ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THP041

HIGH ENERGY HEAVY ION SINGLE EVENT EFFECTS (HE HISEE): PLANNING FOR THE FUTURE OF MICROELECTRONICS

K. LaBel[1,†], K. Avery[1], S. Biedron[1], J. DeFilippi[1], D. Marrujo[1], J. Miller[1], G. Van Dyk[1], M. Bedel[2], E. Everts[3], R. Leonard[3], A. Lowe[3], J. Millspaugh[3], M. Stapleton[4], T. Turflinger[5]
[1]Trusted Strategic Solutions (TSS), Roseville, CA, USA
[2]Naval Surface Warfare Center Crane Division, Crane, IN, USA
[3]JRC Integrated Solutions (JRC), Washington, DC, USA
[4]Scientific Research Corporation, Contractor support to the Test Resource Management Center (TRMC) Nuclear Modernization, Atlanta, GA, USA
[5]The Aerospace Corporation, Chantilly, VA, USA

Abstract

One unique accelerator application is the testing of microelectronics for utilization in space. In particular, space provides two environmental challenges that provide exposure to energetic heavy ions: galactic cosmic rays (GCRs) and solar particle events (SPEs). These particles cause risk by depositing charge in microelectronics, potentially causing operational errors or even destructive failure.

Testing electronics with a variety of ground-based accelerators is not new. What is new is the increasing need for high energy (> 100 MeV/n) heavy ions with ~40% of all testing predicted to require this high energy by 2030. This is primarily for two reasons:

- Mission-enabling advanced stacked microelectronics technologies such as 3D packaged devices that will require higher energy to penetrate to the sensitive locations within these devices.
- Increased demand to perform system-level testing using "large irradiation area" kinematics. This large area also allows for large sample sizes to be irradiated simultaneously for efficiency.

Presently, there is only one domestic accelerator that can achieve high energy heavy ions—Brookhaven National Laboratory's NASA Space Radiation Laboratory. Here, we discuss the requirements needed by the test community and the domestic effort to close the gap in the number of test hours. A current government-funded study is underway to analyze options for the future.

INTRODUCTION

Why are we concerned with GCRs and SPEs? They can cause single event effects (SEEs), see, for example, Refs. [1, 2]. The take home point—an SEE may not cause immediate failures, but they can still have latent damage that causes a failure later-in-time or reduced lifetime. Let's examine.

GCRs (aka heavy ions) are atomic nuclei from which all surrounding electrons have been stripped away during their high-speed passage through the galaxy. Supernova remnants are widely believed to be a major source of cosmic rays, particularly those within our galaxy thought to be accelerated by the powerful shock waves generated during supernova explosions. SPEs are similar particles to GCRs, but they only happen during some solar events. Figure 1 below illustrates what we don't want to see in space: a destructive event. Testing on the ground allows us to determine the sensitivities and find alternatives or safe operational conditions.

There are basically two variants of radiation effects for electronics: long-term/cumulative effects and transient or single-particle effects.

Long-Term/Cumulative Effects

Total ionizing dose (TID) or displacement damage:

- Parametric shifts (e.g., power consumption, operating frequency,…), and /or functional failures;
- Units: krads (material) or displacement damage dose (DDD).

Transient or Single-Particle Effects

Single-event effects (SEEs)

- Soft errors (e.g., bit flip in a memory).
- Hard errors (e.g., device failure or faults that are uncorrectable).
- Single-event latchup (SEL) is a common concern.
- Units: linear energy transfer (LET) in MeV*cm^2/mg (heavy ions); energy in MeV (protons).

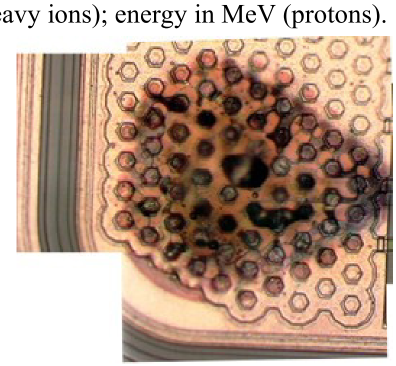

Figure 1: Destructive event in a power device during ground-based SEE testing. Photograph courtesy of NASA.

As seen in Fig. 2, much of what is desired for SEE testing is standard for many facilities that perform science research. However, there are some unique requirements and constraints for SEE testing, see, for example, Ref. [3]. Figure 3 below demonstrates a typical SEE test configuration at a real test. Events are measured on operational

† klabel@tss.llc

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THP041

semiconductors during active irradiation. Test systems are designed to gain visibility on device reaction whether it's functional or a parameter like power consumption.

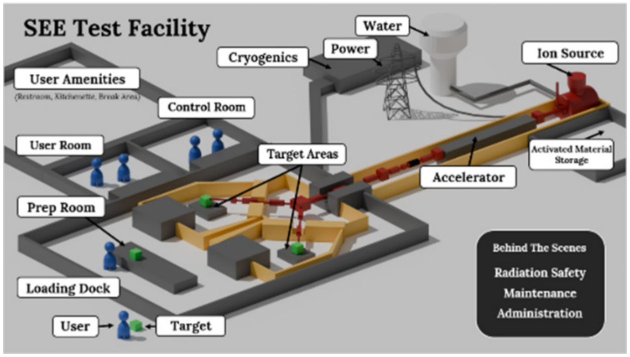

Figure 2: Notional SEE facility architecture (accelerator genre nonspecific). Conceptual image courtesy of Trusted Strategic Solutions.

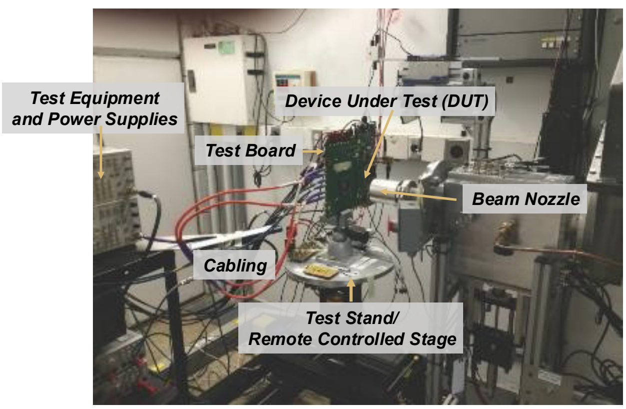

Figure 3: Sample test setup in a Test Chamber at Texas A&M University Cyclotron Facility (TAMU). Photograph courtesy of NASA.

THE ISSUE: CURRENT FACILITIES' CAPACITY IS INSUFFICIENT

We require facilities to perform terrestrial-based effects testing for GCRs and SPEs. Performing ground-based risk analysis requires depositing energy in the sensitive locations of microelectronics.

Microelectronics are becoming more sophisticated, exotic architectures, see, for example Ref. [4]. To understand the ever-evolving microelectronics, we require high LETs. This means we need high energy heavy ion SEE testing. testing electronics with ions of Z=2 to 92 and kinetic energies roughly greater than 100 MeV/amu.

Testing electronics with high energy heavy ions is not new. Work has already included the following topics that demonstrate the utility of such ion-based SEE testing:

- Ion range of penetration (energy deposition at sensitive portions of the semiconductor);
- Angular issues (increased packaging material challenges and ion track effects);
- Assembly/system tests (validation or gross risk evaluation);
- Environment considerations and particle beam physics issues (accuracy and data analysis).

The U.S. has only one facility with this high energy capability—Brookhaven National Laboratories' NASA Space Radiation Lab (BNL NSRL). The issue is that there is presently limited availability on a yearly basis. NSRL has stated that they are turning users away due to limited availability (and have been for several years). Their current availability is ~1000-1250 hours/year for electronics testing.

As microelectronics become more complex, the demand for high energy heavy ions has been, as one would expect, growing. In fact, there have been a couple of studies reflecting the need. The Strategic Radiation Electronics Council (SRHEC) performed an analysis of alternatives (AoA) in 2020 [5] that reflects a demand analysis with a gap of >> 4000 hours by 2030.

SOLUTION

As explained above, SEE is a real hazard for electronics used in space missions, and High Energy Heavy Ion Single Event Effects (HE HISEE) is an essential tool.

To overcome this gap in beam hours in the HE HISEE regime, the Department of Defense (DoD) is conducting market research regarding future HE HISEE domestic accelerator facilities to support DoD requirements through 2040. Our team continues to seek information from experienced organizations to evaluate present technologies and formulate achievable, cost-effective solutions.

The defense community is facing evolving challenges as we continue to integrate increasingly advanced microelectronics components with denser chips, advanced heterogeneous packaging, and AI/edge computing hardware.

To collect information from colleagues in the greater U.S. community, we have taken several approaches. First, we have visited the existing U.S. ion production accelerators already engaged in the community and asked them for written input regarding details such as machines performance, upgrade possibilities, and beam time allocation.

Second, the DoD has issued a request for information (RFI), with a closing date of 19 September 2025. This RFI is posted on the U.S. Government website `sam.gov` [6]. It requests all aspects of facilities, including asking for input on research and development needed as well as workforce.

Third, the DoD hosted a Market Research Day in parallel with the North American Particle Accelerator Conference 2025. The meeting was held at an offsite location as well as virtually, and all known U.S. entities with capabilities and workforce development for the HE HISEE future were contacted and offered an invitation. The goals of this meeting were to:

- Provide updates on future HE HISEE developments and technical requirements for the DoD;
- Understand industry capabilities;
- Gain a clearer picture of the capabilities and readiness of the industry to support this future need, including assessing their ability to meet specific technical requirements;

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THP041

- Gather information from potential accelerator system and subsystem component suppliers, as well as interested sites and organizations, to inform the Analysis of Alternatives (AoA) process;

Facilitate questions and answers around the DoD's recently released request for information (RFI) for a HE HISEE facility, mentioned above.

Fourth, our team presented a poster connected to this paper during the North American Particle Accelerator Conference to discuss the DoD requirements with our colleagues. We also disseminated the information to all known entities who could be willing to respond to the RFI while at the conference.

CONCLUSIONS

Our team has methodically sought input from the U.S. particle accelerator community, including those involved with workforce development for the DoD future high energy heavy ion single event effects (HE HISEE) domestic accelerator facilities to support DoD requirements through 2040. We will keep the community apprised of opportunities to provide further input to the DoD as well as opportunities to formulate proposals for possible future domestic accelerator facilities.

ACKNOWLEDGEMENTS

We gratefully acknowledge the financial support for this work provided by the U.S. Department of Defense (DoD) for the Analysis of Alternatives (AoA). We also acknowledge the efforts of the accelerator community in general and to those providing input to the RFI. Finally, the space and military communities are very thankful for the support over the years from the accelerator facilities, including the Department of Energy (DoE) facilities, for allowing us access for a critical need.

REFERENCES

[1] K. LaBel, "Radiation testing and modelling: practical challenges and shortfalls for the next five years," presented at RADECS'12, Biarritz, France, Sep. 2012. `https://nepp.nasa.gov/files/24755/LaBel_n168_RADECS2012_FutureChallenges_pres.pdf`

[2] J. A. Pellish, "Radiation effects in microelectronics – why we need particle accelerators", presented at NAPAC'22, Albuquerque, NM, USA, Aug. 2022, paper FRCDE3, unpublished. `https://accelconf.web.cern.ch/napac2022/talks/frcde3_talk.pdf`

[3] K. A. LaBel, "High energy single-event effects (SEE) testing and the implications of semiconductor technology and space system evolution," presented at HISEE'21, Apr. 2021. `https://nepp.nasa.gov/workshops/dhesee2021/talks/5b_LaBel-2021-HISEE-Presentation-High%20Energy%20SEE%20Testing%20and%20Technology%20Trends_v3.pdf`

[4] Presentations at the SEMI Industry Strategy Symposium, Half Moon Bay, California, USA, Jan. 2025. `https://www.semi.org/en/connect/events/industry-strategy-symposium-iss#agenda`

[5] J. Franco and J. Ross, "Strategic radiation-hardened (SRH) electronics council (SRHEC) public summary from analysis of alternatives (AoA) for domestic single-event effects (SEE) test facilities," 2021. `https://nepp.nasa.gov/workshops/dhesee2021/talks/6a_SEE%20AoA%20summary%20Nov%202020%20approved%20for%20release.pdf`

[6] High energy heavy ion single event effects testing. `https://sam.gov/workspace/contract/opp/49a84ed5932a44dab029a6edd35fbb23/view`