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SEE Test Methods

Outline

- Introduction
- Basic requirements for SEE testing
- Specifics of the testing for different SEE types
- Choosing the SEE test flow

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Single-Event Effects

Soft Errors:

- SEU
- MBU
- SEFI
- SET

Hard Errors:

- SEL
- SEB
- SEGR (SEDR)
- SES
- SEHE

Soft errors – can be corrected by reprogramming the circuit into its correct logic state or by restarting the algorithm in a central processing unit

Hard errors – are not correctable by reprogramming or by restarting the algorithm

Basic characteristics of SEE-sensitivity

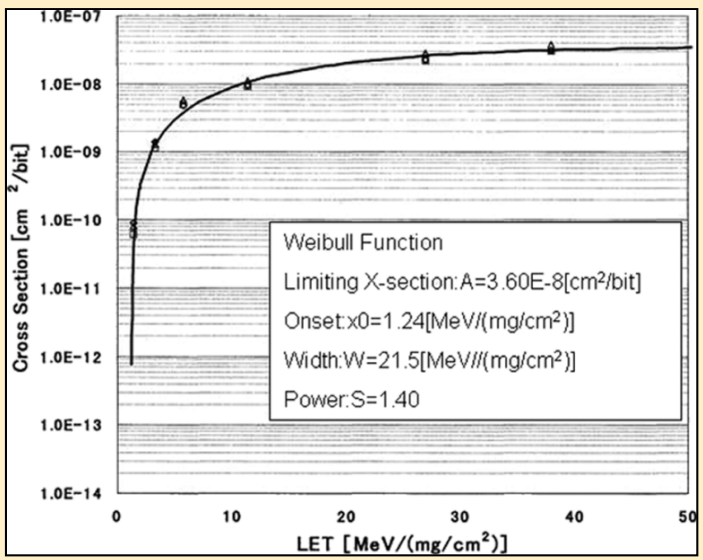
SEE cross section (cm^2 or cm^2/bit)

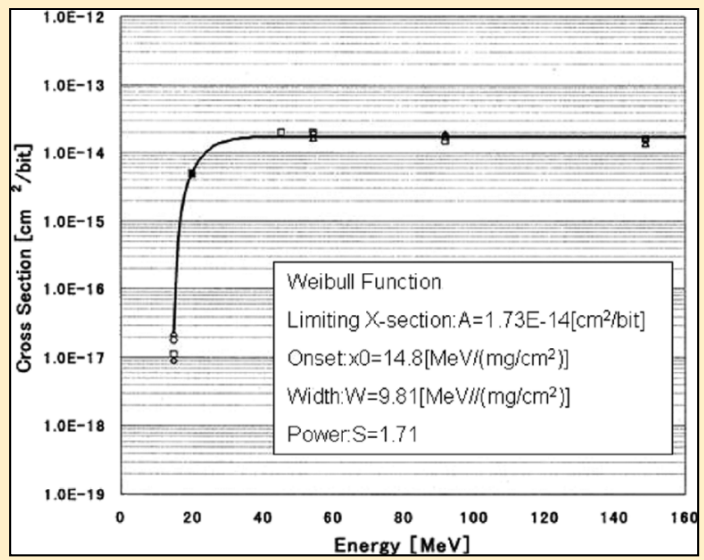
$$\sigma = \frac{N}{\Phi}$$

Number of events (SEU, SEL etc.)

Particle fluence (heavy ions, protons)

64 Mbit DRAM



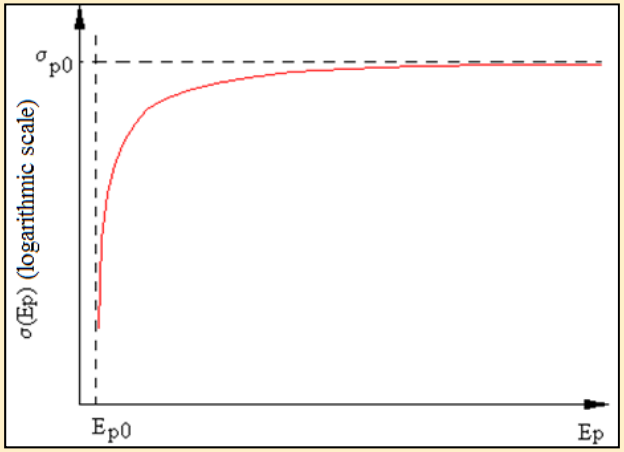


Kimoto Y. et al., IEEE Trans. Nucl. Sci., vol. 52, pp. 1574–1578, Oct. 2005.

Equations for Fitting the Experimental Data

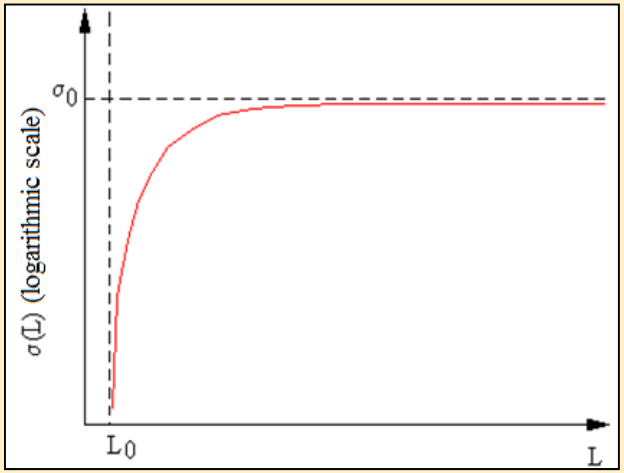
- Bendel 2-parameter equation (for proton induced SEE):

$$\sigma(E_p) = \begin{cases} \sigma_{p0}\left[1-\exp\left(-0{,}18\sqrt{\sqrt{\frac{18}{E_{p0}}}\left(E_p - E_{p0}\right)}\right)\right]^4 & \text{if } E_p \geq E_{p0} \\ 0 \text{ if } E_p < E_{p0} \end{cases}$$



- Weibull 4-parameter equation (for heavy ion and proton induced SEE):

$$\sigma(L) = \begin{cases} \sigma_0\left[1-\exp\left(-\left(\frac{L-L_0}{W}\right)^S\right)\right] & \text{if } L \geq L_0 \\ 0 \text{ if } L < L_0 \end{cases}$$



Standards and Guidelines for SEE Testing

USA:

- **EIA/JESD57:** Test procedures for the measurement of Single Event Effects in semiconductor devices from heavy ion irradiation;
- **ASTM F1192:** Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices;
- **MIL-STD-750 Method 1080:** Single-Event Burnout and Single-Event Gate Rupture.

Europe:

- **ESA/SCC 25100:** Single Event Effects Test Method and Guidelines.

Russia:

- **134-0175-2009:** Heavy-ion and proton induced SEE in digital circuits;
- **134-0191-2011:** Heavy-ion and proton induced SET in analog and mixed-signal circuits;
- **134-0192-2011:** Heavy-ion and proton induced SEB and SEGR in power MOSFETs.

Other Guidelines for SEE Testing

- Poivey C., Buchner S., Howard J., LaBel K. Testing Guidelines for Single Event Transient (SET) Testing of Linear Devices. NASA-GSFC, 2003.
- Buchner S., Marshall P., Kniffin S., LaBel K. Proton Test Guideline Development – Lessons Learned. NASA-GSFC, 2002.
- Schwank J.R., Shaneyfelt M.R., Dodd P.E. Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance. Sandia National Laboratories Document SAND-2008-6851P.
- Schwank J.R., Shaneyfelt M.R., Dodd P.E. Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Test Guideline for Proton and Heavy Ion Single-Event Effects. Sandia National Laboratories Document SAND 2008-6983P.

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Basic Requirements for Heavy Ion Tests

Energy of ions should be selected to provide the required LET and the range in semiconductor

Requirements for range:

- **JESD57:**
  larger than the depth of the charge collection region
- **ESA/SCC 25100:**
  at least 30 μm in Si
- **Russian guidelines:**
  at least 30 μm in Si (max depth of p-n-junction + 15 μm is recommended)

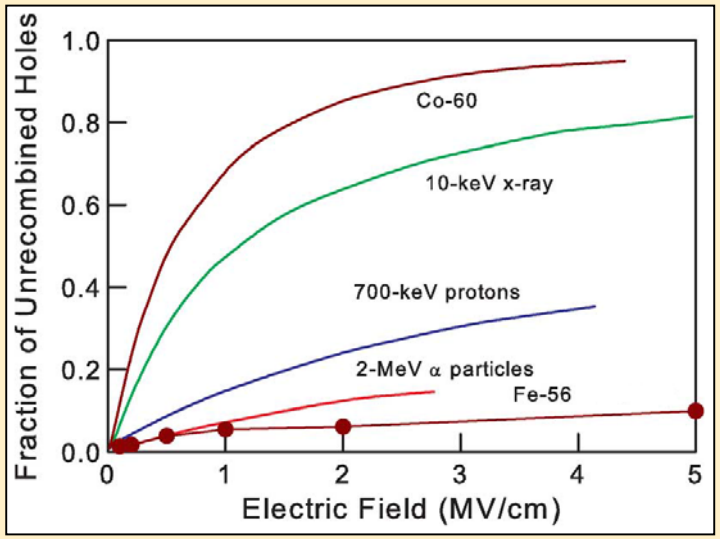
Basic Requirements for Heavy Ion Tests

Flux:

- from 10^2 to 10^5 ions/(cm^2·s)

Fluence:

- Should be adjusted to obtain a statistically significant number of events or 10^7 ions/cm^2 for insensitive device
- Total dose effects have to be taken into account (Guideline 134-0175: the total accumulated ionizing doze for the sum of all irradiations should not exceed 0.5 of TID failure level obtained using Co-60 gamma-source)



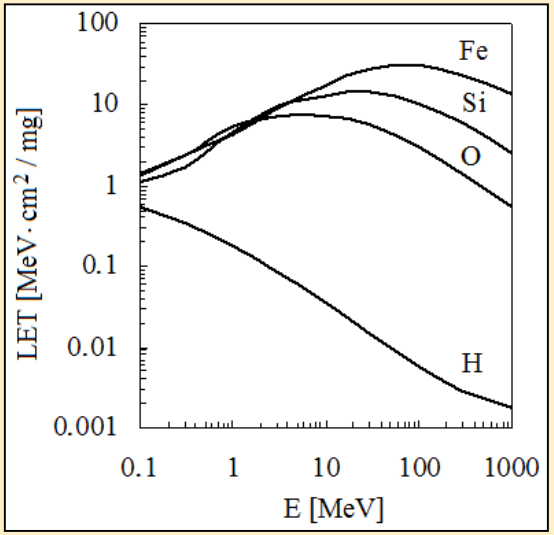
Javanainen A. et al., IEEE Trans. Nucl. Sci., vol. 56, no. 6, pp. 3367-3371, Dec. 2009

Basic Requirements for Heavy Ion Tests

The range of LET:

- From threshold to saturation
- JESD57: if possible, data should be taken up to 2x the LET required for the cross-section to saturate or up to effective LET of 120 MeV/(mg/cm^2)
- Min 5 exposures at different LET are required (Tilt may be used)

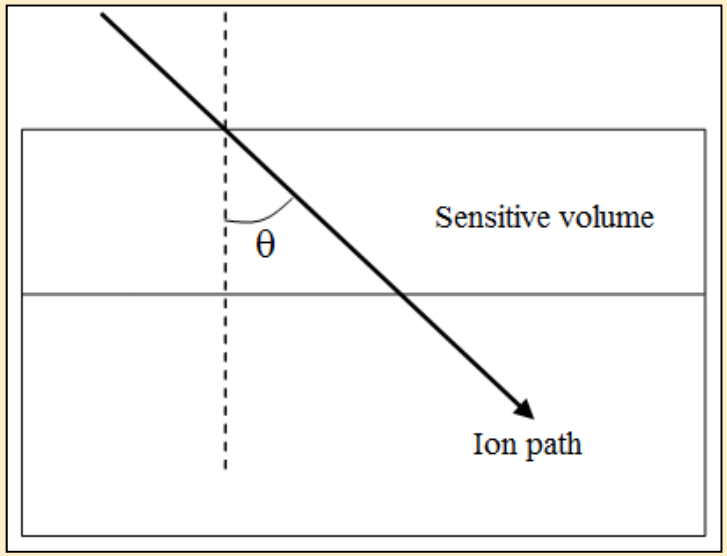
LET for some ions in Si



Calculated with SRIM (www.SRIM.org)

Basic Requirements for Heavy Ion Tests

Effective LET method:



$$LET_{eff} = \frac{LET(0)}{\cos\theta}; \quad \sigma = \frac{N}{\Phi \cdot \cos\theta}$$

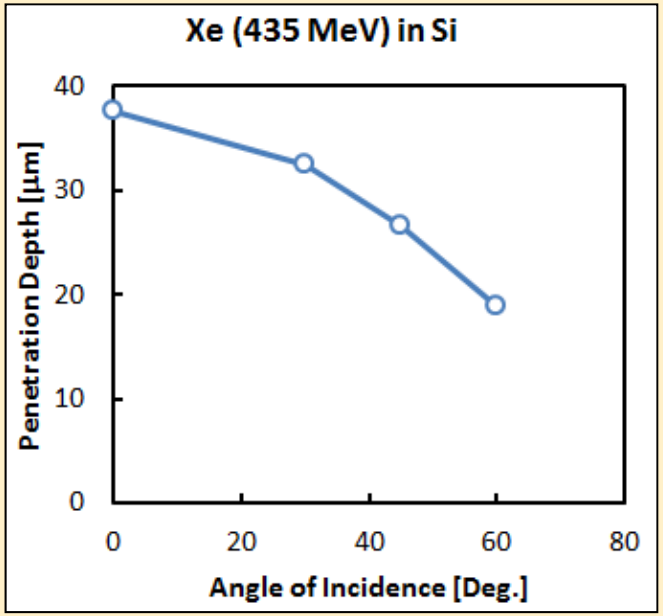
The depth of the sensitive volume has to be small compared to its lateral dimensions

Basic Requirements for Heavy Ion Tests

Limitations for the effective LET method:

- Dimensions of the sensitive volume (the depth of the sensitive volume has to be small, compared to its lateral dimensions)
- Short ion ranges in Si
- Multiple bit upsets
- The sides of device packages, package wells, etc. can shadow the incident ion beam

The beam angle is normally limited to 60 degrees



Basic Requirements for Heavy Ion Tests

Beam control:

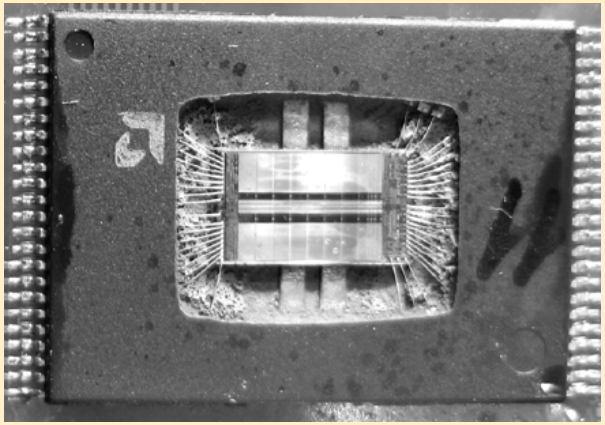
- **Energy –** better than ± 10 %;
- **Purity –** only one ion specie at a time
- **Flux control –** better than ± 10 %
- **Uniformity –** better than ± 10 % on the die
- **Fluence control –** better than ± 10 %

Basic Requirements for Heavy Ion Tests

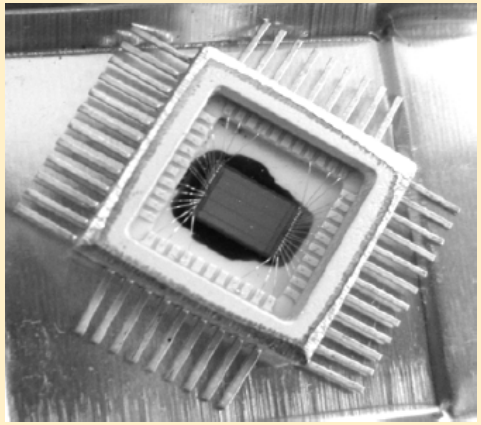
Samples preparation:

- it is necessary to de-package samples prior to testing;
- special care must be taken to ensure that the devices are not damaged before testing

XCV300-5PQ240I



AM29LV800DD-70EC



1637RU1

Basic Requirements for Heavy Ion Tests

Examples of equipment for samples preparation

X-ray system for electronics inspection
Nikon Metrology XT V 160

Ultrasonic tomographic system
Sonikon Velox

Chemical decapsulation:
SESAME 777 Cu

Mechanical decapsulation:
ASAP-1-IPS

Laser decapsulation:
SESAME Laser 1000

Plasma decapsulation:
Plaser 201

Basic Requirements for Heavy Ion Tests

Temperature during irradiation:

- Temperature can affect SEE sensitivity
- SEE tests are carried out in vacuum chamber that causes difficulties with heat removal
  - **Special heater (or cooler) should be used**
  - **Accurate temperature measurements should be carried out**

Basic Requirements for Proton Tests

- Energy: from 20 to 180 MeV (ideally, to 400 MeV)
- Flux: from 10^5 to 10^8 p/cm^2/s
- Fluence: should be adjusted to obtain a statistically significant number of events or 10^{10} p/cm^2 for insensitive device
- Delidding the components is not required
- Irradiations may be performed in air
- Exposure shall be performed at zero angle of incidence
- Beam control:
  - **Energy –** better than $\pm$ 10 %;
  - **Purity –** only one ion specie at a time
  - **Flux control –** better than $\pm$ 10 %
  - **Uniformity –** better than $\pm$ 10 % on the die
  - **Fluence control –** better than $\pm$ 10 %

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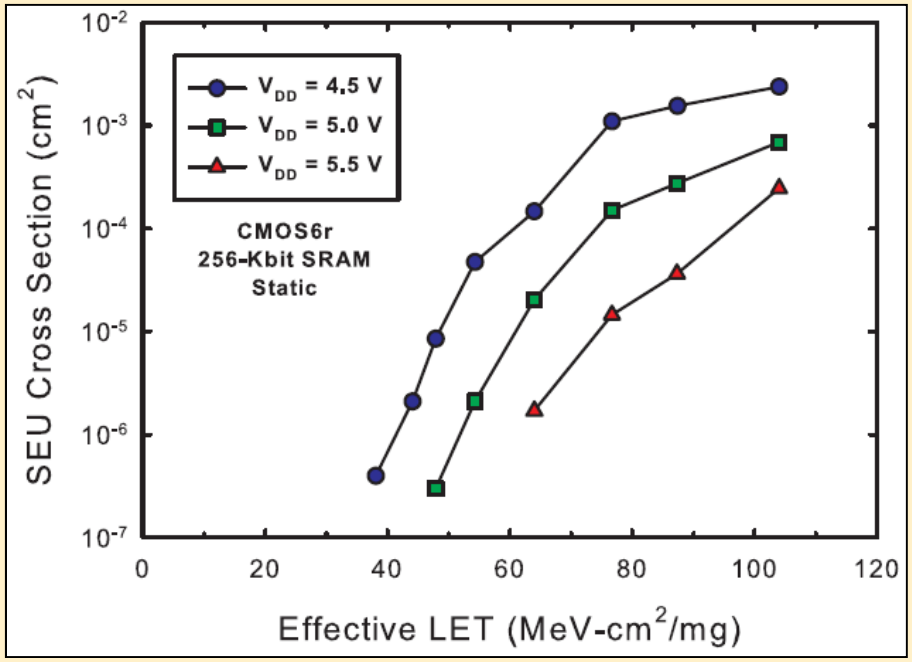
Soft Error Testing Specifics: Bias Voltage

The worst-case bias for SEU is the minimum power supply operating bias expected for the device in the system application

If devices are to be qualified for general use or if the minimum operating bias for the system is unknown, then devices should be characterized at the minimum operating bias as defined by product specification



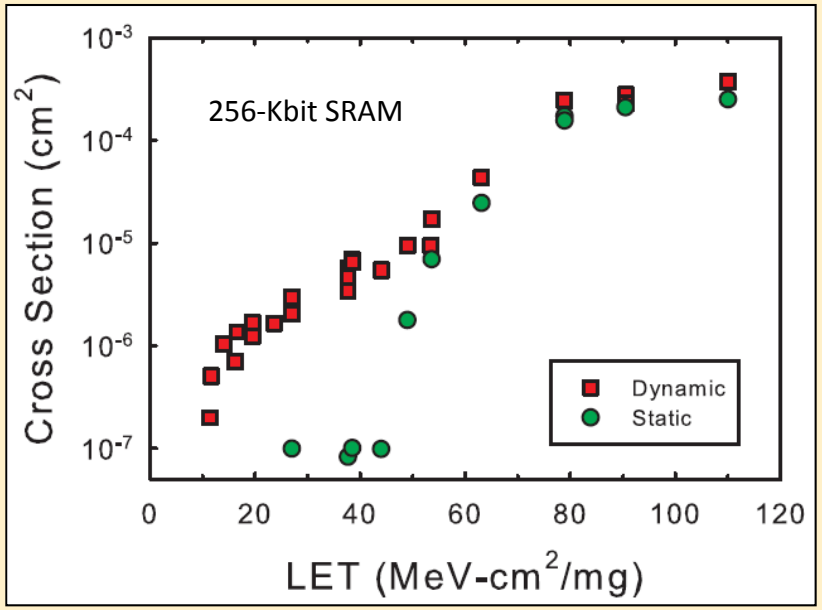
Schwank J.R., Shaneyfelt M.R., Dodd P.E., Sandia National Laboratories Document SAND-2008-6851P

Soft Error Testing Specifics: Pattern/Vector Dependence

- Easiest patterns: all 0's, all 1's, a logical checkerboard (CB).
- The use of physical data patterns (that are related to the actual layout of the IC) is recommended where possible.
- The selected test patterns should consider the possibility of a preferred soft error failure mode for device under test (particularly for dynamic RAMs and logic elements).
- If there is no prior knowledge of pattern dependence, the test pattern that balances the number of 0s and 1s is recommended.
- For ASICs or microprocessors it is desirable to use test vectors that closely approximate the system application that will be used on-orbit.

Soft Error Testing Specifics: Static or Dynamic Mode

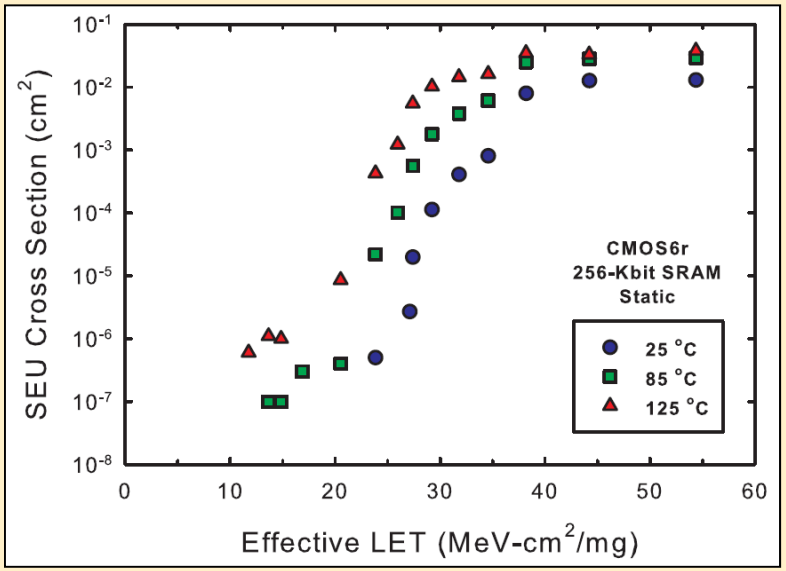
- **Advantages of Static Testing:**
  - Easy to write test program
  - Easy to provide the operation over the long cables
- **Disadvantages of Static Testing:**
  - Some of upset modes can only exist during dynamic operation
  - DUT can contain the circuitry that is only active during dynamic operation
  - Static test gives no direct indication of MBU sensitivity
  - For many classes of ICs only dynamic mode of operation is possible



Schwank J.R., Shaneyfelt M.R., Dodd P.E., Sandia National Laboratories Document SAND-2008-6851P

Soft Error Testing Specifics: Temperature

- In general, SEU tests can be performed at room temperature
- If the DUT contains passive elements that are known to be temperature sensitive, any change in the operative temperature could impact the SEU hardness
- It is useful to perform some initial experiments to determine the worst-case operating temperature for SEU

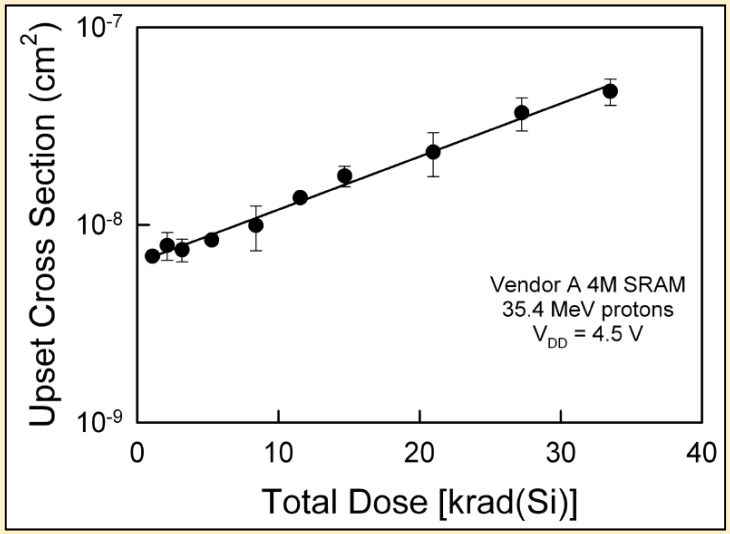


Accurate temperature measurements are the key to repeatable SEU testing at elevated temperatures

Schwank J.R., Shaneyfelt M.R., Dodd P.E., Sandia National Laboratories Document SAND-2008-6851P

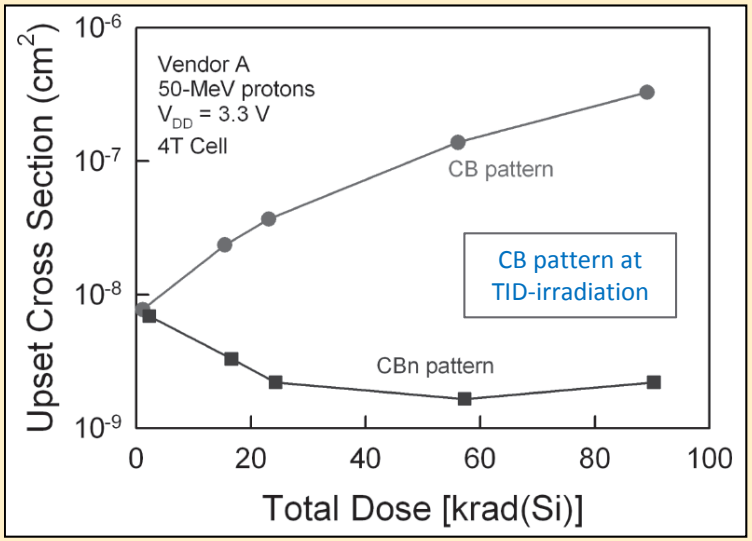
Soft Error Testing Specifics: Total Dose Effects

Total ionizing dose can impact the SEU sensitivity



Schwank J.R., Dodd P.E., Shaneyfelt M.R. et al.,
IEEE Trans. Nucl. Sci., vol. 51, no. 6, pp. 3692-3700, Dec. 2004

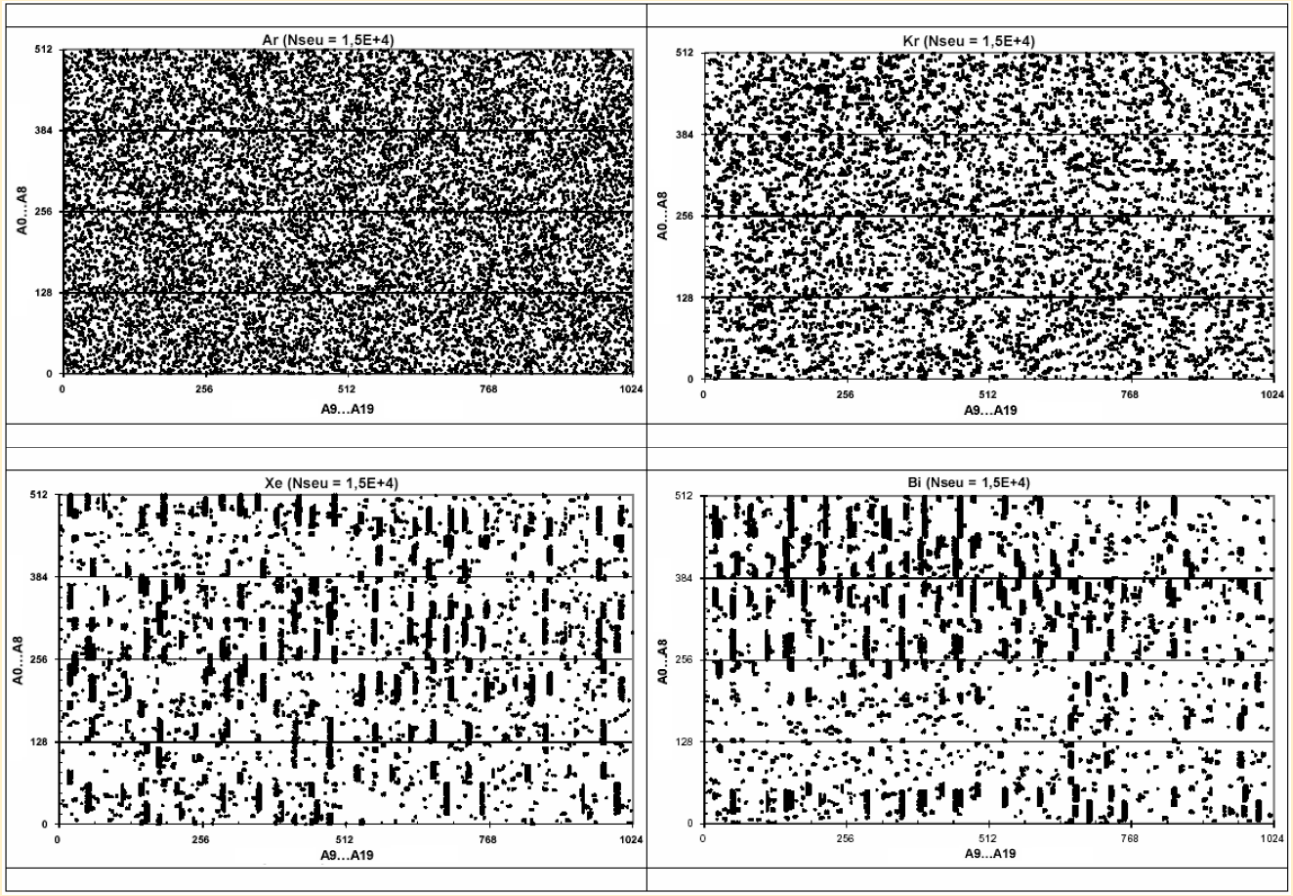
The SEU sensitivity will depend on the irradiation bias configuration



Schwank J.R., Shaneyfelt M.R., Felix J.A. et al.,
IEEE Trans. Nucl. Sci., vol. 53, no. 4, pp. 1772-1778, Aug. 2006

If total dose affects the SEE sensitivity, the SEE characterization has to be carried out at maximum total dose level expected during mission lifetime

Soft Error Testing Specifics: MBU

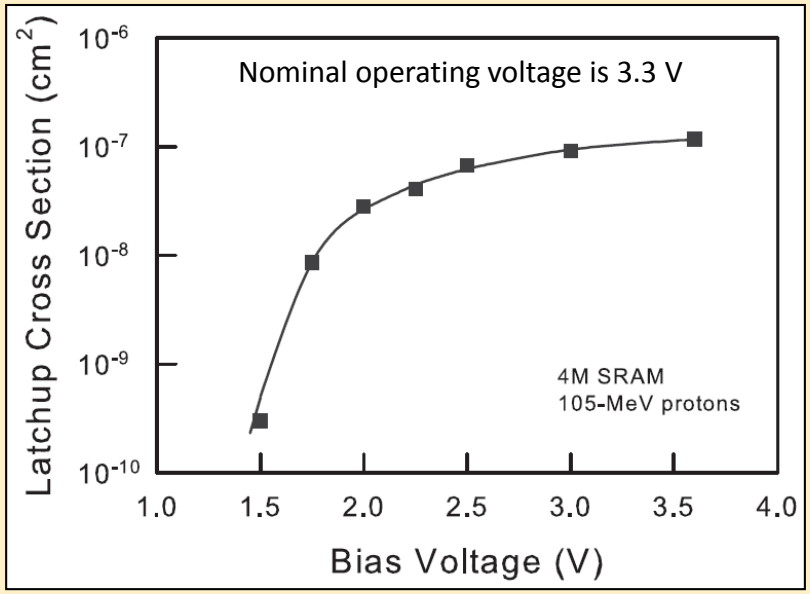


Emelianov V.V. et al., Russian Conference on Radiation Hardness of Electronic Systems, Lytkarino, June 2011.

SEL Testing Specifics: Operating Bias

Worst-case bias condition for both heavy-ion and proton-induced SEL is **the maximum power supply voltage**

If devices are to be qualified for general use or if the maximum operating bias for the system is unknown, then devices should be characterized at the maximum operating bias as defined by the product specification

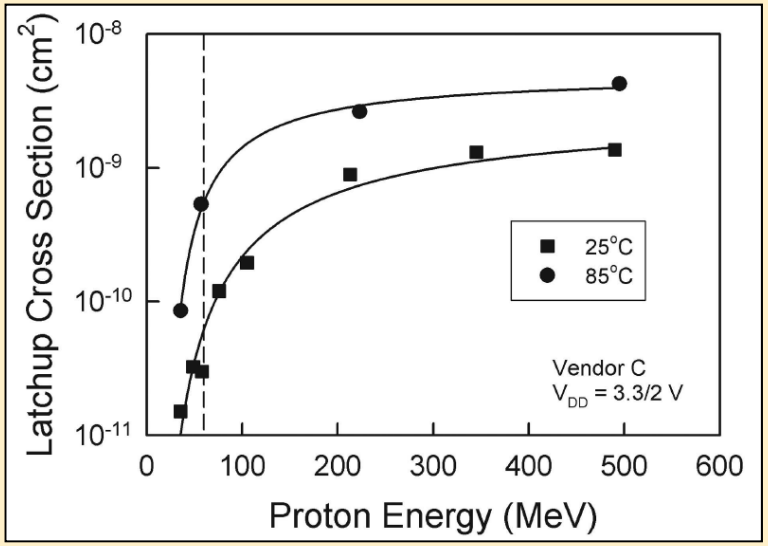


Schwank J.R., Shaneyfelt M.R., Dodd P.E., Sandia National Laboratories Document SAND-2008-6851P

SEL Testing Specifics: Temperature

The worst-case temperature for both heavy-ion and proton-induced SEL is **maximum system temperature**

If devices are to be qualified for general use or if the maximum operating temperature for the system is unknown, then devices should be characterized at the maximum operating temperature as defined by the product specification



Schwank J.R., Shaneyfelt M.R., Baggio J., et al. IEEE Trans. Nucl. Sci., vol. 52, no. 6, pp. 2622-2629, Dec. 2005

SEL Testing Specifics: Latchup Characterization

- Ideally, a latchup test should include both functional testing and current monitoring
- By examining vector maps and by recycling the power supply, SEL (and SES) can be distinguished from SEU, SEFI, etc.
- If functional testing is not practical, the power supply current must be continuously monitored during irradiation
- To measure multiple SELs, after a SEL is first recorded, the power supply voltage must be quickly removed for a short period of time (e.g., 0.5 s) and reapplied
- Dwell tests may be needed

SEL Testing Specifics: Comparison of SEL and SES

Criterion	SES	SEL
Allocation in CMOS ICs	Bipolar parasitic n-p-n-structure	Parasitic p-n-p-n-structure
Excess current flow path	From source to drain along the channel of n-MOSFET	From source of p-MOSFET to source of n-MOSFET
Excess current value	~ 100 mA	~ 100 mA
Method of elimination of high-current state	Removing the power supply voltage or changing the polarity of gate voltage	Removing the power supply voltage

SEB/SEGR Testing Specifics: Operating Bias

Two types of power MOSFET response:

- "Capacitor response" – due to electric field directly across the gate
- "Substrate response" – due to the drain bias on the substrate

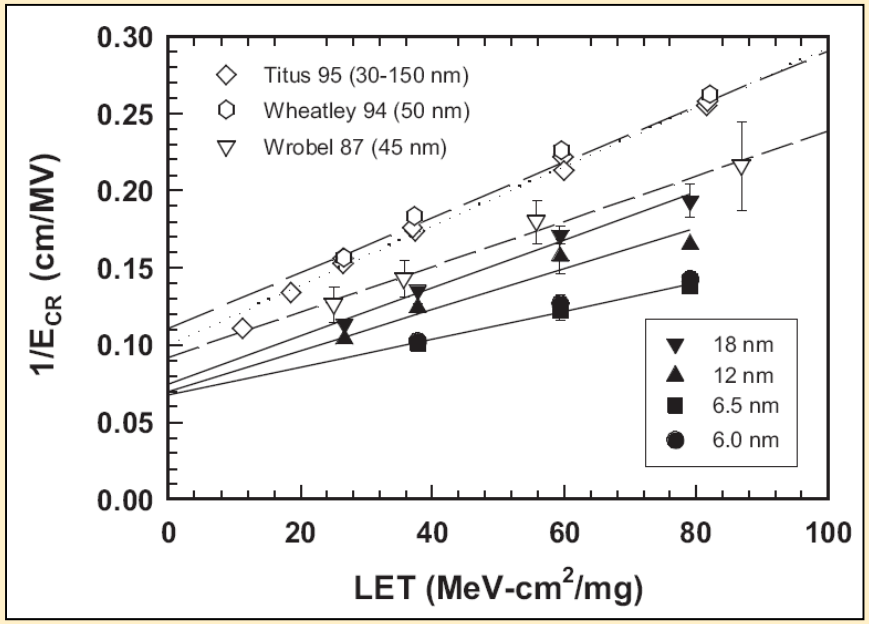
Increasing V_{DS} decreases the V_{GS} at which SEGR is observed for a given heavy ion

Relationship between the SEGR critical field E_{CR} (capacitor response) and LET:

$$E_{CR} = E_0 / (1 + LET / B)$$

E_0 is the intrinsic oxide breakdown field (in the absence of a particle strike)

B is a fitting parameter



Sexton F.W., Fleetwood D.M., Shaneyfelt M.R., et al. IEEE Trans. Nucl. Sci., vol. 44, no. 6, pp. 2345-2352, Dec. 1997

SEB/SEGR Testing Specifics: Operating Bias

- SEGR and SEB testing should be performed at the maximum operating bias expected for the system
- Worst-case bias conditions:
  - Nonvolatile memories – the maximum bias during a write operation;
  - Power MOSFETS – highest V_{GS} and V_{DS} for SEGR testing and highest V_{DS} for SEB testing
  - Other device types – maximum operating voltage
- If devices are to be qualified for general use or if the maximum operating bias for the system is unknown, then devices should be characterized at the maximum operating bias as defined by product specification

SEB/SEGR Testing Specifics: Irradiation Conditions

- **Temperature:**
  - SEGR is known to have little (if any) temperature dependence
  - SEB sensitivity is known to decrease as temperature is raised
  - SEGR and SEB testing is usually performed at room temperature
- **Angle of Incidence:**
  - both SEB and SEGR are worst-case for normally-incident particle strikes
  - SEGR and SEB characterization should be performed at normal incidence
- **Ion Energy:**
  - The penetration of ions should be not less than the full depth of epi-region
  - Maximizing LET while maximizing ion energy will be close to worst case

SEB/SEGR Testing Specifics: Characterization

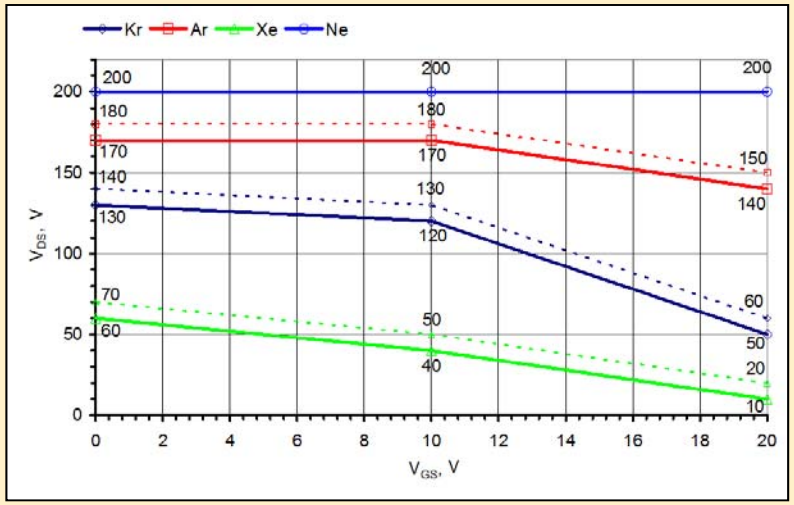
- **SEGR Characterization:**
  - Power MOSFETs – by monitoring the gate-to-source current I_{GS}
  - Nonvolatile memories – by monitoring the static supply current I_{DD}
  - Other devices – by monitoring I_{DD} and checking device functionality
  - Usually SEGR cannot be tolerated and hence it is not important to obtain a complete cross section curve

- **SEB Characterization:**
  - SEB characterization is performed similarly to SEL testing by monitoring the I_{GS} and the I_{DS} for power MOSFETs
  - To avoid catastrophic device failure caused by repeated SEB testing, the device current should be limited to a safe operating value

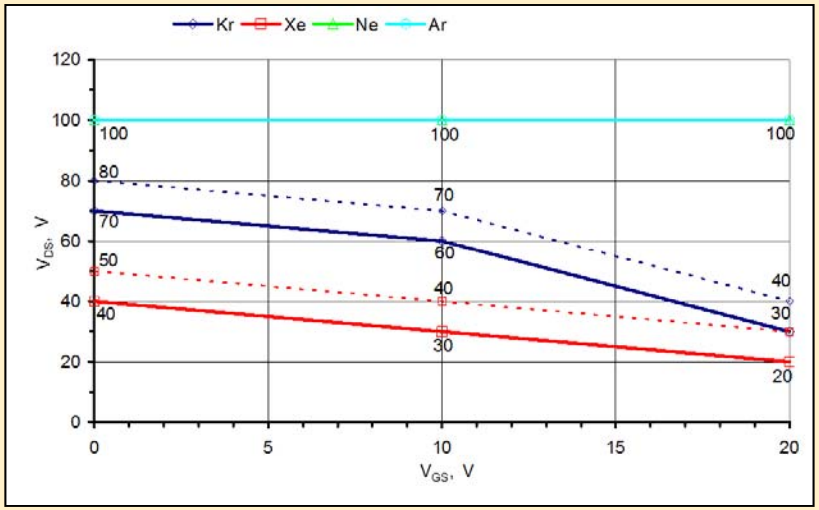
SEB/SEGR Testing Specifics: Test Results

Typical SEB/SEGR test result is the range of safe operation biases for every LET used in testing

KP767V



KP769V

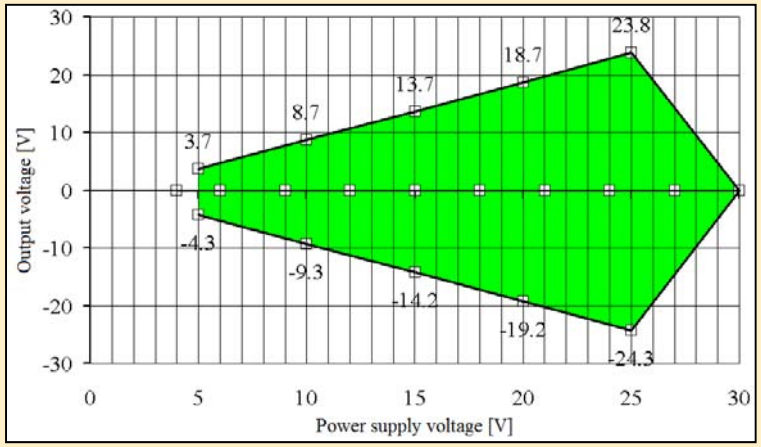


Emelianov V.V. et al., Russian Conference on Radiation Hardness of Electronic Systems, Lytkarino, June 2010.

SEDR Testing Specifics: Test Results for Operational Amplifiers

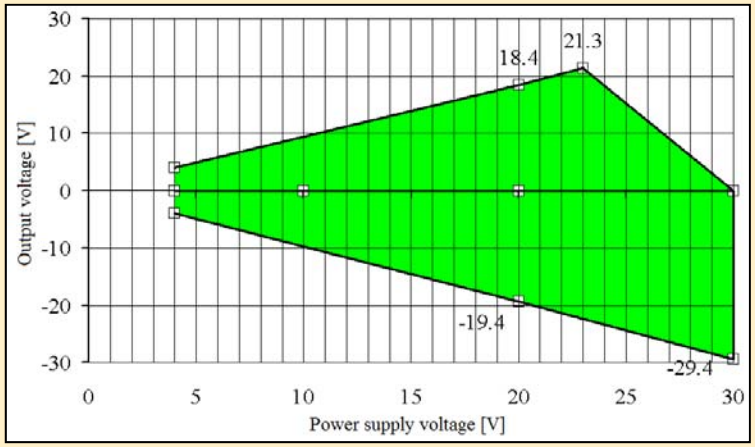
Typical SEDR test result for operational amplifiers is the range of safe operation biases for every LET used in testing

OPA547FKTWT



^{136}Xe, 69 MeV·cm^2/mg

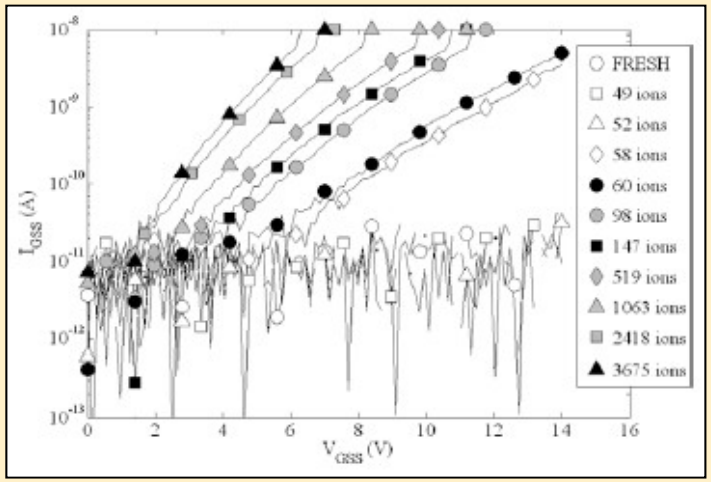
OPA548FKTWT



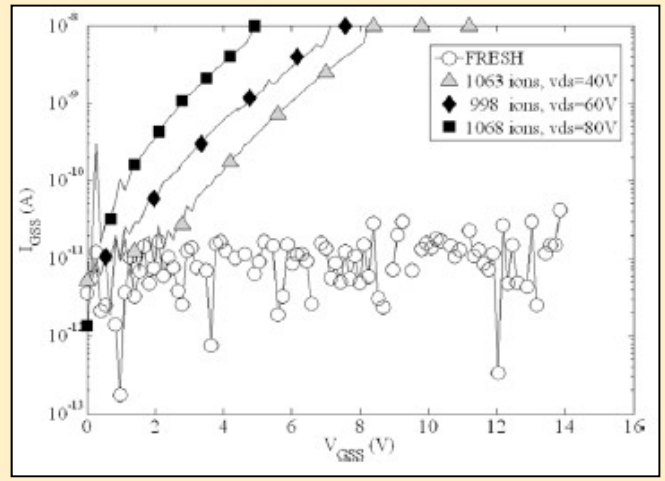
^{84}Kr, 40 MeV·cm^2/mg

SEB/SEGR Testing Specifics: Latent Damage

^{79}Br, 223 MeV



^{79}Br, 223 MeV



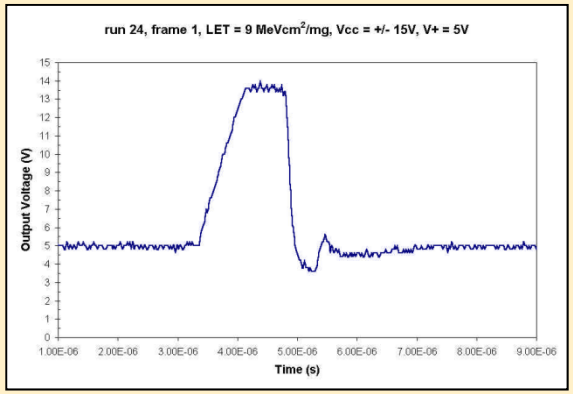
Latent damage depends on operating bias, ion specie (mass), fluence and LET

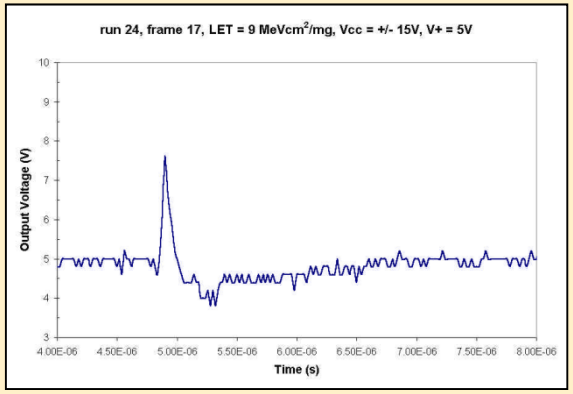
G. Busatto et al., Microelectronics Reliability, vol. 49 (9 – 11), pp. 1033 – 1037, 2009.

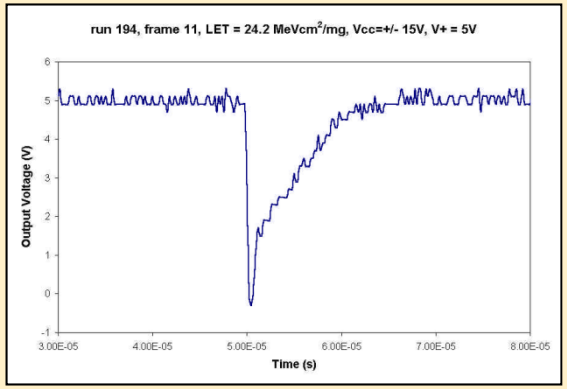
SET Testing Specifics: Impact of Test Conditions

- Each SET has its unique characteristics (polarity, waveform, amplitude, duration) depending on ion or proton impact location, ion or proton energy, device bias condition, and output load.
- On a single device, a large variety of SET waveforms can be obtained.

Examples of SETs in LM124 (NSC)





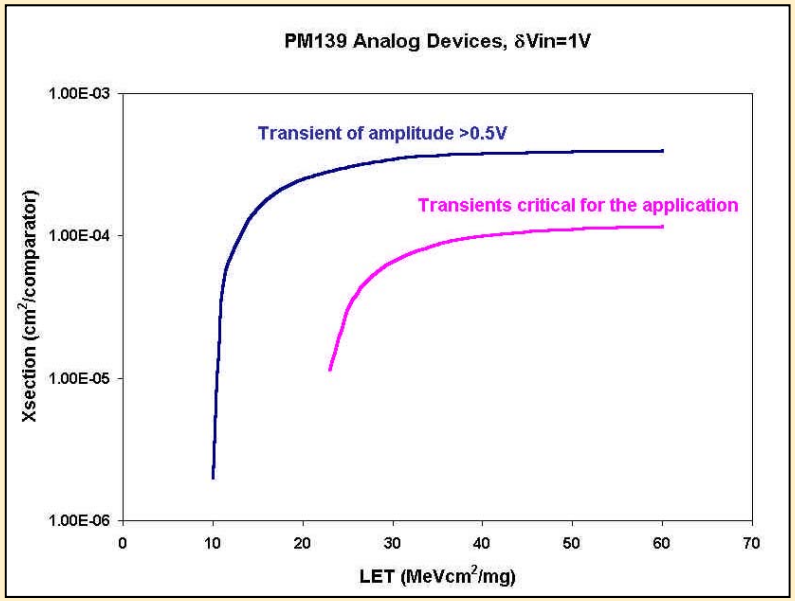


C. Poivey, J. Howard, S. Buchner, et al. IEEE Trans. Nucl. Sci., vol. 48, no. 6, pp. 2180-2186, Dec. 2001

C. Poivey, S. Buchner, J. Howard, K. LaBel, Testing Guidelines for Single Event Transient (SET) Testing of Linear Devices. NASA-GSFC, 2003.

SET Testing Specifics: Data Analysis

- It is necessary to collect all the transients during an experiment and to store them for further analysis at a later date
- Test set-up has to be designed to capture all types of transients that occur during the irradiation
- Only transients with amplitude and/or width critical for the application conditions have to be taken into account during SET cross-section calculation



Johnston A.H., Swift G.M., Miyahira T.F., Edmonds L.D., IEEE Trans. Nucl. Sci., vol. 47, n 6, pp. 2624-2633, Dec. 2000.

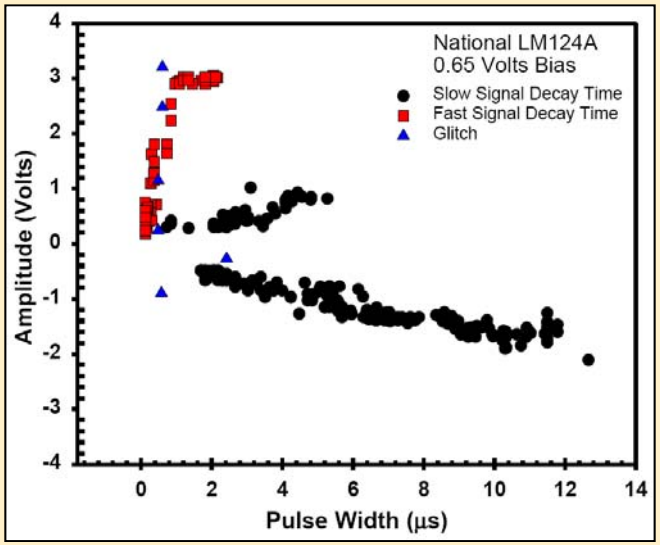
C. Poivey, S. Buchner, J. Howard, K. LaBel, Testing Guidelines for Single Event Transient (SET) Testing of Linear Devices. NASA-GSFC, 2003.

SET Testing Specifics: Data Reporting

Minimally, the report should include:

- Bias conditions
- Measurement conditions (trigger levels)
- Total cross-section curves for each tested bias conditions
- Traces of the different types of waveforms collected with worst-case characteristics (amplitude, duration) and a description of how they contribute to the total cross-section curve.
- A discussion that gives an overview of the transient characteristics (a plot of transient amplitude versus width)

An Example of a Plot of Transient Amplitude vs. Width



C. Poivey, S. Buchner, J. Howard, K. LaBel, Testing Guidelines for Single Event Transient (SET) Testing of Linear Devices. NASA-GSFC, 2003.

Outline

- Introduction
- Basic requirements for SEE testing
- Specifics of the testing for different SEE types
- Choosing the SEE test flow

Different Types of SEE Testing

Type of Testing	Description	Advantages	Disadvantages
Control tests	The purpose is to confirm that threshold LET (threshold E_p) is larger than specified value	The minimum amount of experimentation (the exposure at only one LET or only one E_p is required)	Provides a conservative estimation of sensitivity to SEE
Qualification tests	The purpose is to obtain the plot of SEE cross-section vs. LET (or energy of protons)	Fully characterizes the sensitivity to SEE	Min 5 exposures at different LET (different E_p) are required
"Mixed" tests	1. Measuring SEE cross-section at high LET (or E_p) 2. Calculation the minimal acceptable value of threshold LET (or E_p) according to requirements for SER or probability of failure 3. Control test to confirm that threshold LET (or E_p) is larger than minimal acceptable value	Less conservative as compared with control tests Exposures at only 2 different LET (or E_p) are required	Doesn't provide the full characterization of SEE sensitivity

Different Types of SEE Testing

Type of Testing	SEE Types the Approach Can Be Applied for	The Amount of Experimentations in Relative Units	Cost in Relative Units
Control tests	Typically for hard errors; for SEFI in some cases	1	1
Qualification tests	For all SEE types	5	3
“Mixed” tests	For all SEE types, but typically for hard errors, SETs, SEFIs	2	1.5

SEB/SEGR Testing

Control tests:

- The purpose is to confirm that there are no SEB/SEGR events at maximum required LET (or E_p) and at maximum operating biases (according to system requirements or device specification)

Qualification tests:

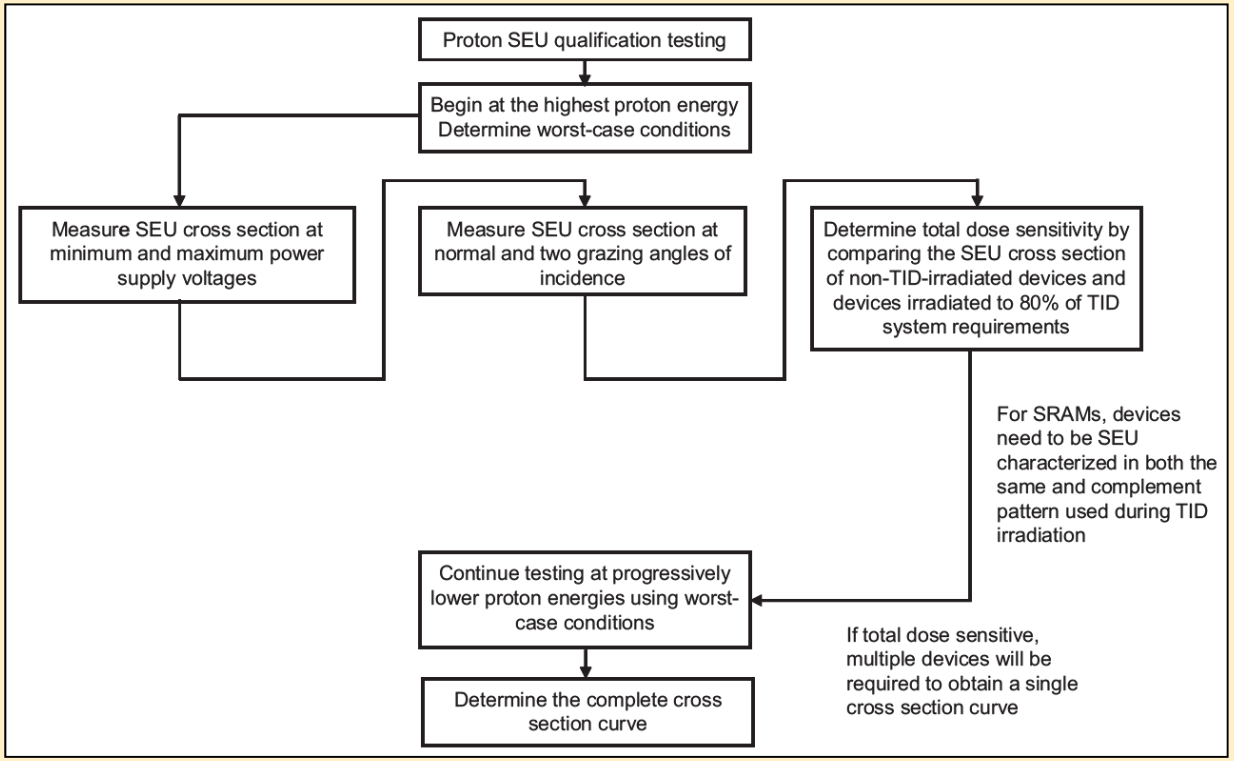
- The purpose is to obtain the range of safe operation biases for every LET (E_p) used in testing and the cross-section curve

The Need for Proton Tests

The need for proton tests can be determined by heavy-ion test results

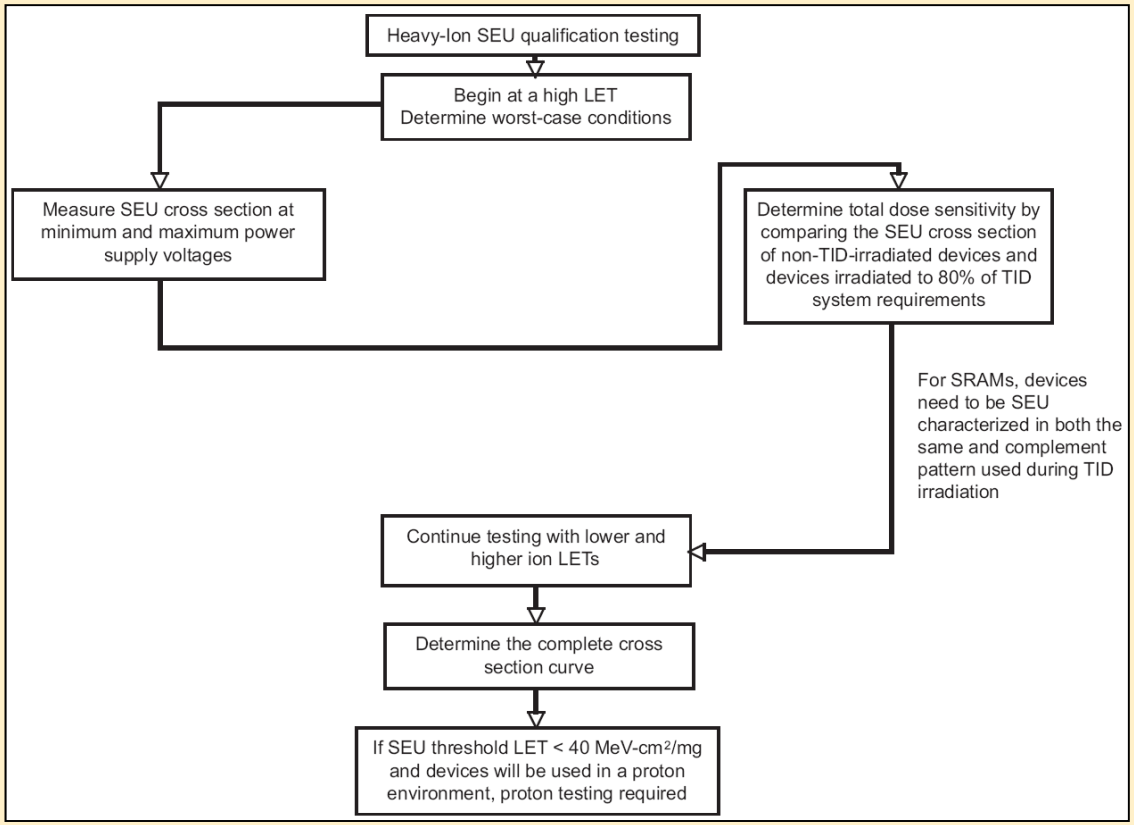
Threshold LET [MeV·cm^2/mg]	Need for Proton Tests
< 15	Full proton testing required
15 … 40	Cross-section measuring at only one high E_p ($E_p \geq 400$ MeV)
> 40	Proton tests are not required

Test Flow for Proton-Induced SEU Hardness Assurance



Schwank J.R., Shaneyfelt M.R., Dodd P.E., Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Test Guideline for Proton and Heavy Ion Single-Event Effects. Sandia National Laboratories Document SAND 2008-6983P

Test Flow for Heavy Ion-Induced SEU Hardness Assurance



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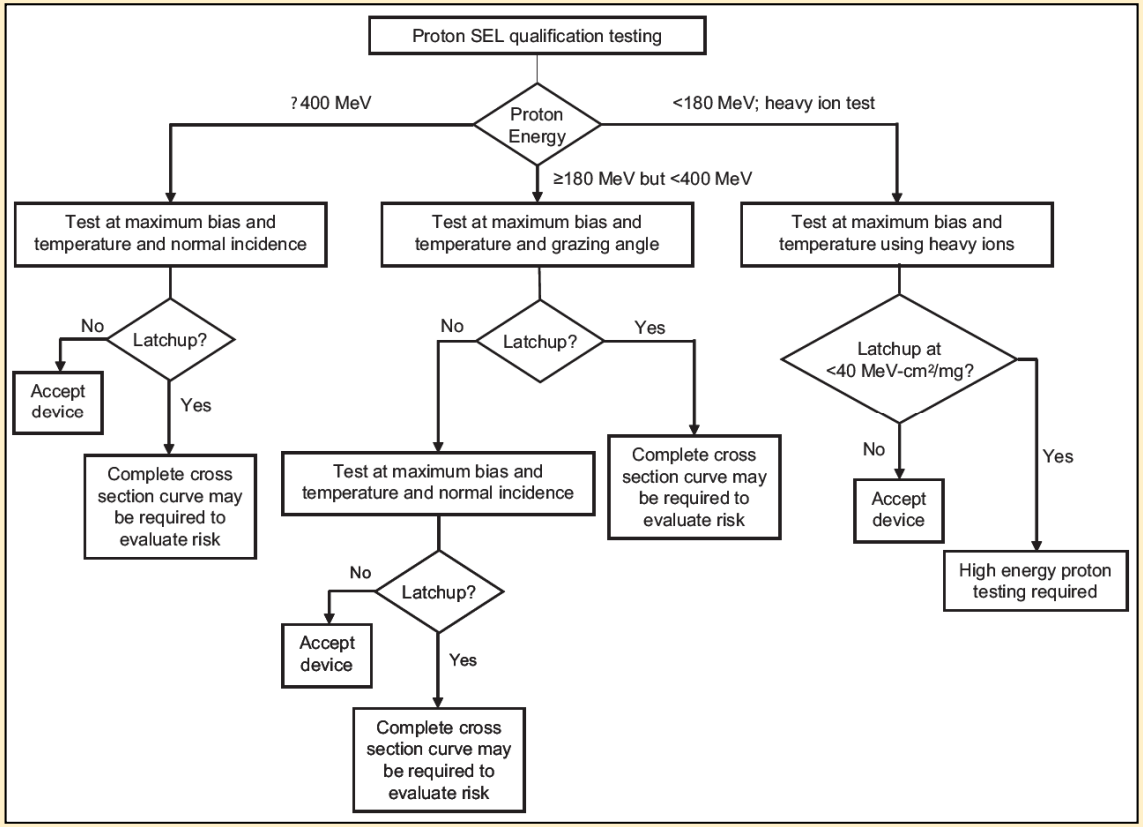
Test Flow for Proton-Induced SEL Hardness Assurance



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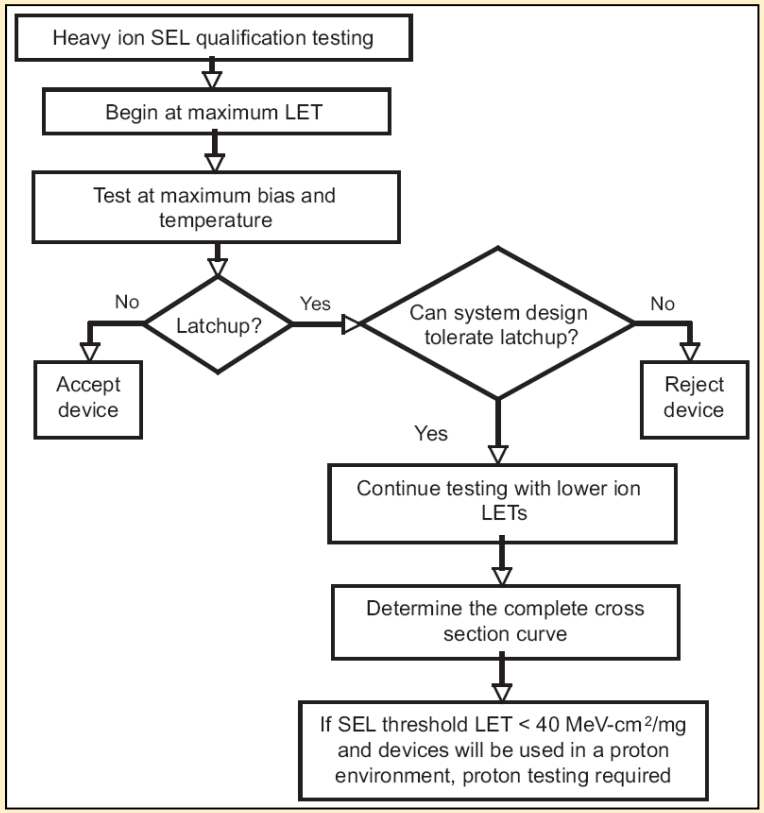
Test Flow for Heavy Ion-Induced SEL Hardness Assurance



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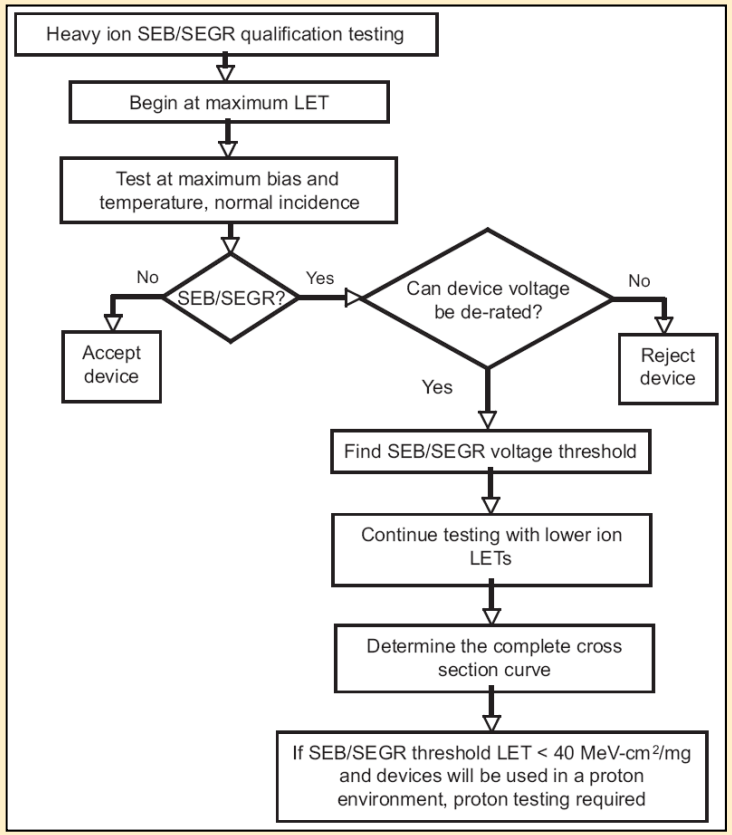
Test Flow for Heavy Ion-Induced SEB/SEGR Hardness Assurance



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Instead of Conclusion: SEE Test Facilities

North America

Facility	Description	Energy Range
Brookhaven National Laboratory SEU Test Facility Upton, NY	Heavy ion Tandem van de Graaff	1-10 MeV/u
Texas A&M University Cyclotron Institute College Station, TX	Heavy ion cyclotron	1-40 MeV/u
Lawrence Berkeley National Laboratory 88-inch Cyclotron Berkeley, CA	Heavy ion cyclotron	4.5-16 MeV/u
Michigan State University National Superconducting Cyclotron Laboratory East Lansing, MI	Heavy ion cyclotron	80-170 MeV/u
Brookhaven National Laboratory NASA Space Radiation Laboratory Upton, NY	Heavy ion boosted synchrotron	200-1000 MeV/u
Indiana University Cyclotron Facility Bloomington, IN	Proton cyclotron	35-200 MeV
TRIUMF Proton Irradiation Facility Vancouver, BC, Canada	Proton cyclotron	20-500 MeV
University of California at Davis Crocker Nuclear Laboratory Davis, CA	Proton cyclotron	1-63 MeV
Francis H. Burr Proton Therapy Center Boston, MA	Proton cyclotron	15-230 MeV

Schwank J.R., Shaneyfelt M.R., Dodd P.E., Sandia National Laboratories Document SAND 2008-6983P

Instead of Conclusion: SEE Test Facilities

Europe – Heavy Ions

High Energy (100 MeV/amu)	France – GANIL
Medium Energy (≥ 10 MeV/amu)	Belgium – CYCLONE / Finland – JYFL
Low Energy (≤ 10 MeV/amu)	France – IPN / Italy – LNL

Europe – Protons

CYCLONE – Belgium	Up to 65 MeV
JYFL – Finland	Up to 60 MeV
CPO – France	Up to 200 MeV
IPN – France	Up to 20 MeV
SIRAD – Italy	Up to 28 MeV
PSI/OPTIS - Switzerland	Up to 63 MeV
PSI/PIF - Switzerland	Up to 300 MeV

From G. Berger, Osmoz Consulting

Instead of Conclusion: SEE Test Facilities

Roscosmos' Test Facilities (Russia)

Heavy ions (based on U400M Accelerator)

Ions	C, O, Ne, Ar, Fe, Kr, Xe, Bi
Energy	3 – 9 MeV/amu
LET in Si	1 – 100 MeV·cm^2/mg
Range in Si	> 30 μm
Flux	10^2 – 10^5 ions/cm^2·s
Maximum irradiation area	200 × 200 mm^2
Uniformity within the irradiation area	Better than ± 15 %
Temperature	+ 25 … + 125 °C

Protons (based on synchrocyclotron accelerator SC-1000 PNPI)

Energy	Up to 1000 MeV
Uncertainty of energy	± 3 %
Flux	10^5 – 10^8 prot./(cm^2·s)
Uniformity within the irradiation area	Better than ± 10 %

Anashin V.S., Chubunov P.A., ISROS 2014 Proceedings, Toulouse, France, 16-20 June 2014.

Thank you for attention!