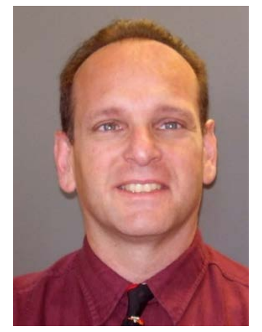


Ken LaBel

The Great Proton Search Continues

Kenneth A. LaBel, Co-Manager, NASA/OSMA, NASA Electronic Parts and Packaging (NEPP) Program

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.

National Aeronautics and Space Administration

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.

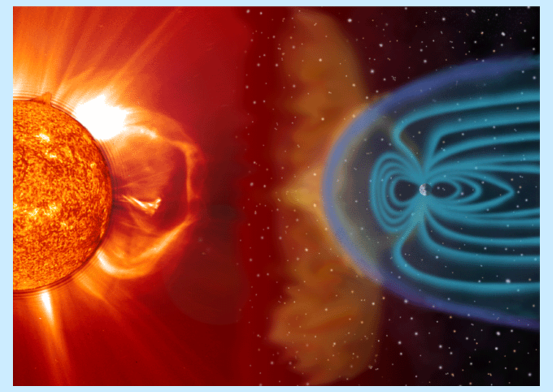
Problem Statement

(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 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)



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

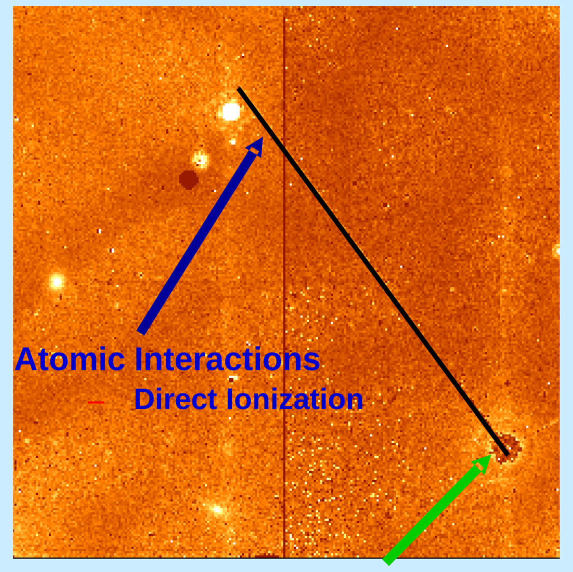
- Hazard experience is a function of orbit and timeframe

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

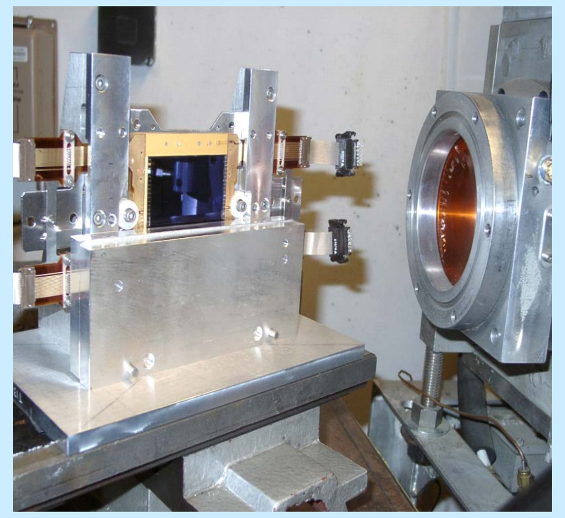


Interaction with Nucleus
- Indirect Ionization
- Nucleus is Displaced
- Secondaries spallated

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/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)
    - 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

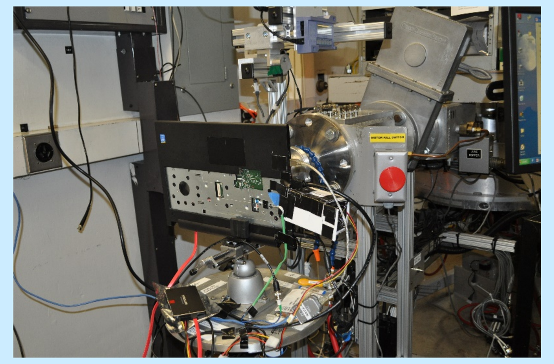
Sample Considerations for Electronics Proton Testing at Cyclotrons

- 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

Domestic Proton SEE Facilities

Proton Facilities for Electronics Testing (200 MeV)

- 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 limited available time beyond current load
    - Have recently installed improvements
  - SCRIPPS Proton Therapy Center
    - Announced bankruptcy on March 2, 2017
    - Has 4 industry user contracts with limited additional users (i.e., "large" users only – 100 hrs/yr)

Medium Energy Proton Cyclotrons (50-125 MeV)

- 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 late summer opening for customers; shakeout test June timeframe
  - Northwestern Chicago Proton Center (former Cadence)
    - IBA Cyclotron taking limited customers
  - Mayo Clinic
    - Two proton facilities (Rochester, MN and Phoenix, AZ) – synchrotron, but unique duty cycle
      - Shakeout test expected in June 2017
      - Research room built and have experience with government contracts
  - Hampton University Proton Therapy Institute (HUPTI)
    - Planning to open research room in 2017
    - Weekdays with beam interleaving w patients
    - "Silent" in last few months- will they or won't they?
  - MD Anderson
    - NASA/JSC evaluating with The Aerospace Corp
  - U Penn Roberts Proton Therapy
    - Research room under commissioning
- Proton Cancer Therapy Facilities – Finishing Commissioning
  - U MD Proton Therapy Center (Baltimore)
    - Planning on taking customers in summer'17 w/ NASA shakeout test prior
    - Planning similar operating mode to SCRIPPS (weekends, large users)
  - University of Florida Proton Health Therapy Institute (UFHPTI)
    - Completing medical commissioning
    - TBD yearly hours available to community but expect ~2-300 hours/year
    - Expect shakeout test in 4Q FY17
- 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.
- 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…
  - New:
    - 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?

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)
- Crocker Nuclear Lab (CNL)
- 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)

To be presented by Kenneth A. LaBel at the Single Event Effects (SEE) Symposium and Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 22-25, 2017.