Team Update on North American Proton Facilities for Radiation Testing

Kenneth A. LaBel - NASA/GSFC

Thomas Turflinger, Thurman Haas, Jeffrey George, Steven Moss, Scott Davis, Andrew Kostic - The Aerospace Corporation

Brian Wie, Integrity Applications Inc.

Robert Reed, Vanderbilt University

Steven Guertin, NASA/Jet Propulsion Laboratories

Jerry Wert, The Boeing Company

Charles Foster – Consultant to NASA

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Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov originally presented at the he 2016 Single Event Effects (SEE) Symposium and the Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 23-26, 2016 and the 2016 NEPP Electronics Technology Workshop (ETW), Goddard Space Flight Center, Greenbelt, Maryland, June 13–16, 2016.

Acronyms

Acronym	Definition
CNL	Crocker Nuclear Lab
Crocker	Crocker Nuclear Lab
DD	Displacement Damage
DOE	Department of Energy
GSFC	Goddard Space Flight Center
HUPTI	Hampton University Proton Therapy Institute
IUCF	Indiana University Cyclotron Facility
LANSCE	Los Alamos Neutron Science Center
LBNL	Lawrence Berkeley National Laboratories (LBNL)
LLUMC	Loma Linda University Medical Center (LLUMC)
MGH	Mass General Francis H. Burr Proton Therapy
NASA	National Aeronautics and Space Administration
NEPP	NASA Electronic Parts and Packaging
Northwestern	Northwestern Medicine Chicago Proton Center
NSRL	NASA Space Radiation Laboratory
OKC	ProCure Proton Therapy Center, Oklahoma City
ProNova	ProNova Solutions, Proton Therapy Treatment Facility
ROM	Rough Order of Magnitude
Rutgers	Rutgers Cancer Institute of New Jersey
SCRIPPS	SCRIPPS Proton Therapy Center
SEE	Single Event Effect
SPEs	Solar Particle Events
TAMU	Texas A&M University
TID	Total Ionizing Dose
TRIUMF	Tri-University Meson Facility
UCD	University of California at Davis
UFHPTI	University of Florida Health Proton Therapy Institute

Outline

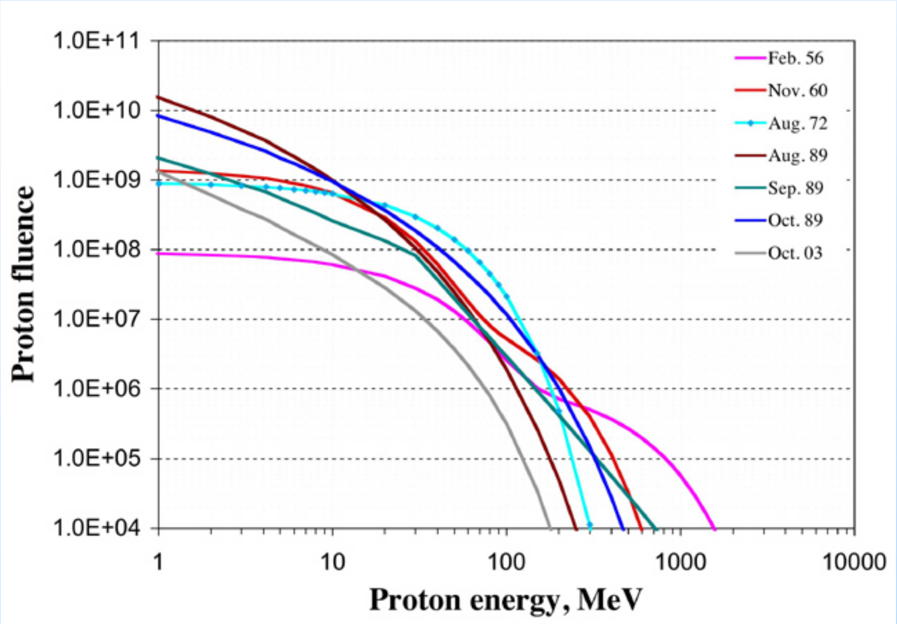
- Background: why we perform proton testing
  - Environment
  - Effects on Electronics
  - Testing on the Ground
- The "Study"
  - Proton Facility Status
    - Plan
    - Status
    - Highlights
  - Other Facilities
- The Future
  - Near Term
  - Future Considerations
- Summary

Sunset from SCRIPPS Proton Therapy Center
9730 Summers Ridge Rd, San Diego, CA 92121

Background

Protons in Space

- **Protons of various energies exist in space.**
  - **Primarily in trapped belts due to magnetic fields, and from,**
  - **Solar Particle Events (SPEs).**
- **The image below shows the proton energy spectra for representative large SPE.**

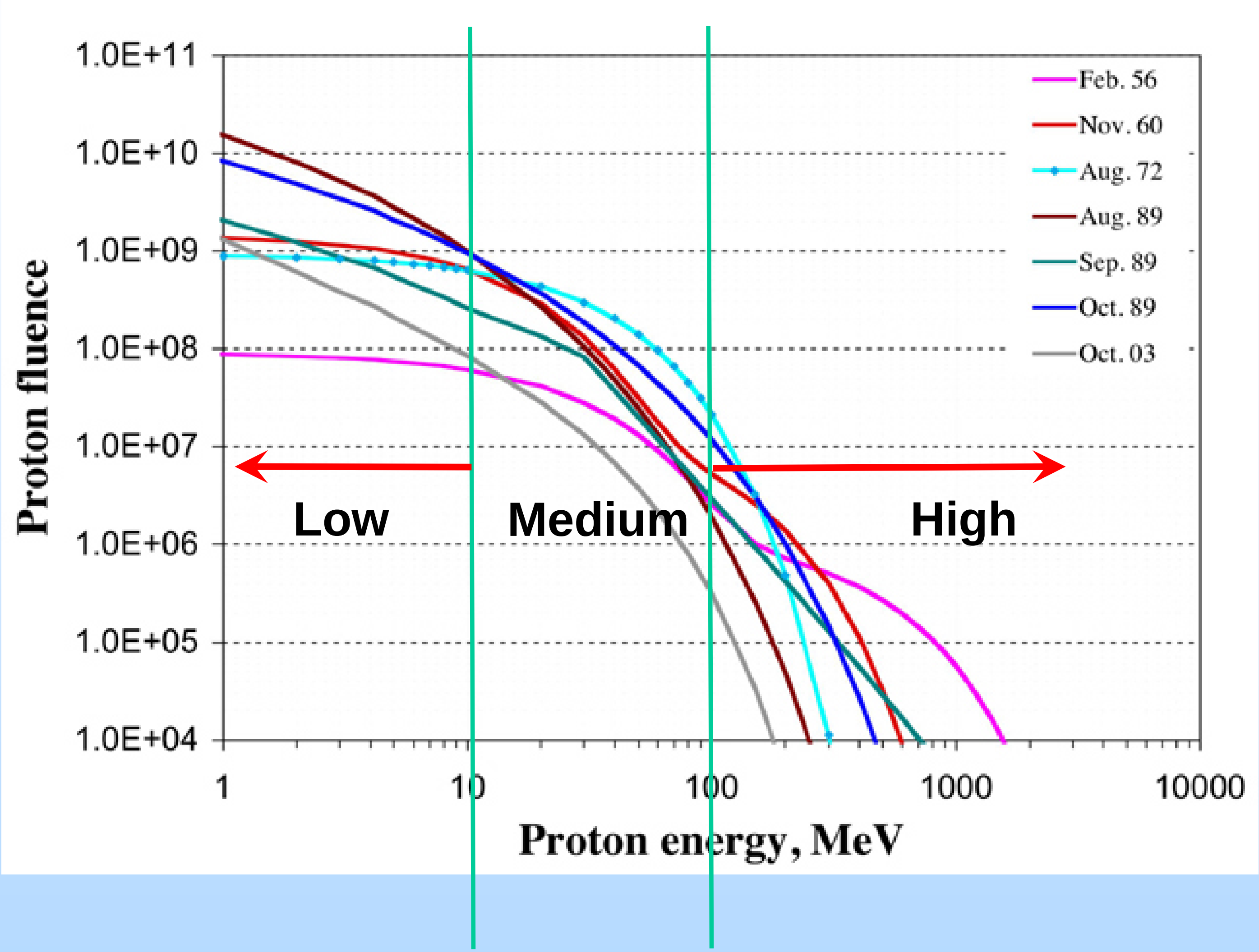


http://journalofcosmology.com/images/StraumeFigure3a.jpg

Protons – Impact on Electronics

- **Single Event Effects (SEEs)**
  - **Two mechanisms for depositing energy that depend on the device sensitivity:**
    - **Indirect ionization: the energy deposited by nuclear recoils with device materials, and,**
    - **Direct ionization: the energy deposited by the proton as it passes through the device.**
  - **Two types of effects observed:**
    - **Soft errors: upsets, interrupts, etc…**
    - **Hard errors (possible destructive): latchup, rupture, etc…**
- **Total Ionizing Dose (TID)**
  - **Cumulative long term ionizing damage due to protons.**
  - **May cause threshold shifts, increased device leakage (& power consumption), timing changes, decreased functionality, etc.**
- **Displacement Damage (DD)**
  - **Cumulative long term non-ionizing damage due to protons.**
  - **May have similar failure modes to TID.**

Proton Energies for Test - nominal break points



Proton Energy Regimes

- **For SEE testing (indirect ionization)**
  - **Most common rate prediction method utilizes the Bendel 2-parameter fit to the test data.**
  - **This method uses data points usually in both the high and medium energy regimes (curve fitting).**
    - **High energy provides the "worst case" device sensitivity (go/no-go).**
- **For SEE testing (direct ionization)**
  - **Testing is performed in the low energy regime.**
- **TID or DD**
  - **May use both medium and high energy protons.**
    - **Medium energy is the "go-to" energy regime for testing optics/sensors/etc…**
  - **Low energy may not have sufficient penetration for a packaged device, but is used for DD such as with solar arrays.**

The Study

Options for Proton Facilities in North America

- While the team has mostly been focused on high energy cyclotrons to replace the now-defunct Indiana University Cyclotron Facility (IUCF), both the low and medium regimes also need to be considered.
- The following charts present the status as we've explored with focus on the high energy proton regime.

Background: Proton Beam Delivery for Cancer Therapy

- **There are two types of facilities being used for proton cancer therapy:**
  - **Cyclotrons, and,**
  - **Synchrotrons.**
- **In addition, there are three types of beam delivery methods used.**
  - **Scatter,**
  - **Wobble/uniform scan, and,**
  - **Pencil beam scan.**
- ***IUCF was a cyclotron and utilized a scatter beam delivery system.***
  - ***Other options require thought and consideration for possible use.***

Basic Study 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 (IC ~ 1cm) to Large > 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 Therapy Site Access – Team Plan

- ✓ **Contact facilities (focus on cyclotrons)**
- ✓ **Site visit to determine interest**
  - – **Technical**
  - – **Access**
  - – **Business case**
- ❑ **Beta tests at interested sites to determine usability**
  - ✓ **Underway**
- ❑ **Work logistics of access**
  - ✓ **Underway**
- ❑ **Determine guidelines for usage of these sites**
  - ✓ **Underway**
- ❑ **Recommendations for modifications and longer term access.**
  - ✓ **Initial planning**

Assumption: Therapy sites will have available 300-500 hours/year each (weekends). Multiple facilities required to replace IUCF in the near term.

Proton Facility Status (200 MeV – North America)

	Facility	Location	Hourly Rate	Type	Access/ Annual Hours	Expected Avail.	Shakeout Test
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Future Facilities	Provision Center for Proton Therapy	Knoxville, TN	TBD	Cyclotron	TBD	Unknown	Unknown
Future Facilities	Dallas Proton Treatment Center	Dallas, TX	TBD	Cyclotron	TBD	On "pause"	TBD
Future Facilities	University of Maryland Proton Treatment Center	Baltimore, MD	TBD	Cyclotron	TBD	CY17	1Q CY17?
Existing Facilities	Tri-University Meson Facility (TRIUMF)	Vancouver, CAN	$750	Cyclotron	4x/year	Yes	Yes
Existing Facilities	Slater Proton Treatment and Research Center at Loma Linda University Medical Center (LLUMC)	Loma Linda, CA	$1,000	Synchrotron	~1000	Yes	N/A
Existing Facilities	Mass General Francis H. Burr Proton Therapy (MGH)	Boston, MA	$650	Cyclotron	~800 hours 12hr weekend days, 3 of 4 weekends – 6 month+ lead time	Yes	Yes
Existing Facilities	NASA Space Radiation Lab (NSRL)	Brookhaven, NY	$4,700	Synchrotron	~1000 hours	Yes	N/A
Indiana University Cyclotron Facility		Bloomington, IN	$820	Cyclotron	2000 hours	No	N/A

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Proton Access - Status

- **Team considers MGH and TRIUMF acceptable higher energy facilities (even before our visits).**
  - **Note that 200 MeV is not the norm at TRIUMF. Higher than 200 MeV is an acceptable alternative for most testing.**
  - **MGH booked solid through CY16 with waiting list >10 deep.**
- **Team has vetted SCRIPPS and Northwestern as viable for all test modes (scattered, continuous beam).**
  - ***SCRIPPS no longer accepting new customers.***
  - ***Northwestern is currently NOT accepting customers.***
- **HUPTI also vetted with a caveat: beam was pulsed so high speed dynamic tests were not validated.**
  - **In essence, they pulsed the beam so that it was always being modulated by the same thickness on the modulation wheel (1/16th duty cycle).**
    - **HUPTI understands this is not ideal.**
  - ***HUPTI accepting new customers.***

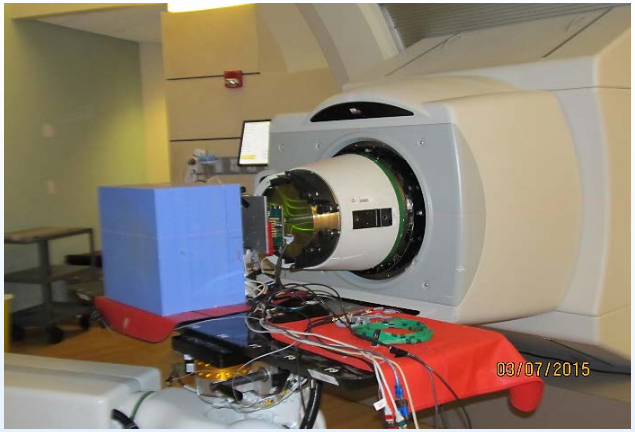
Sample 1 Mbit SRAM data showing good cross-correlation

Trip	Average CS/bit in cm^2	Percentage of MBU Events to All Events
Chicago #1	2.77 E-15	10.26%
Scripps	2.88 E-15	12.61%
Hampton	3.10 E-15	13.76%
Chicago #2	2.74 E-15	11.96%

General Things We've Discovered

- The medical physicists are REALLY bright, but
  - They speak a different language.
    - We talk flux, fluence, and dose in Silicon.
    - They talk beam current, monitor units/counts, and dose in water/tissue.
- Cable run length between the user area and beam line varies wildly.
  - 65-125' depending on the facilities.
  - Some may have limited cable runs already in place.
- The technical is the easy part.
  - Government contracting is a lot different than medical insurance for "paying the bill".
    - Things like "indemnification clauses" and federal procurement regulations are new to them and they're not really set up for this.
- The playing field is very fluid.
  - Which facilities are and how they're interested in working with our community changes nearly continuously.

Pretty Pictures from Testing (1)



Beta testing at
Northwestern Medicine Chicago Proton Center.

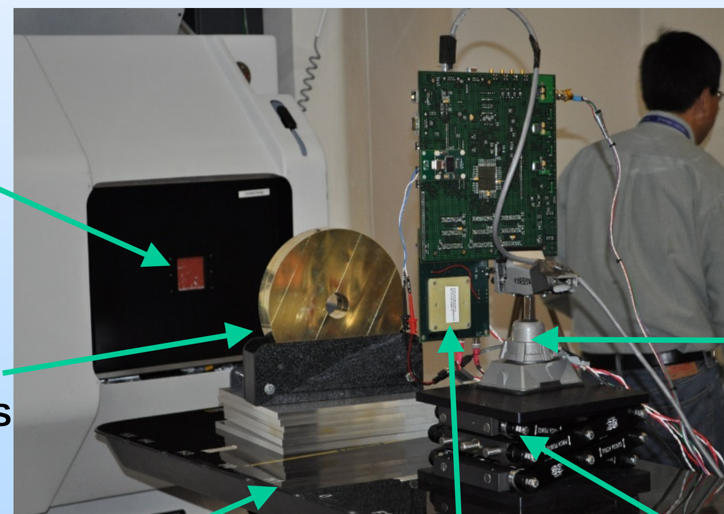
Big blue block is the beam stop.

Not all facilities thought one was necessary.

Beta testing at
SCRIPPS Proton Center.

Beam comes out here

Brass collimator supplied by SCRIPPS



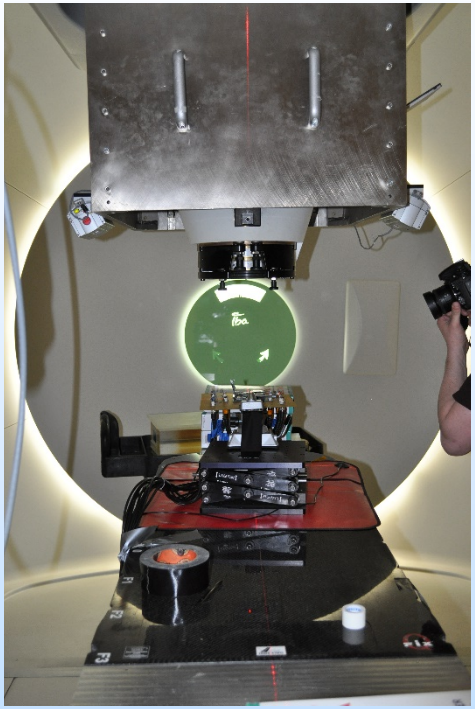
Clamp (NASA equipment)

Robotic patient sled supplied by SCRIPPS

Device Under Test

Table jack (NASA equipment)

Pretty Pictures from Testing (2)

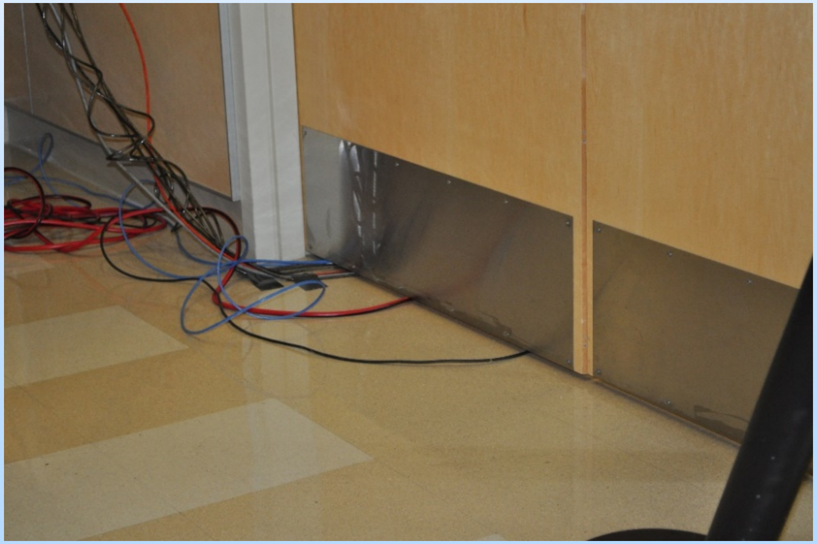


Beta testing at HUPTI.

Gantry was rotated for vertical beam line.

The floor was the beam stop.

Typical cable run under chamber doors.



Non-Cyclotron Options

- **Synchrotron (pulsed beam – timing challenge)**
  - **Accepting new customers:**
    - **Loma Linda University Medical Center (LLUMC) – in use by multiple organizations for testing.**
    - **NASA Space Radiation Laboratory (NSRL) - >>200 MeV available, but at a cost.**
  - **There are numerous other cancer treatment synchrotrons in North America (St. Louis, Rutgers, Roberts Proton, etc…).**
    - ***These are outside the scope of what we were looking for, but they ARE usable for many test types (see next chart).***
- **Possible new development**
  - **LANSCE (up to 800 MeV max)**
    - **Micro-pulsed beam that would need some development for usage down to the 200 MeV regime and to develop appropriate test flux rates.**
    - **They have a white paper on this topic.**

Beam Delivery Recommendations for Proton Testing

Type of Test	Cyclotron	Synchroton	Fixed or Scatter	Wobble/Uniform Scan	Pencil Beam Scan
Static test (Biased, non-clocked)	X	X	X	X	X
Destructive event test	X	X	X	X	X
Dynamic test (device with low proton sensitivity or slow operation) - example, commercial flash memory	X	X	X	X	X
Dynamic test (high proton sensitivity or fast operation) - example, Intel 14nm processor*2	X		X		
System test (board/box level) - example, commercial motherboard	X		X		

***1 - Assuming energy, flux, fluence, uniformity, etc… are met.**

***2 - Timing dependent tests (dynamic operations) especially on very proton sensitive devices require careful thought for using other than an IUCF-like beam (a cyclotron with a scatter mode). Further work is needed to evaluate useful nature of scan beam delivery for these kinds of tests.**

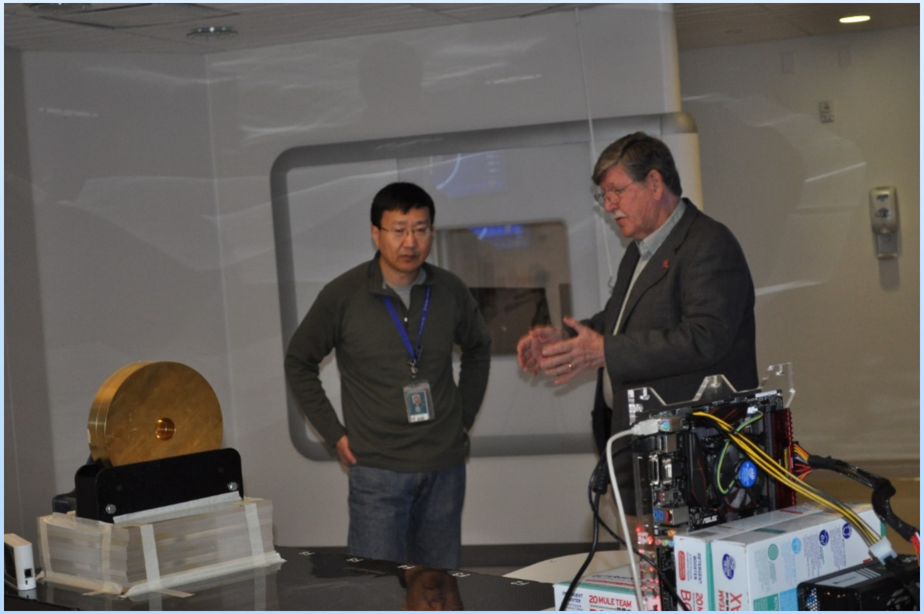
Medium Energy Proton Cyclotrons

- **Commonly used medium energy proton facilities:**
  - **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.**
- **LBNL'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.**
  - ***Had some down time for repairs, but operating and taking customers as of late April.***

**** also in use for low energy proton testing***

Class at SCRIPPS on May 21, 2016

- **Concept was to introduce “newcomers” to cancer therapy facilities on some of the considerations for electronics testing in the “new age”.**
  - **18 organizations attended.**
  - **Video recording was made and the hope is to to edit and post on http://seemapld.org website.**



The instruction was led by Ken LaBel along with support from Carl Szabo (AS&D/NASA) and Dr. Chuck Foster (consultant). Students from 18 organizations took part. Pictured are Dr. Lei Dong (Scripps) and Dr. Foster.

The Future

Near-term Plans

- **Shakeout Tests:**
  - **Summer: UFHPTI**
  - **1Q CY16: Baltimore**
  - **Other? *Do we start looking at synchrotrons?***
- **Visits**
  - **TBD: LANSCE**
- **Guidance**
  - **Proton facility guideline in the "new era"**
  - **Training for newbies as an adjunct to SEE-MAPLD**
- **Technical**
  - **Beam dosimetry**
    - **Determine if a common-core dosimetry system is required for electronics testing versus those used for medical purposes**
- **Logistics (on-going)**
  - **Evaluate logistics challenges (business models)**
  - **Evaluate assured access options**

Protons – Future Considerations

- Scenario 1: Insurance and medical needs stays the same
  - Status quo: we should have enough proton beam time options via existing sites plus new ones being built (20+ total).
  - Mostly weekends
- Scenario 2: insurance and medical industry will not have the need for the number of facilities being built
  - We get more access
  - Some sites may close
  - *Possibility of buying a site or turning it into a dedicated test facility*
  - Notes
    - ProCure (parent of Seattle, OKC, New Jersey) currently in "financial challenge"
    - APT (SCRIPPS, Baltimore, and others) and ProNova looking to expand
- Scenario 3: insurance and medical industry have increased needs for cancer therapy sites
  - We get limited access
  - More sites may be built
  - *We're hosed for using these sites*
- Scenario 4: government determines that assured access to a proton site is needed
  - Upgrade existing facilities (DOE? Crocker? Other?) or build a new site using more modern cyclotron options.

Protons Assured Access – Possible Options

- Government lab - LANSCE (DOE) upgrade
  - Pulsed beam with max energy of 800 MeV
    - Steve Wender has a white paper
    - White paper is on reducing flux to SEE test levels and obtaining 200 MeV regime
- Build a new (government/industry) facility – up to $100M ROM pending land/zoning/capability
  - May include some heavy ion capability
- Upgrade Crocker – they have experience
  - ROM is anywhere from $15-50M – better estimate needed
- Private company builds research facility
  - Former founder of Mevion (cyclotron manufacturer) has expressed interest in a privately funded facility
- *Side note:* discussion held with Zevacor
  - 70 MeV cyclotron near Indianapolis - possible access for both protons and neutrons

Summary

- **An overview of North American Proton Facility status for electronics testing has been shared.**
- **We note that this is a fluid area where the facilities and players change on a regular basis.**
  - **The future may be bright or dark.**

http://www.parabolicarc.com/wp-content/uploads/2013/07/Proton_failure_flames.jpg

Team Update on North American Proton Facilities for Radiation Testing

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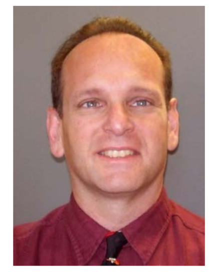
1. NASA GSFC; 2. The Aerospace Corporation; 3. Integrity Applications Inc.; 4. Vanderbilt University; 5. NASA Jet Propulsion Laboratories; 6. The Boeing Company; 7. Consultant to NASA

National Aeronautics and Space Administration

Abstract: In the wake of the closure of the Indiana University Cyclotron Facility (IUCF), this presentation provides an overview of the options for North American proton facilities. This includes those in use by the aerospace community as well as new additions from the cancer therapy regime. In addition, proton single event testing background is provided for understanding the criteria needed for these facilities for electronics testing.



Ken LaBel

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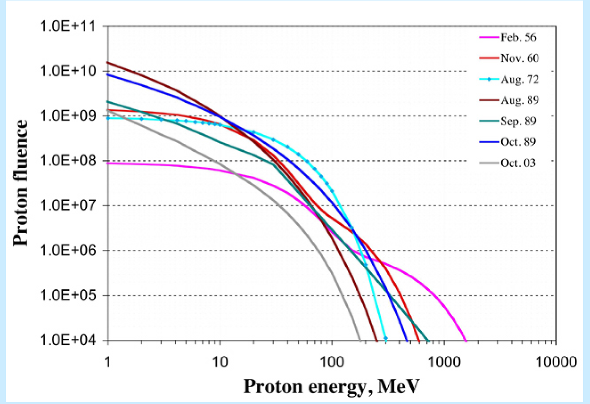

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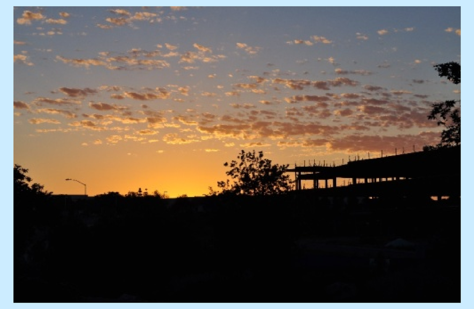

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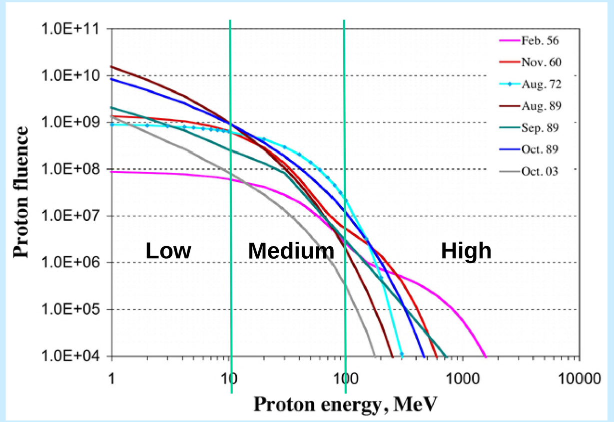

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	Mass General Francis H. Burr Proton Therapy (MGH)	Boston, MA	$650	Cyclotron	~800 hours 12hr weekend days, 3 of 4 weekends – 6 month+ lead time	Yes	Yes
	NASA Space Radiation Lab (NSRL)	Brookhaven, NY	$4,700	Synchrotron	~1000 hours	Yes	N/A
	Indiana University Cyclotron Facility	Bloomington, IN	$820	Cyclotron	2000 hours	No	N/A

Proton Access - Status

- Team considers MGH and TRIUMF acceptable higher energy facilities (even before our visits).
  - Note that 200 MeV is not the norm at TRIUMF. Higher than 200 MeV is an acceptable alternative for most testing.
  - MGH booked solid through CY16 with waiting list >10 deep.
- Team has vetted SCRIPPS and Northwestern as viable for all test modes (scattered, continuous beam).
  - ***SCRIPPS no longer accepting new customers.***
  - ***Northwestern is currently NOT accepting customers.***
- HUPTI also vetted with a caveat: beam was pulsed so high speed dynamic tests were not validated.
  - In essence, they pulsed the beam so that it was always being modulated by the same thickness on the modulation wheel (1/16th duty cycle).
    - HUPTI understands this is not ideal.
  - ***HUPTI accepting new customers.***

Sample 1 Mbit SRAM data showing good cross-correlation

Trip	Average CS/bit in cm²	Percentage of MBU Events to All Events
Chicago #1	2.77 E-15	10.26%
Scripps	2.88 E-15	12.61%
Hampton	3.10 E-15	13.76%
Chicago #2	2.74 E-15	11.96%

Discoveries

General Things We've Discovered

- The medical physicists are REALLY bright, but
  - They speak a different language.
    - We talk flux, fluence, and dose in Silicon.
    - They talk beam current, monitor units/counts, and dose in water/tissue.
- Cable run length between the user area and beam line varies wildly.
  - 65-125' depending on the facilities.
  - Some may have limited cable runs already in place.
- The technical is the easy part.
  - Government contracting is a lot different than medical insurance for "paying the bill".
    - Things like "indemnification clauses" and federal procurement regulations are new to them and they're not really set up for this.
- The playing field is very fluid.
  - Which facilities are and how they're interested in working with our community changes nearly continuously.

Non-Cyclotron Options

- Synchrotron (pulsed beam – timing challenge)
  - Accepting new customers:
    - Loma Linda University Medical Center (LLUMC) – in use by multiple organizations for testing.
    - NASA Space Radiation Laboratory (NSRL) - >>200 MeV available, but at a cost.
  - There are numerous other cancer treatment synchrotrons in North America (St. Louis, Rutgers, Roberts Proton, etc…).
    - These are outside the scope of what we were looking for, but they ARE usable for many test types (see next chart).

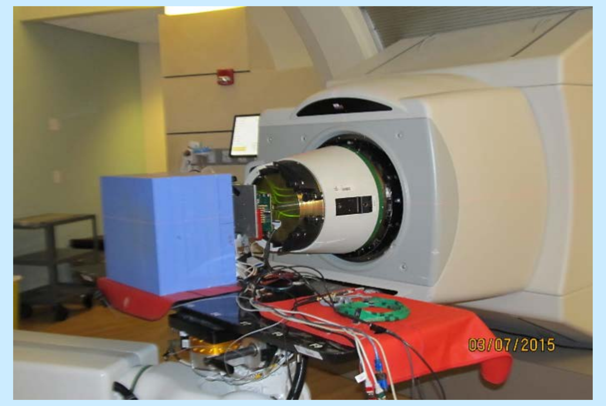
Medium Energy Proton Cyclotrons

- Commonly used medium energy proton facilities:
  - University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) – (63 MeV)*,
  - Lawrence Berkeley National Laboratories (LBNL)* – (50 MeV), and,
  - Texas A&M University (TAMU) – 50 MeV.
- LBNL'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.
  - ***Had some down time for repairs, but operating and taking customers as of late April.***

** also in use for low energy proton testing*

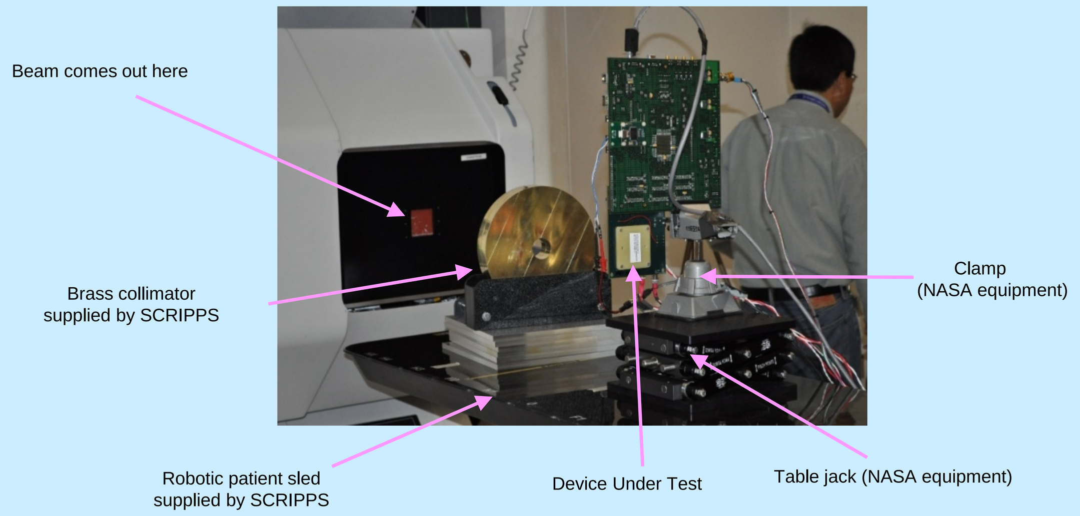
Pictures from Testing

Beta testing at Northwestern Medicine Chicago Proton Center

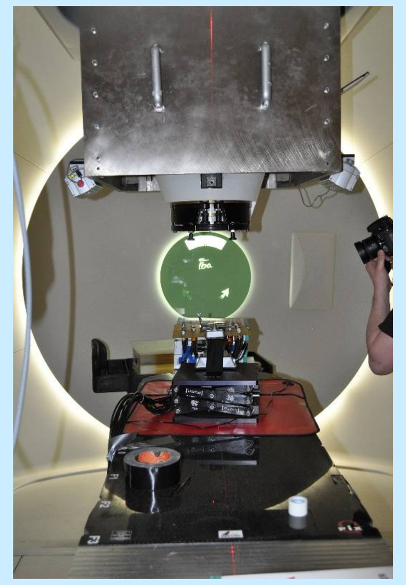


Big blue block is the beam stop.
Not all facilities thought one was necessary.

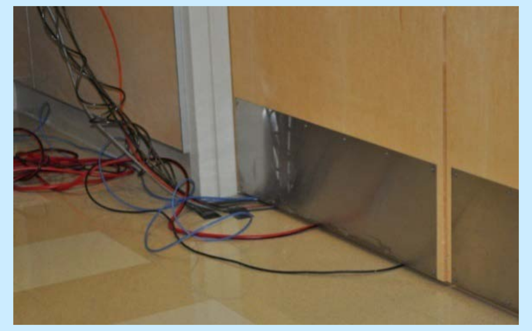
Beta testing at SCRIPPS Proton Center



Beta testing at HUPTI



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



Typical cable run under chamber doors.

Beam Delivery Recommendations for Proton Testing

Type of Test	Cyclotron	Synchroton	Fixed or Scatter	Wobble/Uniform Scan	Pencil Beam Scan
Static test (Biased, non-clocked)	X	X	X	X	X
Destructive event test	X	X	X	X	X
Dynamic test (device with low proton sensitivity or slow operation) - example, commercial flash memory	X	X	X	X	X
Dynamic test (high proton sensitivity or fast operation) - example, Intel 14nm processor*2	X		X		
System test (board/box level) - example, commercial motherboard	X		X		

*1 - Assuming energy, flux, fluence, uniformity, etc… are met.
*2 - Timing dependent tests (dynamic operations) especially on very proton sensitive devices require careful thought for using other than an IUCF-like beam (a cyclotron with a scatter mode). Further work is needed to evaluate useful nature of scan beam delivery for these kinds of tests.

The Future

Plans for FY16

- Shakeout Tests:
  - Summer: UFHPTI
  - > Fall: Baltimore
  - Other?
- Guidance
  - Proton facility guideline in the "new era"
  - Training for newbies as an adjunct to SEE-MAPLD
- Technical
  - Beam dosimetry
    - Determine if a common-core dosimetry system is required for electronics testing versus those used for medical purposes
- Logistics
  - Evaluate logistics challenges (business models)
  - Evaluate assured access options

Protons – Future Considerations

- Scenario 1: Insurance and medical needs stays the same
  - Status quo: we should have enough proton beam time options via existing sites plus new ones being built (20+ total).
  - Mostly weekends
- Scenario 2: insurance and medical industry will not have the need for the number of facilities being built
  - We get more access
  - Some sites may close
  - *Possibility of buying a site or turning it into a dedicated test facility*
  - Notes
    - ProCure (parent of Seattle, OKC, New Jersey) currently in "financial challenge"
    - APT (SCRIPPS, Baltimore, and others) and ProNova looking to expand
- Scenario 3: insurance and medical industry have increased needs for cancer therapy sites
  - We get limited access
  - More sites may be built
  - *We're hosed for using these sites*
- Scenario 4: government determines that assured access to a proton site is needed
  - Upgrade existing facilities (DOE? Crocker? Other?) or build a new site using more modern cyclotron options.

Protons Assured Access Possible Options

- Government lab - LANSCE (DOE) upgrade
  - Pulsed beam with max energy of 800 MeV
    - Steve Wender has a white paper
    - White paper is on reducing flux to SEE test levels and obtaining 200 MeV regime
- Build a new (government/industry) facility – up to $100M ROM pending land/zoning/capability
  - May include some heavy ion capability
- Upgrade Crocker – they have experience
  - ROM is anywhere from $15-50M – better estimate needed
- Private company builds research facility
  - Former founder of Mevion (cyclotron manufacturer) has expressed interest in a privately funded facility
- *Side note:* discussion held with Zevacor
  - 70 MeV cyclotron near Indianapolis - possible access for both protons and neutrons

Summary

- An overview of North American Proton Facility status for electronics testing has been shared.
- We note that this is a fluid area where the facilities and players change on a regular basis.
  - The future may be bright or dark.

http://www.parabolicarc.com/wp-content/uploads/2013/07/Proton_failure_flames.jpg

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