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Single Event Effects (SEE) Testing in the United States: The Current State of Facility Access and Considerations Moving Forward

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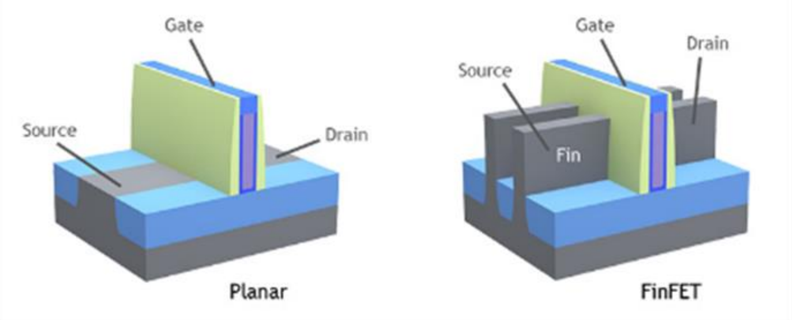
Outline

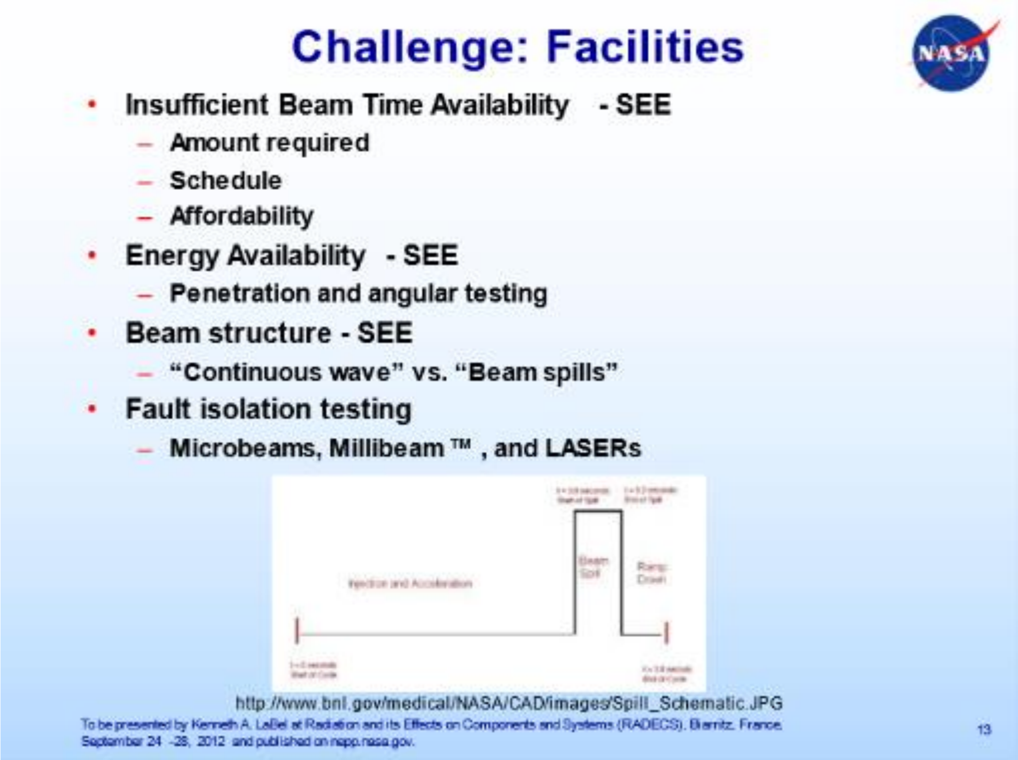
- Abstract and Perspective
- U.S. Heavy Ion Facility Status
  - Efforts to increase capacity and reliability
- U.S. (and Canada) Proton Facilities (>200MeV) Status
- Future Plans and Considerations
  - Capability increases need: higher energy heavy ion testing,
  - Capability increases for fault identification: microbeam,
  - The use of alternate means for SEE testing or increased SEE test efficiency, and,
  - The challenges of access and sustainment of proton medical sites in the U.S..
- Summary Comments



Courtesy Lam Research Corp.
https://blog.lamresearch.com/tech-brief-finfet-fundamentals/

Abstract

- It has been well-documented that the aerospace community has had difficulty in obtaining sufficient access hours to perform SEE testing[1]. The increase in number of “small” and less risk-adverse projects and the associated rise in the use of electronics not necessarily designed for space utilization are primary factors for the limited hours available at SEE test sites being well over-subscribed.
- These considerations are not new as seen in the figure to the right from 2012, but the ever-increasing hours needed have exacerbated the challenge[2].

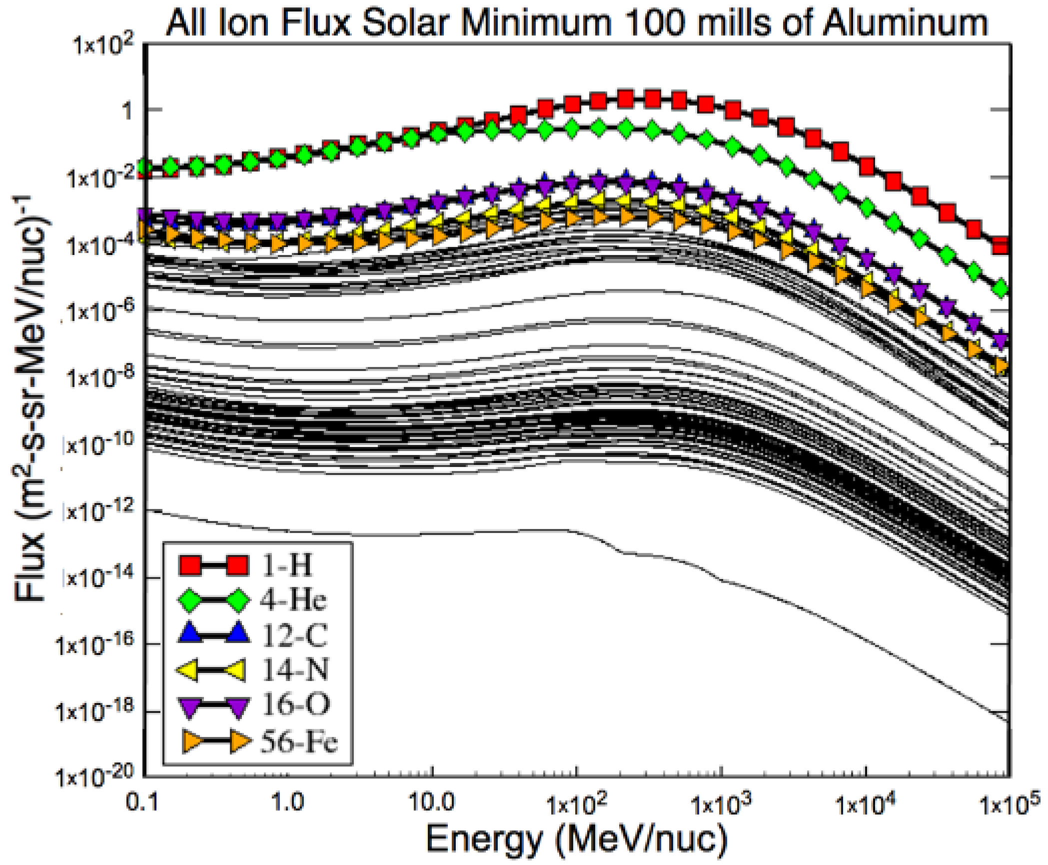


1. Strategic Radiation-Hardened (SRH) Electronics Council (SRHEC) Public Summary from Analysis of Alternatives (AoA) for Domestic Single Event Effects (SEE) Test Facilities, Franco, 2021, https://nepp.nasa.gov/workshops/dhesee2021/talks/6a_SEE%20AoA%20summary%20Nov%202020%20approved%20for%20release.pdf
2. Radiation Testing and Modeling: Practical Challenges and Shortfalls for the Next Five Years, LaBel, 2012, RADECS

Demand >> Capacity: Big Heavy Ion Gap to Fill

- As noted in ref.1 of the abstract, the gap between available capacity and the user demand is high (>5000 hours/year) and trends since that study show it continuing to grow apart.
  - That study made recommendations to ease/remove this gap for the standard energy heavy ions.
- In addition, many of the existing facilities in the U.S. are aging.
  - Reliability issues drive the need for upgrades and modernization.
  - Increased reliability = higher availability of beam = greater capacity (and lower risk)
- Efforts are underway (or even completed)
  - Coming attraction for slide 7!

U.S. Heavy Ion Facilities



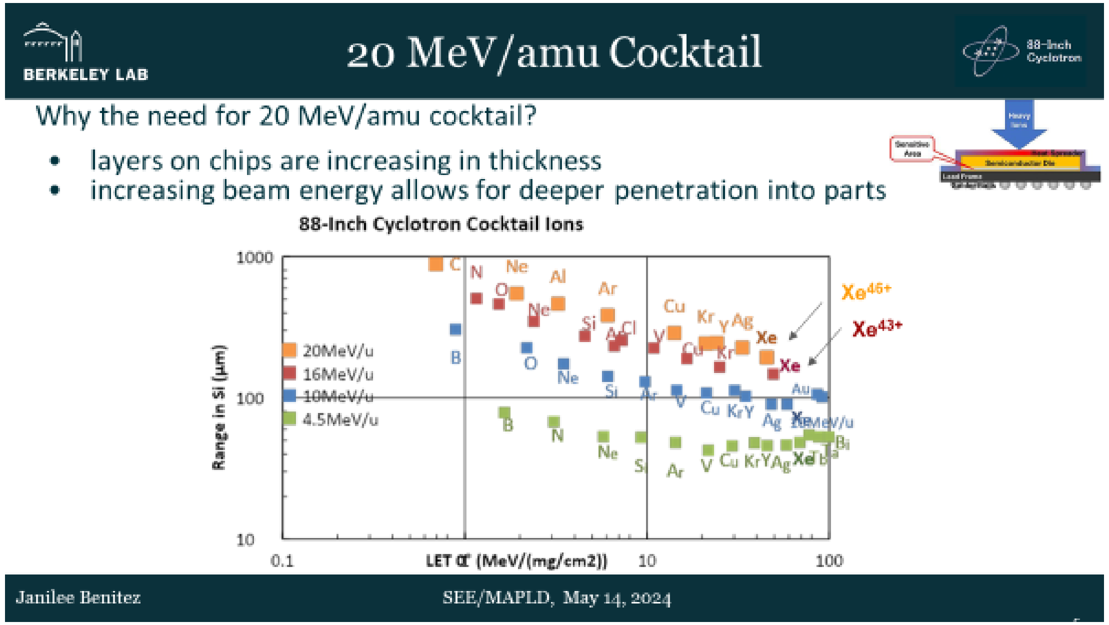
Courtesy of Vanderbilt
https://creme.isde.vanderbilt.edu/

The Landscape for U.S. Heavy Ion

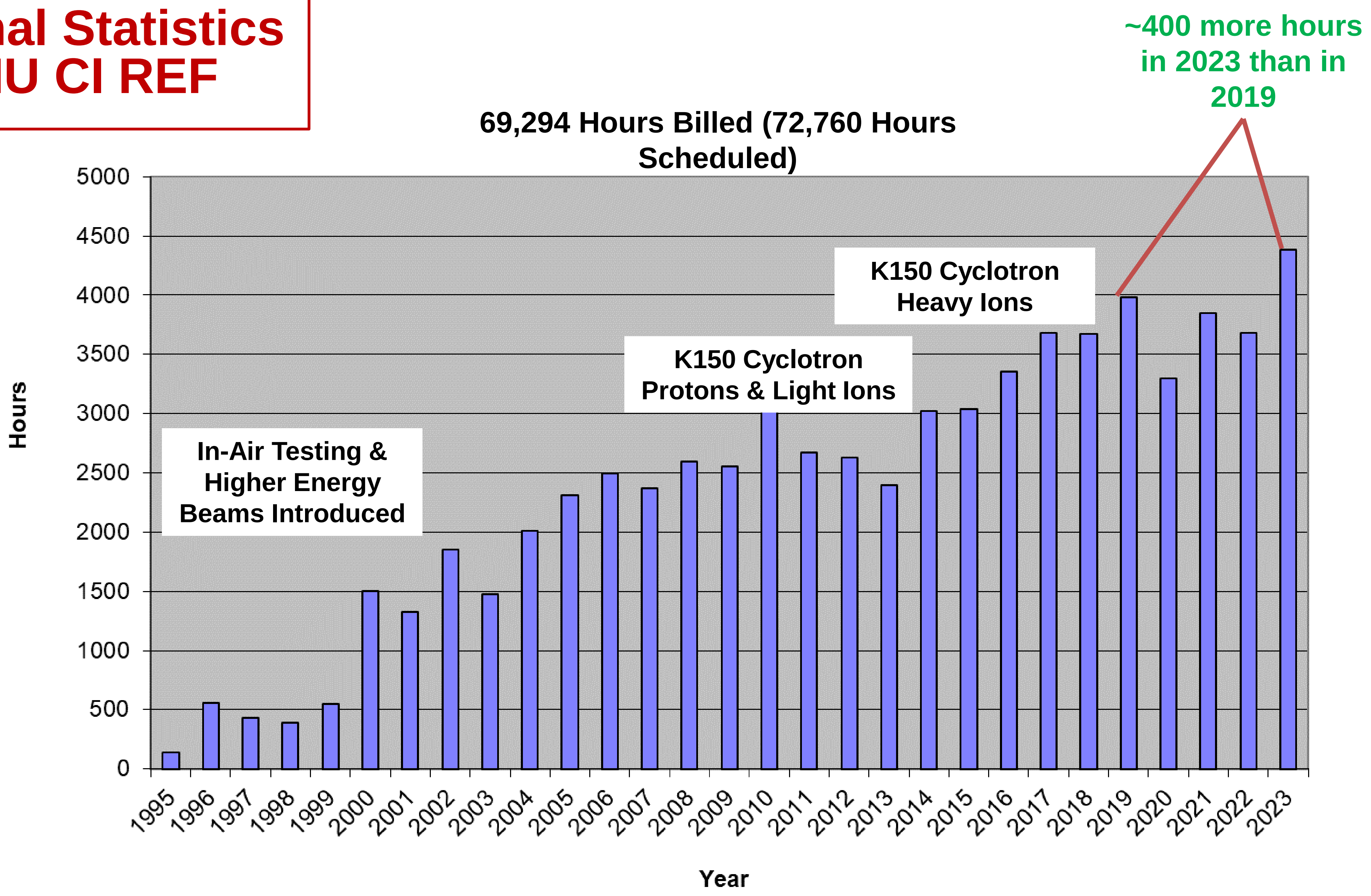
- Three "standard" heavy ion test sites exist in the U.S.
  - Texas A&M University (TAMU) Cyclotron Institute (CI) Radiation Effects Facility (REF)
    - Two cyclotrons: K500, K150
  - Lawrence Berkeley National Laboratories (LBNL) Berkeley Accelerator Space Effects (BASE) Facility
    - One cyclotron: 88-inch (akin to a K150)
  - Michigan State University (MSU) Facility for Rare Isotope Beams (FRIB) SEE (FSEE)
    - Three segment LINAC system with SEE tap off first line segment (LS1)
- One high energy heavy ion site
  - Brookhaven National Laboratories (BNL) NASA Space Radiation Laboratory (NSRL)
    - Synchrotron
- One low energy heavy ion site
  - BNL Single Event Upset Test Facility (SEUTF)
    - Tandem Van de Graaff

Standard Energy Heavy Ions – Efforts Underway or Completed 1

- MSU FSEE LS1
  - Fully operational: ~1500 hours available per year
  - No currently funded additional upgrade activities, but MSU performing continuous improvement (nominal operation)
  - Upgrades under consideration
- TAMU CI REF
  - Objective: Upgrade K150 to reliably provide up to Xe ion
    - New ion source being added to K150 line
    - Improvements to K150 vacuum system
    - General reliability and spares added to K150 and K500
    - CY26 readiness
- LBNL BASE
  - Upgrade 20 MeV/amu tune capabilities and increase machine reliability
    - Improve 88-in vacuum system
    - Add spares and updated equipment for improved reliability
    - CY25 readiness



Operational Statistics @ TAMU CI REF



Standard Energy Heavy Ion – Efforts Underway 2

- MSU K500 Cyclotron
  - Formerly part of a coupled cyclotron system know as National Superconducting Cyclotron Laboratory (NSCL)
    - Shutdown prior to activation of the new FRIB
  - Machine is equivalent to TAMU K500 cyclotron
  - Being repurposed as a standalone machine with SEE as the PRIME purpose of the accelerator (as opposed to science)
    - Refurbishment and modernization underway
  - Expected to add 4000+ hours/yr to available heavy ion access
  - CY25 readiness

"Michigan State University will refurbish its history-making K500 cyclotron and install it as the heart of a new chip-testing facility for next-generation semiconductor devices at the Facility for Rare Isotope Beams. The new facility will be what amounts to the third act for the K500, which made history on the nuclear science scene 40 years ago as the world's first superconducting cyclotron."

https://msutoday.msu.edu/news/2023/msu-to-refurbish-worlds-first-superconducting-cyclotron-for-chip-testing

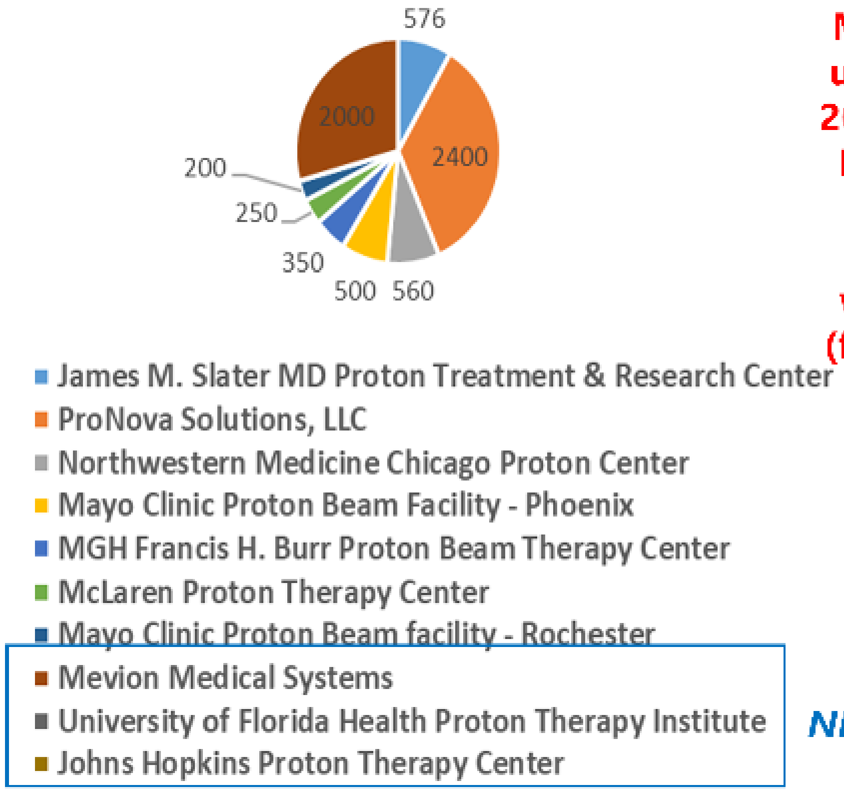
U.S. and Canada Proton Facilities: Focus is >200 MeV

Testing at TRIUMF

Bottom Line: Lots of Folks Selling a Little Time and…

Estimated CY24 Hours Available

6260 hours - current capacity – With 3 new entrants adding TBD time (see below)



NEW!

Risky business
MGH closes for upgrade in Nov 2024 for 2 years; ProNova STILL seeking long-term contract with Covenant (facility owners)

Does not include hours at Tri-University Meson Facility (TRIUMF) – Vancouver, CA
2200 hours spread on 2 accelerators 480/355 MeV, 105 MeV and below.

2025: anyone want to predict what happens next?

ProNova and Mevion (new as of May!) have dedicated research accelerators open weekdays and weekends.
Others use treatment or research rooms at oncology center.

Scan the QR Code to download the full status spreadsheet – new for 2024: current hourly rates where provided

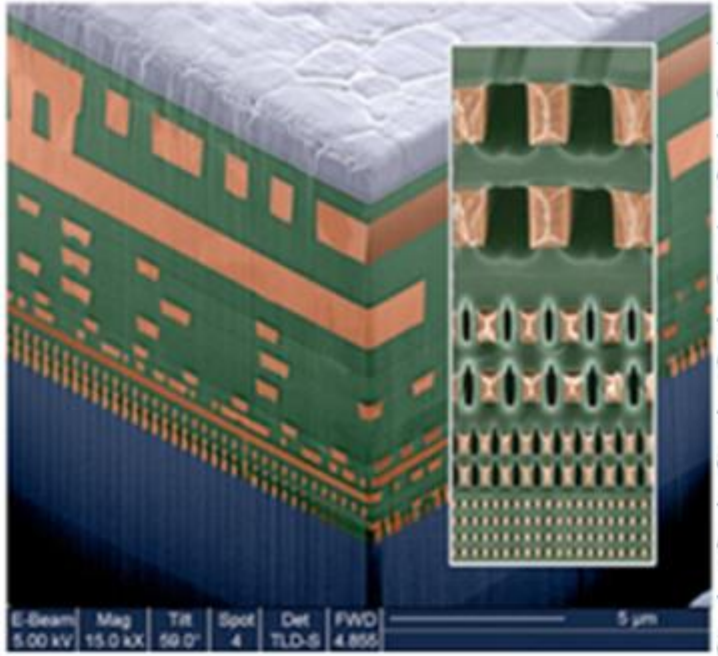
U.S. Proton Accelerator News (>200 MeV prime energy)

- Currently accessible
  - ProNova, MGH, McLaren, NW Medicine, Mayo (2 sites), Loma Linda, Johns Hopkins – Sibley, Univ of FL Health Proton Therapy Institute (UFHPTI), Mevion

***Yellow* = newly available over the past year**

- Concerns
  - MGH – suspending SEE testing in Nov 2024 for major upgrade
    - Hopeful to reopen in CY27 (2 year down time) – lots of TBDs
  - ProNova
    - Nothing draconian, but still no long-term contract with facility owner (Covenant Health)
  - UAB Proton site shuttered on 5 December 2023 – TBD on what's next
- Opportunities
  - Partially completed medical site in Winter Garden, FL (foreclosure sale)
    - Realtor is working towards site completion for research/SEE testing, but unknown future business model and access
  - Potential new development at Auburn University – stay tuned

Future Plans and Considerations



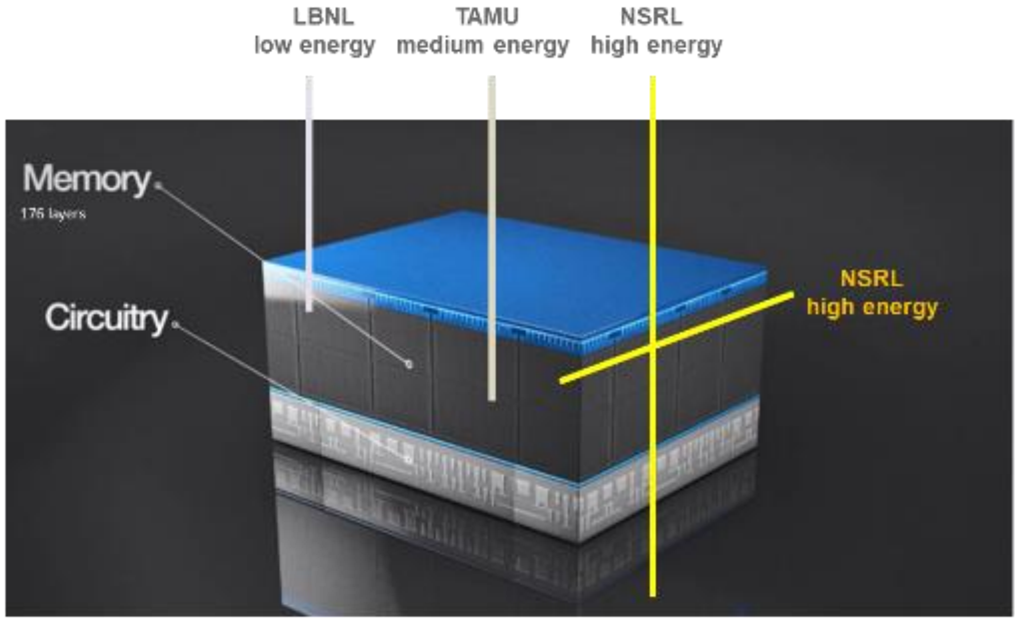
http://images.dailytech.com/nimage/4621_21476.jpg

Courtesy of Daniel Fleetwood, IEEE NSREC 2020 Short Course

The Need for High Energy Heavy Ions

- Definition: testing electronics with ions of Z=2 to 92 with kinetic energies roughly greater than 100 MeV/amu
- Provides two general enabling characteristics:

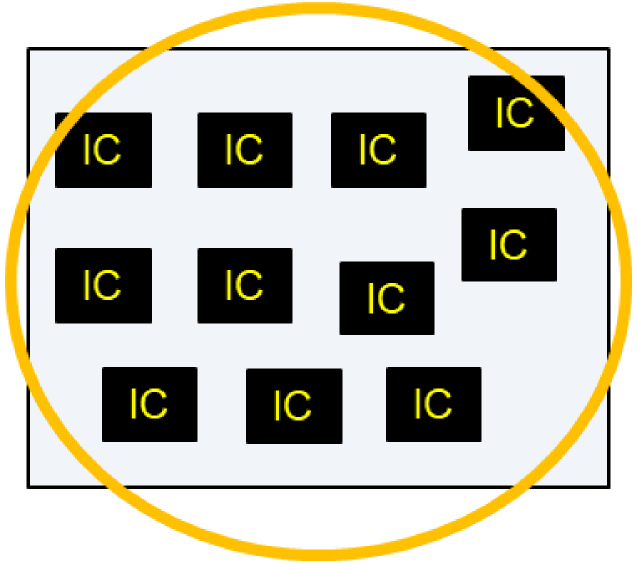
Long range ion penetration



Micron's proprietary CMOS-under-Array technique constructs the multilayered stack over the chip's logic, packing more memory into a tighter space and shrinking 176-layer NAND's die size, yielding more gigabytes per wafer.

Courtesy of Micron, https://www.eetimes.com/micron-leapfrogs-to-176-layer-3d-nand-flash-memory/#

Large simultaneous irradiation areas



Advanced 3D Packaging and Systems Test Push the High Energy Demand

Demand for High Ion Energy Testing is Growing

Low Energy SEE Test

2020

- 90% of SEE test is Low Energy
  - 10-50 MeV/n (Mega-Electron Volts /n)

2030

- 60% of SEE test is Low Energy
  - Economical test for monolithic integrated circuits
  - Issues for flip-chip, stacked die, 2.5/3D packaging, and assemblies
- Access assured with low energy investments
- TAMU K500 & K150, LBNL, FRIB Lin Seg 1, and MSU K500 meet Low Energy demand

High Energy SEE Test

2020

- 10% of SEE test is High Energy
  - >100 MeV/n

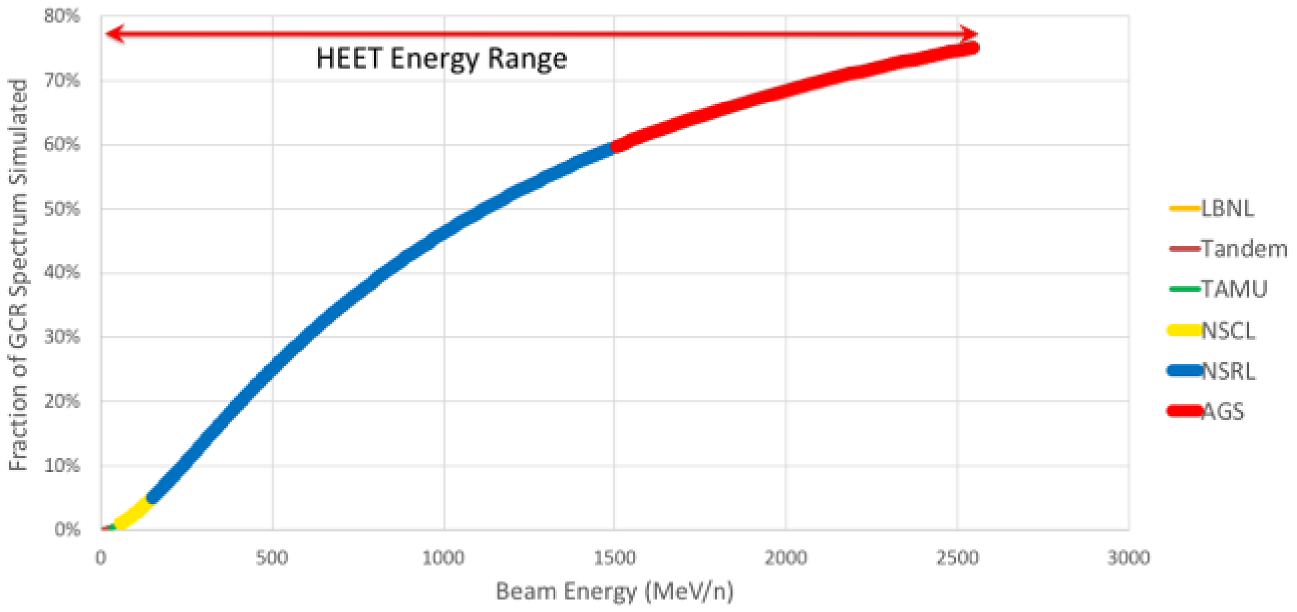
2030

- 40% of SEE test is High Energy
  - New technology and CCA level testing will demand high energy
  - Economical for new technology
- Access assured by high energy investment
- 40% is ~4000 hours/yr
  - BNL AGS or MSU K1200 meets High Energy demand

After Ref 1

Multiple High Energy Solutions Possible Including

- MSU FSEE Line Segment 3 (LS3)
  - New SEE Test Station would provide access to ~ 200 MeV/amu ions
  - Total (standard plus high energy) capacity remains constant
- Adding capacity to BNL NSRL
  - Not a 24/7 operating model currently
  - Main risk would entail the impact of new Science facilities at BNL will have on operations/hourly rates
- Reutilize the BNL Alternating Gradient Synchrotron (AGS)
  - https://radnext.web.cern.ch/blog/webinar-bnl-nsrl/
  - The proposed High Energy Effects Test (HEET) facility
- Or build a new site or ???



Brown, SEEMAPLD La Jolla, Ca May 2024

We Mentioned Large Beam Area, But What About Very Small?

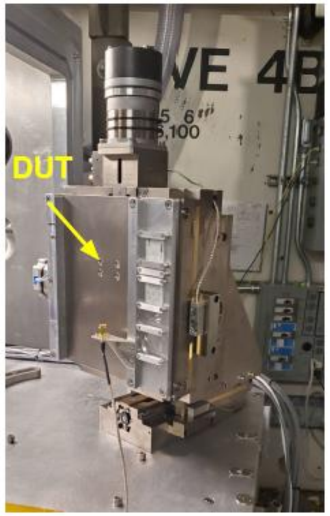
- Heavy Ion Microbeams, LASERs, X-Rays, etc all provide a small spot size that can be used to:
  - Scan areas of a device for sensitivity,
  - Be used for fault/fail isolation analysis,
  - Gather data for design hardening approaches (i.e., the spread of transient sizes that might be observed in an op amp),
  - Screening for go/no-go criteria (perhaps down-selection amongst multiple Flash memories as an example), or,
  - Even validating a test set prior to an expensive heavy ion experiment!
- U.S has only one microbeam heavy ion facility at Sandia National Laboratories
  - Ion Beam Laboratory (IBL)
  - Drawback is that it is low energy (6 MeV Tandem) and low Z: penetration range and energy deposition are limited

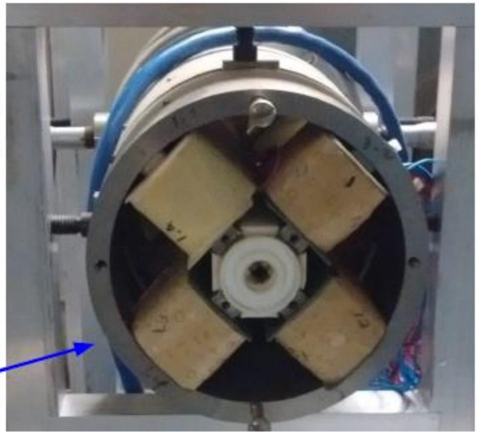
https://www.osti.gov/servlets/purl/1328104

New Microbeam Efforts at LBNL

Microbeam Components

- **Collimator and Quadrupole Magnet**
  - Used to focus the heavy ion beam
- **Image Relay System**
  - System to relay images of the DUT during testing
  - Used for alignment, and to measure beam location and shape
  - Phosphor is mounted to the DUT motion system
- **Dosimetry System**
  - Electron generation foil (0.001” Al) and electron multiplier
- **DUT Motion**
  - 3-axis motion system; each axis has a 0.1 µm absolute encoder



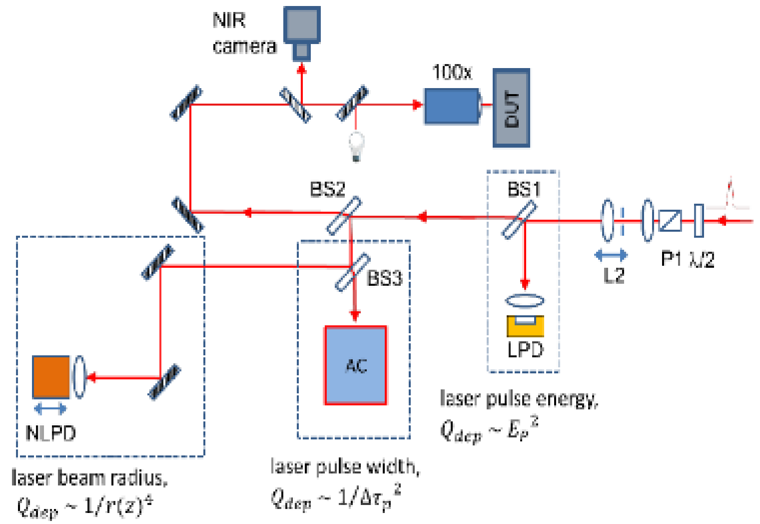


Eventual goal is a 1 µm beam

Donaghue, SEEMAPLD La Jolla, Ca May 2024

Alternate Means for SEE Testing and Increasing Efficiency (aka Reducing Heavy Ion Demand)

- Beyond heavy ions, we also touch on LASERs, X-Rays, and Electrons as tools to deposit energy to simulate heavy ions.
- While none are perfect substitutes, all have the potential for reducing the overall demand for heavy ions.
- LASER usage has been expanding beyond the laboratories as there are at least 3 commercial vendors selling benchtop systems!
  - Correlation to heavy ions is always the question as it will with all the options.
  - It's an active area in the U.S. as more and more in industry, academia, and government all start using LASER systems.
    - The option of NO TRAVEL is often quite appealing. ☺

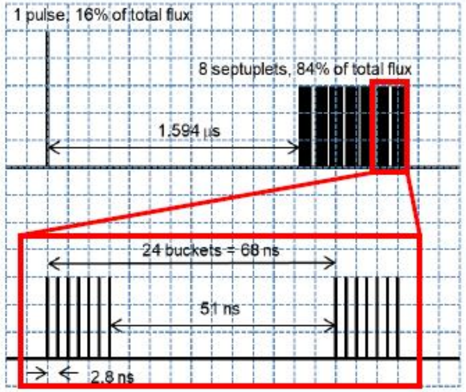


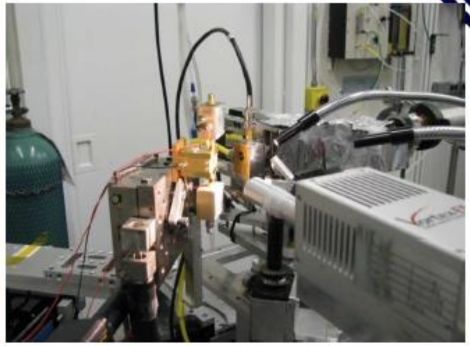
Experimental Setup for doing Two-Photon-Absorption

Courtesy Steve Buchner

X-Rays

Aerospace's SEE Test Station at the Advanced Photon Source





X-ray SEE test stand with translation stages and confocal light microscope for locating beam on device

- Tunable photon energy 4.3 – 27 keV
- Tunable flux (*ergo*, equivalent LET)
  - *Reliably reach equivalent LET of 30 MeV cm²/mg at 12 keV*
  - *Up to 100 MeV cm²/mg if using lower photon energy (for greater absorption)*
  - *Fine control with Al and Mo filters*
- Kirkpatrick-Baez focusing optic (1-2 µm FWHM)

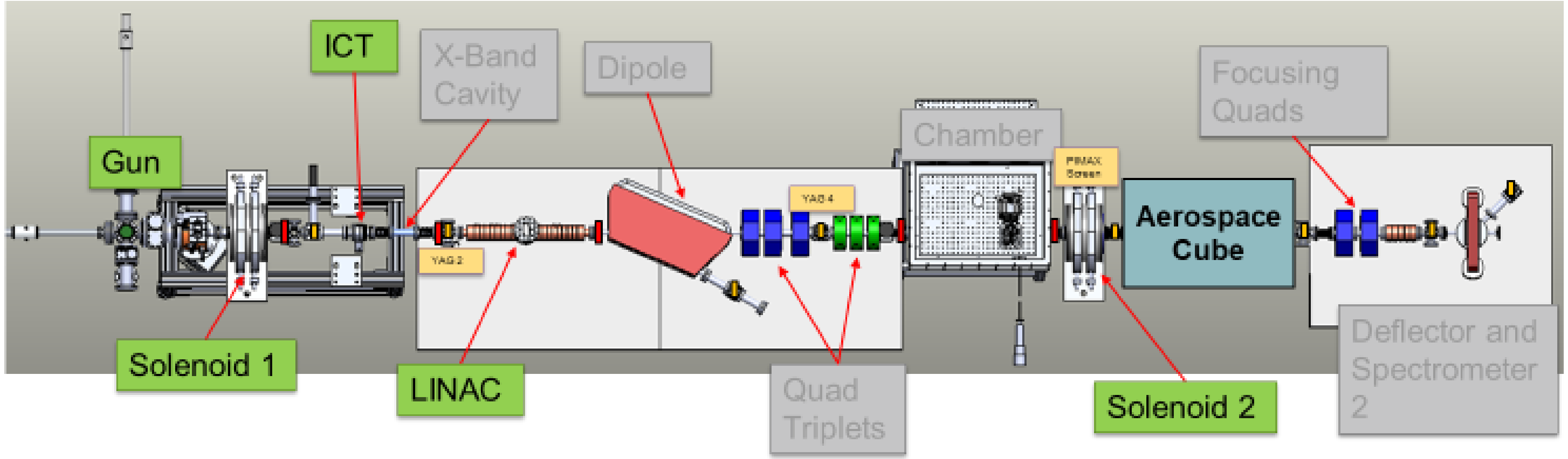
- Hybrid fill mode is pulse picked with a mechanical chopper (271 kHz)
  - *Additional shutter for single shot operation*
  - *Beamline generated clock signals trigger DAQ systems*

Monahan, SEEMAPLD La Jolla, Ca May 2024

Electron Bunches

PEGASUS Electron Beam – UCLA

- Photoelectron Generated Amplified Spontaneous Radiation Source (PEGASUS)
  - photo-generated electron bunch
  - electron energy: 3 – 10 MeV
  - electron pulse width: 100 fs – 2 ps
  - electron bunch charge: up to 100 pC (6x10^8 electrons)
  - Integrated Charge Transformer (ICT) cannot read < 20 fC



5 - G. Tzintzarov

Tzintzarov, SEEMAPLD La Jolla, Ca May 2024

But Wait: A New Program (High Risk, High Reward)

- U.S. Defense Advanced Research Projects Agency (DARPA)
  - ***Advanced Sources for Single-event Effect Radiation Testing (ASSERT) project***
- “ASSERT seeks to develop SEE testing for radiation-hardened electronics that involves beams that simultaneously achieve long range and high-linear energy transfer in silicon while penetrating packaging and metallization; beam optics to achieve spot diameters that replicate the narrow charge track of a heavy ion while also enabling large-area scanning; sources that predict the heavy-ion response across electronic components; and compact and cost-effective sources that can be incorporated into the development process.”
  - https://www.militaryaerospace.com/computers/article/14295511/single-event-effects-see-radiation-hardened-space

Wow! High Penetration PLUS Microbeam Spot Size

The Challenge with Protons (>200 MeV)

- While TRIUMF is readily available (and a great place to test) and BNL NSRL does have high energy protons, logistics issues are problematic for many U.S. organizations.
  - TRIUMF: crossing the border, while viable, does cause extra challenges (and paperwork)
  - BNL NSRL: hourly rates
  - Of course, if you need 500 MeV or greater, both are options.
- That said, the medical sites, on paper, have more accessibility than our current demand by >1000 hours/yr.
  - So, why aren't they selling all their available time?
  - And why do many of the sites express interest and disappear or some just stop selling?
  - **Stay tuned for the next slide to find out why**
- I'll also note that many of the medical facilities have technical limitations for users
  - Dosimetry is configured for patients and may not be applicable
  - Flux rates or hourly fluence to limit activation in the room
  - User may not be able to start/stop the beam themselves, …

Protons and Medical Sites

- Rationale why users are coming even when they say they have demand
  - Hourly rates: we've noted that the facilities that charge >$2000USD/hr have challenges filling time
    - **SEE testers are notoriously cheap** (or at least their organizations are) and would rather wait months to get to a less costly/hr site
  - Location: in the U.S., proton testing seems to thrive in local communities (i.e., testers are nearby organizations within an easy drive)
    - Traveling long distances for 4 or maybe 8 hours of access isn't worth it!
  - Technical limits (as noted previously)

- Medical sites have their own considerations
  - Patients first (and rightfully, so)
    - Fear of equipment damage falls into this category
    - Limited hours as well
  - The big picture: **success or failure of a site is based on patient loads, not SEE users**
    - Foreclosures are not uncommon
  - Changes in management
    - Happens EXTREMELY often in the U.S.
  - Figuring out an appropriate hourly rate
    - In the U.S., medical insurance pays for most of patient treatment costs at a >> rate than we pay (as a rule)
    - In some cases, the business is 3-way discussion (or argument) between university, hospital, and facility management

Not a simple solution on either side.

A research accelerator able to provide time at a reasonable access cost is a probable winner.

Summary

- Investments in the U.S. show a dramatically improved landscape for standard energy heavy ion access over the next few years as upgrades and reuse bring significant capacity
  - The picture for high energy heavy ions is cloudier until efforts are funded and underway
- The big proton question is if the U.S. will ever have a “dominant” proton SEE research machine as in the old Indiana University site
  - With recent activities, the next few years should be “interesting”
- New capabilities and increased use of alternates is happening world-wide
  - As we use more commercial electronics and need more systems testing, this is not unexpected

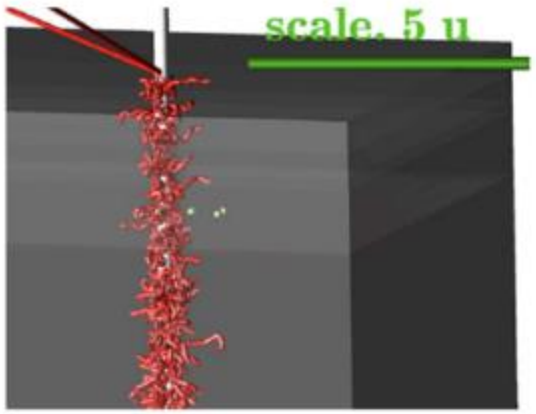


Fig. 6. Simulation of 280 MeV Fe interacting with the simulated SRAM array structure. The solid white tube represents the incident ion track. Red tubes represent generated δ-rays along the ion track. The green structures represent the sensitive volumes of neighboring devices.

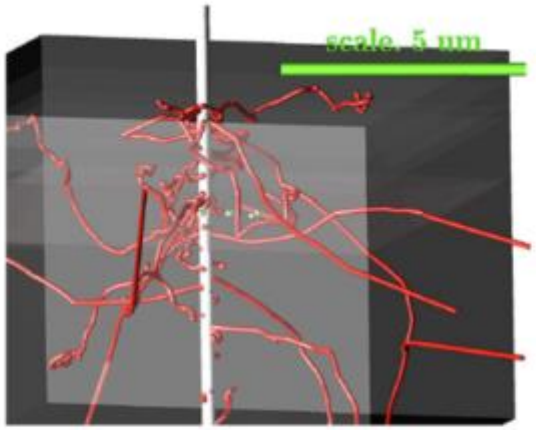


Fig. 7. Simulation of 28 GeV Fe interacting with the simulated SRAM array structure. The solid white tube represents the incident ion track. Red tubes represent generated δ-rays along the ion track. The green structures represent the sensitive volumes of neighboring devices.

KING et al.: THE IMPACT OF DELTA-RAYS ON SINGLE-EVENT UPSETS IN HIGHLY SCALED SOI SRAMS, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 6, DECEMBER 2010

Acknowledgements

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  - My long-time co-conspirator, Tom Turflinger/The Aerospace Corp