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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

Interaction with Nucleus
  – Indirect Ionization
  – Nucleus is Displaced
Typical Ground Sources for Space Radiation Effects Testing

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

*Additional information:

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

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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
- 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

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

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).

<table>
<thead>
<tr>
<th>Ion</th>
<th>Max. Energy (MeV/amu)</th>
<th>LET in Si (MeV-cm²/mg)</th>
<th>Range in Si (µm)</th>
<th>Bragg-Peak LET in Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-36</td>
<td>143</td>
<td>1.50</td>
<td>8860</td>
<td>18</td>
</tr>
<tr>
<td>Kr-78</td>
<td>121</td>
<td>6.08</td>
<td>4440</td>
<td>40</td>
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<tr>
<td>Xe-136</td>
<td>131</td>
<td>14.1</td>
<td>3070</td>
<td>69</td>
</tr>
<tr>
<td>Bi-209</td>
<td>72</td>
<td>42</td>
<td>1100</td>
<td>100</td>
</tr>
</tbody>
</table>


To be presented by Kenneth A. LaBel at the Study on Space Radiation Effects Test Infrastructure (Electronics) Meeting, Washington DC, March 29-31, 2017.
# Sample International (Europe) Heavy Ion SEE Test Facilities

<table>
<thead>
<tr>
<th>SEE Test Facility</th>
<th>Owner</th>
<th>Location</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Accélérateur National d’Ions Lourds (GANIL)</td>
<td>France / Government</td>
<td>Caen, France</td>
<td>High-energy heavy ions; from carbon (a few keV/amu to 95 MeV/amu) to uranium (a few keV/amu to 24 MeV/amu)</td>
</tr>
<tr>
<td>GSI Darmstadt Microprobe</td>
<td>Germany / Government</td>
<td>Darmstadt, Germany</td>
<td>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</td>
</tr>
<tr>
<td>RADEF / University of Jyväskylä (JYFL)</td>
<td>University of Jyväskylä, Finland / University</td>
<td>Jyväskylä, Finland</td>
<td>Proton &amp; 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</td>
</tr>
<tr>
<td>Centre de Ressources du Cyclotron Université Catholique De Louvain (UCL)</td>
<td>UCL / University</td>
<td>Louvain la Neuve, Belgium</td>
<td>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).</td>
</tr>
</tbody>
</table>
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

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

- Type of Source: Synchrotron with 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

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/cm²/sec to 1e9 p/cm²/sec

• Test fluences:
  – 1e9 p/cm² to 1e11 p/cm²

• 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
  - SCIRPPS 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 SCIRPPS
  - 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 GRCI)
  - 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!)
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