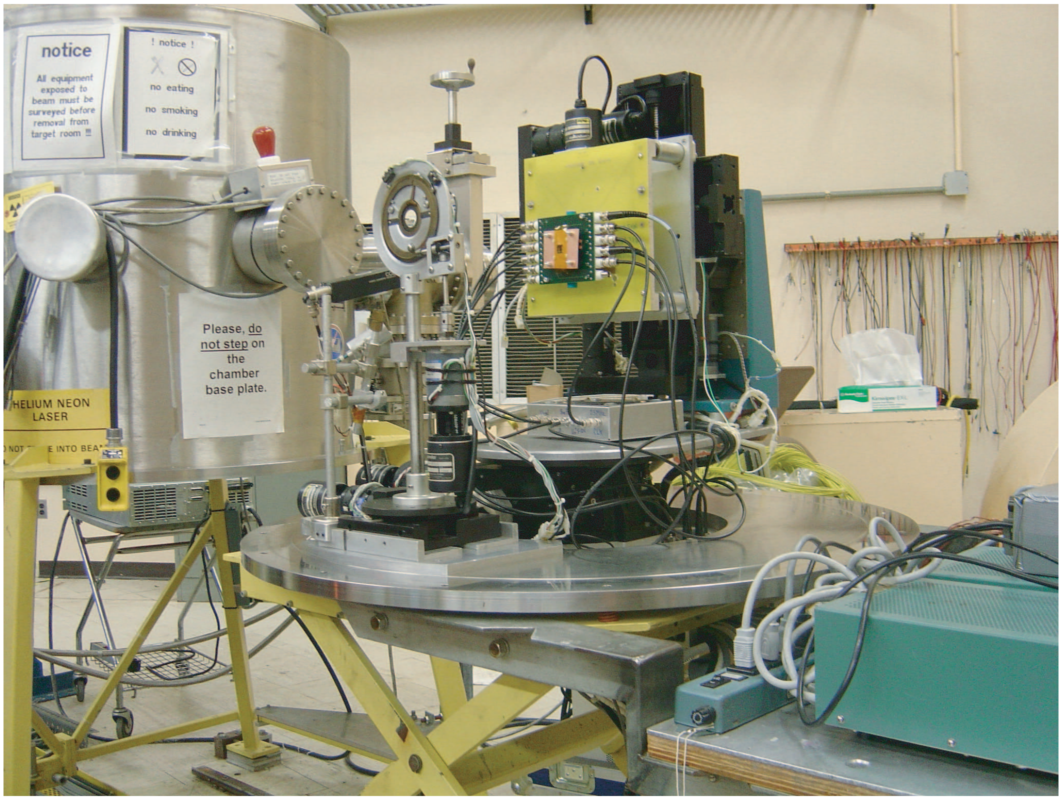

Fig. 8. Typical test board used at Brookhaven National Laboratory's tandem van de Graaff.

5) Cabling: Good cabling is extremely important and should be verified for proper operation before conducting remote site tests. Many problems encountered during testing are related to faulty cabling, i.e., shorted, open, or intermittently shorted or open cables. Proper handling of cables is essential. Cables connecting the test measurement equipment to the test circuit boards should be as short as possible. The cables should have low capacitance and low leakage between wires. The impedance associated with long cables can potentially affect bias levels to the DUT, high frequency measurements, etc. Bias levels should always be verified at the DUT using a voltmeter prior to irradiation. Longer cables can be used to connect the test measurement equipment to computer systems used to control the test equipment, and to collect and analyze data. Cable lengths of greater than 50 feet to connect test equipment to to computer systems used to control the test equipment are not uncommon at many remote test facilities. Users must contact test facility operators prior to the test to determine the minimum lengths of cables required at the facility. Note that for some heavy-ion test facilities (including Texas A&M), the experimenters are in a different room shielded from the beam room (normally by extremely large concrete blocks).

6) Environmental Chamber: For low-energy ($<$ 10 MeV/u) heavy-ion facilities, environmental chambers (e.g., vacuum chambers) are usually used and tests must be conducted under vacuum to prevent excessive energy loss of the heavy ions in air. For higher-energy heavy-ion facilities testing can be performed in the open air, which can greatly simplify test setup and cabling issues.

7) Temperature Control: Temperature can be controlled in several different ways. For example, resistive heater strips can be used between the device under test and the device socket. By controlling the power to the heater strip the temperature can be varied. Another method for controlling temperature is to use an environmental chamber (this method is only feasible for heavy-ion irradiations in the open air). Because the energies of heavy ions available at most heavy-ion test facilities are not high enough to permit ions to penetrate the walls of an environmental chamber, the top of the chamber over the DUT must be clear of all materials. In this method, hot air is forced into the environmental chamber using a heated air gun. By controlling the temperature and air flow of the heat gun, the temperature can be easily varied remotely. This type of heating is especially useful for cases where heater strips cannot be readily placed between the device socket/board and DUT, or where it is desired to heat a larger subsystem.

Accurate temperature measurements are key to repeatable SEE testing at elevated temperatures. For either method of heating, a thermocouple must be connected to the device package to monitor the temperature. Temperature can be controlled automatically by using the measured temperature to control the output of a bias supply. Placement of the thermocouple close to the DUT and maintaining good thermal contact to the DUT are critical for accurate temperature measurements. Ideally, thermocouples should be connected at multiple locations to determine temperature variations across the package. An alternate method for monitoring the temperature is to characterize input diode forward voltage for a given current as a function of temperature. This technique can be used to give accurate measurements of temperature on the test die. Diodes are available on many devices (e.g, input protection diodes, drain-to-substrate diodes, etc.) These diodes can be calibrated in advance using well-controlled thermal environmental chambers, for example by placing the device in a well-characterized oven and measuring the diode forward voltage as the oven temperature is varied. Since the diode voltage is strongly dependent on the die temperature, this method gives a sensitive measurement of the actual die temperature and can be performed prior to the test, with plenty of time allotted for the device to stabilize at the oven temperature. Regardless of the method used for monitoring temperature, the temperature is typically not known within an accuracy better than $\pm$5%. As a result, to ensure that the temperature meets system requirements, the temperature should be set for a value that is 5% higher than the maximum system or device operation temperature (as appropriate).

8) Test Circuit Board Alignment: The DUT must be aligned in the center of the beam at the required angle. The size of the beam will limit the number of devices that can be tested in a single test run. The area to be irradiated must be smaller than the beam diameter. The variation in beam flux can vary considerably across the beam. The beam flux should not vary by more than 20% across the area to be irradiated. Most heavy-ion facilities provide some type of laser alignment. At Texas A&M, lasers and a camera collinear with the beam can be used to align the devices under test in the beam. If the heavy-ion irradiations are to be performed in the open air as can be done at Texas A&M, the distance that ions travel in air must be taken into account when calculating the LET at the device surface. All heavy-ion facilities have apparatus for varying the angle of incidence. Care must be taken to ensure that the sides of the device package do not block the beam at high angles of incidence and that when changing the angle of incidence, the beam is still aligned in the x, y, and z positions. Because of the increased possibility of beam shadowing at high angles of incidence and because the effective LET approximation breaks down for large angles, we recommend limiting the maximum angle of incidence to $\sim$45°, particularly for bulk Si technologies.

9) Upset Characterization: The upset cross section should be characterized using multiple test conditions (e.g., static and dynamic tests if possible) and test patterns. For example, the heavy-ion SEU cross section of SRAMs can be characterized in a static mode. In a static mode, devices are written with a specific pattern to the memory array, irradiated to a given fluence, and after the beam is turned off the parts are read and errors are counted. For this type of test, multiple test patterns can be used for characterization. One typical pattern is a checkerboard pattern (a logical series of 1's and 0's), however, since all 0's and all 1's patterns are usually easy to implement, it is recommended to compare the SEU sensitivity using all three patterns (checkerboard, 1's, and 0's) first to determine if there is any SEU pattern dependence before choosing a pattern for complete characterization. If the logical to physical mapping for an SRAM is known, vector maps should be generated to distinguish between single and multiple bit upsets, and to verify that the upsets are not due to single-event latchup. If possible, this error mapping should be performed in real-time at the test site to assess any beam non-uniformities or shadowing by the package. Of course, to fully characterize ICs in all the different possible test conditions is not possible because of budgets and time constraints. For example, synchronous DRAMs and microprocessors may have many distinctly different modes of operation. Thus, it is important to work with the end users to develop test conditions that closely match actual system use conditions. SEU cross sections are normally specified in units of either SEU-sensitive area per device (e.g., cm^2/device) or SEU-sensitive area per bit (in memories).

10) Latchup Characterization: Ideally, a latchup test should allow for both functional testing and current monitoring. Some parts are known to show only small increases in currents and without functional testing it may be difficult to detect such "microlatchups." Functional tests could also be used to detect single-event snapback in SOI devices where the increase in static power supply current can be very small. By examining vector maps and by recycling the power supply, single-event latchups (and single-event snapback) can be distinguished from single-event upsets, single-event functional interrupts, etc. For cases where functional testing is not practical, devices can be characterized in their preferred power-up logic state, i.e., they do not have to be written with a specific pattern prior to exposure. For this case, the power supply current must be continuously monitored during irradiation. When the power supply current increases to above a preset limit a latchup is recorded. To measure a latchup cross section, multiple latchups must be recorded as a function of proton fluence. To measure multiple latchups, after a latchup is first recorded, the power supply voltage must be quickly removed for a short period of time (e.g., 0.5 s) to clear the latchup state, the power supply voltage must be reapplied, and the latchup test can be continued. (Note that one must account for this dead time when determining the effective SEL cross section at a given heavy-ion LET. Also, to keep the dead time correction small the time between latchups should be much longer than the time period chosen for removing the bias.) The preset limit should be set to a current 10% above the static current for the device. Note that this current can change with temperature and total dose. As a result, it may have to be adjusted as testing continues. To avoid catastrophic device failure caused by repeated latchup testing, the device current should be limited to a safe operating value.

11) Total Dose Irradiation: Because the single-event upset cross section of some devices is sensitive to total dose effects, unless known otherwise, it should be assumed that the SEU cross section of devices under test will be sensitive to total dose effects. Note that whether or not a device will be sensitive to total dose effects can depend on details of both fabrication steps used to make the device and circuit design. As a result, devices built in the same technology by the same manufacturer may have different sensitivities to total dose. If testing is to be performed for satellite systems, devices can be irradiated prior to the tests using standard Co-60 gamma sources because of the long times associated with satellite system operation. Devices should be irradiated using worst-case total dose test conditions. For most devices, this is maximum power supply voltage. To determine if devices are sensitive to total dose effects a set of devices should be irradiated to 80% of the total dose level of the system requirement. Devices must be fully functional immediately after irradiation. Devices can be annealed under bias at room temperature as long as the anneal time is short compared to the duration the devices will be in the system. This actually provides for more realistic simulation of device radiation-induced degradation in satellite environments than if devices are not annealed. The measured upset cross sections on total dose irradiated devices should be compared to the upset cross sections measured on non-total dose irradiated devices. If the maximum cross section for the total dose irradiated devices is more than 10 times the maximum cross section for the non-irradiated devices, the devices should be considered as total dose sensitive. Note that this difference of 10 times is somewhat arbitrary and larger or smaller values may be used depending on the sensitivity of the system to single-event upsets. If the device's SEU cross section is determined to be total dose sensitive, all testing needs to be performed at a minimum on total dose irradiated devices. If time permits and sufficient devices are available, tests should also be performed on non-total dose irradiated devices to determine differences in upset rates during space flight. Note that experimental data taken on present-day SRAMs have shown that only devices that exhibit an increase in static supply leakage current with total dose exhibit a total dose sensitivity of the upset cross section. Hence, if the static supply leakage current does not increase with total dose, it is probably not necessary to compare the upset cross section of total dose irradiated and non total dose irradiated devices and all testing can be performed on non total dose irradiated devices.

B. Heavy-Ion Induced Single-Event Upset Test Flow

A general test flow for heavy ion-induced single-event upset testing is given in Figure 9. The first test should be performed on a device that has not been total dose irradiated. (Unanticipated problems often occur during the first test. By using a non total dose irradiated device for the first test(s), the number of total dose irradiated devices can be kept at a minimum.) Connect cables from the test equipment to the DUT and to the system used to control the tests (normally a computer controlled system). Apply bias to the DUT and verify the bias levels at the DUT using a voltmeter. Test the device using at a minimum the test patterns and bias levels that will be used during the tests. Make sure that it is fully operational (this should have also been performed at some point prior to arriving at the remote site). Align the DUT in the center of the beam. Once the beam is aligned onto the DUT, enclose the DUT in an environmental chamber (if required). Heat the device if required. Allow time for the temperature to stabilize (normally 5 to 10 minutes after reaching the desired temperature). Note that all of this should be performed prior to evacuating the test chamber or closing the doors to the beam room. Once the DUT is determined to be fully functional and the temperature is correctly set, testing can begin.

Close the doors to the beam room using the procedure given by the test facility or evacuate the test chamber as appropriate. Request from the facility that they tune the beam for the desired ion and LET, and approximate flux required for the first test. To determine the facility conditions required to give a desired flux, consultation with a

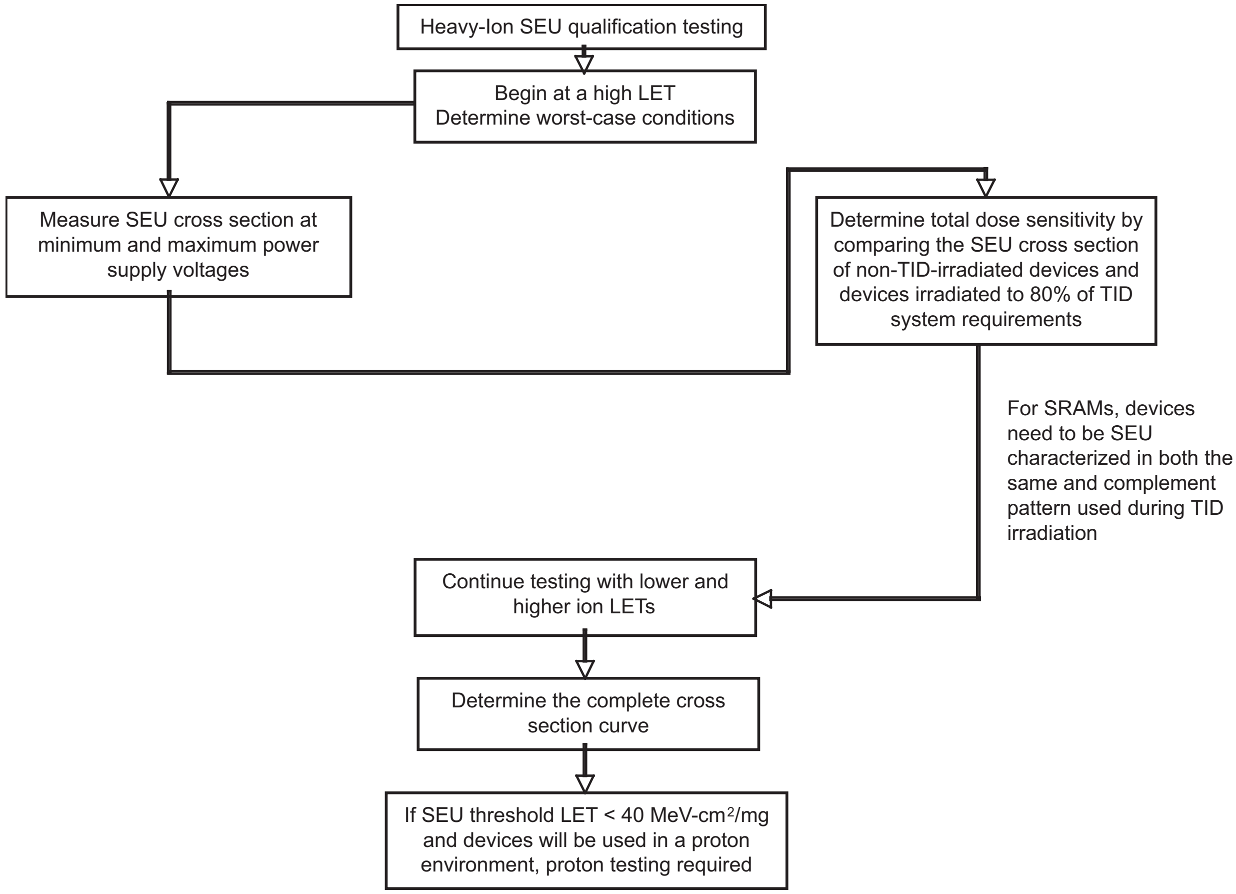

Fig. 9. Test flow for heavy ion-induced SEU hardness assurance.

person experienced in operating the beam may be required. The first test should be performed at a high LET, well above the expected LET threshold on devices that have not been total dose irradiated. Approximate values for the LET threshold can often be found in the literature, can be based on past experience, or determined in consultation with experienced radiation test personnel. For many commercial devices, LETs of greater than 30 MeV-cm^2/mg meet this requirement.

Bias the device using the minimum bias supply voltage and program the device using the same test pattern as was used for the total dose irradiations (if applicable). Set the fluence to the maximum fluence required by system operation. (This value is system dependent.)

1) General Characterization Test: Irradiate the device. For dynamic tests, stop the irradiation when the desired number of upsets is obtained or irradiate to the maximum fluence, whichever comes first. For maximum statistical confidence in the data, the number of upsets should be as high as feasible (>100), but not more than 1% of the total memory if an SRAM or similar device is being tested. For static tests, once the fluence has been reached, read the device and record the number of upsets. If the number of upsets is greater than the desired number of upsets, the test can be stopped. Otherwise, the test should be continued. Estimates of the required fluence may be obtainable from the first measurements. If an SRAM or similar device is being tested and the number of upsets is a significant fraction of the total memory of the device (greater than 1%), tests should be started over to a smaller fluence level (as appropriate to yield the desired number of upsets). Note that after each test, the DUT should be reprogrammed using the same pattern used during irradiation. If no errors are measured, testing can proceed as needed. If errors are measured after reprogramming the DUT, the bias supply should be removed for 0.5 s, the bias should be reapplied, and the device should be reprogrammed. If errors are still detected the device is no longer functional and testing must be continued on a new device. If the device is fully functional after cycling power, this is a possible indication that the device latched up during the test. If the device did latchup, the number of upsets is erroneous and cannot be used to calculate the soft error rate. For the number of errors to be valid, the DUT cannot latchup during testing. If latchups continually occur during testing at a high rate, it may not be possible to measure the upset cross section for the device. Whether or not the device is usable will depend on system application and the heavy-ion LETs at which the latchups occur. Note that the bias supply voltage that normally corresponds to worst-case conditions for SEU testing is normally the least sensitive bias conditions for SEL testing.

2) Determine Total Dose Sensitivity: Compare the upset cross sections on devices total dose irradiated to 80% of the maximum total dose of the system to the upset cross section on non total dose irradiated devices. If an SRAM or similar device is being tested, the upset cross sections must be determined at a minimum on devices characterized in the same and complement memory patterns as used for the total dose irradiated devices. If the upset cross section is determined to be sensitive to total dose, then all further testing must be performed on total dose irradiated devices (at a minimum).

3) Determine Worst-Case Bias: The next test should determine the worst-case bias supply voltage. This does not need to be done for standard bulk-silicon devices. However, it may be a concern for silicon-on-insulator and other types of devices. Bias the device using the maximum bias supply voltage and if applicable program the device using the worst-case test pattern as determined above. Set the fluence as required to obtain the approximate number of desired upsets (based on the above tests). Irradiate the device and measure the number of upsets as described above. Compare the cross sections for minimum and maximum bias supply voltages. Henceforth, use the worst-case bias supply voltage. If there is no appreciable difference in the cross sections, use the minimum bias supply voltage.

4) Upset Cross Section Versus Heavy-Ion LET: Using the results from the above tests, the worst-case conditions are now known. The next step is to measure the upset cross section versus heavy-ion LET. This is required to determine the soft error rate in space environments. Without changing the ion or its energy, increase the angle of incidence to increase the effective ion LET. Typical angles of incidence could be 0, 30, and 45 degrees. For bulk silicon devices it is not recommended to exceed 45 degrees, since the effective LET approximation becomes more inaccurate above this angle. Care must be taken to ensure that the sides of the device package do not block the beam. If the SEU cross section varies with total dose, mount a device total-dose irradiated to 80% of the total dose expected for the system level. If the SEU cross section does not vary with total dose, mount either a device previously total dose irradiated or a device not total dose irradiated. Bias the device using the worst-case bias supply voltage and if applicable program the device using the worst-case test pattern as determined above. For static tests, set the fluence as required to obtain the desired number of upsets (based on the above tests). Irradiate the device. For static tests, once the fluence has been reached, stop the test and record the number of upsets. If the number of upsets is close or greater than the desired number of upsets, the test can be stopped. Otherwise, the test should be continued up to the maximum fluence level. (Note that as the ion LET is increased the cross section tends to increase, thus, progressively higher fluence levels will result in more upsets. Conversely, as the ion LET is decreased the cross section tends to decrease and higher fluence levels will be required to obtain the desired number of upsets.) If a dynamic test is being performed, the number of upsets can be determined during irradiation and the fluence can be set at the maximum fluence level. The test can be stopped when the desired number of upsets are recorded. Once completed, change to a different ion and repeat the tests until the LET has been sufficiently decreased such that the LET threshold has been determined. We suggest a minimum fluence of 5×10^7 ions/cm^2 be used to determine the LET threshold at which upsets no longer occur. Similarly, increase the LET until the SEU cross section has saturated or the maximum LET of the facility has been reached. It may be useful to plot the SEU cross section vs. LET on a log-log plot to determine if saturation has occurred. If the SEU threshold LET is observed to be < 40 MeV-cm^2/mg and the device will be used in a proton environment, we recommend that proton testing also be performed to determine the proton SEU sensitivity of the device. Conversely, if no upsets are observed below 40 MeV-cm^2/mg, proton testing is not necessary. For this reason it is sometimes more efficient to perform heavy ion testing of a part prior to proton testing, since the heavy ion results may rule out the necessity for subsequent proton testing.

C. Heavy-Ion Induced Single-Event Latchup Test Flow

A general test flow for heavy ion-induced single-event latchup testing is given in Figure 10. The first step is to tell the facility operators to tune the beam to the ion and energy that gives the highest LET of the facility and to the approximate flux required for the first test. To determine the facility conditions required to give a desired flux, consultation with a person experienced in operating the beam may be required. The flux can normally be as high as possible, unless a latchup cross section curve is being determined. In this case, the flux must be low

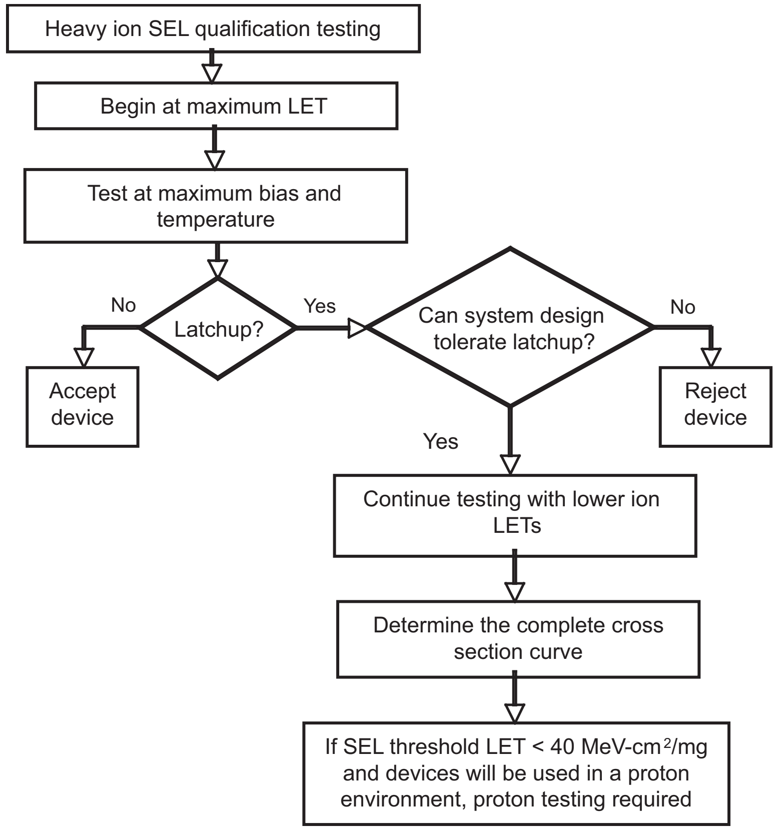

Fig. 10. Test flow for heavy ion-induced SEL hardness assurance.

enough to ensure that the time between latchups is significantly longer than the length of time required to reset power and clear a latchup. For example, if power is removed for 0.5 s when a latchup is detected, the flux should be low enough to prevent latchups occurring more often than every $\sim$10 s. On the other hand, the flux must be high enough to complete the tests in a reasonable time period. Note that for many test facilities, the flux cannot be sufficiently lowered to meet this requirement for some commercial technologies. If this is the case, the real SEL cross section will be much higher than the measured cross section. To account for this, the dead time associated with removing the bias must be subtracted from the irradiation time to determine the effective flux (fluence) to the device while it is in a biased state.

Connect cables from the test equipment to the DUT and to the system used to control the tests (normally a computer controlled system). Apply bias to the DUT and verify the bias levels at the DUT using a voltmeter. Make sure that the device is fully operational (this should have also been performed at some point prior to arriving at the remote site). Align the DUT in the center of the beam at normal angle of incidence and at the required distance from the exit port of the beam. Once the beam is aligned onto the DUT, enclose the DUT in an environmental chamber (if required). Heat the device to the maximum system operating temperature specification. Allow time for the temperature to stabilize (normally 5 to 10 minutes after reaching the desired temperature). Note that device operating current is often temperature dependent. Because of this and the fact that higher operating currents may lead to larger voltage drops in the test cabling, the DUT bias level should be re-verified once the temperature has stabilized. These steps should be performed prior to closing the doors to the beam room. Once the DUT is determined to be fully functional and the temperature is correctly set, testing can begin.

Close the doors to the beam room using the procedure given by the test facility. Request beam. At some facilities a facility operator must be called and at other facilities this can be done using computer systems provided by the facility.

Bias the device using the maximum bias supply voltage and program the device if functional testing is to be performed. Set the fluence to the maximum fluence level. (This value is system dependent and should take into account the aggregate fluence if multiple devices of the same part type are used in the system.) Set the current level for recording a latchup to a value ten percent higher than the static bias supply current.

Irradiate the device. If a single latchup cannot be tolerated in system application, stop the irradiation if a latchup is recorded. The device has the failed the test. If no latchups are recorded at the maximum fluence level, the device passed the test and no further testing is required.

If some probability of latchup is acceptable, then a complete SEL cross section curve will be required to evaluate the risk of using the device in the system. If the latchup cross section is being determined, stop the irradiation if more than 100 latchups are recorded or irradiate to the maximum fluence, whichever comes first. Note that after each recorded latchup, the bias supply voltage must be removed for 0.5 s, and then the bias supply voltage must be reapplied and the device reprogrammed (if functional testing is being performed). If the number of latchups is greater than 100, the test can be stopped. If functional testing is being performed and at some point the device is no longer fully functional, latchup testing has caused permanent failure in the device and testing needs to be stopped. If no latchups are measured, the device should be retested for functionality. If functional testing is not possible at the facility, functional tests should be performed after return from the facility.

Vary the ion LET by first changing the angle of incidence and second by changing the ion. Repeat the tests until no further latchups are measured at the maximum fluence level. If the SEL threshold LET is observed to be < 40 MeV-cm^2/mg and the device will be used in a proton environment, proton testing must be performed to determine the proton SEL sensitivity of the device. Conversely, if no upsets are observed below 40 MeV-cm^2/mg, proton testing is not necessary. For this reason it is sometimes more efficient to perform heavy ion testing of a part prior to proton testing, since the heavy ion results may rule out the necessity for subsequent proton testing.

D. Heavy-Ion Induced Single-Event Burnout Test Flow

A general test flow for heavy ion-induced single-event burnout and gate rupture testing is given in Figure 11. The first step is to tell the facility operators to tune the beam to the ion and energy that gives the highest LET and to the approximate flux required for the first test. Setup the DUT as described above. Connect cables from the test equipment to the DUT and to the system used to control the tests (normally a computer controlled system). Apply bias to the DUT and verify the bias levels at the DUT using a voltmeter. Make sure that the device is fully operational by taking transistor current-voltage curves. Align the DUT in the center of the beam at normal angle of incidence and at the required distance from the exit port of the beam. Once the DUT is determined to be fully functional, testing can begin.

Close the doors to the beam room using the procedure given by the test facility. Request beam. At some facilities a facility operator must be called and at other facilities this can be done using computer systems provided by the facility.

Bias the device using the maximum drain bias supply voltage. Set the fluence to the maximum fluence level. (This value is system dependent and should take into account the aggregate fluence if multiple devices of the same part type are used in the system.) Set the drain current level for recording an SEB event to a value ten percent higher than the static drain bias supply current. If non-destructive SEB testing is to be performed, limit the maximum drain current that can be drawn, for example by inserting a current-limiting resistor in the drain leg of the test circuit. Irradiate the device at normal angle of incidence (varying the angle of incidence to vary the effective LET is not allowed for SEB testing). If a single SEB event cannot be tolerated in system application irradiate to the maximum fluence level. Stop the irradiation if an SEB event is recorded. The device has the failed the test. If no SEB events are recorded at the maximum fluence level, the device passed the test and no further testing is required. If some risk of SEB can be accepted or if the device voltage can be de-rated (lowered), then it is advisable to map out the SEB cross section and/or the SEB voltage threshold vs. ion LET.

If the SEB cross section is being determined, stop the irradiation if more than 100 SEB events are recorded or irradiate to the maximum fluence, whichever comes first. Note that after each recorded SEB event, the bias supply voltages must be removed for 0.5 s, and then the bias supply voltages must be reapplied. If the number of SEB events is greater than 100, the test can be stopped. If no SEB events are measured, the device should be retested for functionality (i.e., current-voltage curves should be taken).

Vary the ion LET by changing the ion or its energy. Repeat the tests until no further SEB events are measured at the maximum fluence level. If the SEB threshold LET is observed to be < 40 MeV-cm^2/mg and the device will be used in a proton environment, proton testing must be performed to determine the proton SEB sensitivity of the device. Conversely, if no upsets are observed below 40 MeV-cm^2/mg, proton testing is not necessary.

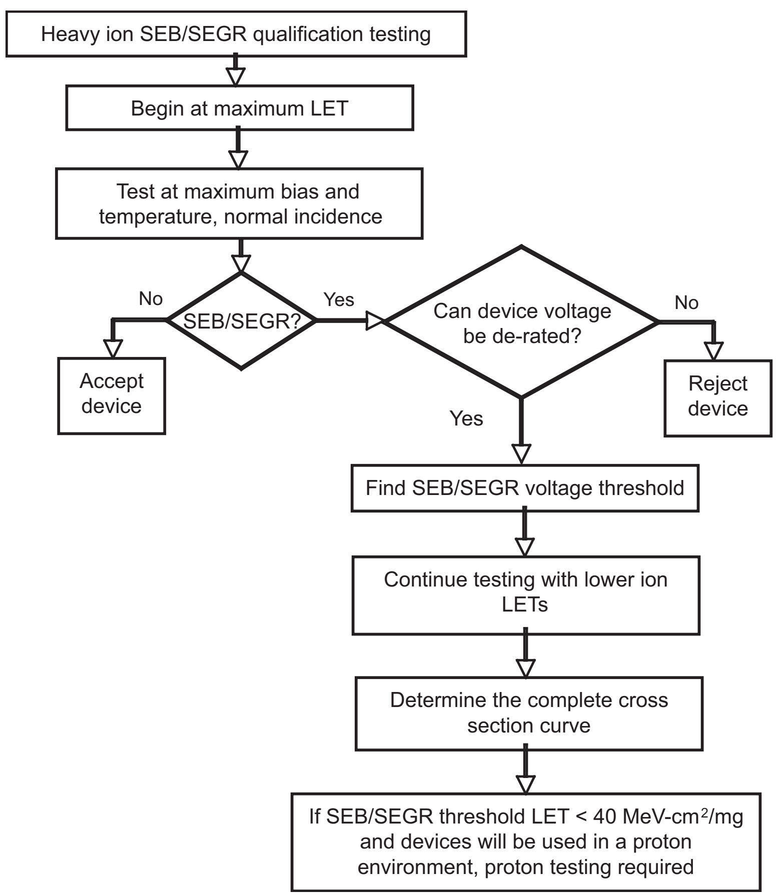

Fig. 11. Test flow for heavy ion-induced SEB/SEGR hardness assurance.

E. Heavy-Ion Induced Single-Event Gate Rupture Test Flow

A general test flow for heavy ion-induced single-event burnout and gate rupture testing is given in Figure 11. The first step is to tell the facility operators to tune the beam to the ion and energy that gives the highest LET and to the approximate flux required for the first test. Setup the DUT as described above. Connect cables from the test equipment to the DUT and to the system used to control the tests (normally a computer controlled system). Apply bias to the DUT and verify the bias levels at the DUT using a voltmeter. Make sure that the device is fully operational by taking transistor current-voltage curves or testing a memory for functionality. Align the DUT in the center of the beam at normal angle of incidence and at the required distance from the exit port of the beam. Once the DUT is determined to be fully functional, testing can begin.

Close the doors to the beam room using the procedure given by the test facility. Request beam. At some facilities a facility operator must be called and at other facilities this can be done using computer systems provided by the facility.

Bias the device using the maximum gate bias supply voltage for a transistor, and input and bias supply voltages to result in the maximum write voltage for a nonvolatile memory. Other device types should be biased at the maximum power supply voltage level. Nonvolatile memories should be tested in a write operation. Set the fluence to the maximum fluence level. (This value is system dependent and should take into account the aggregate fluence if multiple devices of the same part type are used in the system.) For a transistor, set the gate current level for recording an SEGR event to an appropriate value (well above the noise of the system, but small enough to detect noticeable increases in gate current; values from 1 nA to 1 μA normally meet this criteria). Irradiate the device at normal angle of incidence (varying the angle of incidence to vary the effective LET is not allowed for SEGR testing). For transistors or discrete devices, stop the irradiation if the current increases dramatically. If possible, measure the current-voltage characteristic to confirm that an SEGR has occurred. If so, the device has the failed the test at that LET. For nonvolatile memories or other ICs, irradiate to the maximum fluence level and test the IC for functionality and increases in static supply leakage current. If the IC is no longer functional or large permanent increases in supply current have resulted, the device has the failed the test at that LET. If no SEGR events are recorded at the maximum fluence level, the device passed the test and no further testing is required. If some risk of SEGR can be accepted or if the device voltage can be de-rated (lowered) for the system application, then it is advisable to map out the SEGR cross section and/or the SEGR voltage threshold vs. ion LET. Derating a higher-voltage device is often used for power MOSFET applications, since it lowers the oxide electric field and reduces the SEGR sensitivity.

Further testing can be performed to determine the threshold LET for SEGR (if desired). Vary the ion LET by changing the ion or its energy. Repeat the tests until no further SEGR events are measured at the maximum fluence level and at the desired voltage level. Similarly, the SEGR threshold voltage for a given ion LET can be determined by lowering the gate voltage of the device until SEGR is no longer observed. If the SEGR threshold LET is observed to be < 40 MeV-cm^2/mg and the device will be used in a proton environment, proton testing must be performed to determine the proton SEGR sensitivity of the device. Conversely, if no upsets are observed below 40 MeV-cm^2/mg, proton testing is not necessary.

VI. Radiation Test Facilities

Table II lists several commonly used SEE test facilities in the U.S. and Canada. Each of these facilities has user programs that allow external customers to perform experiments. Some facilities operate as paid user facilities, where time is simply scheduled with the listed contact and a purchase order can be processed for payment. Other facilities are run primarily as research programs and require that a scientific proposal be submitted to and approved by an experiment evaluation committee before time can be scheduled. In all cases, time must be scheduled well in advance, typically 2-3 months prior to the test date since beam time at these facilities is limited.

TABLE II

Single-event effects test facilities.

Facility	Description	Energy Range	Reference	Contact
Brookhaven National Laboratory SEU Test Facility Upton, NY	Heavy ion Tandem van de Graaff	1-10 MeV/u	[9]	Chuck Carlson (631) 344-5261
Texas A&M University Cyclotron Institute College Station, TX	Heavy ion cyclotron	1-40 MeV/u	[10]	Henry Clark (979) 845-1411
Lawrence Berkeley National Laboratory 88-inch Cyclotron Berkeley, CA	Heavy ion cyclotron	4.5-16 MeV/u	[11], [12]	Peggy McMahan (510) 486-5980
Michigan State University National Superconducting Cyclotron Laboratory East Lansing, MI	Heavy ion cyclotron	80-170 MeV/u	[13]	Raman Anantaraman (517) 333-6337
Brookhaven National Laboratory NASA Space Radiation Laboratory Upton, NY	Heavy ion boosted synchrotron	200-1000 MeV/u	[14]	Betsy Sutherland (631) 344-3380
Indiana University Cyclotron Facility Bloomington, IN	Proton cyclotron	35-200 MeV	[15], [16]	Barbara von Przewoski (812) 855-2913
TRIUMF Proton Irradiation Facility Vancouver, BC, Canada	Proton cyclotron	20-500 MeV	[17], [18]	Ewart Blackmore (604) 222-7461
University of California at Davis Crocker Nuclear Laboratory Davis, CA	Proton cyclotron	1-63 MeV	[19], [20]	Carlos Castaneda (530) 752-4228
Francis H. Burr Proton Therapy Center Boston, MA	Proton cyclotron	15-230 MeV	[21], [22]	Ethan Cascio (617) 724-9529

VII. Experiment Planning and Data Analysis

A. Test Planning

To ensure a successful test campaign, good pre-test planning and execution are critical. Test plans should comprehensively cover the type of tests to be performed, test equipment to be used for each experiment, a detailed listing of required test devices, and testing priorities. The test plan will help ensure that preparations for each experiment are completed and that all necessary equipment is shipped to the test site. At the test site, test plans are also very useful for ensuring that all tests are performed in the manner intended. This is especially important for 24-hour per day tests where multiple shifts of workers are required to execute the test campaign. While results and events on-site at a test facility often (always?) require deviations from the original test plan, an agreed-to priority list helps to keep the experiment on track and ensure that tests are completed within the time available. A detailed example test plan would be too lengthy to include here, but important information to cover in a test plan includes any special environmental safety and health (ES&H) concerns, contact information for the facility as well as all experimenters (including those not at the experiment who may be able to troubleshoot any software/hardware problems), contract information for the purchase of beam time in case there are any issues, a handy reference to beams available at the facility, any necessary details on operating test software/hardware, and a complete listing of items to be shipped to the test site.

B. Datalogs

An important part of any experiment is thorough documentation of how the experiment was performed, and a complete record of the results obtained. This ensures that questions later about experimental techniques can be answered accurately, all necessary data for later analysis is recorded, and if necessary an experiment could be repeated. It is recommended that sufficient information be recorded so that an independent team could replicate the experiment at a later date if it were necessary. Figure 12 shows a typical raw datalog from a heavy ion SEU experiment on memory devices. Information that should be recorded for a given experiment of course varies depending on the device type(s) being tested.

C. Plotting Results

It is always a good practice to plot data in real time whenever possible. Experimental problems can often be detected as data is plotted, therefore plotting data at the facility as it is being collected can save considerable time and expense. For example, if the angle of incidence is too high during heavy ion SEU characterization, the sides of the package well can block the beam. This is easily detected by plotting the SEU cross section versus LET. If there is a sudden drop in SEU cross section as the angle of incidence is increased, this is a probable indication that the package well is blocking the beam. Alternatively, plotting maps of the physical location of observed errors can provide a direct indication of beam non-uniformity and shadowing. Although beam time is expensive ($\sim$\$600/hour for protons and $\sim$\$1000/hour for heavy ions), taking a little time to understand the data while they are being taken can pay dividends in directing further experiments and ensuring that the data are valid.

D. SEE Statistics

It is important to realize that all SEE data are inherently statistical in nature. That is to say, a finite number of protons or heavy ions impinge on the device under test, and each one has some probability of causing an effect. The more particles that are incident, the better the statistical accuracy of the experiment, and the more closely the measured characteristic (for example, an SEU cross section) reaches its true value. Most SEE data are assumed to be described by Poisson statistics, and therefore the statistical uncertainty due to the finite number of events observed is approximated by $1/\sqrt{N}$, where N is the number of events observed. SEE data should always be plotted using error bars to represent this statistical error so that the reader can readily judge the statistical accuracy of the data. We recommend that data be plotted with "two sigma" error bars, or $2/\sqrt{N}$. This approximation works well for $N > 50$ but is poor for cases where the number of observed events is small, as is almost always the case near the event threshold. For $N < 50$, Swift has recommended the correction factors shown in Table III, which give the statistical limits for 95% confidence (essentially two sigma) [23]. To use this table, calculate the event cross section in the usual way, i.e., $\sigma = N/\phi$, where ϕ is the fluence for the irradiation. The upper and lower statistical

Shot	*Tester*	*Computer*	*Manufacturer*	*Tech*	*Part*	*Lot*	*Wafer*	*S/N*
138	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
136	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
140	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
85	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
84	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
81	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
149	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
148	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
146	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
143	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
88	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
91	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
94	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
97	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
132	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
133	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
135	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
134	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
76	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
77	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
78	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
79	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
80	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	14
147	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
145	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
142	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
87	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
90	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
93	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17
96	Certimax1	Certimax	SNL	CMOS7	Eiger	VA065301B	6	17

VDD (V)	*Test*	*Mode*	*Vector*	*Temp*	*Ion*	*Energy (MeV/amu) @ Si*	*Energy (MeV) @ Si*	*Angle (degrees)*	*LET (MeV-cm2/mg) @ Si*	*Effective LET (MeV-cm2/mg) @ Si*	*Effective Range (um)*
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	30	55.9	64.5	74.3
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	38	56	71.1	66.6
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	45	56.3	79.6	58.6
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	30	89.5	103.3	72.9
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	38	89.7	113.8	65.3
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	45	89.9	127.1	57.4
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	0	55.6	55.6	87.5
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	30	55.9	64.5	74.3
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	38	56	71.1	66.6
2.89	RAM	Dynamic	CKBD	RT	Xe	8.2	1052	45	56.3	79.6	58.6
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	0	89.3	89.3	85.9
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	30	89.5	103.3	72.9
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	38	89.7	113.8	65.3
2.89	RAM	Dynamic	CKBD	RT	Au	8.1	1594	45	89.9	127.1	57.4
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	0	55.6	55.6	87.5
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	0	55.6	55.6	87.5
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	38	56	71.1	66.6
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	45	56.3	79.6	58.6
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	0	89.3	89.3	85.9
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	0	89.3	89.3	85.9
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	30	89.5	103.3	72.9
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	38	89.7	113.8	65.3
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	45	89.9	127.1	57.4
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	30	55.9	64.5	74.3
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	38	56	71.1	66.6
2.89	RAM	Static	CKBD	RT	Xe	8.2	1052	45	56.3	79.6	58.6
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	0	89.3	89.3	85.9
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	30	89.5	103.3	72.9
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	38	89.7	113.8	65.3
2.89	RAM	Static	CKBD	RT	Au	8.1	1594	45	89.9	127.1	57.4

Flux	*Fluence*	*Rad Time (s)*	*Dose (rad)*	*Errors*	*Cross Section (cm2)*	*Cross Section Lower Limit (cm2)*	*Cross Section Upper Limit (cm2)*
1.07E+06	1.00E+08	107.8	1.03E+05	0	1.00E-08	0.00E+00	3.70E-08
1.17E+06	1.00E+08	107.6	1.14E+05	0	1.00E-08	0.00E+00	3.70E-08
1.25E+06	1.00E+08	112.9	1.27E+05	3	3.00E-08	6.00E-09	8.80E-08
6.15E+05	1.00E+08	187.7	1.65E+05	39	3.90E-07	2.77E-07	5.33E-07
6.12E+05	1.00E+08	207.7	1.82E+05	104	1.04E-06	8.36E-07	1.37E-06
6.08E+05	1.00E+08	232.9	2.04E+05	178	1.78E-06	1.51E-06	2.18E-06
9.46E+05	1.00E+08	105.9	8.92E+04	0	1.00E-08	0.00E+00	3.70E-08
9.02E+05	1.00E+08	127.9	1.03E+05	1	1.00E-08	1.00E-09	5.60E-08
9.34E+05	1.00E+08	135.4	1.14E+05	0	1.00E-08	0.00E+00	3.70E-08
1.16E+06	1.00E+08	122.4	1.28E+05	2	2.00E-08	2.00E-09	7.20E-08
3.83E+05	1.00E+08	261.3	1.43E+05	5	5.00E-08	1.60E-08	1.17E-07
4.12E+05	9.98E+07	280.1	1.65E+05	49	4.91E-07	3.62E-07	6.49E-07
3.10E+05	1.00E+08	409.5	1.82E+05	168	1.68E-06	1.42E-06	2.16E-06
2.59E+05	1.00E+08	546.8	2.04E+05	359	3.59E-06	3.21E-06	4.22E-06
5.81E+05	4.71E+06	8.12	4.20E+03	0	2.12E-07	0.00E+00	7.86E-07
1.15E+06	1.00E+08	86.8	8.90E+04	0	1.00E-08	0.00E+00	3.70E-08
1.16E+06	1.00E+08	108.7	1.14E+05	0	1.00E-08	0.00E+00	3.70E-08
1.16E+06	1.00E+08	122.3	1.28E+05	3	3.00E-08	6.00E-09	8.80E-08
9.95E+04	5.03E+06	50.55	7.19E+03	1	1.99E-07	1.99E-08	1.11E-06
5.28E+05	1.00E+08	189.3	1.40E+05	4	4.00E-08	1.00E-08	1.02E-07
5.52E+05	1.00E+08	209.1	1.65E+05	19	1.90E-07	1.15E-07	2.96E-07
5.45E+05	1.00E+08	232.9	1.82E+05	51	5.10E-07	3.67E-07	6.85E-07
5.70E+05	1.00E+08	248.3	2.04E+05	149	1.49E-06	1.25E-06	1.85E-06
8.97E+05	1.00E+08	129.2	1.04E+05	0	1.00E-08	0.00E+00	3.70E-08
1.02E+06	1.00E+08	124	1.14E+05	1	1.00E-08	1.00E-09	5.60E-08
1.19E+06	1.00E+08	119.2	1.28E+05	2	2.00E-08	2.00E-09	7.20E-08
1.04E+05	1.00E+08	957.7	1.43E+05	6	6.00E-08	2.20E-08	1.31E-07
3.98E+05	1.00E+08	290.3	1.66E+05	45	4.50E-07	3.28E-07	6.02E-07
3.45E+05	1.00E+08	367.9	1.82E+05	140	1.40E-06	1.16E-06	1.80E-06
3.03E+05	1.00E+08	467.4	2.04E+05	264	2.64E-06	2.32E-06	3.15E-06

Fig. 12. Example datalog from a heavy ion test campaign.

TABLE III

LOWER AND UPPER STATISTICAL LIMITS FOR 95% CONFIDENCE FOR SMALL NUMBERS OF EVENTS N.

N	Lower Limit	Upper Limit		N	Lower Limit	Upper Limit
0	0.000	3.700				
1	0.100	5.600		26	0.654	1.462
2	0.100	3.600		27	0.659	1.452
3	0.200	2.933		28	0.664	1.443
4	0.250	2.550		29	0.669	1.434
5	0.320	2.340		30	0.673	1.427
6	0.367	2.183		31	0.677	1.419
7	0.400	2.057		32	0.681	1.409
8	0.425	1.975		33	0.688	1.403
9	0.444	1.900		34	0.691	1.397
10	0.470	1.840		35	0.694	1.391
11	0.491	1.791		36	0.697	1.383
12	0.517	1.750		37	0.703	1.378
13	0.531	1.715		38	0.705	1.374
14	0.550	1.679		39	0.710	1.367
15	0.560	1.653		40	0.715	1.363
16	0.588	1.625		41	0.717	1.356
17	0.582	1.600		42	0.721	1.352
18	0.594	1.578		43	0.723	1.347
19	0.605	1.558		44	0.727	1.341
20	0.610	1.540		45	0.729	1.338
21	0.619	1.524		46	0.730	1.333
22	0.627	1.509		47	0.734	1.330
23	0.635	1.496		48	0.735	1.325
24	0.642	1.483		49	0.737	1.322
25	0.648	1.472		50	0.740	1.318
				51+	$1\text{-}2/\sqrt{N}$	$1+2/\sqrt{N}$

limits for the event cross section are then given by multiplying the cross section by the factor shown in Table III corresponding to the number of events observed.

The case of N = 0 (i.e., no events were observed) deserves special mention. This point should be plotted with a cross section that assumes one event would have occurred just after the irradiation was stopped. The lower limit is indeed a cross section of zero, while the upper limit is 3.7 times the cross section calculated assuming one event. It is often useful to mark this point in a way that clearly indicates to the reader that no events were actually observed at this point. For example, one method is to mark the point with a downward pointing arrow.

VIII. CONCLUSIONS

In this document we have presented test guidelines, conditions, and test flows for single-event effects testing. Proton and heavy ion testing have been covered, including both nondestructive (SEU) and potentially destructive (SEL/SEB/SEGR) testing. The test flows given for each effect serve as a starting point for performing SEE characterization, and the details of test conditions can be used to flesh out the experiment plan. Common SEE test facilities and their characteristics were listed, including contact information for learning more or scheduling beam time. Finally, we briefly discussed some issues regarding test planning and data analysis for SEE characterization, including datalogging and small number statistical interpretation of SEE data. For more information on *why* SEE tests are performed the way they are and how the test conditions were chosen, we recommend reading a companion document to the present one, entitled “Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance.”

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