

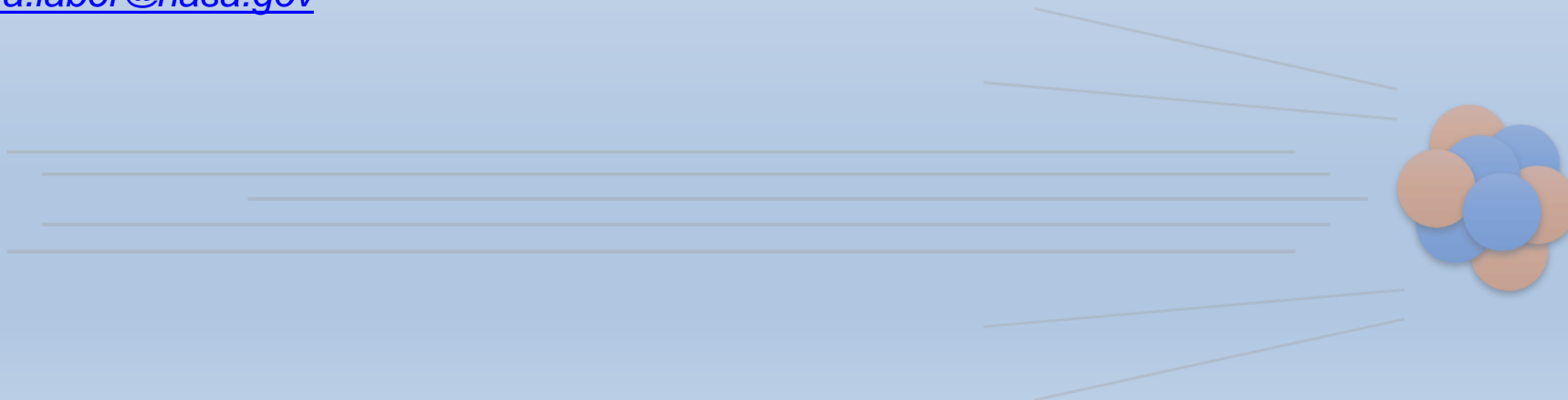


Space and Terrestrial Considerations for Access to High Energy U.S. Proton Accelerators for the Electronics Community

Kenneth A. LaBel, NASA-retired

SSAI, Inc., work performed for NASA-GSFC

kenneth.a.label@nasa.gov



Acronym List

- Coronavirus disease (COVID)
- Displacement Damage Dose (DDD)
- Department of Defense (DoD)
- Device Under Test (DUT)
- Hampton University Proton Therapy Institute (HUPTI)
- Integrated Circuits (ICs)
- University Cyclotron Facility (IUCF)
- linear energy transfer (LET)
- monitor counts/units (MC/MU)
- Massachusetts General Hospital (MGH) Francis H. Burr Proton Beam Therapy Center
- National Aeronautics and Space Administration (NASA)
- ProVision CARES Proton Therapy Center (ProVision)
- Scripps Proton Therapy Center (SCRIPPS)
- Synchronous Dynamic Random Access Memory (SDRAM)
- Single Event Effects (SEE)
- Science Systems and Applications, Inc. (SSAI, Inc.)
- Total ionizing dose (TID)
- Tri-University Meson Facility (TRIUMF) Proton Irradiation Facility
- University of Alabama at Birmingham (UAB)
- University of Alabama-Birmingham (UAB)

Problem Statement

- Problem Statement (Space/Military Electronics)
 - Particle accelerators are used to evaluate **Single Event Effects (SEE)** risk and qualify electronics for usage in the space/military radiation environment
 - » Protons
 - Simulate solar events and protons trapped in planetary magnetic fields*
 - Are used as a surrogate for neutrons for avionics and weapons environment*
 - 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”** – reaching out to the growing network of proton therapy (medical) sites for parasitic access

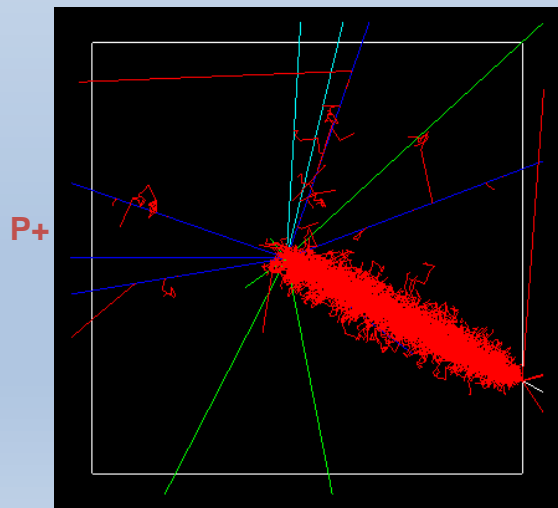
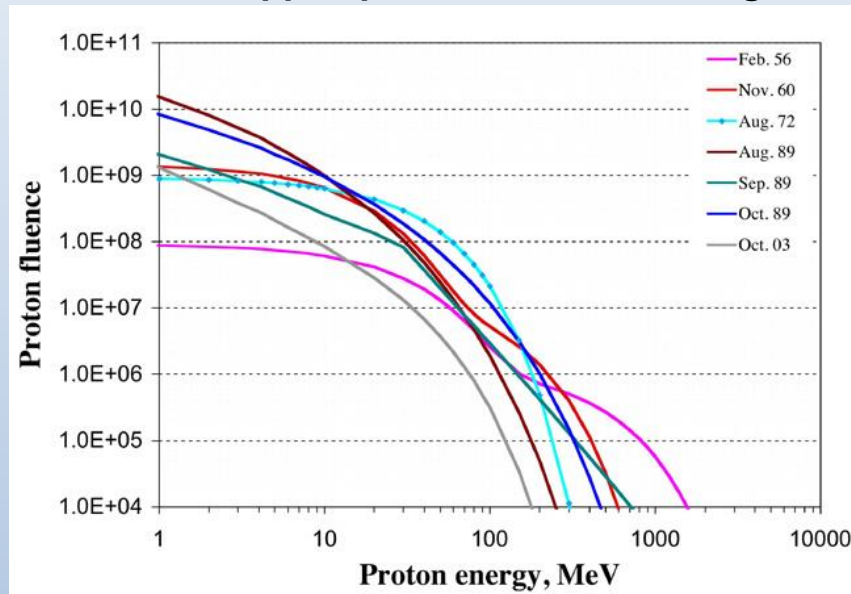


Figure is of a simulated 100 MeV proton reaction in a 5 um Si block
Reactions have a range of types of secondaries and energy depositions
Energy deposition by protons (displacement, spallation, etc...) have impacts on electronic functionality
(after Weller, Trans. Nucl. Sci., 2004)

Why >200 MeV Protons for Electronics?

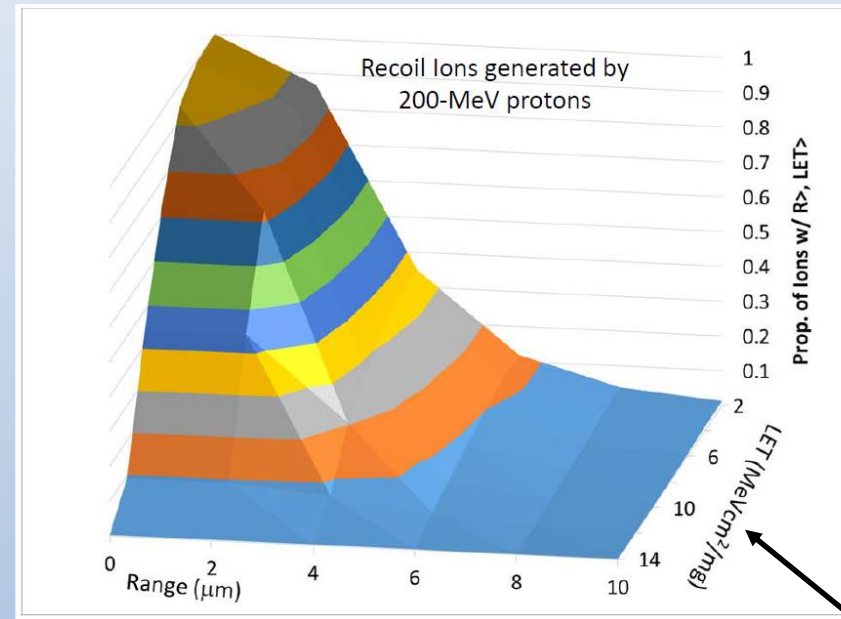
Used to simulate the space proton hazard
(solar events, trapped protons in Earth's magnetic field)



Representative solar events and their proton spectra
Courtesy Straume, NASA

200 MeV is fairly accessible and a reasonable bounding energy for SEE sensitivity

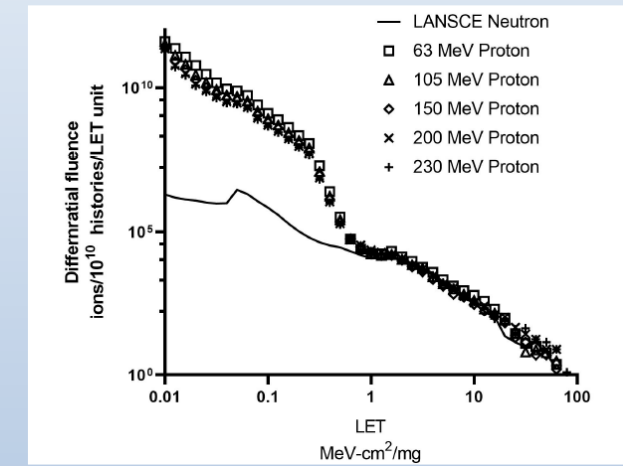
Prime Proton SEE Mechanism



Reaction of protons interacting with semiconductor materials causes secondary recoil ions – Indirect Ionization
Secondaries have various Linear Energy Transfers (LETs) and penetration ranges
Courtesy Ladbury/NASA

Surrogate uses for protons

Neutron SEE



Due to similar mechanisms, used to bound terrestrial, avionics, and other neutron SEE sensitivities

<https://www.mdpi.com/2076-3417/10/9/3234>

Heavy Ion SEE

Used as screen for lower LET sensitivities, down-select testing, fault tolerance validation, etc

Proton Physics for SEE

- **Total *nuclear* production cross section**

- # ions out/#protons in

Energy(MeV)	Sigma (cm ⁻²)
50	4.76E-06
100	3.89E-06
200	3.46E-06
500	5.37E-06

- **These secondary particles have a distribution of linear energy transfer (LET) as well as usually being of short range.**

- These are particle kinematic effects to consider when establishing a proton fluence:
 - » Number of interactions that occur that have secondary ion spallations,
 - » Distribution of the secondary ions, and
 - » Risk coverage versus mission environment, sample size, geometry, etc...
- Is 10^{12} protons/cm² a realistic choice? Approximates the 10^7 ions/cm² often used for heavy ion test runs.

*Be wary of total dose or displacement damage at higher fluence levels:
- consider more samples of the DUT at lower fluence levels.*

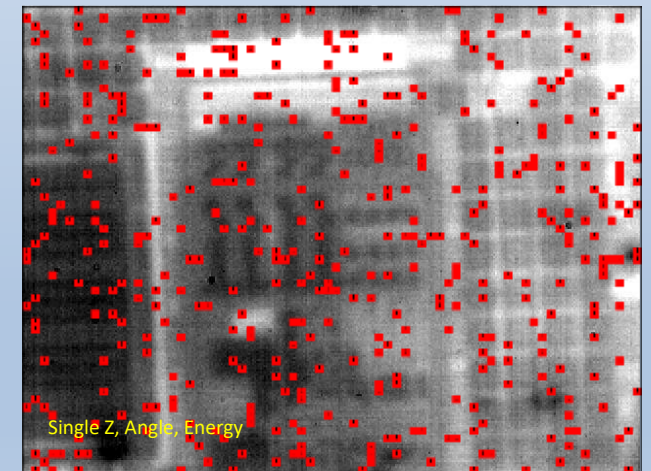
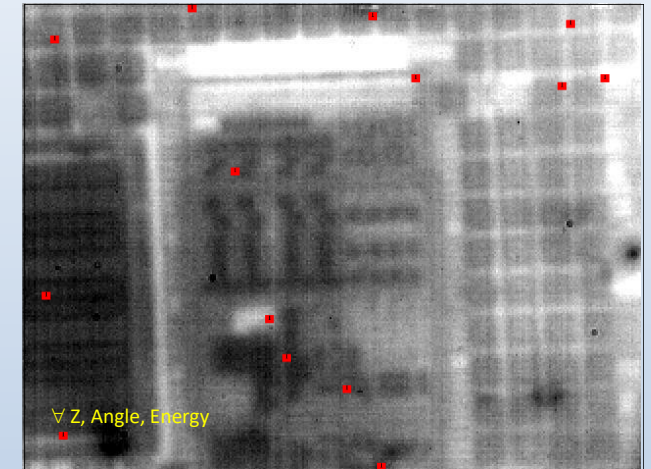
Heavy Ions vs. Protons for SEE Testing

Bottom Line: Proton facilities are usually more readily available, but insufficient to qualify hardware for deep space environments

SEE Proton testing relies on proton nuclear interactions and spallation effects to generate secondary heavy ions. This secondary environment presents the following limitations:

- **Reduced feature coverage**
 - Infrared micrograph of a portion of a 512 Megabit (Mb) synchronous dynamic random access memory (SDRAM) $\sim 60 \times 70 \mu\text{m}^2$
 - Shows both memory cells and control logic (10 yr. old tech.);
 - » Red spots are simulated ion hits
- **Maximum theoretical LET of 14 MeV-cm²/mg (for 200 MeV protons)**
 - 8 MeV-cm²/mg more realistic
 - Most programs/organizations want a higher LET such as 37, 60, or 75 MeV-cm²/mg
- **Limited penetration (range)**
 - Insufficient to cause some destructive effects that would occur in space
- **Caveats include dose during testing and material activation**

Coverage from $1\text{E}11$ 200 MeV protons/cm²

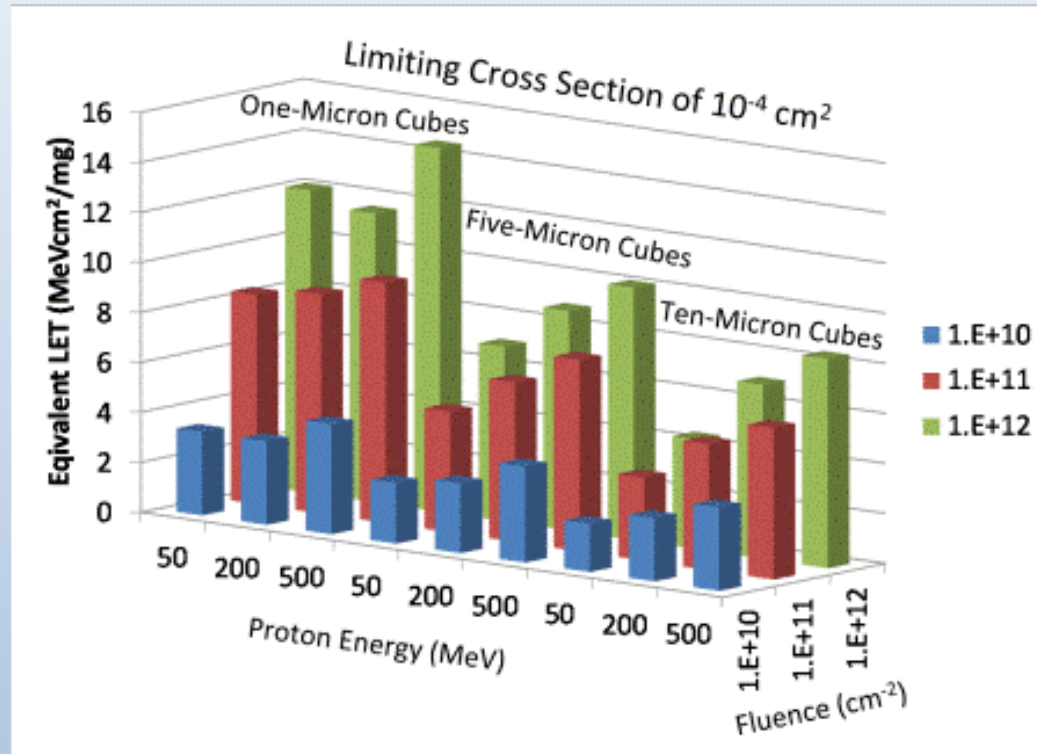


Coverage from $1\text{E}7$ heavy ions/cm²

After Ladbury, TNS-2017-TN35833

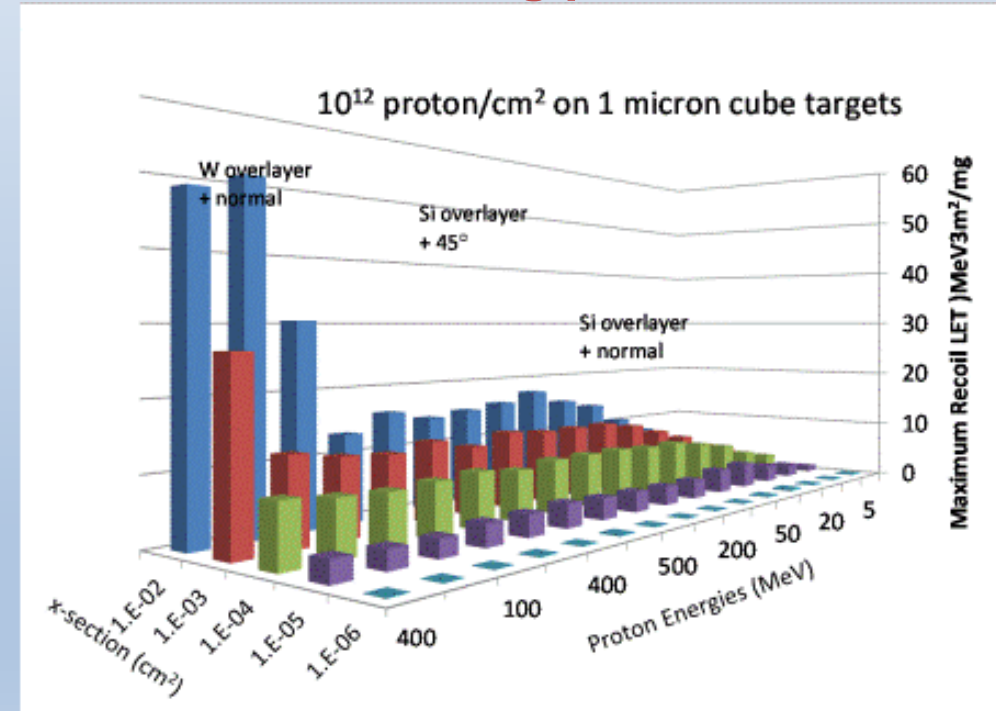
Visual Protons for SEE

(courtesy R. L. Ladbury and J.-M. Lauenstein, NASA/GSFC)

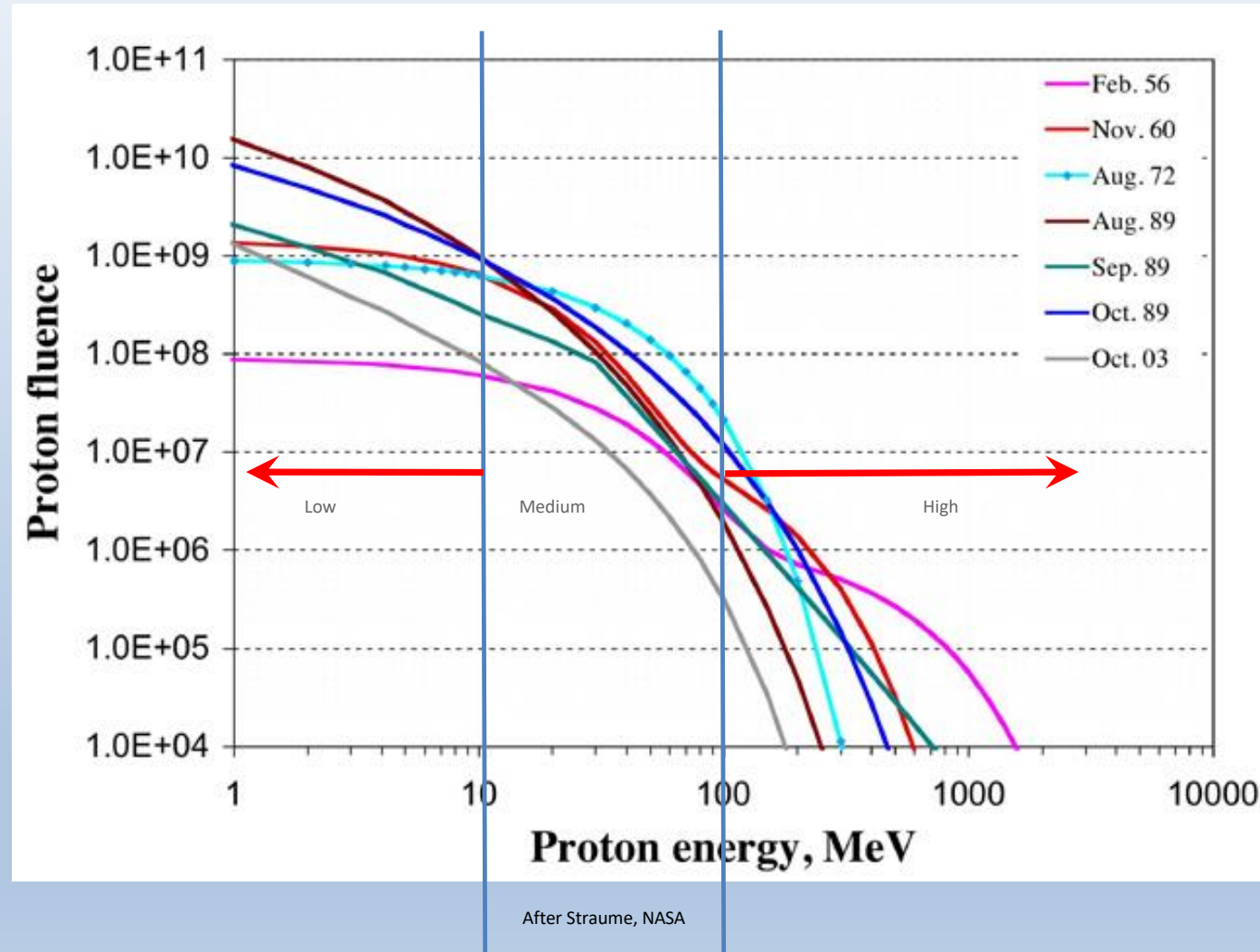


How good are protons at simulating heavy ions?

Silicon's not the only culprit
In creating problems



Proton Energies for SEE Testing - nominal break points



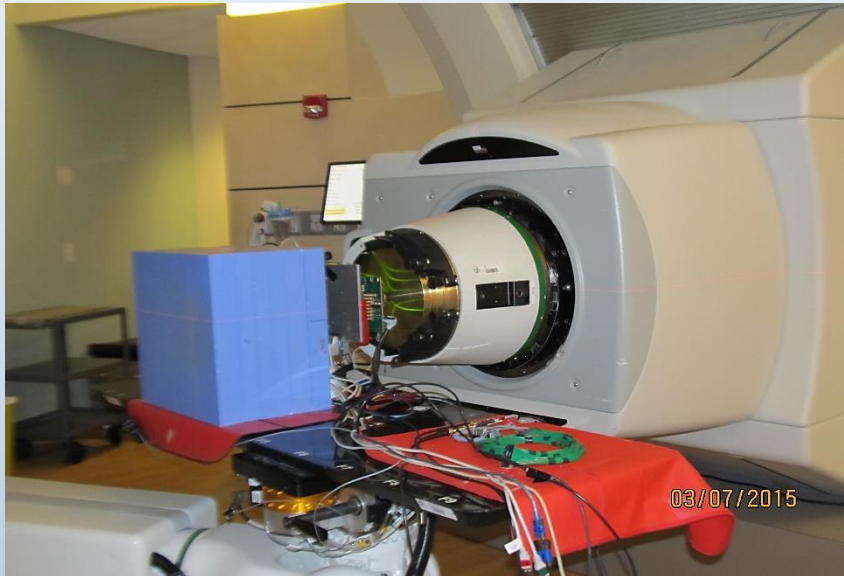
Proton Energy Regimes – Electronics Testing

- **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 (<10 MeV).
- **Total ionizing dose (TID) or Displacement Damage Dose (DDD) on electronics**
 - 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 testing of devices such as solar cells.

Basic Proton SEE Requirements from Medical Accelerators

- **Energy range:**
 - 125 MeV to > 200 MeV (some machines 70-250 MeV)
- **Proton flux rates (f):**
 - $1e7$ to $1e9$ p/cm²/sec
- **Test fluences (F):**
 - $1e9$ to $1e11$ or $1e12$ p/cm²
- **Irradiation area:**
 - Small (single chip ~ 1cm²) 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)

Pretty Pictures from Medical Facility Testing (1)

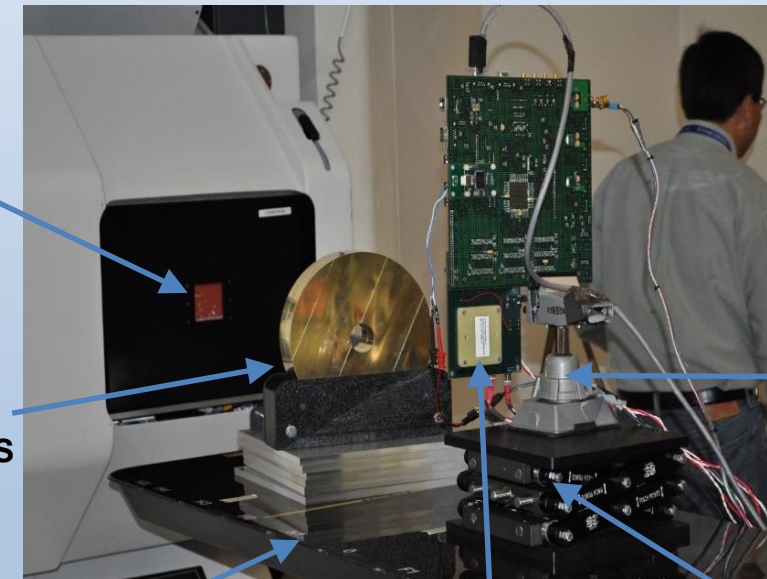


*Northwestern Medicine
Chicago Proton Center.*

Big blue block is the beam
stop.

Not all facilities thought one
was necessary.

SCRIPPS Proton Center (now California Protons)



Beam comes out here

Brass collimator
supplied by SCRIPPS

Robotic patient sled
supplied by SCRIPPS

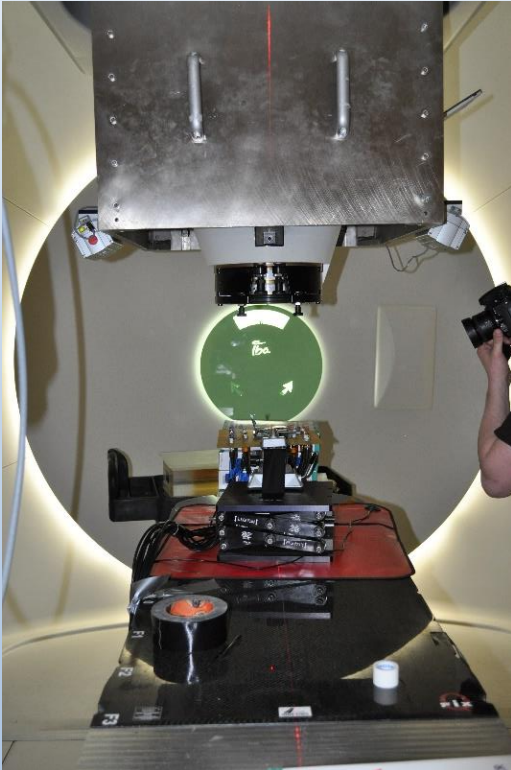
Clamp
(NASA equipment)

Device
Under Test

Table jack (NASA equipment)

Pretty Pictures from Medical Facility Testing (2)

**Hampton University
Proton Therapy Institute (HUPTI)**



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

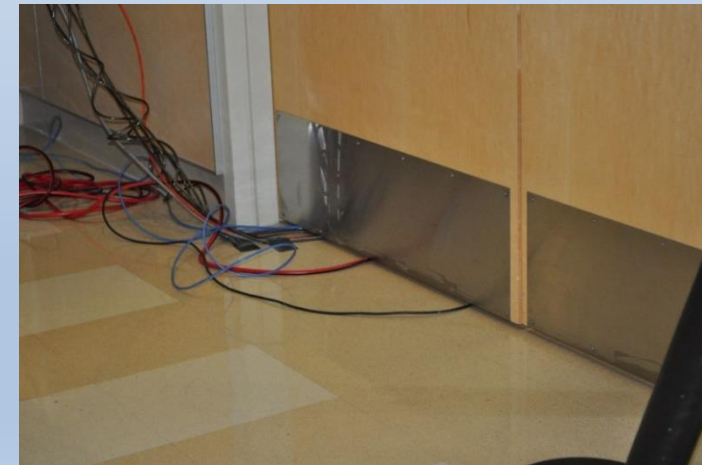
Device under test (target) on an electronics board.
Brass (square) collimator and Poly sheets used to protect other devices on the board from stray neutrons

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

SCRIPPS



Neutron protection
For ancillary test equipment
In the target room



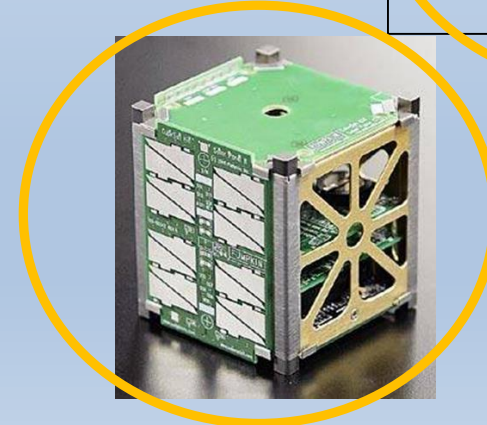
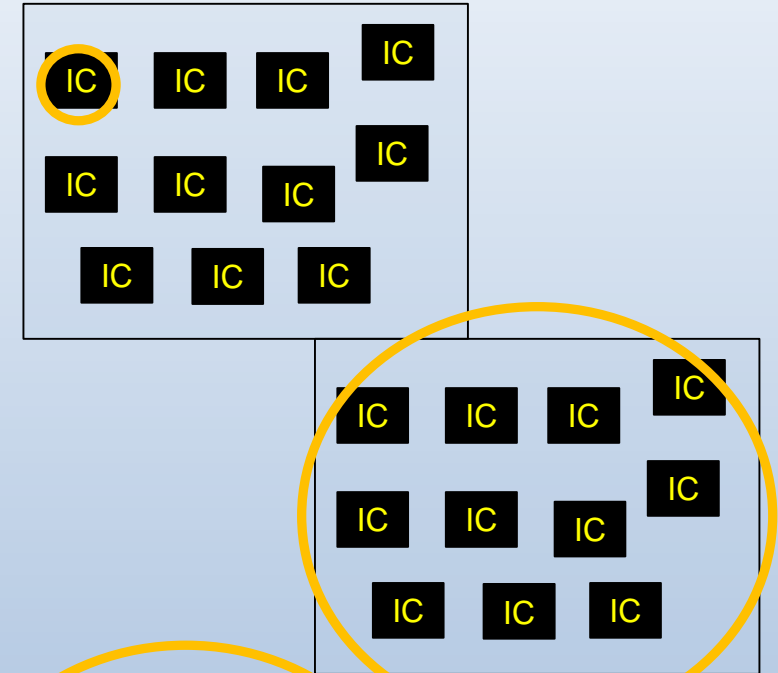
Electronics and Proton Effects

Sample Customer Base for Protons – beyond medical treatments and research

- **Space/military products**
 - Evaluate proton SEE risk
 - » Device level tests
 - » System level tests
 - » Technology/architecture research
 - VALIDATION of radiation tolerance approaches
- **Space/military 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
- **Nuclear data research**
- **Isotope production**
 - Higher intensity needed than proton therapy machines
- **Surrogate for neutrons**
 - **Commercial – terrestrial**
 - » Provides higher performance, but have proton/neutron sensitivities (terrestrial)
 - **Automotive**
 - » Largest commercial growth area in the electronics market
 - » Have safety critical aspects (self-driving and driver assist)
 - » Systems validation is growing area
 - **Aviation/Aeronautics**
 - » Increased use of sensitive electronics in new airplanes, drones, etc...
 - » System manufacturers use protons for validation
 - **Medical equipment**
 - » High reliability requirement

Sample Proton SEE Test Scenarios

- **Baseline: traditional IC test**
- **Board-level test: testing of large amounts of individual ICs on a single test board**
 - 2 sub-scenarios: one part at a time or multiple parts at a time
- **Board-level test: functional purpose board (e.g., space computer) – system response test**
- **Board-level test: SEE mitigation validation**
- **Assembly or stacked board test**



*Image courtesy of
Vanderbilt University*

Factors that are Increasing Proton Demand (Space)

Expanding communities of interest (see Customer Base – see previous slide)

Increases in commercial space segment (new companies and more launches)

Increases in the Small Sat space segment (increasing constellations and launches) including universities

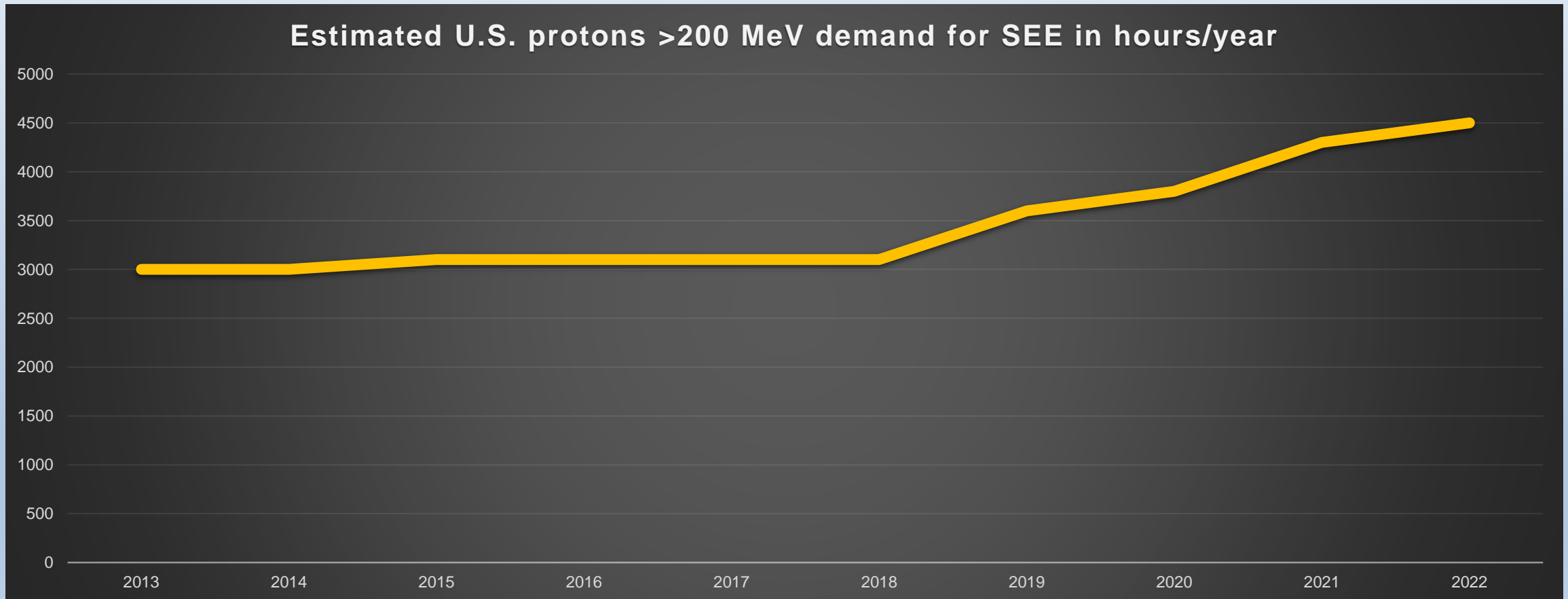
Limited time availability at heavy ion sites

- Protons used as pre-selection tools and for risk reduction

Ability to test large devices/boards/systems

Ability to penetrate complex packaging and materials (testability)

Protons >200 MeV: U.S. Demand since 2013



Factors that Affect Proton Capacity (Therapy Sites)

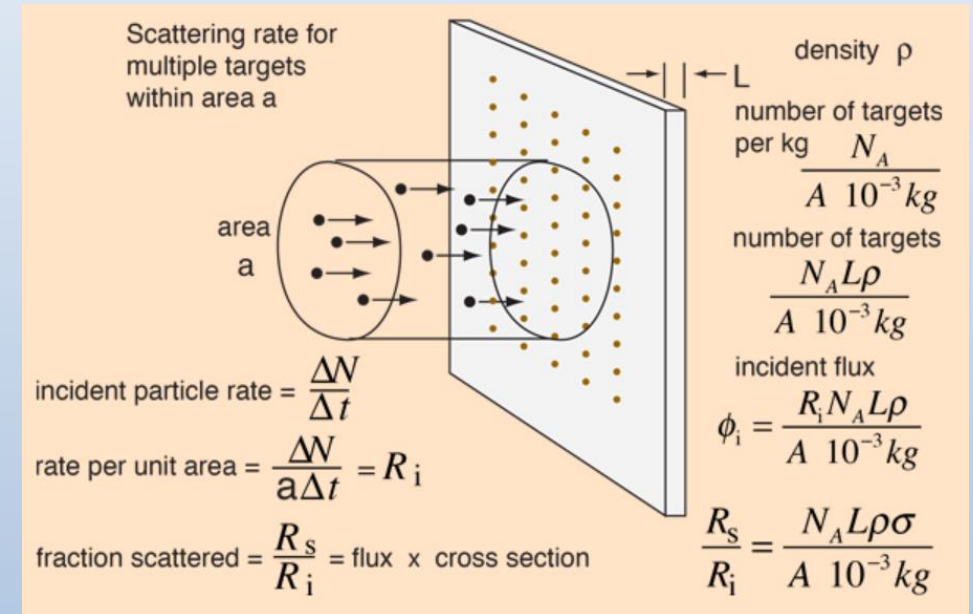
- **Business model**
 - **Ownership/management changes at proton therapy sites (volatility)**
 - » Often changes accessibility with little warning
 - **Fiscal issues: on-going challenges with medical insurance acceptance of proton therapy**
 - » Several have undergone Chapter 11 and/or undergone significant reorganization and removed access (e.g., ProVision, SCRIPPS – aka California Protons)
 - **Beam costs – medical sites are used to medical cost models and while electronics research is “simpler”, sites are uncertain how to handle/cost**
 - **Non-interference with patients**
 - **Access only during non-patient treatment or regular maintenance hours**
 - **Staffing limitations may not allow for “extra” hours to be used**
 - **Perceived Risk**
 - **Concern over potential liability and/or damage to expensive medical equipment – few sites have dedicated research rooms.**
 - **Maintenance**
 - **Older machines require refurbishment/repair (reliability risk)**
 - **Increased medical therapy research (FLASH therapy)**
- Trend: new sites are more likely to be a single treatment room (rather than multiple) and will have very limited potential for electronics test access**

Possible Business Models for “Selling” Protons (Medical Treatment Sites)

- **Available hours**
 - **Weekends**
 - One day or both days
 - 2 weekends a month, 3 out of 4 weekends a month
 - 8, 12, or 16 hours each day
 - **Evenings**
 - After patient treatment
 - 4-8 hours (electronics tester personnel are 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*
 - Model changes if no patients are being treated with a machine
- **Pricing**
 - Ranges from ~\$1000 to >\$2000 hr (depends on parent organization)
 - Contracts, purchase orders, cash, check, charge – NO medical insurance needed

Background: Proton Beam Delivery

- There are two types of accelerators being used for proton cancer therapy:
 - Cyclotrons (relatively continuous beam), and,
 - Synchrotrons/Synchrocyclotrons (pulsed beam, aka beam spills).
- In addition, there are three types of beam delivery methods used.
 - Scatter,
 - Wobble/uniform scan, and,
 - Pencil beam scan.
- Newest treatment method is “FLASH” therapy (high dose rate - reduces tumor irradiation from minutes to seconds)
 - Still in research/trial phase in the U.S.
- *IUCF was a **cyclotron** and utilized a **scatter** beam delivery system.*
 - *This is preferred, but not 100% necessary.*



This is a figure depicting ion beam particle interaction with a target at a cyclotron

Courtesy of Rod Nave

<http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/imgnuc/crosec.gif>

Translating the terms: medical vs electronics

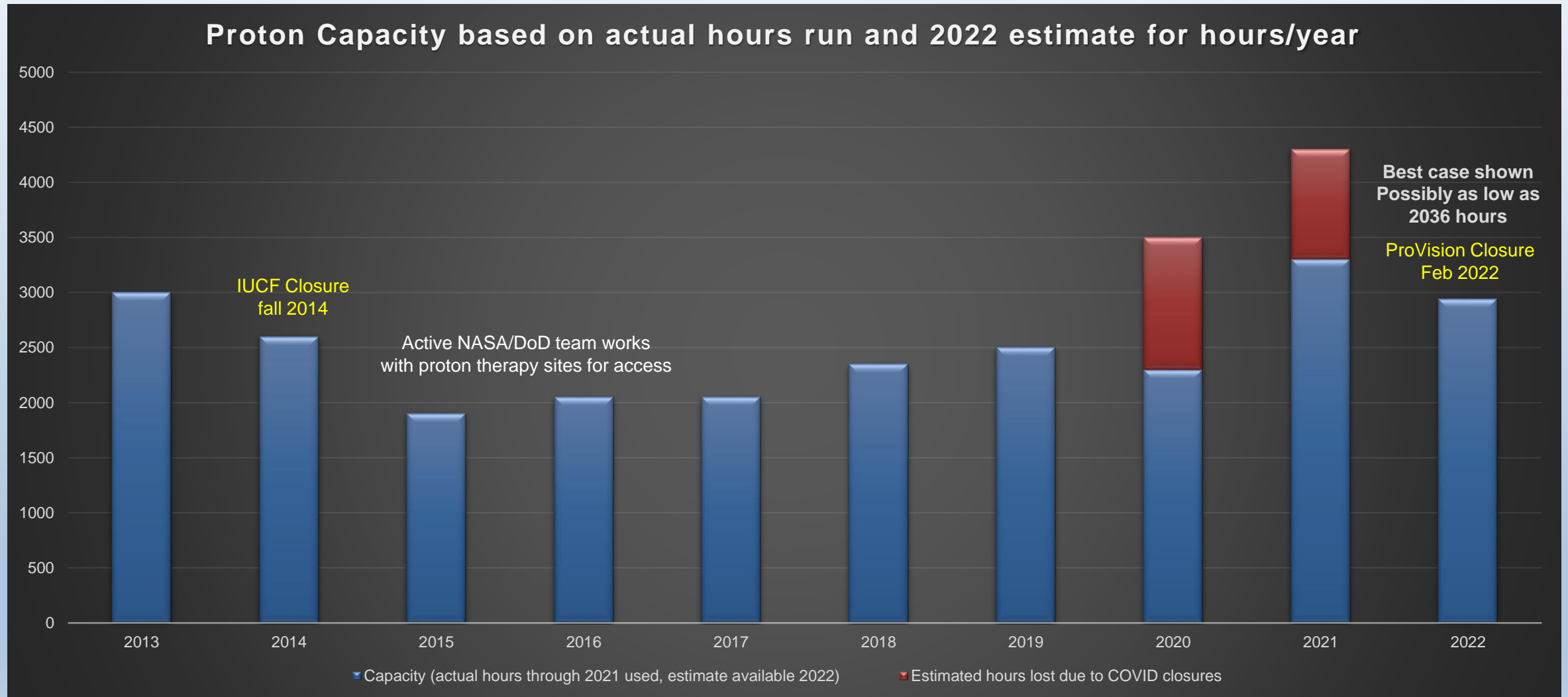
Patient (target)

- **Measurement**
 - Dose (tissue/water), monitor counts/units (MC/MU)
- **Beam penetration**
 - Use Bragg peak to STOP beam in patient
- **Exposure stop**
 - Cumulative dose, MC/MUs
- **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

Protons >200 MeV: U.S. capacity since 2013



Protons >200 MeV: U.S. facilities currently providing access

Prime locations selling time

- James M. Slater MD Proton Treatment & Research Center
- Mayo Clinic Proton Beam Facility - Phoenix
- Mayo Clinic Proton Beam facility - Rochester
- Massachusetts General Hospital (MGH) Francis H. Burr Proton Beam Therapy Center
 - MGH has been struggling with recovery from unexpected maintenance
 - Unclear on actual availability, but best case for 2022 is ~300 hours (<50% of max pre-COVID and maintenance)
- Northwestern Medicine Chicago Proton Center
- ~~Provision CARES Proton Therapy Center~~
 - Due to new management (Covenant Health), facility was **closed** as of 1 Feb 2022.
 - This was the U.S. site with most access for electronics testing (1500 hours/year+ - only “dedicated” research proton accelerator for SEE, etc)

Intending to sell

- Johns Hopkins University Proton Therapy Center
- Proton International at University of Alabama-Birmingham (UAB)

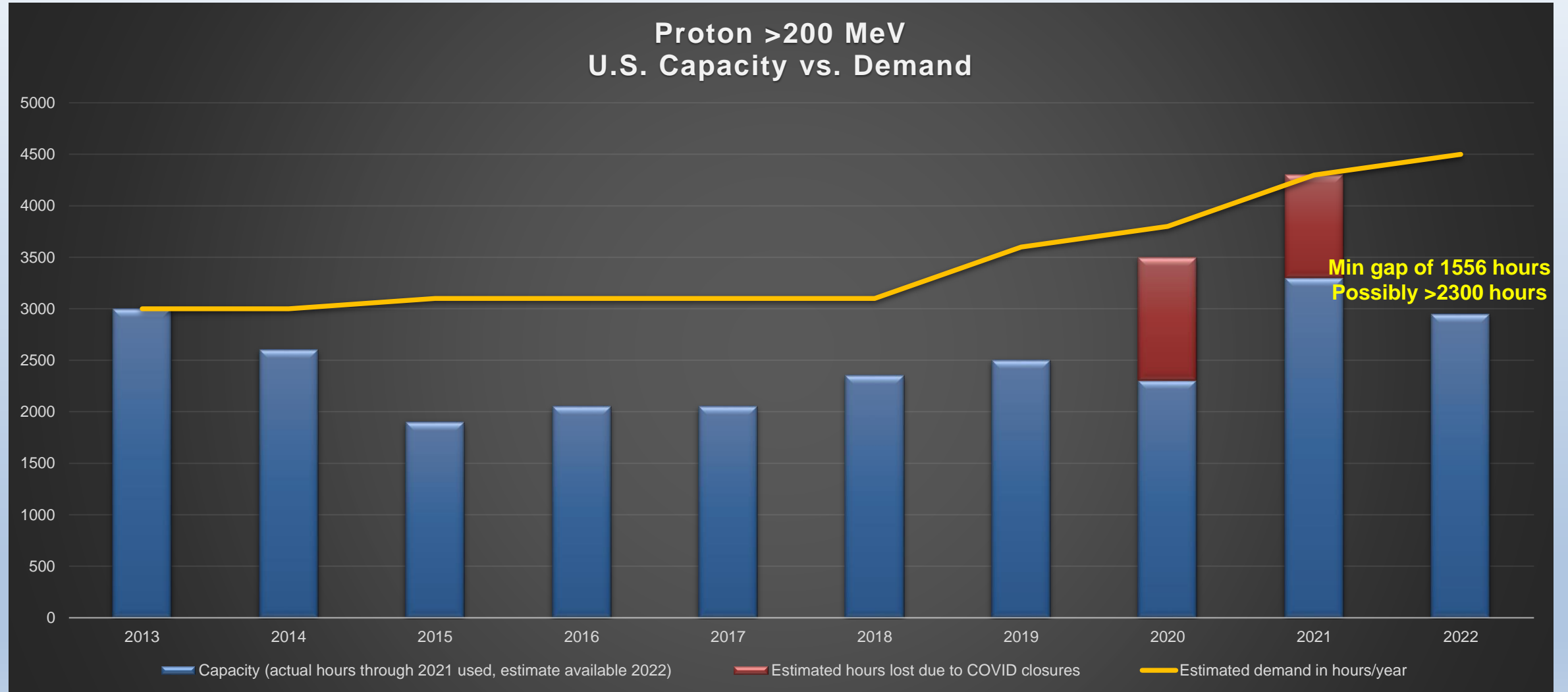
Canada

- Tri-University Meson Facility (TRIUMF) Proton Irradiation Facility

No guaranteed access facility exists domestically.

- **The mix of who is providing access changes on a regular basis (tracked quarterly).**

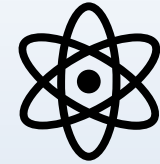
Protons >200 MeV: U.S. capacity vs demand since 2013



Possible Options

- With the current emphasis on the even worse accessibility issues related to heavy ions, finding solutions (and funding) won't be simple
- ***Proton therapy center success is not guaranteed***
 - Continuing issues with insurance acceptance
 - Patient loads are uneven (utilization rates)
 - FLASH therapy versus traditional irradiation
 - Carbon ion therapy considerations (more efficient irradiation with even less peripheral damage)
- Possibilities...
 - ProVision gets resurrected
 - Private industry finds funding (public/private) for a new facility
 - Another proton therapy site undergoes bankruptcy, ...

Summary and Comments



- **What's Needed Now - Better demand study**
 - Current demand is based on general trends of usage and inputs from facilities
 - Actual user inputs are required for more appropriate demand signal (and which segments it is critical to) – survey
- **Private industry has expressed interest in “solving” the problem possibly in a public-private venture**
 - Reuse potential for older or financially challenged sites?
 - » Medically installed machines have lots that we “don’t need” in a building
- **Right now, there are ~38 proton therapy sites active in the U.S and more planned**
 - May be able to get some additional access, but given the historical volatility, uncertainty exists for stable access (with a few exceptions)