The Great Proton Search Continues

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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

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Acronyms

- Three Dimentional (3D)
- Air Force Space and Missiles Center (AFSMC)
- also know as (AkA)
- Automated Test Equipment (ATE)
- Californium (Cf)
- Crocker Nuclear Laboratory (CNL)
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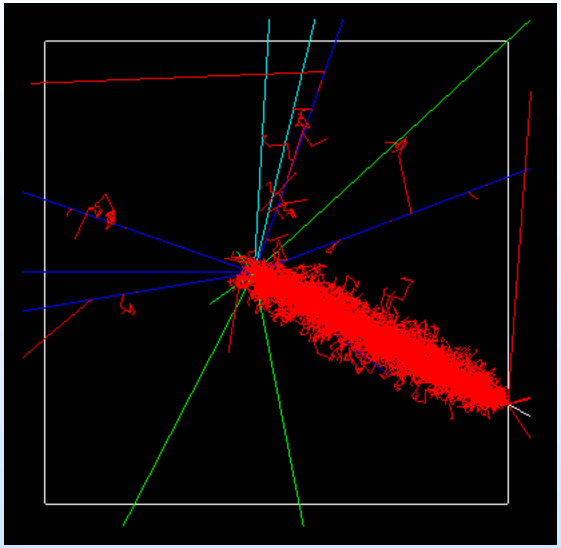
- TBD - current year 2017 ??? (CY17)
- Displacement damage dose (DDD)
- Department of Energy (DOE)
- Device Under Test (DUT)
- Galactic Cosmic Rays (GCRs)
- Glenn Research Center (GRC)
- Hampton University Proton Therapy Institute (HUPTI)
- International Business Machines Corporation (IBM)
- Integrated Circuits (ICs)
- Indiana University Cyclotron Facility (IUCF)
- Johnson Space Center (JSC)
- 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)
- Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center
- Military Standard (MIL-STD)
- Math and Physics Sciences (MPS)
- n-type charge coupled device (n-CCD)
- NASA Electronic Parts and Packaging (NEPP) Program
- National Reconnaissance Office (NRO)
- Office of Safety and Mission Assurance (OSMA)
- research and development (R&D)
- South Atlantic Anomaly (SAA)
- SCRIPPS Proton Therapy Center (SCRIPPS)
- second (sec)
- Single Event Effects (SEE)
- Soft Error Rate (SER)
- size, weight, and power (SWaP)
- Texas A&M University (TAMU)
- to be determined (TBD)
- Total ionizing dose (TID)
- Tri-University Meson Facility (TRIUMF)
- University of Maryland Proton Therapy Center, Baltimore (U MD)
- University of California at Davis (UCD)
- University of Florida Proton Health Therapy Institute (UFHPTI)
- Van de Graaff (VDG)
- Van de Graaffs (VdGs)

Outline

- **Abstract and Problem Statement**
- **Proton Effects on Electronics**
- **Potential Users**
- **Electronics Testing with Protons**
- **Domestic Proton SEE Facilities**
  - **High Energy (>200 MeV)**
  - **Medium Energy (50-125 MeV)**
- **Summary/Comments**



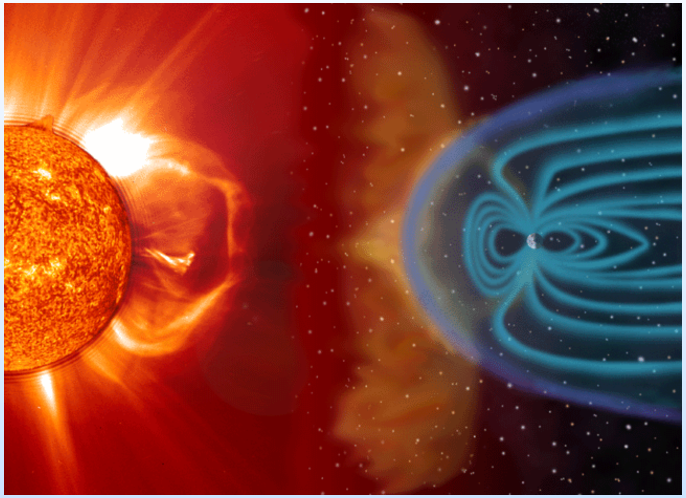
Sample 100 MeV proton reaction in a 5 um Si block.
Reactions have a range of types of secondaries and LETs.
Complicating statistics and testing.
(after Weller, Trans. Nucl. Sci., 2004)

Abstract and Problem Statement

- **Abstract**
  - **This presentation is an outbrief of the current team status for access to domestic high (>200 MeV) energy proton facilities. In addition, future considerations will be discussed.**
- **Problem Statement (Space Electronics)**
  - **Particle accelerators are used to evaluate risk and qualify electronics for usage in the space radiation environment**
    - **Protons simulate solar events and trapped proton in planetary magnetic fields**
    - **Domestic sources for these particles are becoming more limited due to facility closures or reduction of accessible hours.**
      - **Indiana University Cyclotron Facility (IUCF) – CLOSED 2014 - ~2000 hours of space electronic user needs annually**
      - **SCRIPPS Proton Therapy Center – announces bankruptcy on March 2, 2017**

Proton Radiation Effects and the Space Environment

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

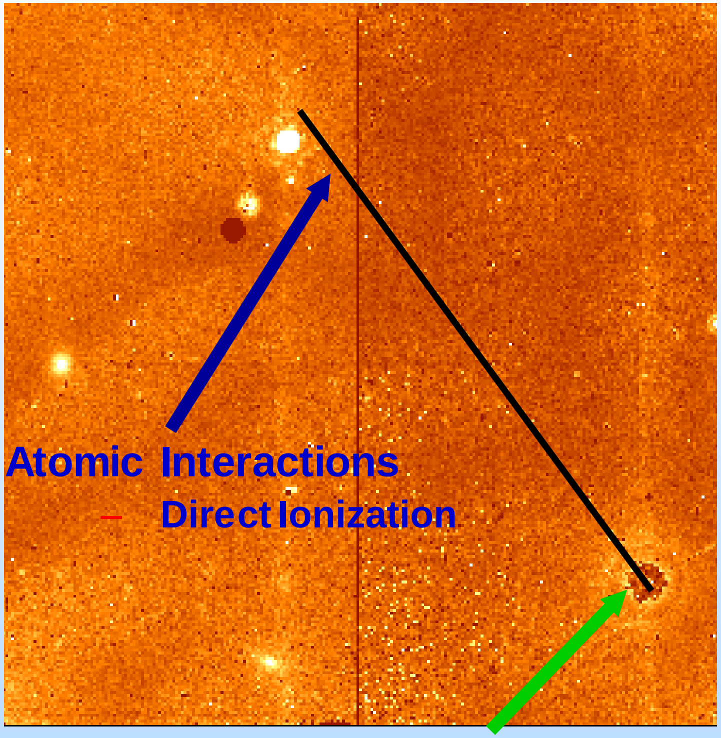
Radiation Effects and Electronics

- **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.**
    - **Useful for SEE and DDD evaluation**

Particle interactions with semiconductors

Image from the Space Telescope Science Institute (STScI), operated for NASA by the Association of Universities for Research in Astronomy

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

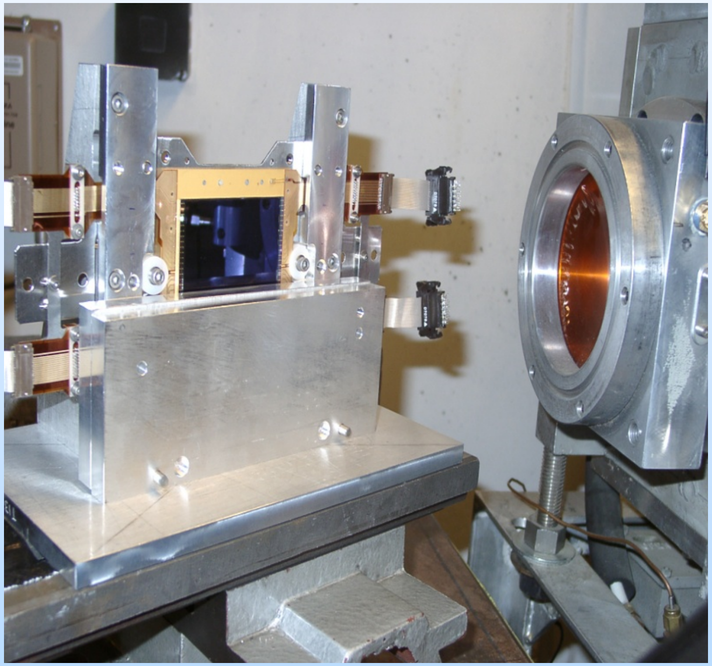


Interaction with Nucleus
- **Indirect Ionization**
- **Nucleus is Displaced**
- **Secondaries spallated**

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) – primarily nuclear interactions
    - E>200 MeV is "space sweetspot"
  - Protons (~1 MeV) – direct ionization effects in very sensitive electronics
  - Cyclotrons, synchrotrons

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



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

Space Electronics Users

NASA, other Government, Industry, University – International base

- **Space Electronic Systems – Projects, Manufacturers**
  - **Perform qualification tests on integrated circuits (ICs)**
  - **Perform system validation/risk tests on assembled hardware (boards/boxes)**
- **Semiconductor 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 – Product Development/Validation**
  - **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 is Interested in Proton Research Facilities

- **Other Space Users**
  - **Human Radiation Protection (biological sciences)**
  - **Material/shielding Studies (physical sciences)**
  - **Solar cells (damage studies)**
- **Terrestrial Soft Error Rate (SER) Simulation**
  - ***Protons may be used as an accelerated test for terrestrial neutron effects***
  - **Important for**
    - **Automotive (Safety Critical Electronics)**
    - **High Reliability Computing, etc…**
    - **Medical Electronics**
      - **Example: Reliability of implantable electronics**
- **Atmospheric Neutrons**
  - **Aircraft and avionics systems**

Space and Other Researchers - Comments

- When IUCF closed in 2014, ~2000 research hours (mostly used by space electronics and semiconductor manufacturers)
  - This need has not diminished, but has INCREASED
    - Semiconductor industry – Increased reliability concerns from space to ground
      - Advanced technologies (ex., <14nm feature size devices)
      - New architectures (3D structures)
      - New materials (roles of secondaries and fission products)
      - Replacement testing for terrestrial neutron effects (can do in hours what may take weeks in a neutron source)
    - Space Users
      - Increased use of commercial electronics for higher performing and smaller size, weight, and power (SWaP) systems. Examples:
        - » Advent of CubeSats – interest in risk reduction tests
        - » Commercial Space – companies like SpaceX and OneWeb use protons for electronic assurance
    - Automotive
      - Exploding industry for automotive electronics (driver assist, self-driving, etc…) – Safety Critical aspects

Basic Space Electronic Requirements for High Energy Proton Facility

- **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)**
    - **Pulsed beam acceptable for some applications**
  - **Fixed spot or scatter (random particle delivery over area)**
    - **Scanning beams MAY be acceptable but need to consider device or system under test operations versus timing of beam spots**

Sample Considerations for Electronics Proton Testing at Cyclotrons

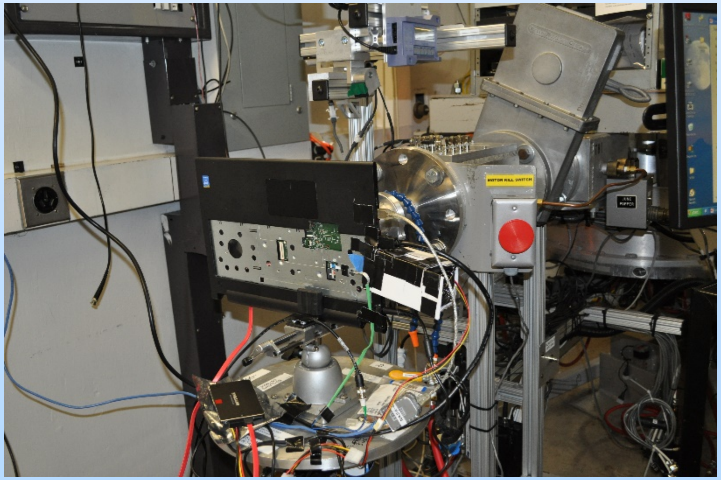
- **Particle**
  - Dosimetry/particle detectors
  - Uniformity
  - Energy mapping to the space environment
  - Particle localization
  - Stray particles (neutrons, for example)
    - Beware of “scatter” design
  - Particle range
  - Flux rates and stability
  - Beam structure
    - Beam spills

- **Practical**
  - Cabling
  - Thermal
  - Speed/performance
  - Test conditions
  - Power
  - Mechanical
  - Staging area
  - Shipping/receiving
  - Activated material storage
  - Operator model (who runs the beam)

Diatribe: Increasingly 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**
- **Challenge:**
  - **Beam time optimization versus "risk management"**

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

Proton Facilities for Electronics Testing – 200 MeV regime

- **Active 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 with two beam lines (105 and 500 MeV)
    - Very busy with semiconductor and terrestrial electronics
  - Loma Linda University Medical Center (LLUMC)
    - Weekend usage with some available time beyond current load
    - Have recently installed improvements
  - SCRIPPS Proton Therapy Center
    - Announced bankruptcy on March 2, 2017 – tbd future
    - Has 4 industry user contracts with limited additional users (i.e., "large" users only – 100 hrs/yr each)

Proton Facilities for Electronics Testing – 200 MeV regime

- **Proton Cancer Therapy Facilities – Nearly Research Ready or Limited Access**
  - Cincinnati Children's Proton Therapy Center
    - Nice separate research room with model similar to IU (interleaving weekdays with patients – no weekends)- Same cyclotron as SCRIPPS
    - Expect fall '17 opening for customers; shakeout test planned later in '17
  - Northwestern Chicago Proton Center (former Cadence)
    - IBA Cyclotron taking limited customers (NASA only?)
  - Mayo Clinic
    - Two proton facilities (Rochester, MN and Phoenix, AZ) – synchrotron, but unique duty cycle
      - Shakeout test in June 2017 in Rochester; expect limited sales later in '17
      - Research room built and have experience with government contracts
  - Hampton University Proton Therapy Institute (HUPTI)
    - Planning to open research room later in 2017
    - Weekdays with beam interleaving w patients
    - Still in planning
  - MD Anderson
    - NASA/JSC evaluating with The Aerospace Corp
  - U Penn Roberts Proton Therapy
    - Research room under commissioning

Proton Facilities for Electronics Testing – 200 MeV regime

- **Proton Cancer Therapy Facilities – Finishing Commissioning**
  - U MD Proton Therapy Center (Baltimore)
    - Planning on taking customers later in'17 w/ NASA shakeout test prior
    - Possible similar operating mode to SCRIPPS (weekends, large users – 200 hrs/yr total)
  - University of Florida Proton Health Therapy Institute (UFHPTI)
    - Completing medical commissioning
    - TBD yearly hours available to community but expect ~200 hours/year
    - Expect shakeout test later in '17
- **Proton Research Facilities – Unknown Status**
  - Case Western University Hospital Seidman Cancer Center
    - NASA GRC working an agreement with expected visit – on hold?
      - Waiting on lawyers
    - Small facility with expected limited hours (but great location for GRC!)
  - ProVision (Knoxville)
    - TBD – 2 rooms opening with TBD excess capacity in TBD timeframe in 2017 – limited responsiveness
- **Proton Research Facilities – Proposals for Dedicated Research**
  - 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. FY18 budget question for Dept of Energy…
- CNL continues to support electronics test user community
  - Reorganized under Math and Physics Sciences (MPS) Department
  - Currently have 43 contracts in place with our community
    - Facility has been a staple for testing of optics/sensors/etc…
  - Comments from CNL (March 2017)
    - Pursuing a large multi-disciplinary DOE radioisotope development program which will support more lab staff, operations, and R&D.
      - "The additional work will only add stability to the lab for the SEE community." - Spencer Hartman, Head Space and Radiation Effects Facility & Cyclotron Laboratory, CNL
    - Also adding a neutron spallation beam line
      - A high flux beam line (1E15 p/cm^2-s) for Large Hadron Collider research and development.

** also in use for low energy proton testing*

Summary

- **Volatility is the name of the game for proton research access**
  - **The uncertainty of cancer therapy facilities for utilization and business models (insurance, physician acceptance, locality) make assured access questionable.**
  - **However, near term access appears to be improving… but give it a week and it may change**
    - **Hope to add several facilities to the “truly available access” list**
- **Need is clearly growing and could be marketed more effectively**
  - **Participation in electronics radiation effects conferences, for example**
- **Unclear if there’s a business case for dedicated research facility unless government subsidized**
  - **LANSCE?**
  - **Purchase of “failed” therapy center?**
  - **Other?**