External Radiation Test Facilities for Testing of Electronics: NASA Overview with Emphasis on Single Event Effects (SEE)

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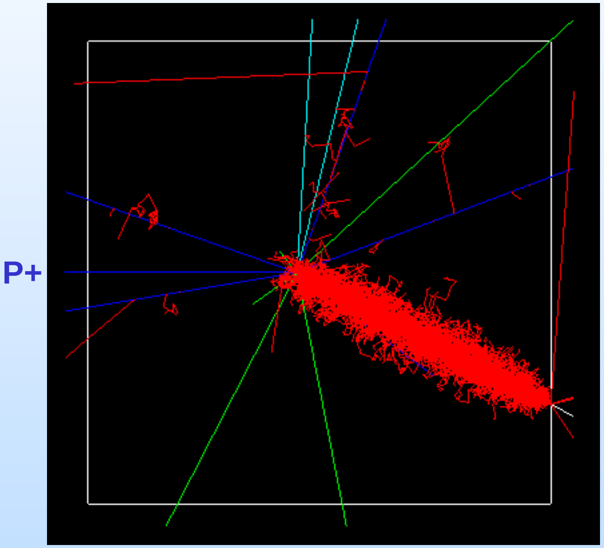
To be presented by Kenneth A. LaBel at the Study on Space Radiation Effects Test Infrastructure (Electronics) Meeting, Washington DC, March 29-31, 2017.

Acronyms

- Air Force Space and Missiles Center (AFSMC)
- Automated Test Equipment (ATE)
- Californium (Cf)
- Crocker Nuclear Lab (CNL)
- Displacement damage dose (DDD)
- Department of Energy (DOE)
- Device Under Test (DUT)
- Failure In Time (FIT)
- Facility for Rare Isotope Beams (FRIB)
- Grand Accélérateur National d'Ions Lourds (GANIL)
- Galactic Cosmic Rays (GCRs)
- Hampton University Proton Therapy Institute (HUPTI)
- Integrated Circuits (ICs)
- Indiana University (IU)
- Indiana University Cyclotron Facility (IUCF)
- Joint Mission Assurance Council (JMAC)
- NASA Jet Propulsion Laboratory (JPL)
- University of Jyväskylä (JYFL)
- Los Alamos National Laboratory (LANL)
- Los Alamos Neutron Science Center (LANSCE)
- Lawrence Berkeley National Laboratories (LBL)
- linear energy transfer (LET)
- Cyclotron, linear accelerator (LINAC)
- Loma Linda University Medical Center (LLUMC)
- Maintenance and Operation (M&O)
- Michigan State University (MSU)
- National Academies of Science (NAS)
- NASA Electronic Parts and Packaging (NEPP) Program
- National Reconnaissance Office (NRO)
- National Superconducting Cyclotron Laboratory (NSCL)
- National Science Foundation (NSF)
- NASA Space Radiation Laboratory (NSRL)
- Office of Safety and Mission Assurance (OSMA)
- Rough Order of magnitude (ROM)
- South Atlantic Anomaly (SAA)
- SCRIPPS Proton Therapy Center (SCRIPPS)
- Single Event Effects (SEE)
- Soft Error Rate (SER)
- Single Event Upset Test Facility (SEUTF)
- Sandia National Laboratories (SNL)
- Texas A&M University (TAMU)
- Tethered Balloon System (TBS)
- Total ionizing dose (TID)
- Tri-University Meson Facility (TRIUMF)
- Tandem Van de Graaff (TVdG)
- University of Maryland Proton Therapy Center, Baltimore (U MD)
- Centre de Ressources du Cyclotron Université Catholique De Louvain (UCL)
- University of Florida Proton Health Therapy Institute (UFHPTI)
- Van de Graaff (VDG)
- Van de Graaffs (VdGs)

Outline

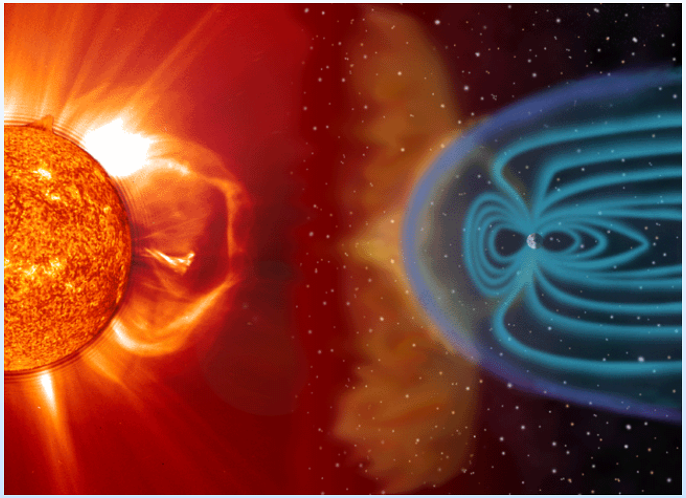
- **Basic Radiation Effects on Electronics**
- **Radiation Effects and Sources**
- **Domestic SEE Facilities**
  - **Heavy Ion**
  - **Proton**
  - **"Specialty"**
- **Other Radiation Test Facilities**
  - **Space**
  - **"Other"**
- **Summary/Comments**



Sample 100 MeV proton reaction in a 5 um Si block.
Reactions have a range of types of secondaries and LETs.
Complicating statistics and testing.
(after Weller, Trans. Nucl. Sci., 2004)

Radiation Effects and the Space Environment

- **Three portions of the natural space environment contribute to the radiation hazard**
  - **Solar particles**
    - **Protons and heavier ions**
  - **Free-space particles**
    - **Galactic Cosmic Rays (GCRs)**
      - **For earth-orbiting craft, the earth's magnetic field provides some protection for GCR**
  - **Trapped particles (in the belts)**
    - **Protons and electrons including the South Atlantic Anomaly (SAA)**
- **Hazard observed is a function of orbit and timeframe**



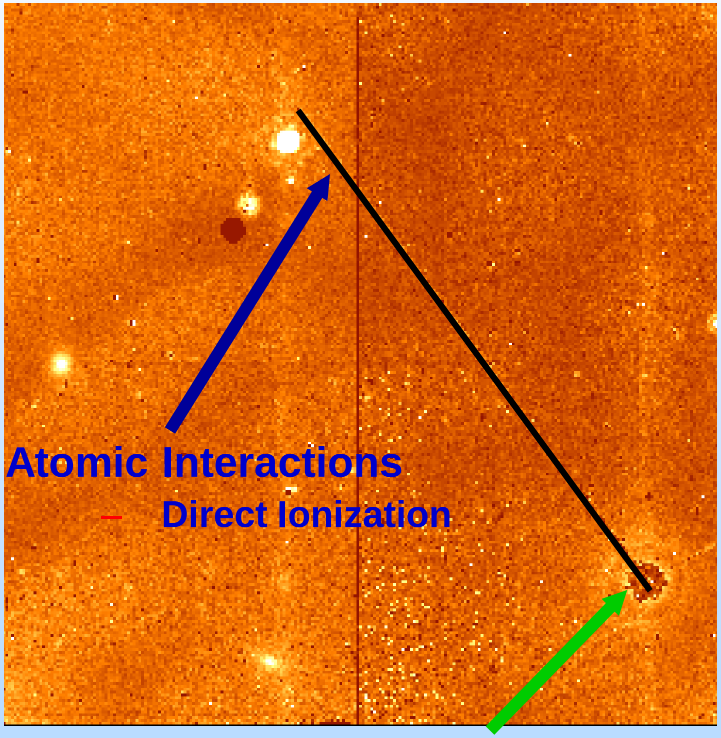
The sun acts as a modulator and source in the space environment,
after Nikkei Sciences
J. Barth, NSREC Short Course, 1998.

Radiation Effects and Electronics

- Ground testing is performed to qualify electronics for space usage
  - Long-term cumulative degradation causing parametric and/or functional failures
    - Total ionizing dose (TID)
    - Displacement damage dose (DDD)
  - Transient or single particle effects (Single event effects or SEE)
    - Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy
    - Heavy ion tests on the ground are used to bound risk for space exposure to GCRs and some solar particles
    - Proton tests on the ground aid risk analysis for any orbits exposed to trapped protons (Space Station, for example) or solar protons.

Particle interactions with semiconductors

http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html



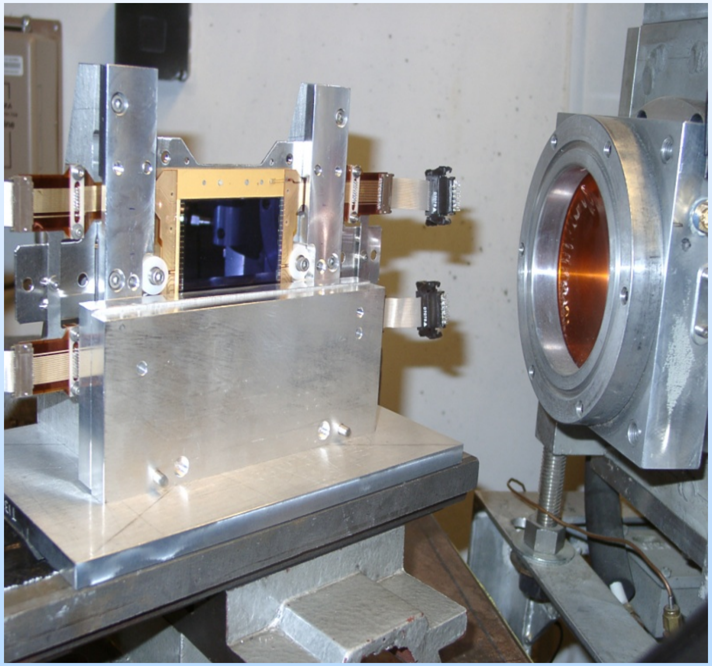
Interaction with Nucleus
- Indirect Ionization
- Nucleus is Displaced

Typical Ground Sources for Space Radiation Effects Testing

- **Issue: TID**
  - Co-60 (gamma), X-rays, Proton

TID is typically performed at a local source with nearby automated test equipment (ATE). All others require travel and shipping with commensurate limitations/costs.

- **Issue: DDD**
  - Proton, neutron, electron (solar cells)
  - Cyclotron, linear accelerator (LINAC), Van de Graaff (VDG) accelerator
- **SEE (GCR)**
  - Heavy ions
  - Cyclotrons, synchrotrons, VDGs
    - Lesser utility: Cf sources
- **SEE (Protons)**
  - Protons (E>30 MeV)
  - Cyclotrons, synchrotrons



Hubble Space Telescope Wide Field Camera 3 E2V 2k x 4k n-CCD in front of Proton Beam at UC Davis Crocker Nuclear Lab (CNL).
Photo by Paul Marshall, consultant to NASA

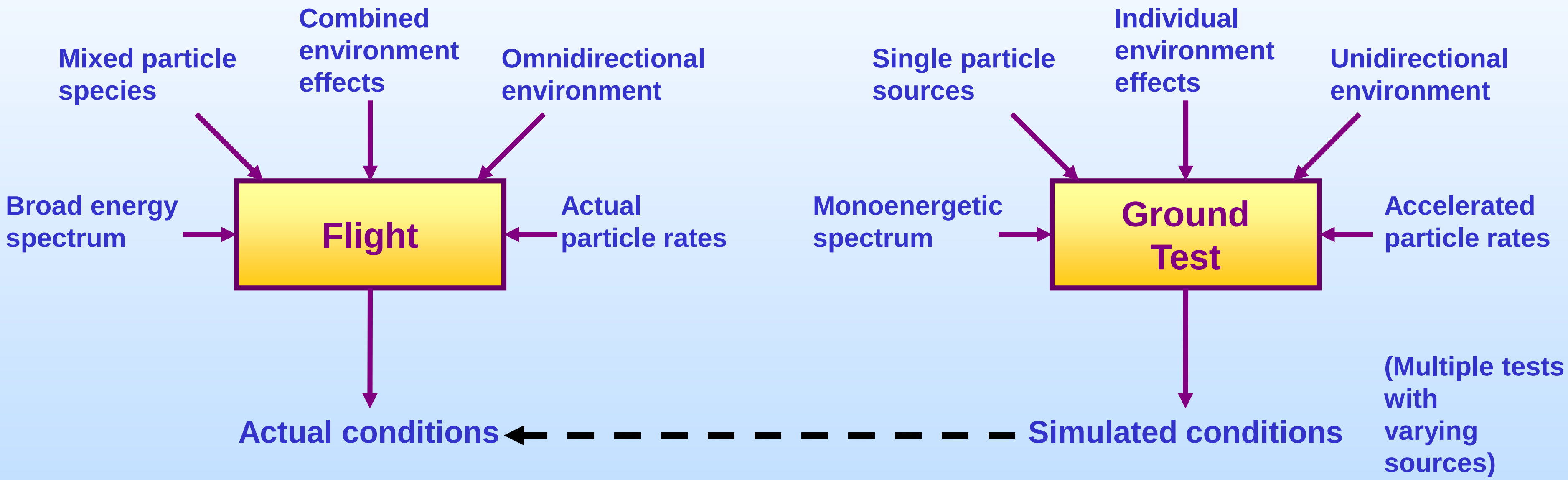
Define the Problem - SEE

- ***Particle accelerators*** **are used to evaluate risk and qualify electronics for usage in the space radiation environment**
- **Two different particle types are used depending on the mission**
  - **Heavy ions (galactic cosmic ray (GCR) simulation)**
  - **Protons – (solar events and trapped proton simulation)**
- **Domestic sources for these particles are becoming more limited due to facility closures or reduction of accessible hours.**
  - **Examples:**
    - **Indiana University Cyclotron Facility (IUCF) – CLOSED 2014 (protons)**
    - **Lawrence Berkeley National Laboratories 88in Cyclotron (LBL) – Reduced user available hours in FY16 (heavy ions)**
    - **SCRIPPS Proton Therapy Center – announces bankruptcy on March 2, 2017**

Sample Issues for Radiation Effects Simulation at Cyclotrons

- **Particle**
  - Dosimetry
  - Uniformity
  - Energy mapping to the space environment
  - Particle localization
  - Stray particles (neutrons, for example)
  - Particle range
  - Flux rates and stability
  - Beam structure
    - Beam spills
- **Practical**
  - Cabling
  - Thermal
  - Speed/performance
  - Test conditions
  - Power
  - Mechanical
  - Vacuum

Radiation Test Issue - Fidelity



How accurate is the ground test in predicting Space Performance?

After Stassinopoulos, NASA

Users of These Facilities - Electronics

- Space Flight Projects
  - Perform qualification tests on integrated circuits (ICs)
  - Perform system validation/risk tests on assembled hardware (boards/boxes)
- Research
  - Perform exploratory technology sensitivity tests on new devices/technology in advance of flight project usage or to evaluate radiation hardening techniques
  - Perform testing to develop and define qualification (test) methods
- Semiconductor Industry
  - Performs tests on their new products for MIL-STD qualification as well as preliminary sensitivity tests on devices under development
  - Commercial terrestrial products use protons for soft error rate (SER) testing in lieu of neutrons
  - Avionics, automotive, etc… test for safety critical validation

Who Else Uses These Facilities

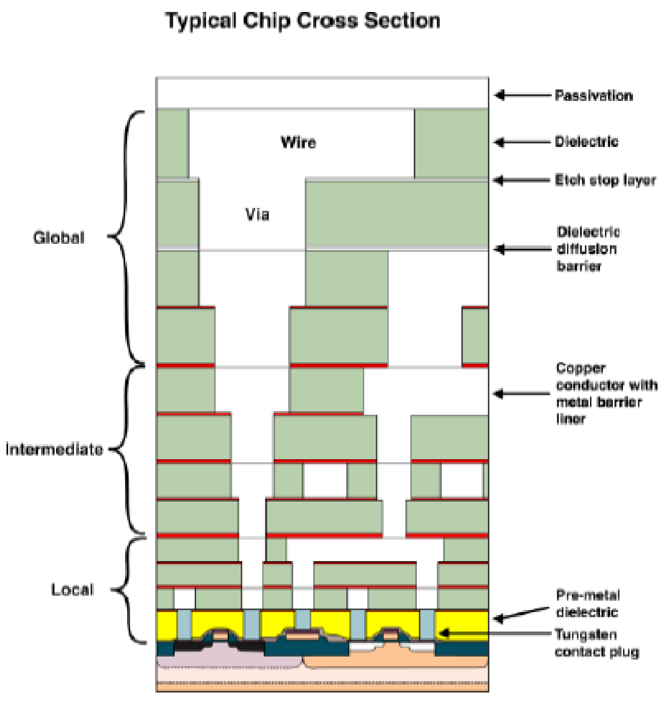
- Other Aerospace - Government, Industry, International, University
  – Similar to usage on previous slide
- NASA
  – Human Radiation Protection (biological sciences)
  – Material/shielding Studies (physical sciences)
  – Solar cells (damage)
- Medical
  – Oncology treatment
  – Isotope development
  – Implantable electronics
- Science
  – DOE, NSF, Universities

Studies on U.S. SEE Test Facilities

- The Aerospace Corporation for AFSMC (released 2015)
  - Noted aging radiation test infrastructure and uncertainty of future access to needed test sites
- National Reconnaissance Office (NRO) (2015) – unreleased
- Ad hoc proton "team" formed by NASA OSMA/NEPP along with Air Force Space and Missiles Center (AFSMC), NRO, and Department of Energy (DOE) with support from industry and university partners (see later in presentation)
- This study: National Academies of Science (NAS) study on space radiation test infrastructure (electronics)
  - NASA OSMA/NEPP, DOE, and AFSMC are supporting the study.
    - Facilities and related resources necessary to characterize radiation stress induced failure modes of electronic components;
    - Simulation capabilities and related theory and modeling;
    - Facilities and related resources available for undertaking those simulations;
    - The workforce available to conduct such simulation and characterization; and
    - The training and research experience programs in place to prepare a workforce for these activities.
- Topic has been discussed at Joint Mission Assurance Council (JMAC) and radiation test facilities have been on Critical Technologies List

Heavy Ion Test Sources

- SEE heavy ion ground tests use a *macrobeam* source
  - Think of it as buckshot sent at a target
    - We know how many particles per cm^2, but not where the individual particles hit
  - Different sources have different energies and test constraints
    - Particle (ion) availability
    - Energy
    - Penetration range, etc…
  - Metric: linear energy transfer (LET)
  - Primary NASA usage for electronic parts qualification and for technology evaluation (research)
    - Texas A&M University (TAMU) Cyclotron, and,
    - Lawrence Berkeley Laboratories (LBL) Cyclotron
  - Secondary facilities
    - NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratories (BNL)



Ion must have sufficient energy/range to penetrate to sensitive area of the device. Particles in space often have much higher energies

Heavy Ion Facilities – High Use

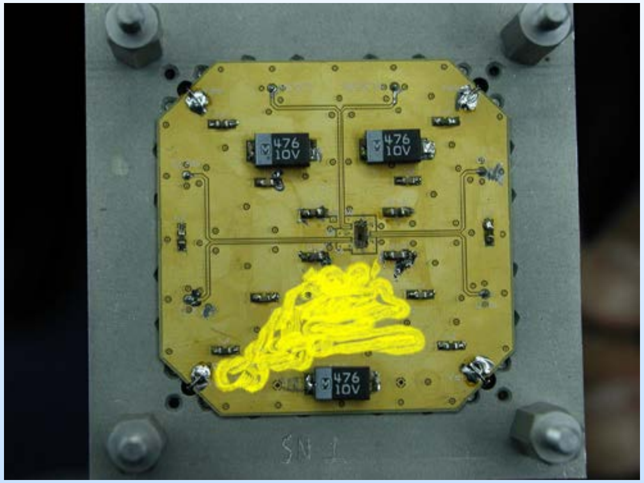
- **TAMU**
  - **Provides ~3500 hours a year to electronics test community**
    - **NASA uses ~400 hours a year (includes JPL, but not NASA contractors)**
    - **Cost ~$800-1200/hr**
  - **However, OVERSUBSCRIBED and access delays of 6 months are common already**
    - **2nd accelerator on-line for protons (~50 MeV) with heavy ions planned within a year**
- **LBL**
  - **Provides ~2000 hours a year to electronics test community**
    - **NASA uses ~200 hours a year (includes JPL, but not NASA contractors)**
    - **Cost ~$1600/hr**
  - **However, in the past, AFSMC and NRO have provided funds to DOE to support maintenance and operation (M&O) continuity**
    - **Currently, only AFSMC providing added M&O support**
      - **NASA is internally reviewing options to provide support**
    - ***LBL cut available hours in FY17***
    - **DOE will continue to find "useful science" if other Agencies support additional M&O costs for electronics testing**

Heavy Ion Facilities – Other Domestic

- NSRL at BNL
  - Provides up to a few hundred hours a year to electronics test community
    - NASA uses ~100 hours a year (includes Jet Propulsion Laboratory (JPL), but not NASA contractors)
    - Cost ~ $5000/hr
  - Critical need for certain tests, but not an "every day" test facility
- BNL Single Event Upset Test Facility (SEUTF)
  - Lower energy facility used by NASA flight projects on a limited basis (technical reasons)
    - NASA uses ~80 hours a year (includes JPL, but not NASA contractors)
    - Cost ~ $1500/hr
- Michigan State University (MSU) National Superconducting Cyclotron Laboratory (NSCL)
  - Facility closing for new DOE science facility
  - Limited NASA usage due to cost and ion availability (tuning cost)
    - Cost ~$5000/hr

Heavy Ion Facility – TAMU Cyclotron Facility

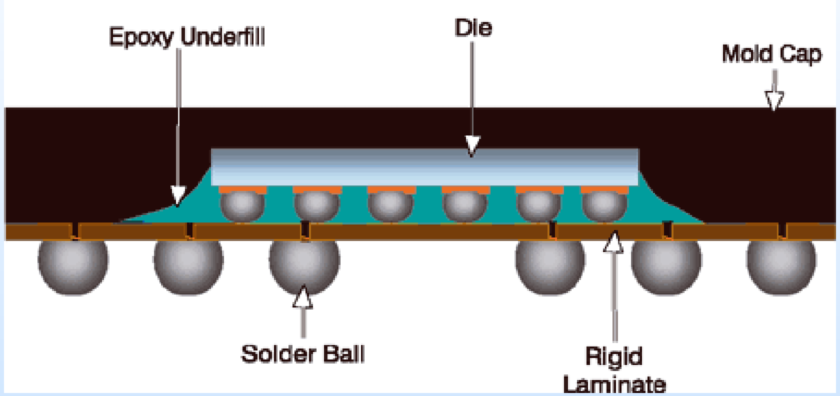
- Type of Source: Cyclotron (K500)
- Energies: Moderate-High
  - Penetration okay for most devices; challenge for advanced packaged
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: Fair
  - Competes with science experiments
  - Scheduled in 3 month windows with rare last minute access
  - OVERSUBSCRIBED (~3500 hours/year)
- Good for:
  - Most devices
  - Used often for qualification tests
- Not good for:
  - Assemblies or stacked devices
- Comments
  - Cost ~$800-1200/hr w Industry/NASA as prime users (international user base)
  - K150 coming on line with moderate energy availability (planned 2017) – protons to 50 MeV available now



Even in air, high-speed high-power technologies need custom fixturing to deal with thermal issues.
Photo by Paul Marshall, consultant to NASA

Heavy Ion Facility – LBL

- Type of Source: Cyclotron (88")
- Energies: Moderate
  - Penetration okay with some penetration range limits
- Test constraint: Vacuum (w/limited air)
  - Provides thermal, power, cabling constraints
- Accessibility: Limited
  - Scheduled with an on-line calendar
- Good for:
  - Standard device packages, test structures
  - Used often for qualification tests
- Not good for:
  - Highly packaged devices or needing extreme angle tests
- Comments
  - Cost ~$1600/hr w/ DoD, Industry, and NASA as prime users
  - Quick ion changes
  - Also has protons to ~55 MeV



Modern IC packaging such as the flip-chip ball-grid array shown above, make direct die access impossible.
Thinning of silicon or device repackaging are options, but have many risks.

Heavy Ion Facility – NSRL

- **Type of Source: Synchrotron**
- **Energies: Very High**
  - Excellent penetration range (but varies with actual ion species)
- **Test constraint: Air**
  - Decreases thermal, power, cabling constraints
- **Accessibility: Fair**
  - Electronics testing can be scheduled as a secondary user during the 3 windows of yearly access up to a few hundred total hours
  - Limited access: best to schedule >6 months in advance
- **Good for:**
  - Electronics assemblies and all packaged devices (plus extreme angular tests)
- **Not good for:**
  - Some dynamic operations (beam structure limit – pulsed synchrotron, not continuous beam cyclotron)
- **Comments**
  - Expensive! Cost > $5000/hr with NASA-Johnson Space Center (JSC) and NRO as prime users
  - Improved availability of multiple ion species during single day testing

Cost, accessibility, and beam structure limit usage as qualification facility

Other Heavy Ion Facilities

- **Lightly used facilities**
  - **BNL SEUTF**
    - **Tandem Van de Graaff (TVdG) Accelerator**
    - **User facility developed by NASA and NSA in 1980's has limited usability due to relatively low energies available, but viable for simpler devices**
  - **MSU NSCL**
    - **Facility closing for new DOE science facility**
- **International facilities**
  - **Europe and Japan have several test facilities that could be used (see later slide).**
  - **However, besides their own technical limitations, travel/shipping, and export issues exist (tested devices are technically "activated" – how would we get these parts back?)**
  - **Assured access is a question**

Heavy Ion Facility – BNL SEUTF

- Type of Source: TVdG
- Energies: Low
  - Penetration limited
- Test constraint: Vacuum
  - Provides thermal, power, cabling constraints
- Accessibility: Very Good
  - Often available on short notice
- Good for:
  - Lower linear energy transfer (LET) work or test structures
- Not good for:
  - Power devices, any complex integrated circuit (IC)
- Comments
  - Good user interface
  - Cost > $1250/hr

Brookhaven National Laboratories' Single Event Upset Test Facility (SEUTF),

Photo by Ken LaBel, NASA

Vacuum Chamber

User equipment area

Limited usability for many electronics

Heavy Ion Facility – National Superconducting Cyclotron Lab (NSCL) at Michigan State University (MSU)

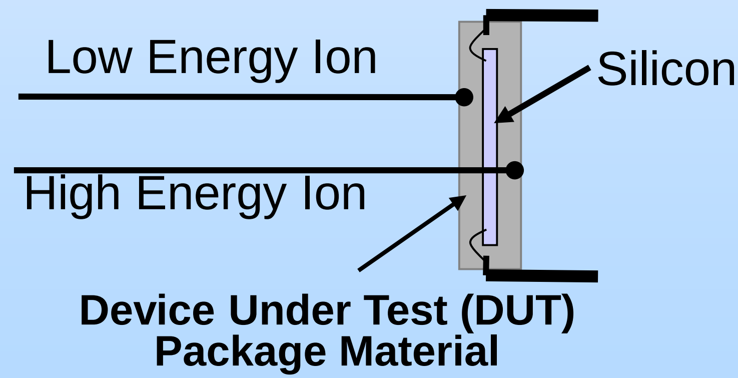
- Type of Source: Two Coupled Cyclotrons
- Energies: High
  - Penetration okay for most packaged components
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: Limited
  - Very few users from electronics community
  - TBD current access mode
- Good for:
  - Most devices and some electronics assemblies; Destructive test qual
- Not good for:
  - Stacked or similar thicknesses
- Comments
  - Expensive! Cost ~ $5000/hr
  - Full LET spectra would require multiple ions

Facility is CLOSING.
DOE replacing with *Facility for Rare Isotope Beams* (*FRIB*).

AVAILABLE IONS, RANGES, AND LETS

Ion	Facility	Max. Energy (MeV/amu)	LET in Si (MeV•cm^2/mg)	Range in Si (μm)	Bragg-Peak LET in Si
Ar-36	NSCL	143	1.50	8860	18
Kr-78	NSCL	121	6.08	4440	40
Xe-136	NSCL	131	14.1	3070	69
Bi-209	NSCL	72	42	1100	100

after Ladbury, et al, Trans. Nucl. Sci.,, 2004

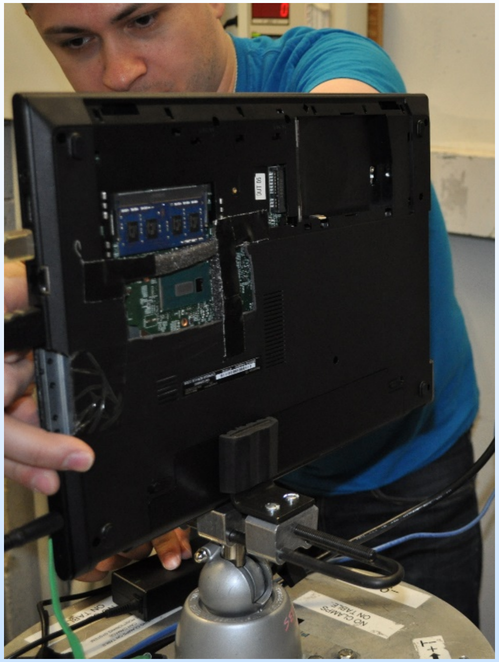


Sample International (Europe) Heavy Ion SEE Test Facilities

SEE Test Facility	Owner	Location	Notes
(limit 50 characters)	Government Entity, Company, University	City, State/Country	
Grand Accélérateur National d'Ions Lourds (GANIL)	France / Government	Caen, France	High-energy heavy ions; from carbon (a few keV/amu to 95 MeV/amu) to uranium (a few keV/amu to 24 MeV/amu)
GSI Darmstadt Microprobe	Germany / Government	Darmstadt, Germany	High-energy heavy ion microbeam; Protons to uranium ions at typically 5 MeV/amu; specific energy LETs from 13 keV/um to 27000 keV/µm in silicon
RADEF / University of Jyväskylä (JYFL)	University of Jyväskylä, Finland / University	Jyväskylä, Finland	Proton & heavy ion cyclotron (K130); Protons: 0 to 60 MeV; High energy cocktail 9.3 MeV/amu: 15N, 20Ne, 30Si, 40Ar, 56Fe, 82Kr, 131Xe. Low energy Cocktail 3.6 MeV/amu: 12C, 30Si, 54Fe, 84Kr, 132Xe. Other ions/energies
Centre de Ressources du Cyclotron Université Catholique De Louvain (UCL)	UCL / University	Louvain la Neuve, Belgium	Protons (62 MeV primary beam on DUT, down to 14 MeV using plastic degraders), neutrons (broad spectra mean E at 23 MeV, energy filter for n lower than 1 MeV, max E 50 MeV; quasi-monoenergetic beams between 20 and 65 MeV), heavy ions (low-energy cocktail 3.7 MeV/amu; high-energy cocktail 9.3 MeV/amu), and pulsed laser (1064 nm, 50 ps single shot up to 1 MHz).

Heavy Ion Sources - Microbeam

- **Microbeams are used to deterministically inject a single ion (or simulated ion) to a single transistor**
  - **Think of it as a single particle sent at a target**
    - **We know where the particle has gone**
    - **Only one US facility**
  - **LASER simulation is also an option**
    - **Has its own challenges**



Preparing an INTEL processor for test at TAMU.
When we see an error at a macrobeam source, how do we identify what the cause was within the device?
Photo by Ken LaBel, NASA

Used in collaboration with standard heavy ion tests and does not replace

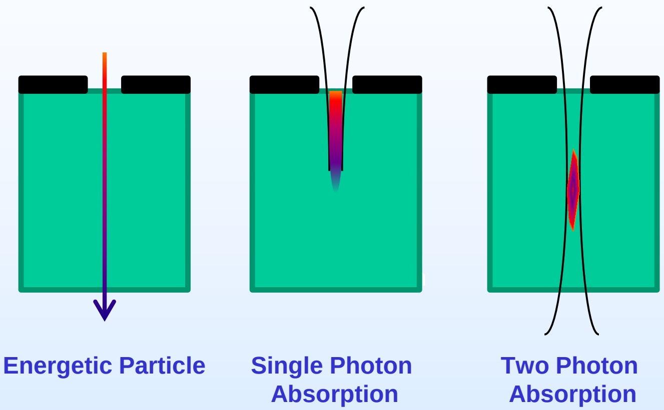
Heavy Ion Microbeam Facility – Sandia National Labs

- **Type of Source: TBS**
- **Energies: Very Low**
  - **Can penetrate almost NOTHING**
- **Test constraint: Vacuum w/small area**
  - **Increases thermal, power, cabling constraints**
- **Accessibility: Fair**
  - **Contract w/DOE/SNL required**
  - **Normally ~3 months**
- **Good for:**
  - **Test structures that are sensitive at low LETs only**
- **Not good for:**
  - **Anything complex**
  - **Any need above single digit LETs**
- **Comments**
  - **Fairly high. ~ $TBS/hr**

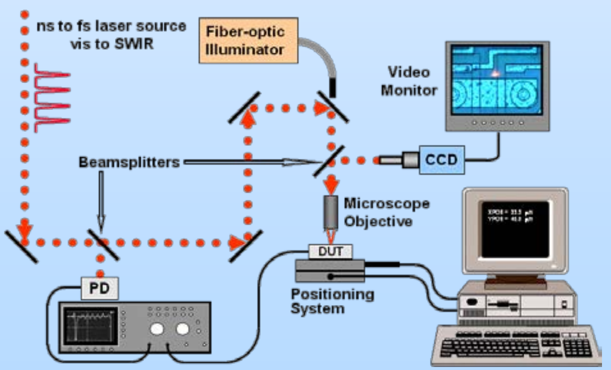
A High-Energy Microbeam Facility was identified as a major need for the future by a NEPP funded a white-paper study on feasibility in FY06

LASER-Induced Simulations of SEE

- Type of Source: LASER
- Energies: Not applicable, but various wavelengths can be available
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: Good
  - Navy Research Labs (NRL) and The Aerospace Corporation have most widely used U.S. facilities
  - JPL and Vanderbilt also have options
  - Normally <1 month
- Good for:
  - Simple devices with die access and few metal layers or through two-photon backside tests
  - Precision localization of sensitive nodes
- Not good for:
  - Some modern higher performance devices
  - Space event rate prediction
- Comments
  - Does not replace standard heavy ion testing



Excitation modes
Courtesy The Aerospace Corporation

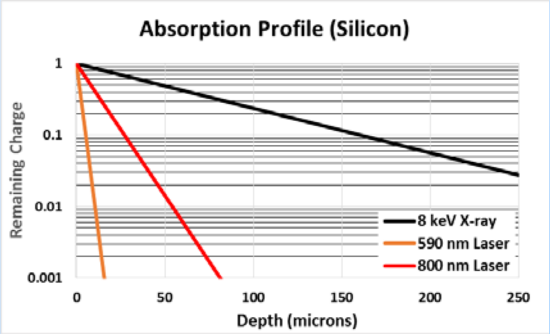


Experimental laser test set-up
Courtesy The Aerospace Corporation

Synchrotron Pulsed X-ray Test Facility - Advanced Photon Source (APS)

- Type of Source: Synchrotron w focusable pulsed X-rays
- Energies: Nominally 8-12 keV; other photon energies (4.3 – 27 keV) available upon request
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: 3-6 Weeks/year
  - Test dates are in March, July and November
  - Access via open proposal process or mediated by Aerospace Corporation
- Good for:
  - Simple to medium complexity devices regardless of metal coverage
  - Precision localization of sensitive nodes (2 μm spot)
  - Focused TID testing
- Not good for:
  - Basic exploration of very large devices
  - Space event rate prediction
- Comments
  - Smaller spot sizes (300nm – 1 μm) available via planned upgrades

The Advanced Photon Source is an Office of Science User Facility operated for the U.S. DOE Office of Science by Argonne National Laboratory.
https://www1.aps.anl.gov/



Short pulsed x-rays generate charge tracks similar to those produced by energetic particles.
Courtesy, The Aerospace Corporation

Proton "Team"

- **Government, industry, university – led by**
  - **Ken LaBel, NASA**
  - **Tom Turflinger, The Aerospace Corp**
- **Ad hoc team formed after closure of IUCF to try and fill void**
  - **NASA**
  - **AFSMC**
  - **NRO**
  - **Boeing**
  - **BAE Systems**
  - **Vanderbilt University**
  - **Information shared with DOE (SNL, LANL) and Navy**
- **Trying to replace about 2000 hours of IUCF beam time**

Basic Study Requirements for High Energy Proton Facility

- **Note: Team (NASA, AF, NRO, industry, others) formed after closure of Indiana University Cyclotron Facility (IUCF) –most highly used proton facility in U.S. for SEE testing**
  - **Review North American Proton options (research/medical)**
- **Energy range:**
  - **125 MeV to > 200 MeV**
- **Proton flux rates:**
  - **1e7 p/cm^2/sec to 1e9 p/cm^2/sec**
- **Test fluences:**
  - **1e9 p/cm^2 to 1e11 p/cm^2**
- **Irradiation area:**
  - **Small (single chip ~ 1cm) to board/assembly > 15cm x 15cm**
- **Beam uniformity:**
  - **>80%**
- **Beam structure:**
  - **Cyclotron *preferred* (random particle delivery over time)**
  - **Fixed spot or scatter (random particle delivery over area)**

Proton Facilities – 200 MeV regime

- Prime Proton Research Facilities
  - Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center
    - Provides 24 hours for 3 out 4 weekends a month
    - Highly used by industry and all Agencies
      - Overbooked already for CY17!
  - Tri-University Meson Facility (TRIUMF) – Vancouver, CAN
    - Runs 4 cycles a year
- Proton Cancer Therapy Facilities Taking Customers
  - Loma Linda University Medical Center (LLUMC)
    - Weekend usage with limited available time beyond current load
  - SCRIPPS Proton Therapy Center
    - Announced bankruptcy on March 2, 2017
    - Has 4 industry user contracts with no additional users (i.e., "large" users only – 100 hrs/yr)
  - Hampton University Proton Therapy Institute (HUPTI)
    - Planning to open research room in May-June 2017
      - NEPP and OneWeb supporting planning
    - Weekdays with beam interleaving w patients
    - Hourly costs - TBD
  - Northwestern Chicago Proton Center (former Cadence)
    - NASA biological dosimetry folks have gone there recently and NEPP has tentative 5/13/17 date
  - Cincinnati Children's Proton Therapy Center
    - Nice separate research room with model similar to IU (interleaving weekdays with patients – no weekends)
    - Expect late summer opening for customers
- New to the Discussion (research rooms opening this year) – visits in April
  - U Penn Roberts Proton Therapy
- Proton Cancer Therapy Facilities – Pending Access
  - U MD Proton Therapy Center (Baltimore)
    - Planning on taking customers in summer'17 w/ NASA shakeout test prior
    - Planning similar mode to SCRIPPS
  - University of Florida Proton Health Therapy Institute (UFHPTI)
    - Completing medical commissioning
    - TBD yearly hours available to community but expect ~300 hours/year
    - Expect shakeout test in 4Q FY17
  - Case Western University Hospital Seidman Cancer Center
    - NASA GRC working a SAA with expected visit?
      - Waiting on lawyers
    - Small facility with expected limited hours (but great for GRC!)
  - Mayo Clinic
    - Two proton facilities (Rochester, MN and Phoenix, AZ) – synchrotron, but unique duty cycle
      - Visited in 1QFY17
      - Research room built and have experience with government contracts
      - Shakeout test expected in June FY17
  - ProVision (Knoxville)
    - TBD – 2 rooms opening with TBD excess capacity in TBD timeframe in 2017 – limited responsiveness
- Proton Research Facilities – Proposals
  - Los Alamos Neutron Science Center (LANSCE)
    - Has 800 MeV proton source with white paper to modify for SEE test purposes
    - Visited in 1QFY17 – requested support and aid in obtaining funding
    - Question remains on beam structure

Medium Energy Proton Cyclotrons

- Commonly used medium energy proton facilities (some SEE, some DDD):
  - University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) – (63 MeV)*,
  - Lawrence Berkeley National Laboratories (LBNL)* – (55 MeV), and,
  - Texas A&M University (TAMU) – ~50 MeV.
- LBL's future is uncertain for continued access.
  - Trade space between government sustaining funds and return on science and aerospace needs.
- CNL has been struggling with reduced user loads.
  - Facility has been a staple for testing of optics/sensors/etc…
    - They've raised their rates, but are struggling with obtaining sufficient customers.

** also in use for low energy proton testing*

Protons Assured Access – Possible Options

- Government lab – LANSCE (DOE) upgrade
  - Pulsed beam with max energy of 800 MeV
    - White paper available: focus on reducing flux to SEE test levels and obtaining down to 250 MeV regime
    - Higher energy would do a better job on destructive SEE tests
    - Internal DOE/LANL and NNSA support
      - Still in planning/discussion phase
      - Looking for support
    - Question on usability of the beam structure
- Build a new (government/industry) facility – ~$100M ROM pending land/zoning/capability
  - May include some heavy ion capability
- Buy a failed proton therapy site?
  - Challenges for M&O
- Upgrade CNL– they have experience
  - ROM is anywhere from $15-50M – better estimate needed
- Private company builds research facility
  - Former founder of Mevion (proton source manufacturer) has expressed interest in a privately funded facility

Other Radiation Test Facilities

- **Space**
  - **TID**
    - **Usually Co-60 or X-ray sources for electronics test and qualification**
    - **Electron sources used for specific mission issues (Jovian, for example)**
    - **Protons sometime used (>50 MeV)**
  - **DDD**
    - **Proton, electron, neutron sources**
      - **Low energy (1 MeV equivalent) for solar cells**
      - **>30 MeV protons for electronics**
  - **SEE**
    - **Low energy (~1 MeV) protons for very sensitive technologies (CNL, LBL, multiple orgs have VdGs)**
- **Military (not a main NASA issue)**
  - **Linear accelerators, flash x-ray, neutron,…**

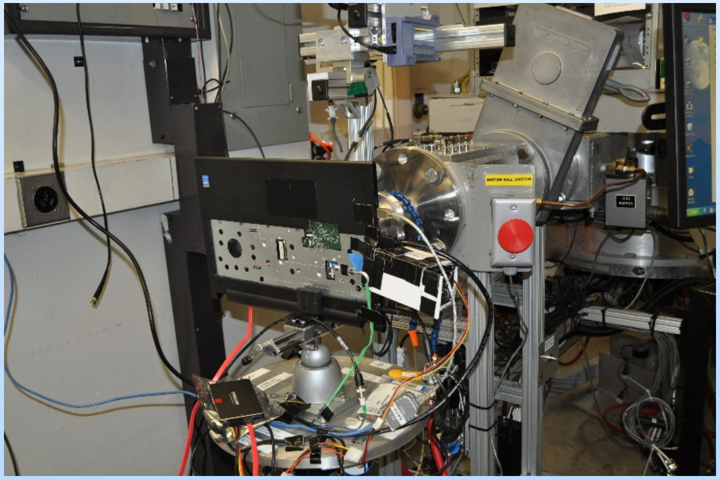
Comments/Questions/Issues - Random

- Age and upkeep of many facilities (LBL, CNL, …) and key personnel across the space radiation field
- Stability of proton therapy sites (insurance, physicians, fiscal)
- Burgeoning interest by commercial space (CubeSats, launch providers)
  - Increasing proton facility needs already observed
- Increased device complexity requires increasing number of hours to characterize at a radiation test facility (see next chart)
- Decreasing feature size electronics increases terrestrial SER concerns
  - Increasing proton facility needs already observed
- ISO 26262 Functional Safety Standard (Automotive)
  - Ultra-low failure in time (FIT) rate for safety critical electronics such as in self-driving vehicles
  - Potential increasing need for protons (SER) for terrestrial reliability
- Drone electronics reliability?
  - May be a new customer
- How good are protons to predict heavy ions?
- How good are our risk modeling tools?
- Business model? – TAMU is "Au" standard

Diatribe: Complex Electronics

- Two drivers for SEE response during testing:
  - Geometric: number of transistors (ion targets) in DUT
  - Temporal: when the target is hit versus operations in a device
    - Aka, state-space coverage.

Billion transistor device + Billion operating states = Impossibility of Full Coverage during a Test Campaign (or in our lifetime!)



Testing of Intel Broadwell Processor at TAMU, Ken LaBel

Summary

- **The U.S. Government has a need for these facilities for risk management of space electronics.**
  - **The question is: what are the best approaches to ensuring this risk management?**
    - **Heavy ion: few domestic options**
    - **Proton (200 MeV): changing landscape, but assured?**
- **Near-term issues:**
  - **"Replacement" for IUCF (protons)**
    - **Making progress with proton therapy sites**
  - **Access to LBL (heavy ions)**
    - **Even with TAMU adding a 2nd cyclotron to the equation brings "assured access" into the question**
- **Longer term issues:**
  - **Sustained (and cost-effective) access**
  - **Retiring/aging expertise**
  - **Modeling/tool efficacy for the future**