

Protons, Aerospace, and Electronics: A National Interest

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The Aerospace Corporation

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



Acronyms

- **Three Dimensional (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)**



Problem Statement

- **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
 - Protons trapped in planetary magnetic fields
 - When Indiana University Cyclotron Facility (IUCF) closed in 2014, the prime U.S. facility for doing these tests was lost (2000 hrs/year)
 - *Thus began, the “Great Proton Search”*

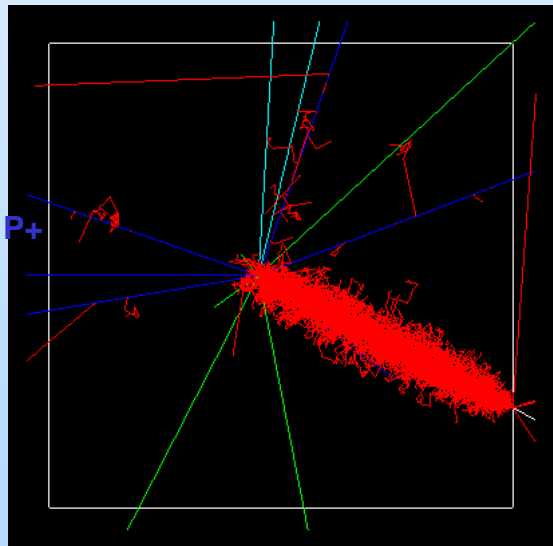
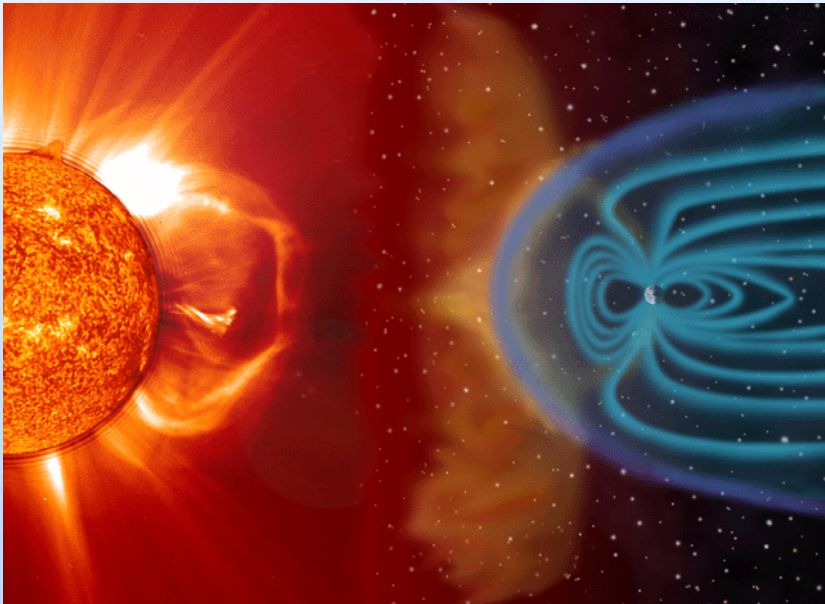


Figure is of a simulated 100 MeV proton reaction in a 5 um Si block
Reactions have a range of types of secondaries and energy depositions
Energy deposition by protons (displacement, spallation, etc...)
have impacts on electronic functionality
(after Weller, Trans. Nucl. Sci., 2004)



Outline

- **Why the aerospace business, semiconductor manufacturers, and others are interested in proton facility access**
- **Some of the basics of a typical test on electronics**
- **Discussion of working models for proton medical sites**
- **Current status on progress of our search**



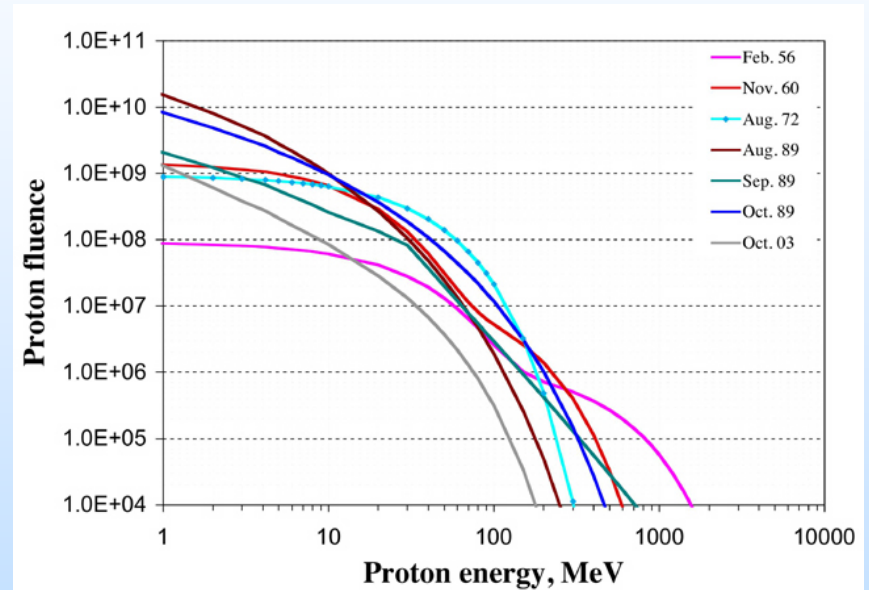
The Sun-Earth Proton Radiation Environment

- Sun (left) acts as a source of protons (solar events) and its solar cycle (max, min) modulates the environment
- Protons are trapped in the earth's magnetic fields (right)
after K. Endo, Nikkei Sciences



Protons and the Space Environment

- Three portions of the natural space environment contribute to the radiation hazard
 - Free-space particles
 - Galactic Cosmic Rays (GCRs)
 - Solar particles
 - *Protons* and heavier ions
 - Trapped particles (in magnetic fields)
 - *Protons* and electrons including the earth's South Atlantic Anomaly (SAA) (dip in dipole moment causing protons at lower altitude)
- Mission hazard is a function of orbit (where) and timeframe (when, how long), and sensitivity of the electronics



Representative solar events and their proton spectra
<http://journalofcosmology.com/images/StraumeFigure3a.jpg>



Radiation Effects and Electronics

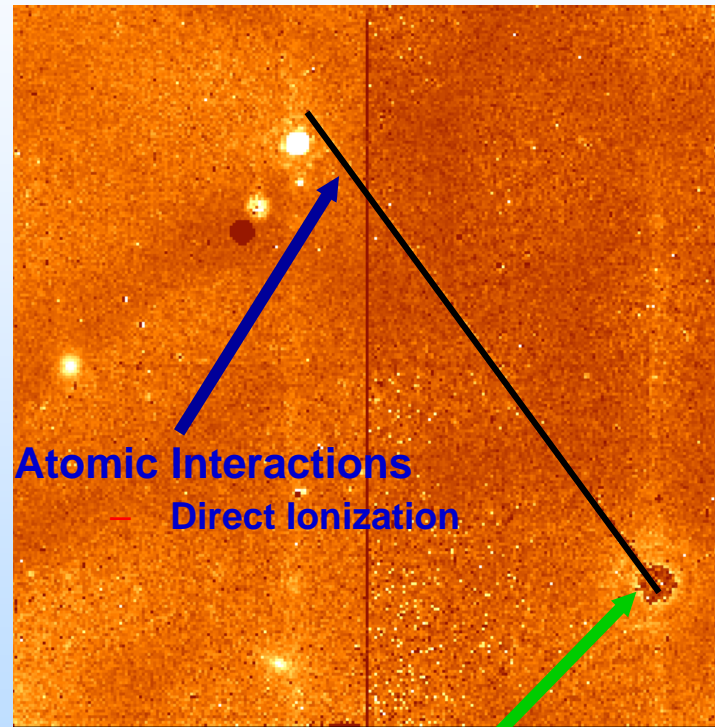
- **Long-term cumulative degradation**
 - Ionization damage aka Total Ionizing Dose (TID)
 - Non-Ionizing Damage aka Displacement Damage Dose (DDD)
- **Single particle effects (aka Single Event Effects or SEE)**
 - Soft or hard errors caused by protons (mostly nuclear interactions) or heavy ions (direct energy deposition)

- **Protons induce**
 - SEE, TID, and DDD
 - Higher energy (~200 MeV) key for SEE

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



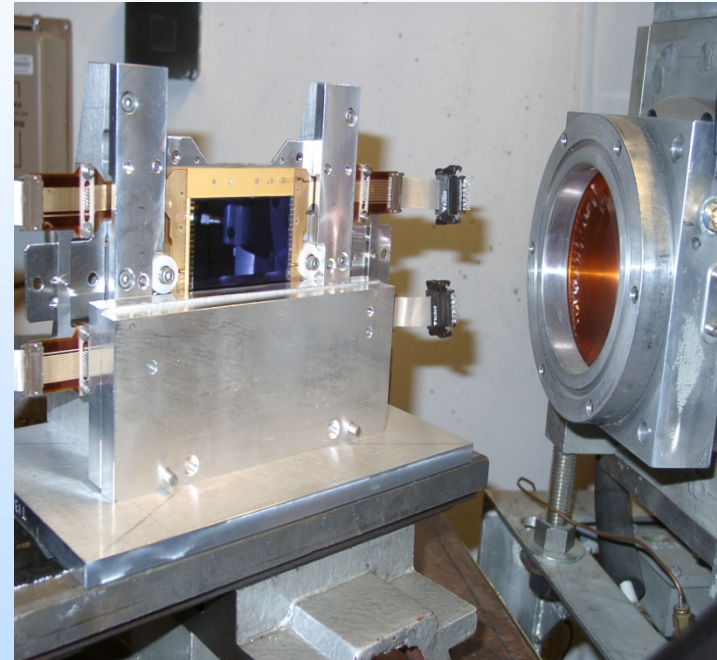
Actual Space Anomalies Observed During Major Solar Event in 2003

Type of Event	Notes
Spontaneous Processor Resets in main computers	3 events; all recoverable
Spontaneous Processor Resets in main computers	Seen on other spacecraft; recoverable
Spontaneous Processor Resets in main computers	Spacecraft tumbled and required ground command to correct
High Bit Error Rates	Communication link
Magnetic Torquers Disabled	Guidance system
Star Tracker Errors	Excessive event counts in guidance system
Star Tracker Errors	Star Tracker Reset occurred
Read Errors	Entered safe mode; recovered
Failure	One mission failure noted
Memory Errors	19 errors on 10/29
Memory Errors	Increase in correctable error rates on solid-state recorders noted in many spacecraft



Typical Ground Sources for Space Radiation Effects Testing

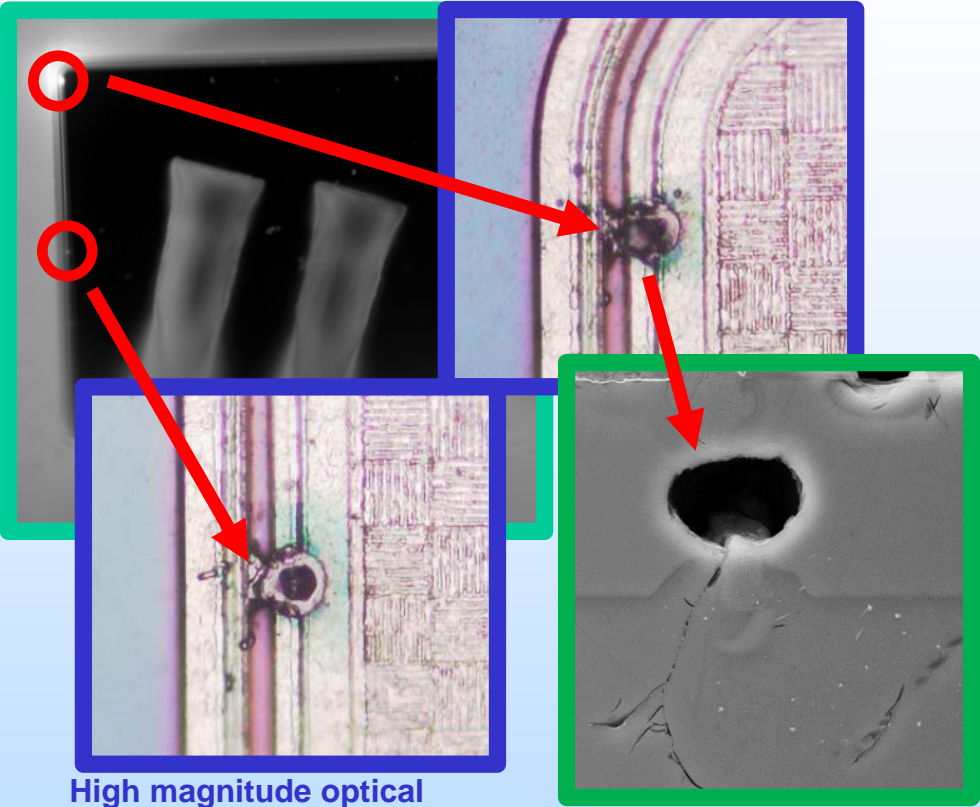
- Issue: TID
 - Co-60 (gamma), X-rays, **Proton**
- Issue: DDD
 - **Proton**, neutron, electron (solar cells)
 - Cyclotron, linear accelerator (LINAC), Van de Graaff (VDG) accelerator
- SEE (GCR)
 - Heavy ions
 - Cyclotrons, synchrotrons, VDGs
 - Other: Cf, LASERS
- SEE (**Protons**)
 - Protons ($E > 30$ MeV) – primarily nuclear interactions
 - $E > 200$ MeV is “space sweetspot”
 - Protons (~ 1 MeV) – direct ionization effects in **very** sensitive electronics
 - Cyclotrons, synchrotrons



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



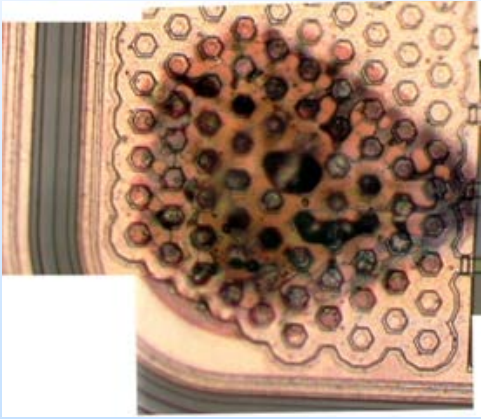
SEE Effects – Hard Failures



High magnitude optical images of failure locations

Cross-section of failure location

Failure images in a diode

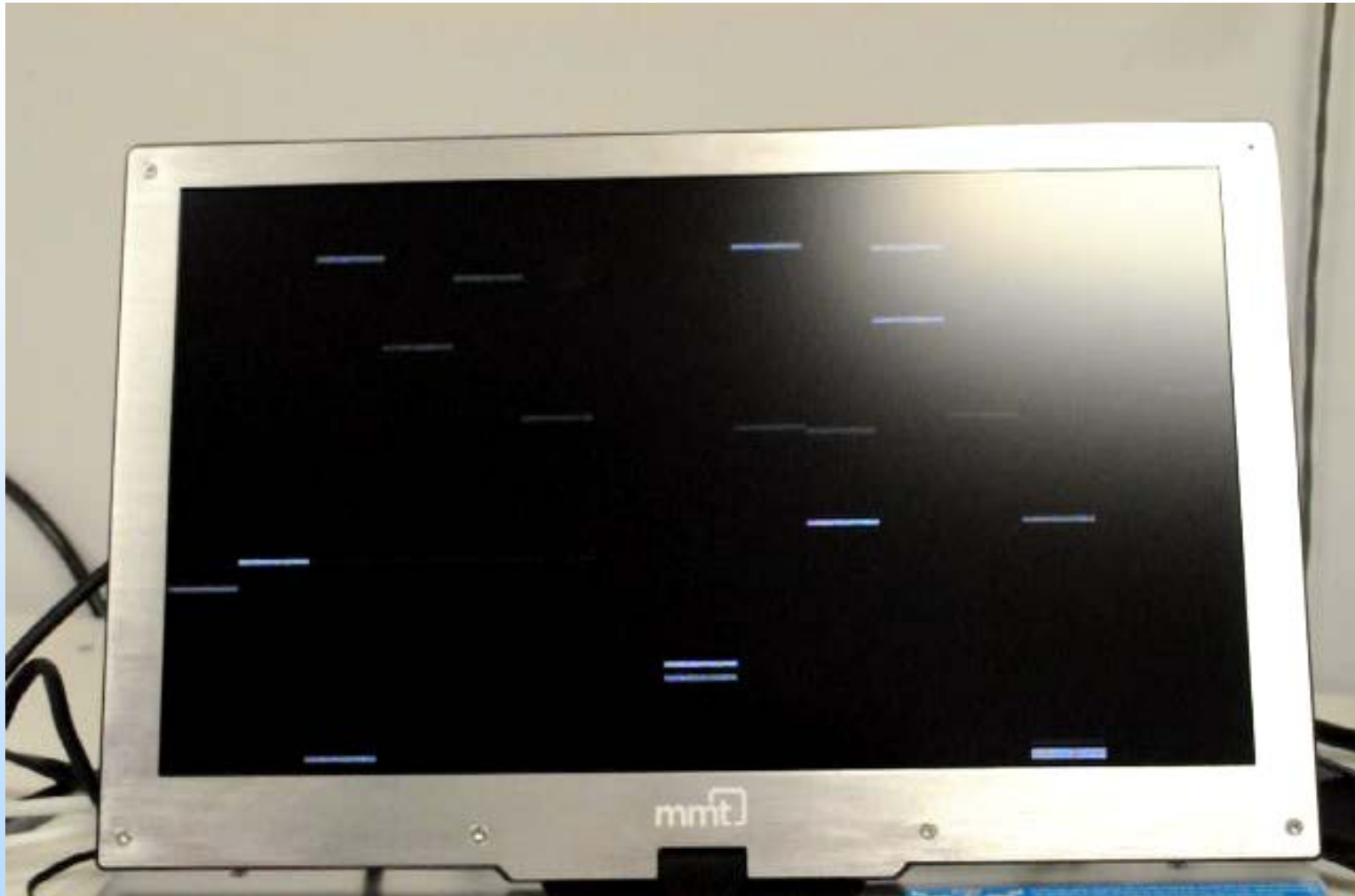


Failure in a Power Device

**These types of failures are MISSION ending –
Why we test with protons on the ground**



SEE Effects – Soft Failures

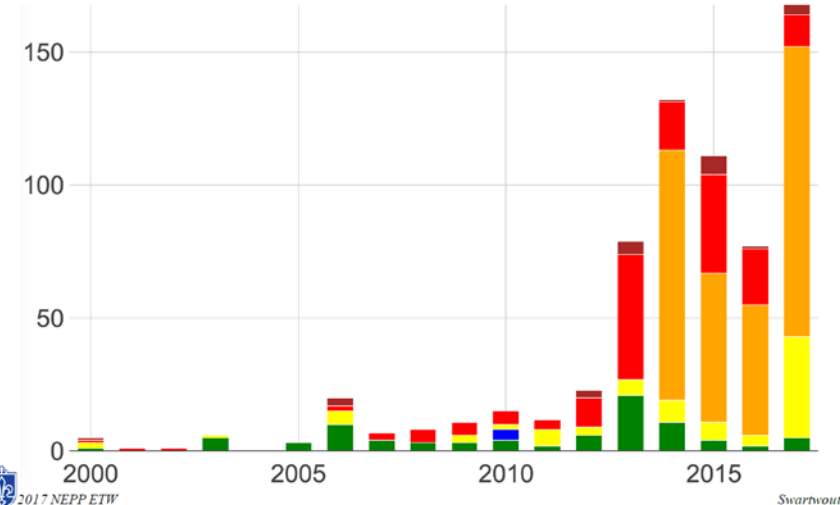


These are often recoverable, but understanding of the failure modes and rates of events is critical pre-flight to reduce risks



A Growing Market

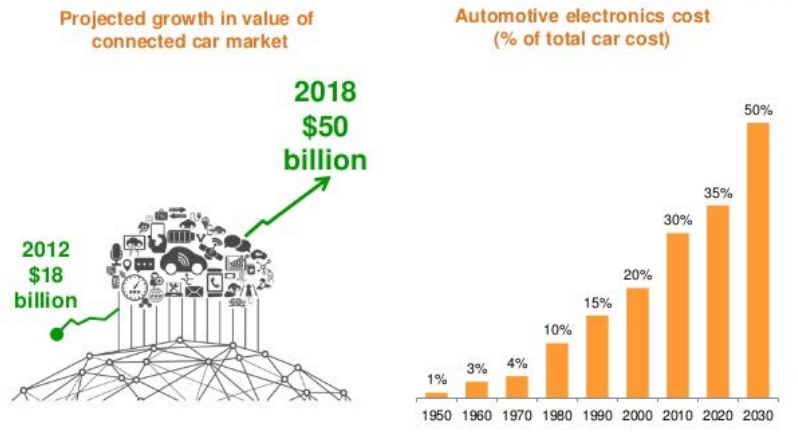
CubeSat by Mission Type



The two major trends in the aerospace community are driving the use of more non-space/radiation hardened products that require proton testing:

- The advent of small spacecraft, and,
- The increased use of “commercial” space providers.

Cars transforming into mobility platforms



Automotive Electronics sustaining growth opportunities
Page 8 Source: PWC analysis

As an example of the growth of the automotive market, consider that the newer cars have OVER 100 processors on board and the advent of self-driving. **Reliability concerns (including neutron/proton) are on the rise.**
<https://www.slideshare.net/VisteonCorporation/xiv-congreso-internacional-2016>



Electronics and Proton Effects

The Customer Base

- **Space products**
 - Many of these are designed for radiation tolerance
 - Protons are used to VALIDATE radiation tolerance approaches or in development
 - Device level tests
 - System level tests
- **Space researchers**
 - Uses protons to develop test methods or knowledge of tolerance of new technologies or electronic designs
 - Other space research with protons – human protection and material studies
 - Instrument calibrations
- **Commercial – terrestrial**
 - Provide higher performance, but have proton sensitivities
 - Manufacturers use protons to test for terrestrial neutron reliability
- **Automotive**
 - Largest growth area in the electronics market
 - Have safety critical aspects (self-driving and driver assist)
 - Systems validation is growing area
- **Aviation**
 - Increased use of electronics in new planes, drones, etc...
 - System manufacturers use protons for validation
- **Medical**
 - High reliability requirement



Sample Considerations for Electronics Proton Testing at Cyclotrons

- **Particle**

- Test energies
- Dosimetry/particle detectors
- Uniformity
- Particle range
- Spot size/collimation
- Test levels
 - Flux and fluence rates
 - Beam stability
- Particle localization
- Stray particles
 - Beware of “scatter” designs (neutrons)
- Beam structure

We suggest defining what capabilities you are willing to provide and have the users define what they need within this scope prior to a test

- **Practical**

- **Technical**

- Mechanical/mounting
- Cabling/feedthroughs
 - Ethernet, Wi-Fi,...
- Power
- Ancillary test equipment location (in vault or user area)
- Test specific issues
 - Thermal
 - Speed/performance
 - Test conditions

- **Logistics**

- Contracts/purchase
- Safety rules (patients first)
 - Personal dosimeters?
- Shipping/receiving
- Staging/user areas
- Operator model
- Activated material storage



Patient vs. Electronics Proton Exposure

Patient

- **Measurement**
 - Dose (tissue/water)

- **Beam penetration**
 - Use Bragg peak to STOP beam in patient
- **Exposure stop**
 - Cumulative dose

- **Target size**
 - Tumor

- **Beam delivery**
 - Pencil beam, wobble, uniform scan or fixed point/scatter
- **Beam timing structure**
 - Timing can be important

- **Patient exposure**
 - A few minutes

- **Beam movement**
 - Gantry or fixed/scan

Electronics (typical)

- **Measurement**
 - Dose (material – Si, SiO₂, GaAs, ...) and particle rates (Fluence -protons/cm², and flux - protons/cm²/sec)

- **Beam penetration**
 - Beam goes THROUGH target
 - Suggest having a beam stop behind target

- **Exposure stop**
 - Cumulative dose or Fluence or
 - Number of recorded events or degradation or
 - “Unusual” event or failure

- **Target size**
 - Single chip (1cmx1cm) to full assembly (20cm x 20cm or larger)

- **Beam delivery**
 - Prefer fixed point/scatter

- **Beam timing structure**
 - When particle arrives versus electronics operation CAN be important (but not always)

- **Target exposure**
 - Seconds to minutes to ??? Depending on STOP criteria – usually under 2 minutes
 - Often MANY exposures (test runs) per target (10’s to 100’s)

- **Beam movement**
 - Fixed



Study Team – Nominal Proton Capabilities Sought

- **Energy range:**
 - 125 MeV to > 200 MeV
- **Proton flux rates:**
 - $1e7$ to $1e9$ p/cm²/sec
- **Test fluences:**
 - $1e9$ 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 structure acceptable for *many* (but not all) applications
 - Fixed spot or scatter (random particle delivery over area)
 - Scanning beams MAY be acceptable (needs consideration)

Notes:

There are always users looking for levels outside of the above.
Study team usually visits and performs a shakeout test
(representative test setups) to provide familiarity on both sides.



Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center - Sample Data from 2013-2017

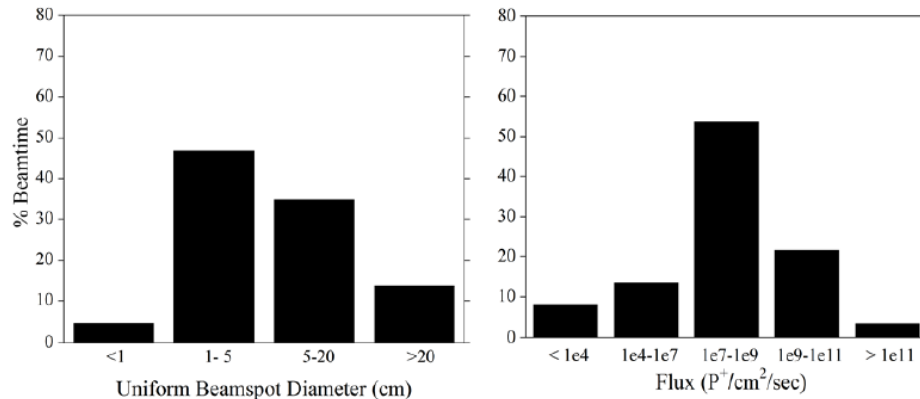


fig. 1a. Uniform beam spot sizes for all users. fig. 1b. Flux levels for all users.

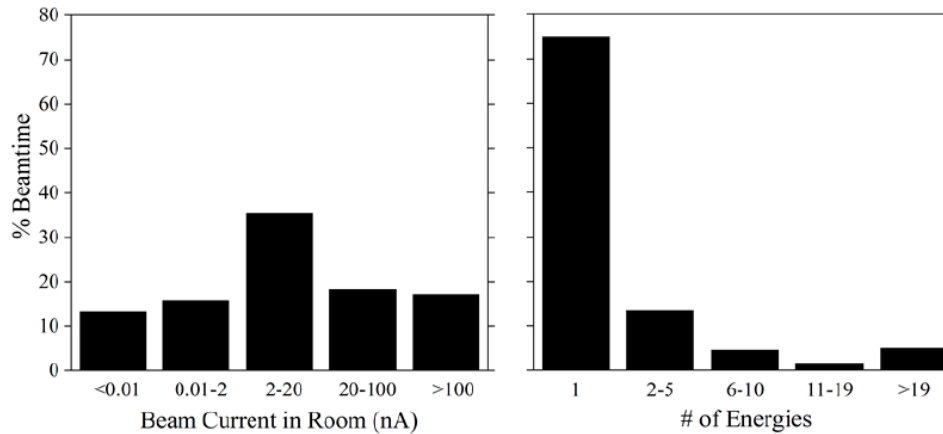


fig.2a. Total beam currents delivered to room for all users. fig.2b. Number of energies per test run for all users.

Courtesy Ethan Cascio, MGH

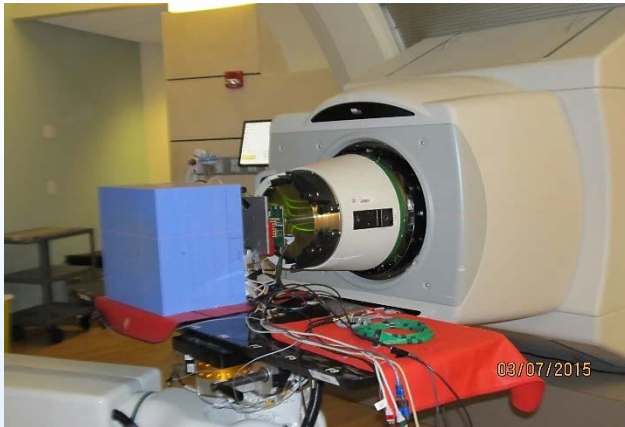


Business Models for “Selling” Protons (Therapy Sites)

- Available hours (up to 800 hours a year)
 - Weekends
 - One day or both days
 - 2 weekends a month, 3 out of 4 weekends a month
 - 6, 12, or 16 hours each day
 - Evenings
 - After patient treatment
 - 4-8 hours (we’re used to “the graves”)
 - Interleaving during the patient treatment hours
 - Lowest priority patient model
 - Assumes “Isolation” from patient area (dedicated research room)
 - ~15 minutes of beam per hour (in 2-3 minute blocks)
 - 15-20 minutes of beam per hour is a sweet spot for users
 - *Minimizes additional staffing*
- Pricing
 - Ranges from ~\$800 to \$1500/hr
 - Contracts, purchase orders, cash, check, charge



Pretty Pictures from Testing (1)



**Northwestern Medicine
Chicago Proton Center.**

Big blue block is the beam stop.

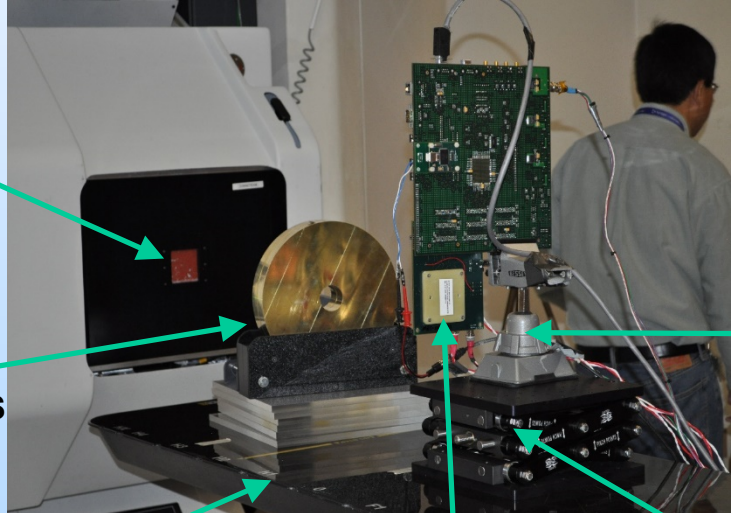
Not all facilities thought one was necessary.

California Protons.

Beam comes out here

**Brass collimator
supplied by SCRIPPS**

**Robotic patient sled
supplied by SCRIPPS**



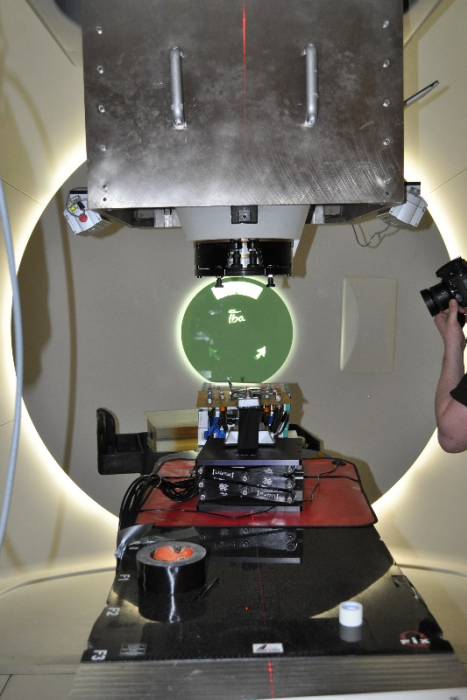
**Clamp
(NASA equipment)**

Device Under Test Table jack (NASA equipment)



Pretty Pictures from Testing (2)

Hampton University Proton Therapy Center

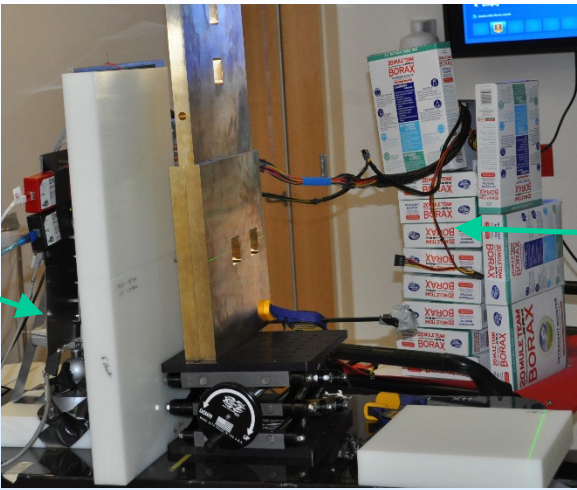


Device under test (target) on an electronics board.
 Brass (square) collimator and Poly sheets used to protect other devices on the board from stray neutrons

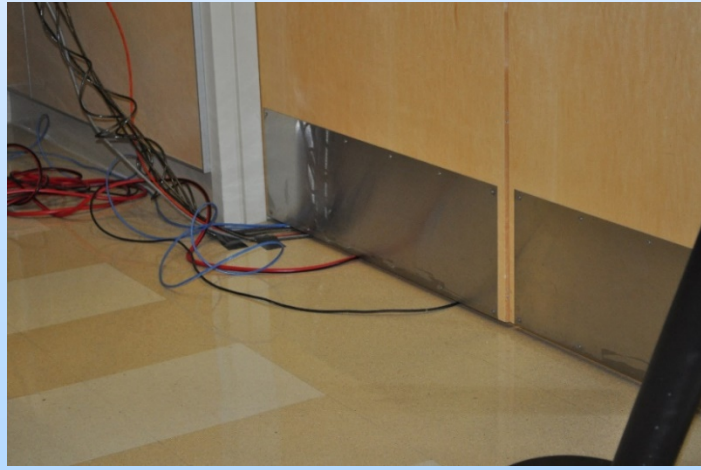
Gantry was rotated for vertical beam line.
 The floor was the beam stop.

Typically, cables are run from target area to user/control area for monitoring and control of test electronics.

California Protons



Neutron protection
 For ancillary test equipment
 In the target room

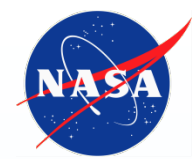




Snapshot on Where We Test

- **Facilities (veterans of the biz)**
 - Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center
 - Tri-University Meson Facility (TRIUMF) – Vancouver, CAN
 - James M. Slater, M.D. Proton Treatment and Research Center at Loma Linda University Medical Center (LLUMC)
- **Newer locations that are selling time**
 - Northwestern Medicine Chicago Proton Center
 - California Protons (formerly SCRIPPS Proton Therapy Center) – have recently contacted and have expressed interest
- **Coming “soon” – either currently willing or planning on access**
 - Mayo Clinic Proton Beam Therapy Program, Rochester, Minnesota and Scottsdale, Az
 - NASA currently discussing contract options
 - Cincinnati Children’s Proton Therapy Center
 - Load by patients/internal research has been higher than anticipated slowing down external user access
 - Hampton University Proton Therapy Institute, Hampton, Virginia
 - Building a dedicated research room with planned June/July readiness
- **Possibilities**
 - Miami Cancer Institute Baptist Health South Florida Proton Center – visit in March 2018
 - Texas Center for Proton Therapy – in discussion
 - Oklahoma City’s ProCure Proton Therapy Center
 - The Roberts Proton Therapy Center at University of Pennsylvania Health System – now building several satellite sites in the area
 - Maryland Proton Treatment Center, Baltimore, Maryland
 - Have determined a “not yet”
 - M.D. Anderson Cancer Center's Proton Center, Houston

Always open to discussions with ANY location



Questions?