Jet Propulsion Laboratory
California Institute of Technology

# Radiation Assurance for Space Applications

Presented by:

Sammy Kayali, Deputy Director, Office of Safety and Mission Success

May 31, 2017

Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, CA, USA

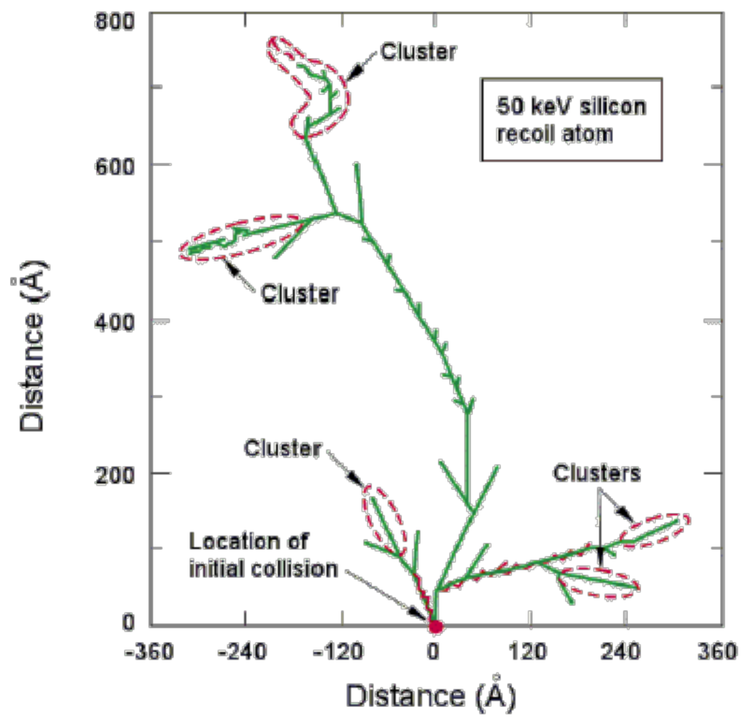
# Acknowledgements


- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under the contract with the National Aeronautics and Space Administration.

  Contributions by Leif Scheick, Charles Barnes, and Greg Allen.

# Outline

- Overview of Radiation Threats
- Radiation Effects on Spacecraft Systems
- Mitigation Engineering and Testing
- Data Analysis
- Summary and Recommendations




High energy proton displacing silicon atoms out of positions

# Space Radiation Challenge

## Radiation Sources

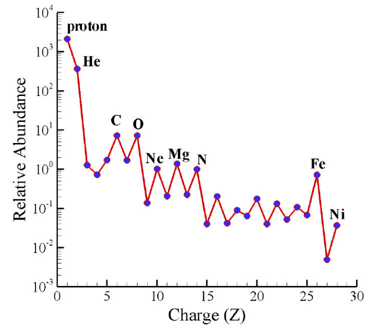
- Solar wind and flares from the sun
- GCRs from super-novae
- Trapped particles in magnetic fields
- Deep space
  - GCRs are a constant threat
  - Solar flares
- Secondary neutrons

## Radiation Types

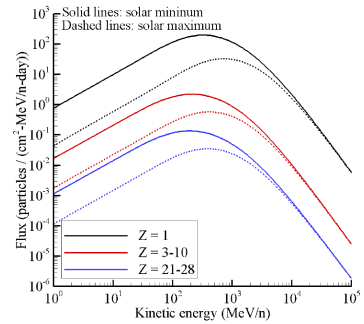
- Protons
  - Single particle that deposits a small amount of energy
  - Higher energy protons will induce nuclear reactions
- GCR – heavy ions
- Electrons
- Photons

## Radiation Effects

- Ionization
  - Caused by ions, protons and electrons
- Displacement Damage
  - Caused by ions, neutrons, protons, electrons




Relative abundance of elements in the 1977 solar minimum GCR environment, normalized to neon

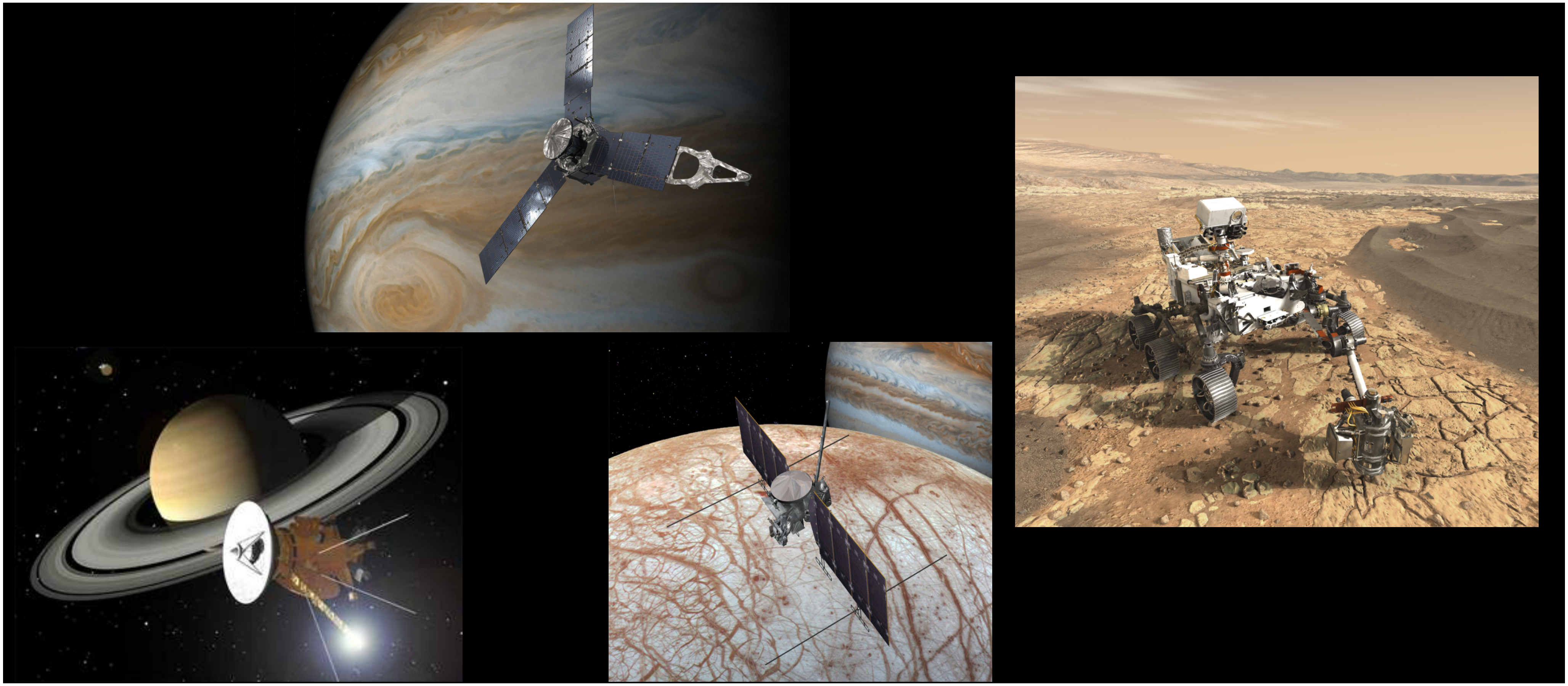



GCR flux at solar minimum and solar maximum

MSL and other Mars missions are designed to 1 to 10 krad(Si)

Juno mission to Jupiter was designed to survive 50 krad(Si)

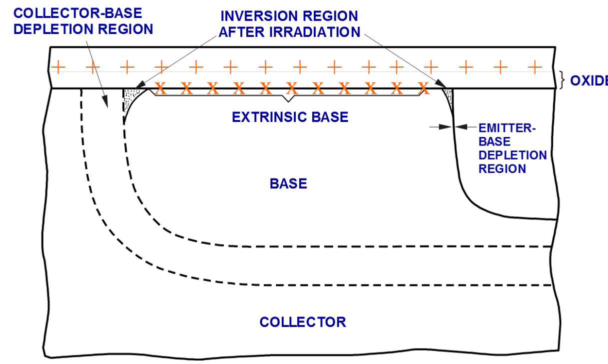
Planned Europa Clipper Mission would have to endure 300 krad(Si)



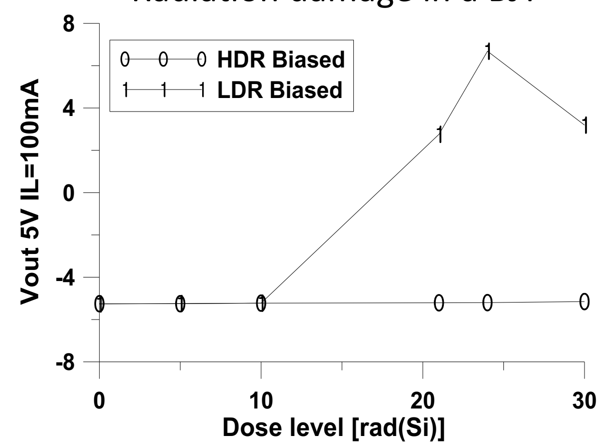
# Radiation Effects On Spacecraft Systems

# Radiation Effects on Electronic Devices – The Aggregate Total Dose

- Ionized charges become trapped in insulators
  - Can be positive or negative
- Displaced atoms will affect parameters
- Trapped charges or displaced atoms will alter parameters and may result in device failure
- Solar cells may degrade
  - Photovoltaic cell output voltage may drop
- Circuits with degrading devices may fail
  - Parametric shift may be too large for circuit to operate properly



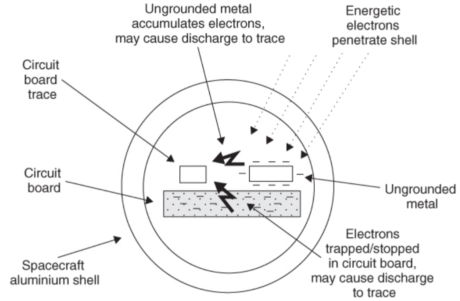

Radiation damage in a BJT



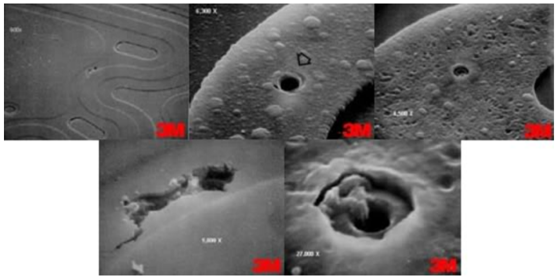

Dose failure of voltage regulator

# Spacecraft Charging Effects on Circuits and Materials

- Surface charging in and out of the spacecraft
- Internal charging is charging within devices and other components
- Plastic Degradation
  - Wire insulators
  - Teflons and plastics can powderize or become sticky
  - PCB boards may degrade
- Glass Darkening
  - Lenses for cameras
- Effects on adhesives

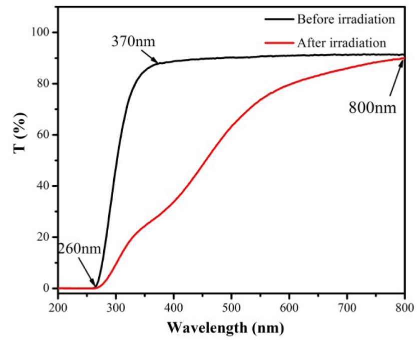



Charging mechanisms for a circuit board



Damage result from statics discharge

Glass darkened by radiation

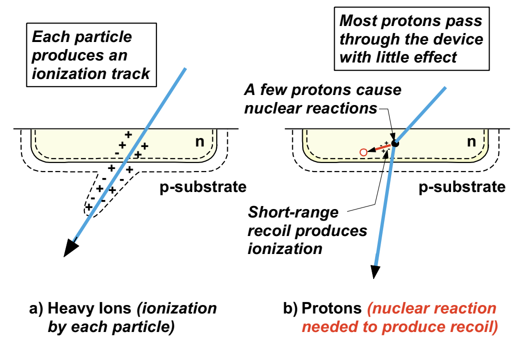



Xiaodong Chen, et al, "Gamma radiation induced darkening in barium gallo-germanate glass," Opt. Express **24,** 9149-9156 (2016);

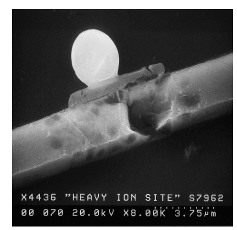
Darkening depend on radiation and the material

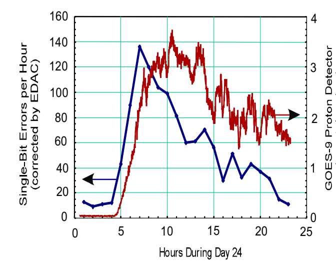
# The Single Event Effect

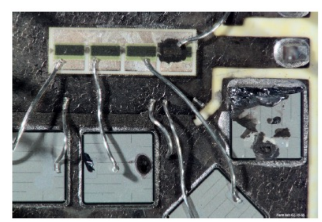
- A single-event effect (SEE) is caused by a single heavy ion, proton or neutron
- Ionized charge in a device creates a pulse of current that can affect the device
- High current events may result in internal device shorts, hot spots, and/or trace melting.
- Total device destruction is a common observable
- Bit errors in memories is a routine design challenge for error correction codes




Ions deposition energy in a electric field is the root of an SEE



# Mitigation Engineering and Testing

# Mitigating Radiation Effects Starts with Thorough Engineering

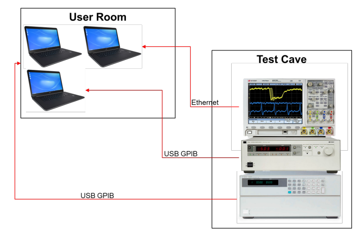
- Proper environmental modeling
  - GIRE, CREME96, AE9, AP9
- Proper transport analysis
  - NOVICE, SRIM, CREME96
- Parts and materials list assurance
  - Review of EEE parts and material
  - Device Testing
- Circuit reliability Considerations
  - WCA, SEEA, Stress Analysis
- Systems reliability Considerations

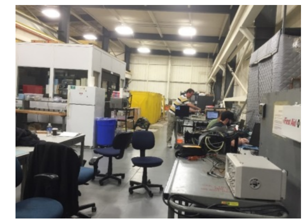
{

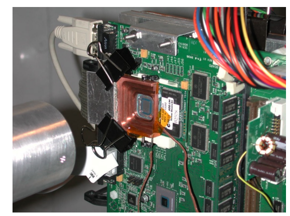
- Radiation Testing
  - Single-event effects
  - Total ionizing dose
  - Displacement damage dose
  - Internal charging
  - Surface charging
  - Materials
  - EMC
  - Solar cell

# Single Event Effects Testing

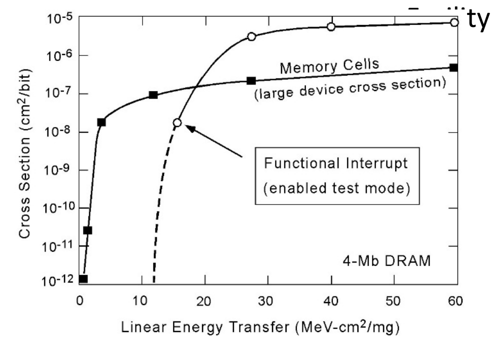
- High-end testers or custom test setup must be transported to the test site
- Tests are often more complex on new, advanced devices with dozens of SEE modes
- Setup may range from a power supply to several computers and other complex devices to count events as particles travel through test article.
- Cyclotrons have high electromagnetic background and are not-cleanrooms





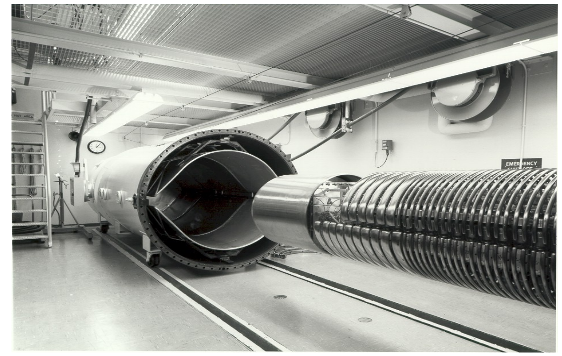
Texas A&M Cyclotron



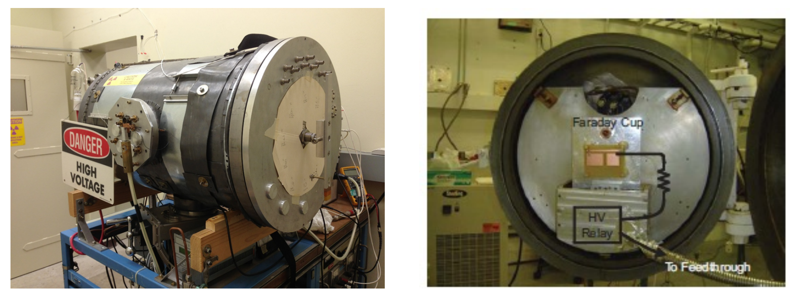

Device sensitivity vary with ion, SEE mode and technology

# JPL Irradiation Test Facilities – Electron Sources

- Dynamitron
  - Energy of 0.5 – 3 MeV electrons
  - Flux of $10^8 – 10^{12}$ e/cm$^2$/s
  - Temperature control under vacuum from -180 °C to +150 °C
  - Vacuum to $10^{-6}$ Torr
- Low energy electron gun
  - 10 keV to 100 keV electrons
  - Current densities from 100 pA/cm$^2$ to 50 nA/cm$^2$



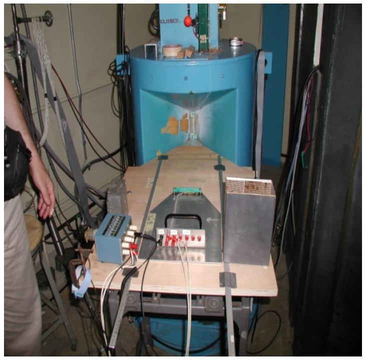
Dynamitron Test Facility




Charging Test Setup and Chambers

# JPL Irradiation Test Facilities – Gamma Irradiators

- HDR irradiator is a JL Shepherd Model-81260 whole room irradiator.
  - 15 ft by 22 ft facility
  - Supports dose rates from 50 rad(Si)/s to 100 mrad(Si)/s
- LDR irradiator is a JL Shepherd Model-8124 whole room irradiator.
  - 20 ft by 20 ft facility
  - Supports dose rates from 100 mrad(Si)/s to 0.001 mrad(Si)/s



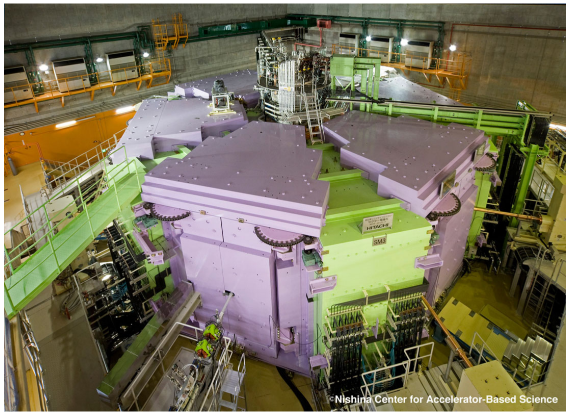
A Typical Gamma Cell Irradiator


Testing Device Requires Special Test Circuit

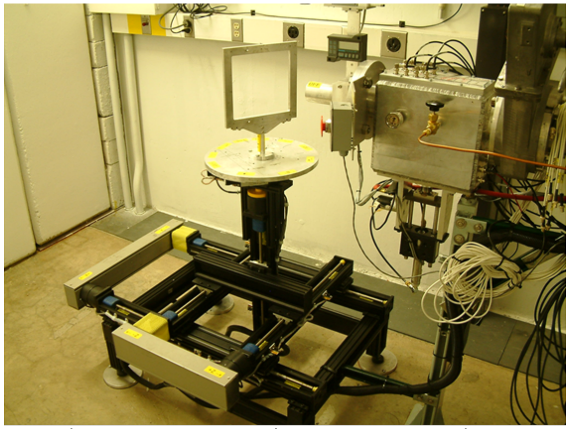
Precise Measurements for Dose Testing Require Dedicated ATEs

# Offsite Facilities – Heavy Ion

- **Texas A&M University Radiation Effects Facility**
  - Average use of 200 hrs per year
  - Up to 40 MeV/u
- **Lawrence Berkeley National Laboratory Berkeley Accelerator Space Effects**
  - Average use of 150 hrs per year
  - Up to 16 MeV/u
- **Brookhaven National Laboratory – Tandem van de Graff**
  - Average use of 60 hrs per year
  - Up to 10 MeV/u
- **European Space RADiation Effect Facility (RADEF) located at Jyväskylä, Finland**
  - Average use of 24 hrs per year
  - Up 16 MeV/u
- **NASA Space Radiation Laboratory at BNL**
  - Average use of 24 hrs per year
  - Up to 1GeV/u

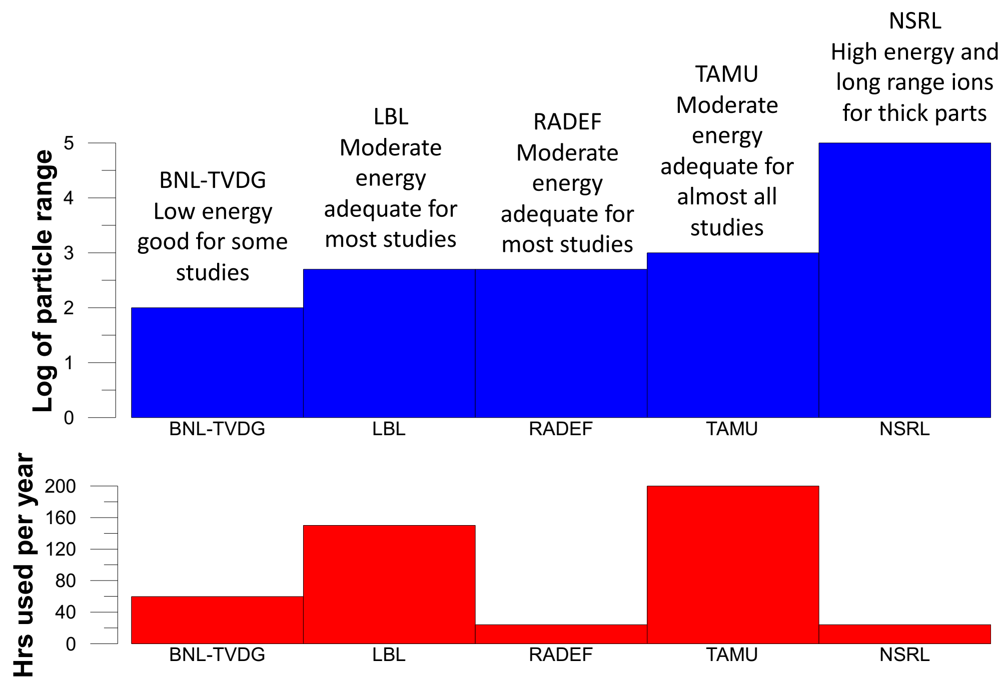


Cyclotron at TAMU


The Target Room at the Texas A&M Cyclotron

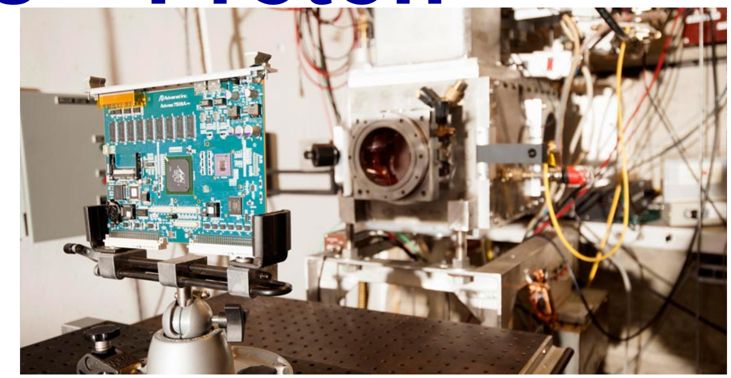
# Offsite Facilities – Heavy Ion

- Five cyclotron facilities address North America's and Europe's heavy ion needs
- Choice of facility is dependent on the desired energy range and characteristics of the test article
- Test Demand is going up due to increase in commercial space efforts

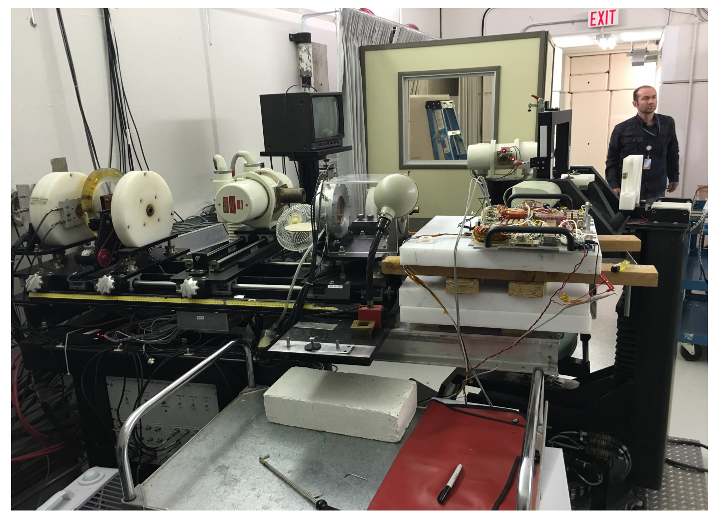


# Offsite Facilities – Proton

- University of California - Davis' Crocker Nuclear Lab (CNL)
  - Protons up to 65 MeV
  - Adequate for most device testing with protons
- Tri-University Meson Facility (TRIUMF) - Canada
  - One cyclotron provides a proton beam with energy up to 100 MeV and the other provides energies up to 500 MeV
- Texas A&M University Radiation Effects Facility
  - 50 MeV protons
- Lawrence Berkeley National Laboratory Berkeley Accelerator Space Effects
  - 60 MeV protons



The target room at UC-Davis

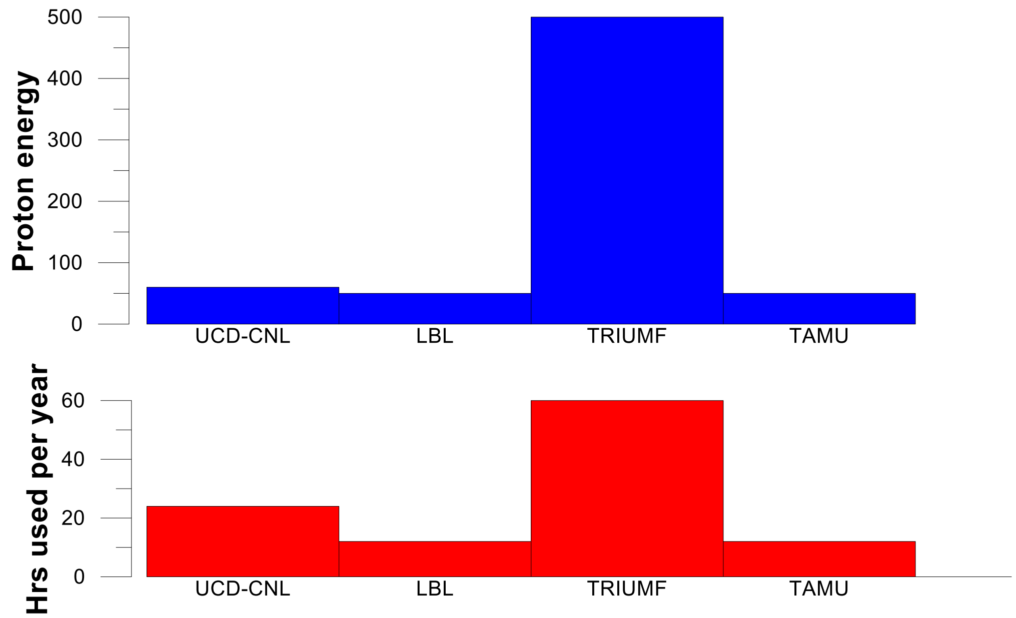



The target room at TRIUMF

# Offsite Facilities – Proton

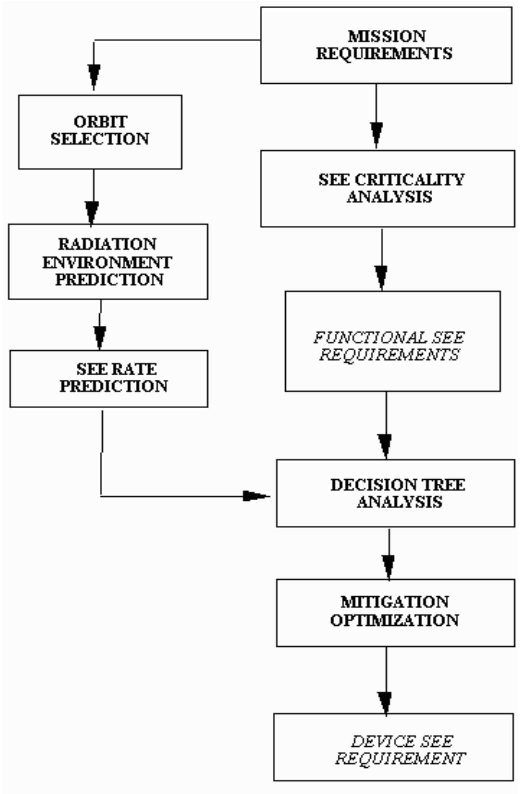
- Most protons facilities are used for cancer treatment
- Space assurance demand is increasing with an interest in expanding medical proton facilities for space assurance
- We currently utilize the TRIUMF and UC-Davies facilities for majority of proton testing needs.
- Can utilize local medical facilities but use condition and access do not facilitate frequent use.

TRIUMF (Canada) has high energy protons and can cover all space effects of interest. Other sites are adequate for most testing.



# Data Analysis

- Radiation data informs device and system analysis
  - Worst case circuit analysis (WCCA) circuit performance with test device data
  - Single-event effect analysis (SEEA) uses SEE data to analyze a circuits response
  - Systems analysis determines any residual effect at the spacecraft/system level



# Summary and Recommendations

- Design of systems intended for operation in a radiation environment must factor device, circuit, and materials degradation effects.
- Radiation testing requires substantial effort in planning, implementation, and analysis.
- JPL utilizes internal and external radiation sources and facilities to address space mission needs.
- Access to the Lawrence Berkeley National Laboratory facility may be at risk due to lack adequate stable customer base; establishing a stable service facility is critical for future space radiation testing needs.
- Currently JPL has not experienced issues with access to proton test facilities. However, the increased demand from the commercial space industry may affect future access.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov