WHY NASA AND THE SPACE ELECTRONICS COMMUNITY CARES ABOUT CYCLOTRONS

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Acronyms

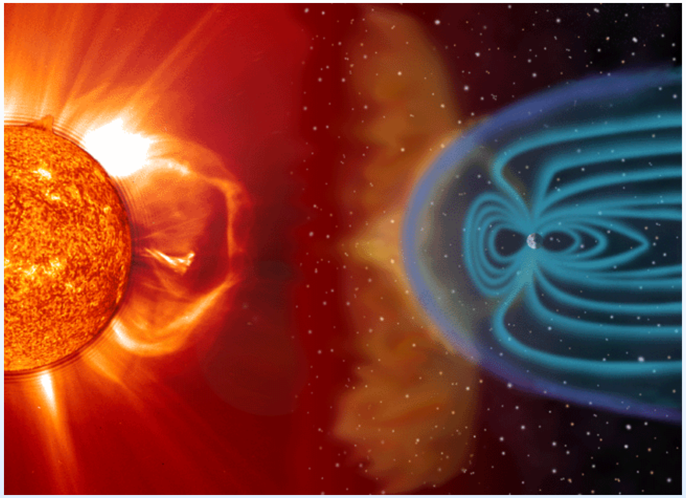
- Three Dimensional (3D)
- Also know As (AkA)
- Advanced Photon Source (APS)
- Brookhaven National Laboratory (BNL)
- Californium (Cf)
- Coronal Mass Ejection (CME)
- Crocker Nuclear Lab (CNL)
- Displacement damage dose (DDD)
- Department of Defense (DoD)
- Department of Energy (DOE)
- Device Under Test (DUT)
- Galactic Cosmic Rays (GCRs)
- Integrated Circuits (ICs)
- Johnson Space Center (JSC)
- Lawrence Berkeley National Laboratories (LBL)
- linear energy transfer (LET)
- linear accelerator (LINAC)
- Military Standard (MIL-STD)
- National Aeronautics and Space Administration (NASA)
- n-type charge coupled device (n-CCD)
- NASA Electronic Parts and Packaging (NEPP) Program
- National Reconnaissance Office (NRO)
- NASA Space Radiation Lab (NSRL)
- Office of Safety and Mission Assurance (OSMA)
- rectangular parallel-piped (RPP)
- South Atlantic Anomaly (SAA)
- Single Event Effects (SEE)
- Soft Error Rate (SER)
- Single Event Upset Test Facility (SEUTF)
- Sandia National Laboratories (SNL)
- Space Telescope Science Institute (STScI)
- size, weight, and power (SWaP)
- Texas A&M University (TAMU)
- Thermal Batteries (TBs)
- Total ionizing dose (TID)
- Tandem Van de Graaff (TVdG)
- Van de Graaff (VdG)

Abstract and Outline

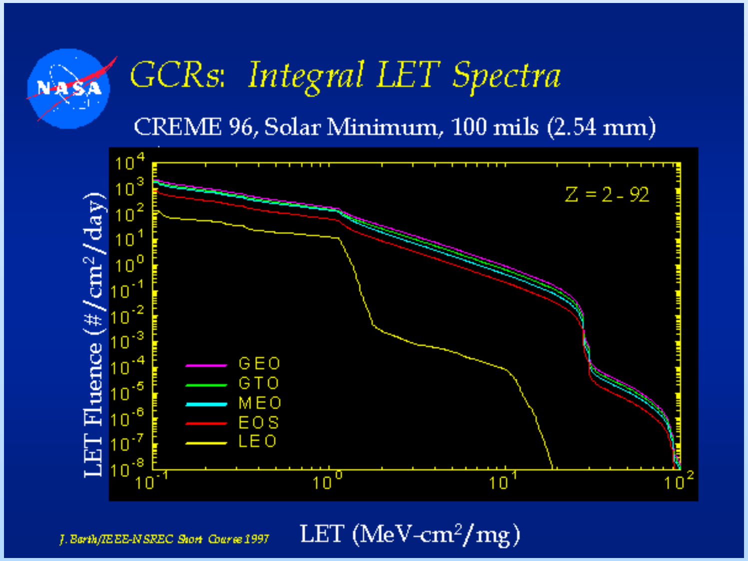
- NASA and the space community are faced with the harsh reality of operating electronic systems in the space radiation environment. Systems need to work reliably (as expected for as long as expected) and be available during critical operations such as docking or firing a thruster.
- This talk will provide a snapshot of the import of ground-based research on the radiation performance of electronics. Discussion topics include:
  - The space radiation environment hazard,
  - Radiation effects on electronics,
  - Simulation of effects with cyclotrons (and other sources),
  - The space/electronics user base,
  - Risk prediction for space missions, and,
  - Real-life examples of both ground-based testing and space-based anomalies and electronics performance.
  - The talk will conclude with a discussion of the current state of radiation facilities in North America for ground-based electronics testing.

The Space Radiation 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)
- Hazard experienced is a function of orbit and timeframe

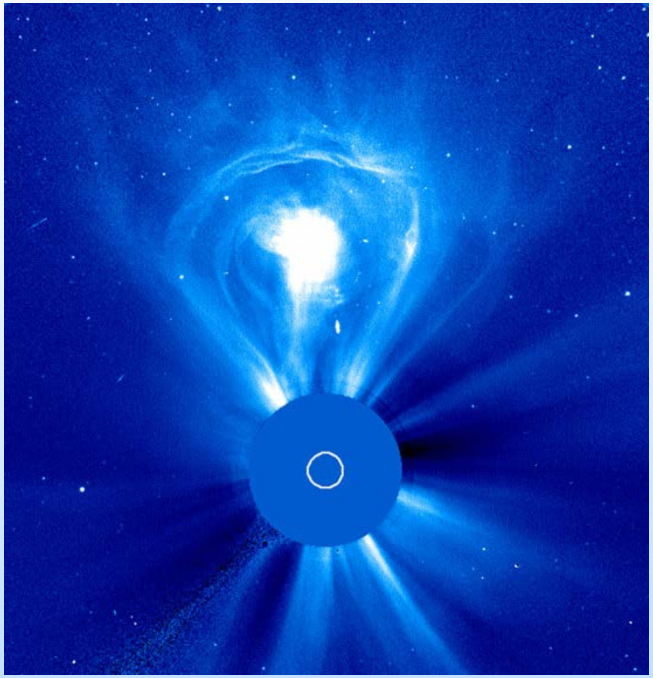


The sun acts as a modulator and source in the space environment, *after K. Endo, Nikkei Sciences*



Solar Cycle Effects: Modulator and Source

- Solar Maximum
  - Trapped Proton Levels Lower, Electrons Higher
  - GCR Levels *Lower*
  - Neutron Levels in the Atmosphere Are Lower
  - Solar Events More Frequent & Greater Intensity
  - Magnetic Storms More Frequent --> Can Increase Particle Levels in Belts
- Solar Minimum
  - Trapped Protons Higher, Electrons Lower
  - GCR Levels *Higher*
  - Neutron Levels in the Atmosphere Are Higher
  - Solar Events Are Rare



Light bulb shaped Coronal Mass Ejection (CME) courtesy of SOHO/LASCO C3 Instrument

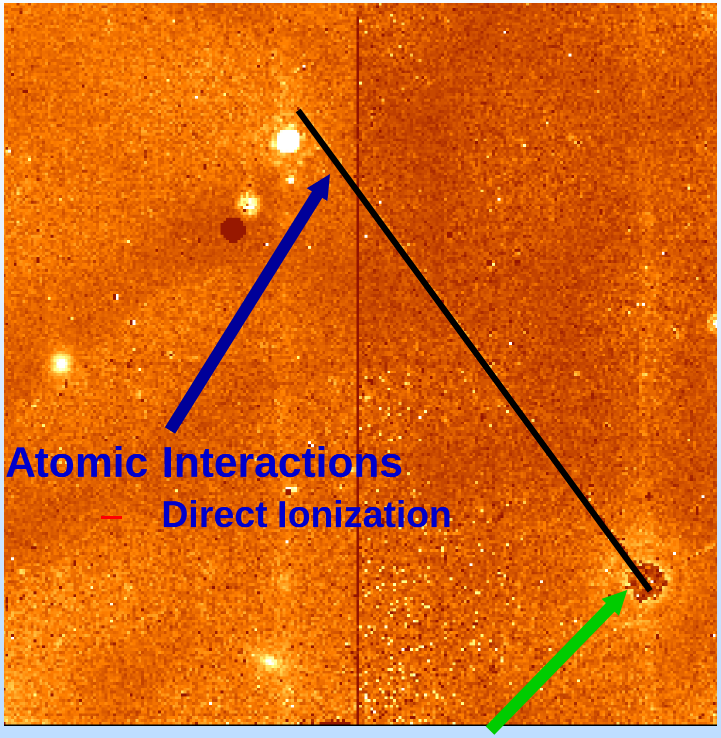
Radiation Effects and Space Electronics

- **Particle accelerators/sources are used to evaluate risk and qualify electronics for usage in the space radiation environment**
  - **Long-term cumulative degradation (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**
  - ***Protons* simulate solar events and trapped protons in planetary magnetic fields**
    - **SEE, TID, and DDD**

Particle interactions with semiconductors

Image from the Space Telescope Science Institute (STScI), operated for NASA by the Association of Universities for Research in Astronomy

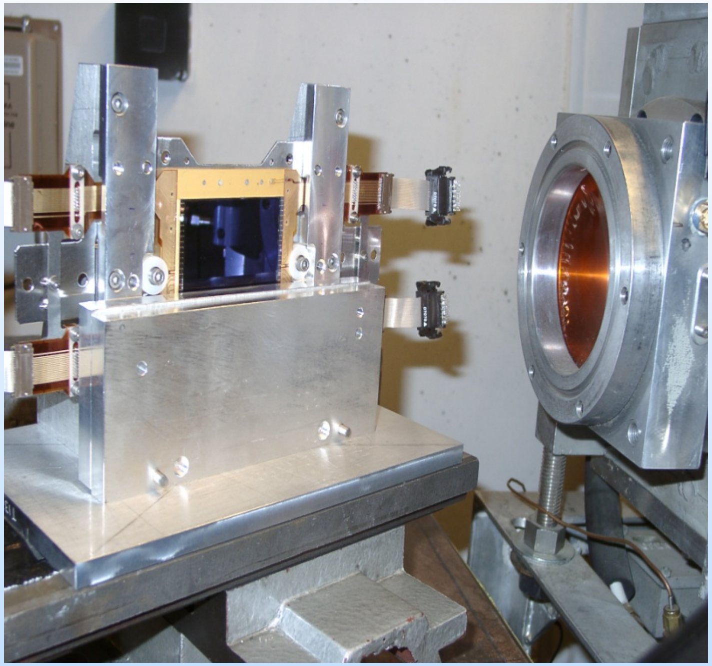
http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html



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

Ground Test Simulation for Space Radiation Effects Testing

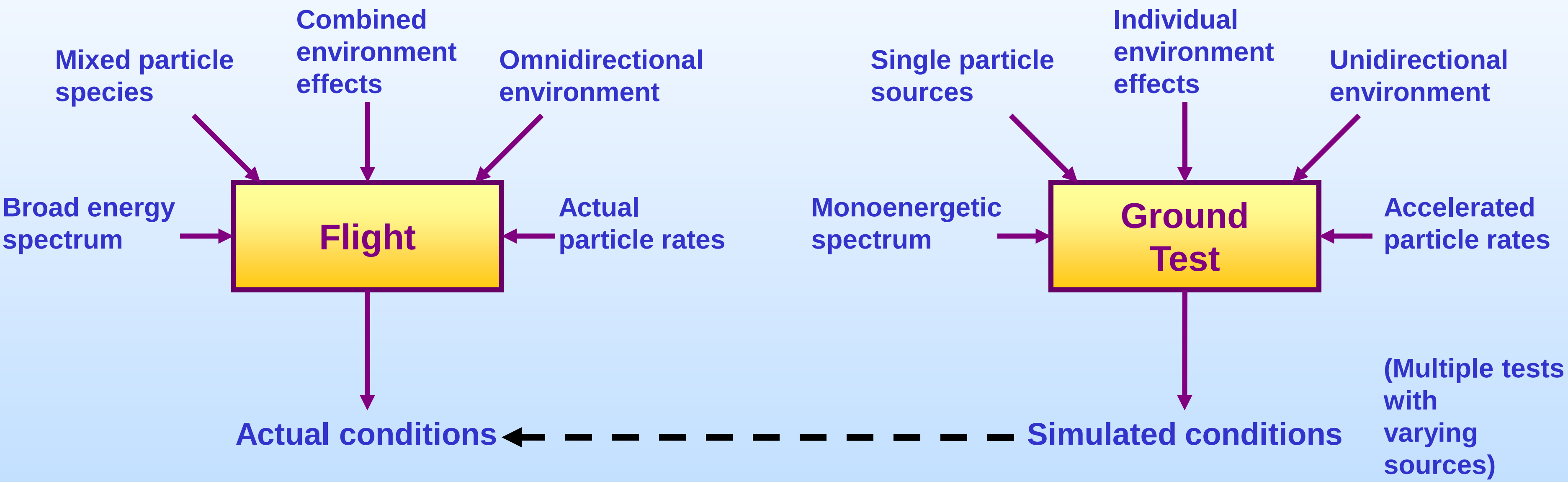
- **Issue: TID**
  - Co-60 (gamma), X-rays, *Proton*
- **Issue: DDD**
  - Proton, neutron, electron (solar cells)
  - Cyclotron, linear accelerator (LINAC), Van de Graaff (VdG) accelerator
- **SEE (GCR)**
  - Heavy ions
  - Cyclotrons, synchrotrons, VDGs
    - Lesser utility: Cf sources
- **SEE (Protons)**
  - Protons (E>30 MeV) – primarily nuclear interactions
  - 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

Radiation Test Issue - Fidelity



How accurate is the ground test in predicting Space Performance?

After Stassinopoulos, NASA

Space Electronics Users

NASA, other Government, Industry, University – International base

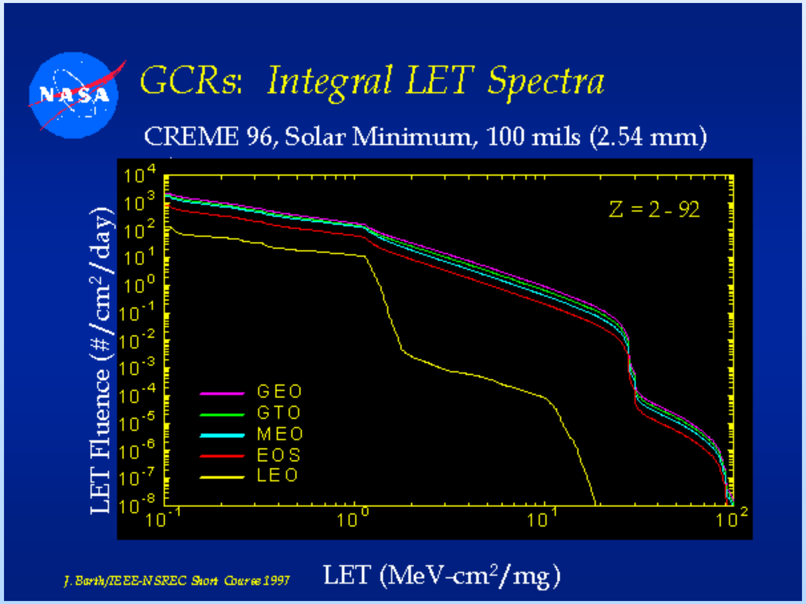
- Space Electronic Systems – Flight Projects, Manufacturers
  - Perform qualification tests on integrated circuits (ICs)
  - Perform system validation/risk tests on assembled hardware (boards/boxes)
- Semiconductor Research
  - Perform exploratory technology sensitivity tests on new devices/technology 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
  - Avionics, automotive, medical electronics, etc… may test for safety critical and high reliability validation
  - Commercial terrestrial companies may use protons for soft error rate (SER) testing in lieu of neutrons
- Other Space Users
  - Human Radiation Protection (biological sciences)
  - Material/shielding Studies (physical sciences)

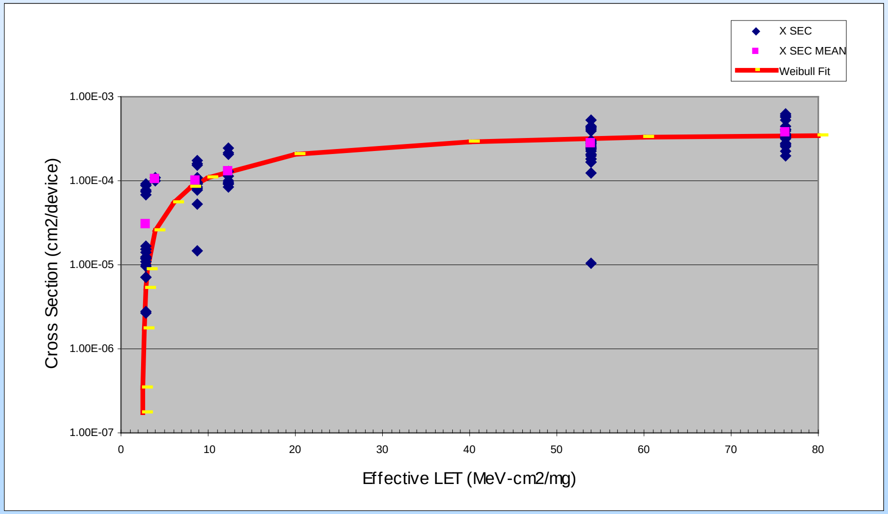
Space and Other Researchers – *Growing Needs*

- Space Users
  - Increased use of commercial electronics for higher performing and smaller size, weight, and power (SWaP) systems. Examples:
    - Advent of Small Space, aka, CubeSats – interest in risk reduction tests
    - Commercial Space – companies like SpaceX and OneWeb use protons for electronic assurance
- 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)
- Automotive
  - Exponential growth industry for automotive electronics (driver assist, self-driving, etc…) – *Safety Critical* aspects

SEE Risks for Space Missions

- **Several items are needed to determine actual risks caused by SEEs**
  - **Prediction of the environment (based on mission orbit, time of launch, and mission lifetime)**
  - **Heavy ion test data and/or proton test data (depending on orbit, etc…)**





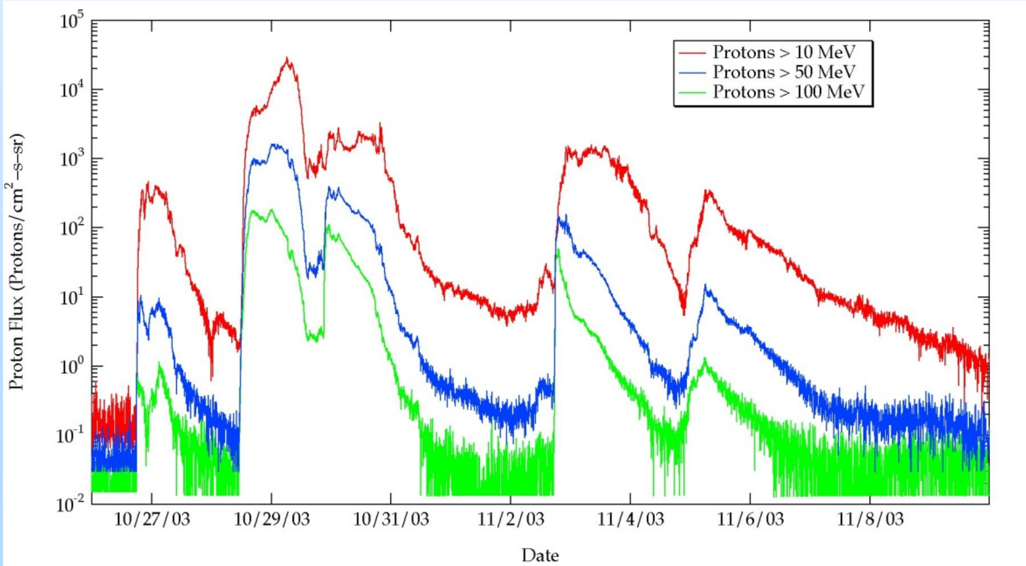
Sample Heavy Ion Test Results

SEE Risk - Prediction

- **While the reality has many complications, the simple view is that we:**
  - **Either convolve environment with test data, or**
  - **Use volumetric sensitivity models (i.e., a given volume of silicon representing the sensitive “node” – a rectangular parallel-piped (RPP) is the norm).**
- **Tools exist to enable the risk calculations as rates:**
  - ***https://creme.isde.vanderbilt.edu/* is an example of commonly used toolsuite.**
  - **Rates are in events (upsets or other) over a time period such as day or year.**
- **New methods are under development that provide true reliability type numbers such as 99.94% probability of success during some time window.**

Solar Events – When Space Radiation Attacks

- In Oct-Nov of 2003, a series of X-class (BIG X-45!) solar events took place
  - High particle fluxes were noted
  - Many spacecraft performed safing maneuvers
  - Many systems experienced higher than normal (but correctable) data error rates
  - Several spacecraft had anomalies causing spacecraft safing
  - Increased noise seen in many instruments
  - Drag and heating issues noted
  - Instrument FAILURES occurred
  - Two known spacecraft FAILURES occurred
- Power grid systems affected, communication systems affected…



Science Spacecraft Anomalies During Halloween 2003 Solar Events

Type of Event	Spacecraft/ Instrument	Notes
Spontaneous Processor Resets	RHESSI	3 events; all recoverable
	CLUSTER	Seen on some of 4 spacecraft; recoverable
	ChipSAT	S/C tumbled and required ground command to correct
High Bit Error Rates	GOES 9,10	
Magnetic Torquers Disabled	GOES 9, 10, 12	
Star Tracker Errors	MER	Excessive event counts
	MAP	Star Tracker Reset occurred
Read Errors	Stardust	Entered safe mode; recovered
Failure?	Midori-2	
Memory Errors	GENESIS	19 errors on 10/29
	Many	Increase in correctable error rates on solid-state recorders noted in many spacecraft

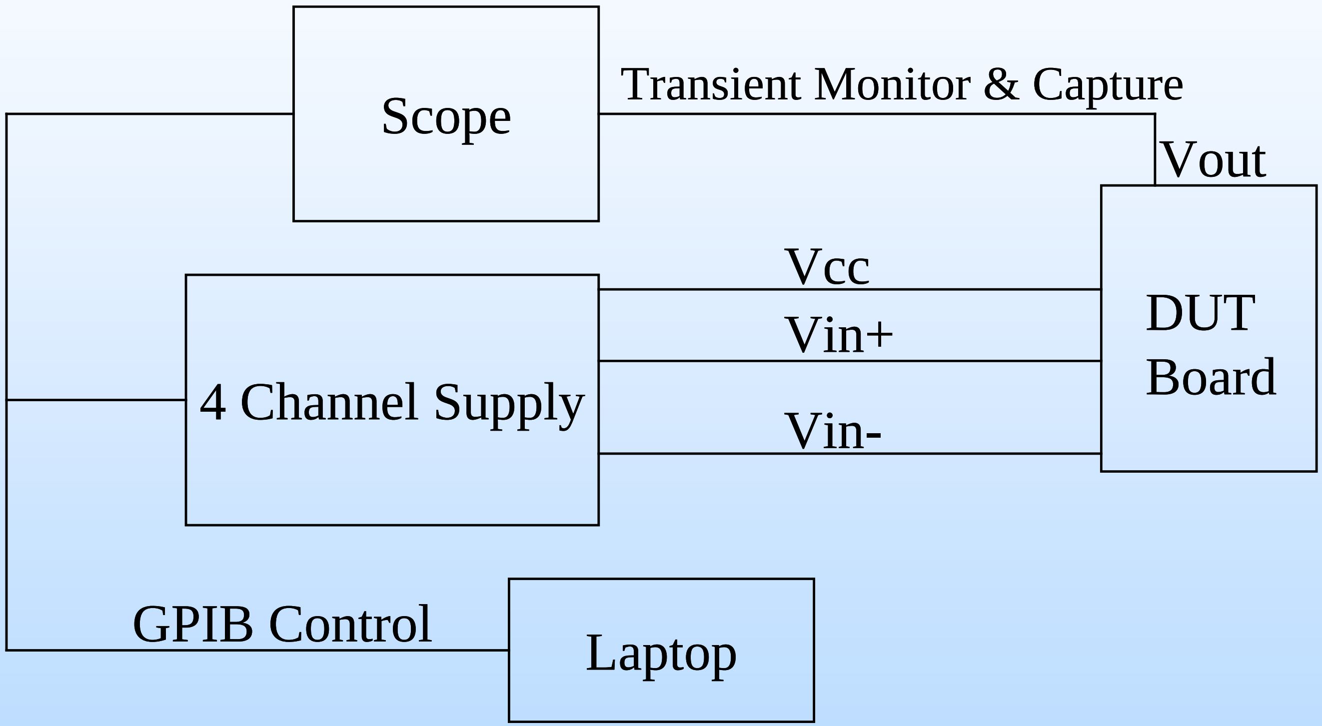
Science Instrument Anomalies During Halloween 2003 Solar Events

Type of Event	Spacecraft/ Instrument	Notes
Instrument Failure	GOES-8 XRS	
	Mars Odyssey/Marie	S/C also had a safehold event – memory errors
	NOAA-17/AMSU-A1	Lost scanner
Excessive Count Rates	ACE, WIND	Plasma observations lost
	GALEX UV Detectors	Excess charge – turned off high voltages; Also Upset noted in instrument
	ACE	Solar Proton Detector saturated
Upset	Integral	Entered Safe mode
	POLAR/TIDE	Instrument reset spontaneously
Hot Pixels	SIRTF/IRAC	Increase in hot pixels on IR arrays; Proton heating also noted
Safe Mode	Many	Many instruments were placed in Safe mode prior to or during the solar events for protection

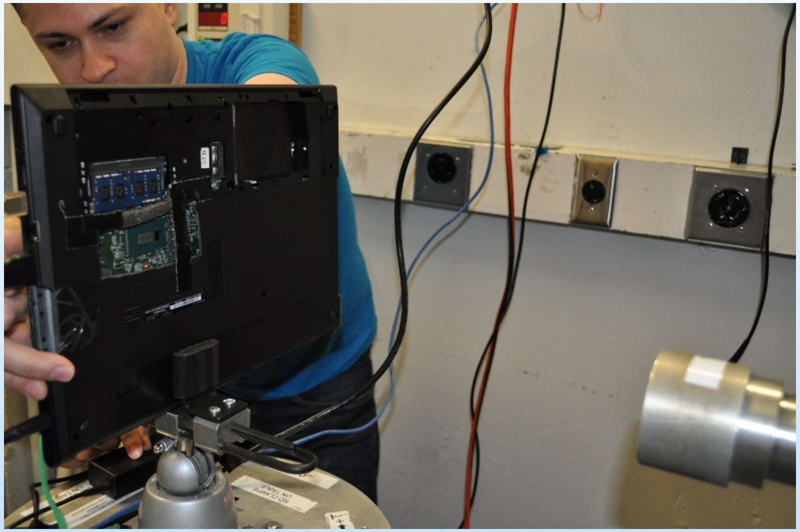
Sample Considerations for Electronics Testing at Cyclotrons

- **Particle**
  - Dosimetry/particle detectors
  - Uniformity
  - Energy mapping to the space environment
  - Particle localization
  - Stray particles (proton testing - neutrons, for example)
  - 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)

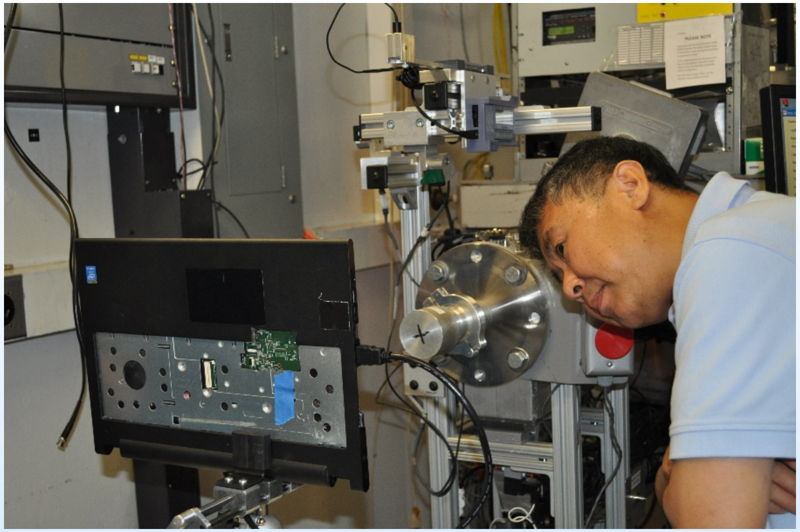
Sample Test Configuration Simple Device



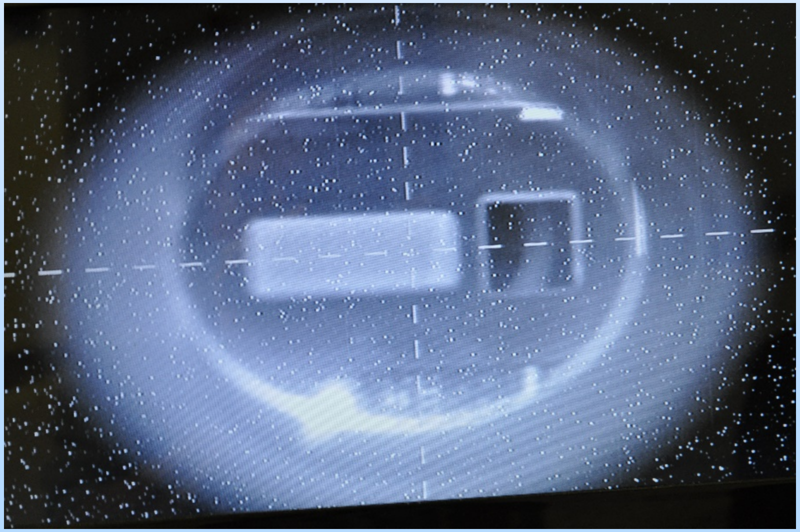
Pretty Pictures from Testing (1)



Mounting an INTEL processor for heavy ion testing

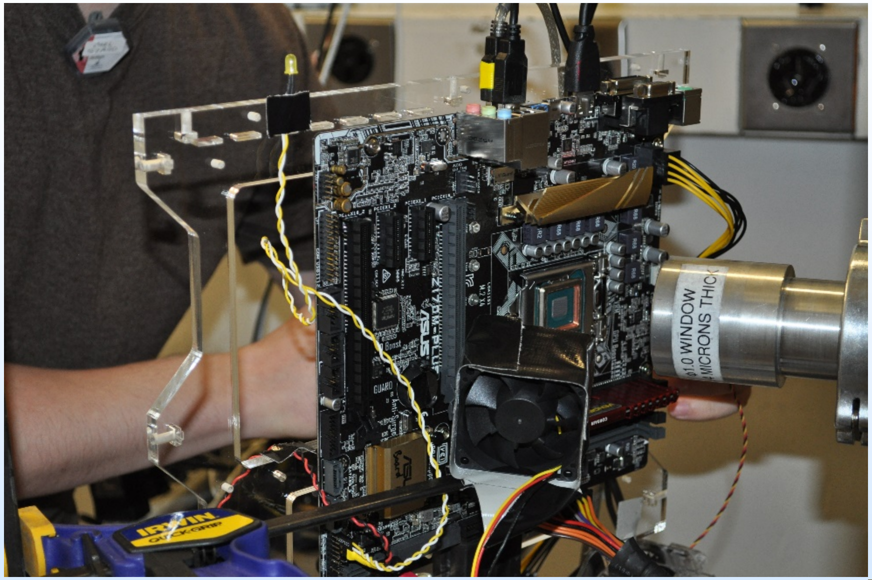


Aligning the DUT to the beam line



All photos are courtesy of Kenneth LaBel, NASA/GSFC

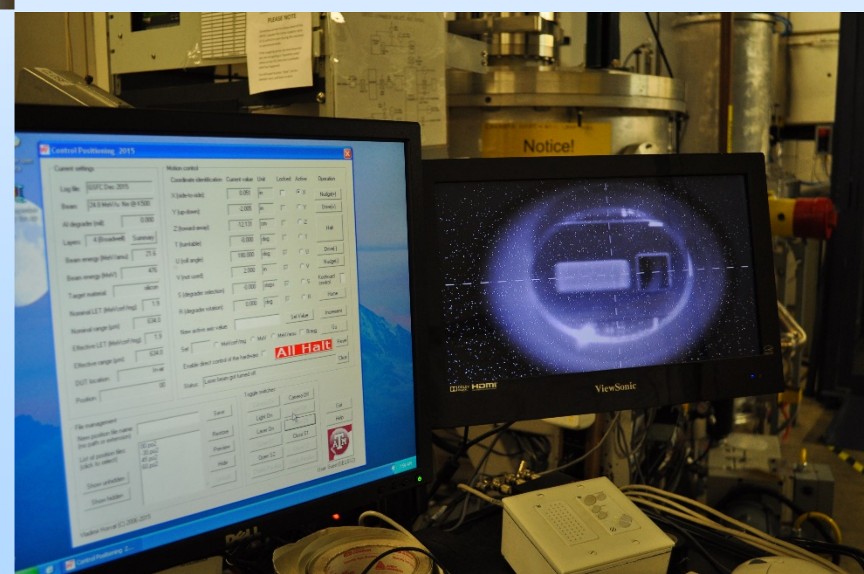
Pretty Pictures from Testing (2)



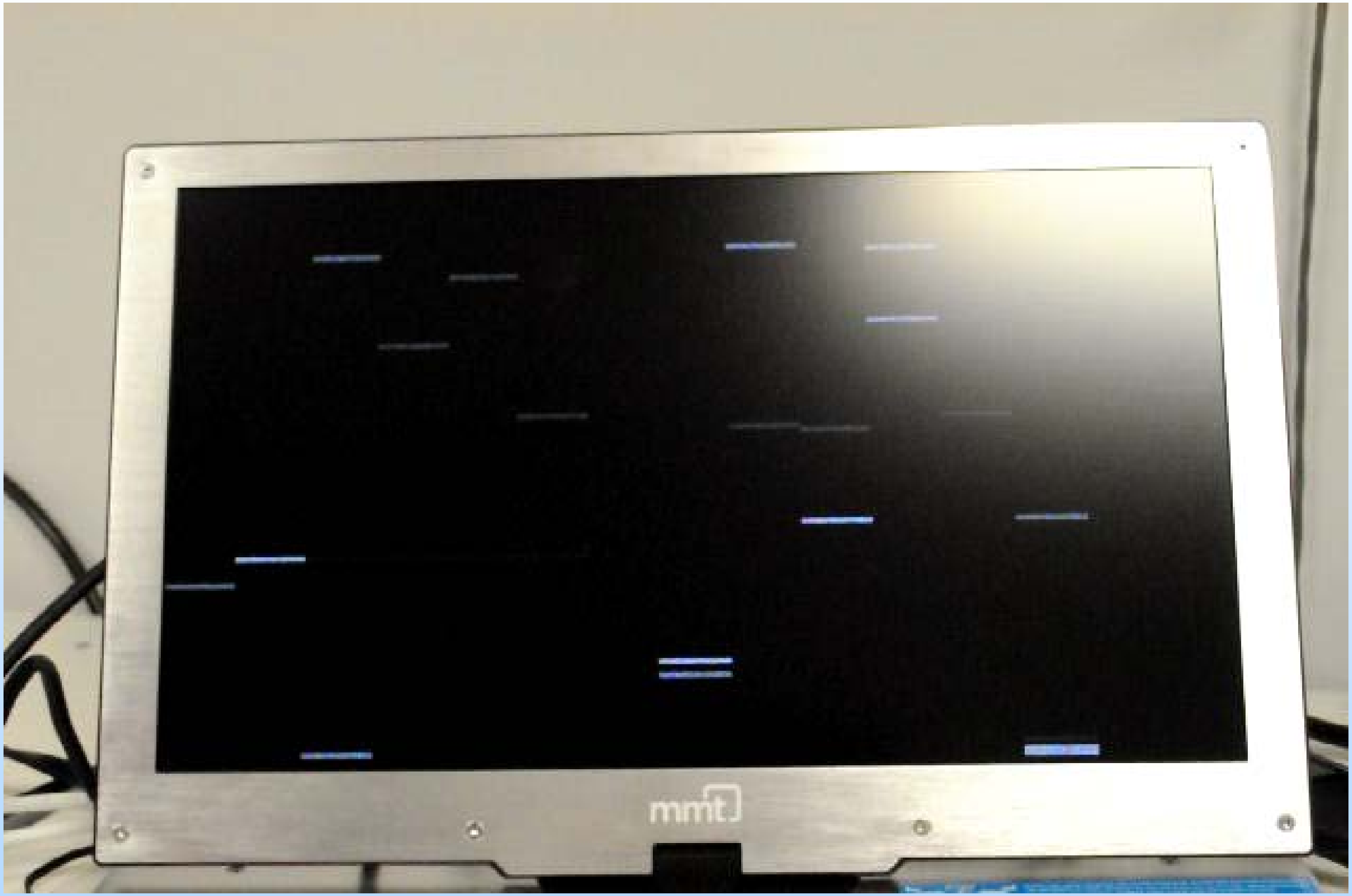
A deprocessed device getting ready for the beam,

Cables are run to user area where we monitor/control experiments.

TAMU beam control to set operations and DUT positioning

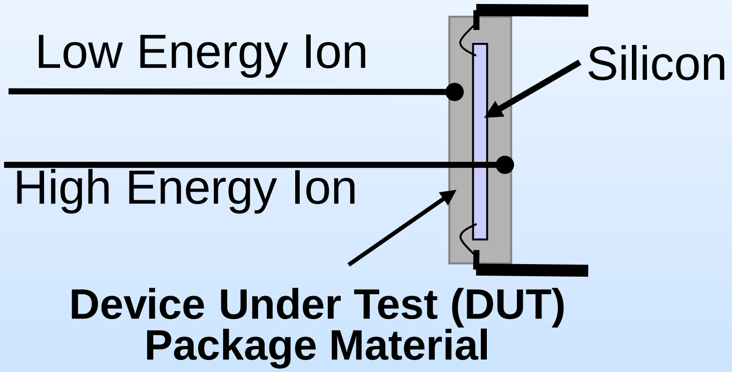


When a Graphics Processor Gets an Event



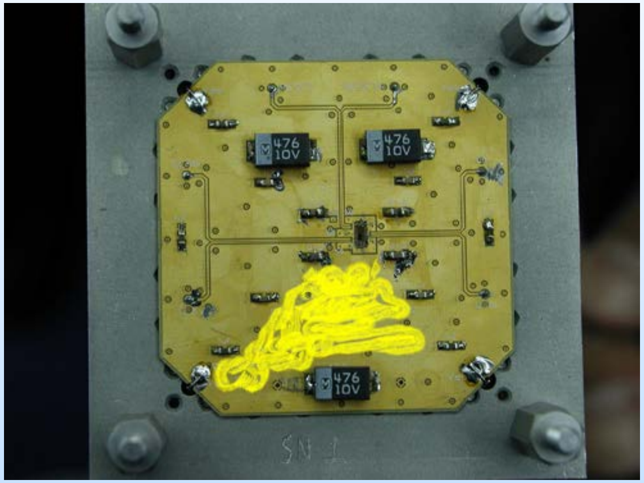
Heavy Ion Test Sources

- SEE heavy ion ground tests use a *macrobeam* source
  - We know how many particles per cm^2, but not where the individual particles hit
  - Different sources have different energies and test constraints
    - Particle (ion) availability
    - Energy
    - Penetration range, etc…
  - Metric: linear energy transfer (LET)
  - Primary NASA usage for electronic parts qualification and for technology evaluation (research)
    - Texas A&M University (TAMU) Cyclotron, and,
    - Lawrence Berkeley Laboratories (LBL) Cyclotron
  - Secondary facilities
    - NASA Space Radiation Laboratory (NSRL), Single Event Upset Test Facility (SEUTF) at Brookhaven National Laboratories (BNL)
    - National Superconducting Cyclotron Laboratory (NSCL



TAMU Cyclotron Facility

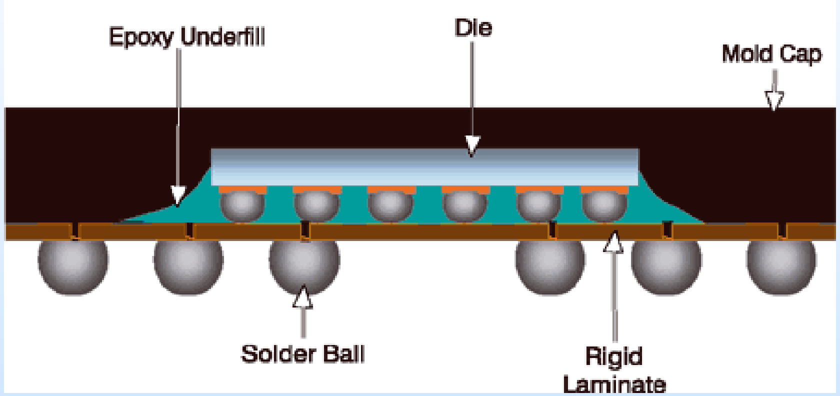
- Type of Source: Cyclotron (K500, K150)
- Energies: Moderate-High
  - Penetration okay for most devices; challenge for advanced packaged (i.e., 3D stacked)
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: Good, but…
  - Competes with science experiments
  - Scheduled in 3 month windows with occasional last minute access (cancellation)
  - HIGHLY SUBSCRIBED (~3500 hours/year)
- Good for:
  - Most devices
  - Used often for qualification tests
- Comments
  - Cost ~$800-1200/hr w Industry/NASA as prime users (international user base)
  - K150 coming on line with moderate energy availability (near future) – protons to 50 MeV available now



Even in air, high-speed high-power technologies need custom fixturing to deal with thermal issues.
Photo by Paul Marshall, consultant to NASA

LBL

- Type of Source: Cyclotron (88")
- Energies: Moderate
  - Penetration okay with some penetration range limits (material overlayers, 3D)
- Test constraint: Vacuum (w/limited air)
  - Provides thermal, power, cabling constraints
- Accessibility: Limited
  - Scheduled with an on-line calendar
- Good for:
  - Standard device packages, test structures
  - Used often for qualification tests
- Comments
  - Cost ~$2400/hr w/ DoD, Industry, University, and NASA as prime users
  - Quick ion changes
  - Also has protons to ~55 MeV



Modern IC packaging such as the flip-chip ball-grid array shown above, make direct die access impossible.
Thinning of silicon or device repackaging are options, but have many risks.

NSRL

- **Type of Source: Synchrotron**
- **Energies: Very High**
  - **Excellent penetration range (but varies with actual ion species)**
- **Test constraint: Air**
  - **Decreases thermal, power, cabling constraints**
- **Accessibility: Fair**
  - **Electronics testing can be scheduled as a secondary user during the 3 windows of yearly access up to a few hundred total hours**
  - **Limited access: best to schedule >6 months in advance**
- **Good for:**
  - **Electronics assemblies and all packaged devices (plus extreme angular tests)**
- **Not good for:**
  - **Some dynamic operations (beam structure limit – pulsed synchrotron, not continuous beam cyclotron)**
- **Comments**
  - **Expensive! Cost > $5000/hr with NASA-Johnson Space Center (JSC) and NRO as prime users**
  - **Improved availability of multiple ion species during single day testing**

BNL SEUTF

- Type of Source: TVdG
- Energies: Low
  - Penetration limited
- Test constraint: Vacuum
  - Provides thermal, power, cabling constraints
- Accessibility: Very Good
  - Often available on short notice
- Good for:
  - Lower linear energy transfer (LET) work or test structures
- Not good for:
  - Power devices, any complex integrated circuit (IC)
- Comments
  - Good user interface
  - Cost > $1500/hr

Brookhaven National Laboratories' Single Event Upset Test Facility (SEUTF),

Photo by Ken LaBel, NASA

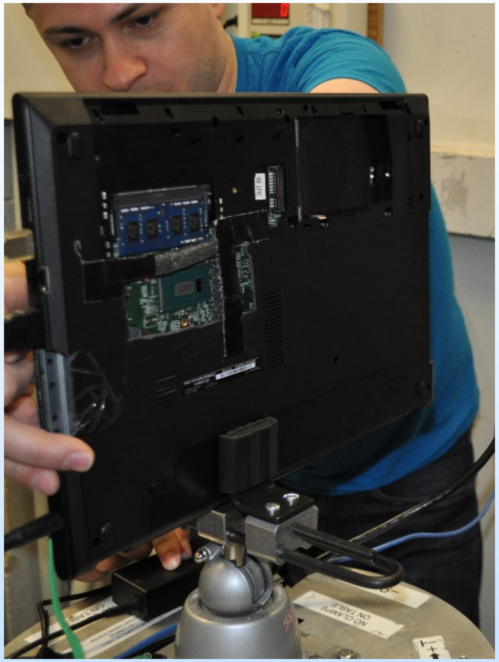
Limited usability for many electronics

Sample International (Europe) Heavy Ion SEE Test Facilities

SEE Test Facility	Owner	Location	Notes
(limit 50 characters)	Government Entity, Company, University	City, State/Country	
Grand Accélérateur National d'Ions Lourds (GANIL)	France / Government	Caen, France	High-energy heavy ions; from carbon (a few keV/amu to 95 MeV/amu) to uranium (a few keV/amu to 24 MeV/amu)
GSI Darmstadt Microprobe	Germany / Government	Darmstadt, Germany	High-energy heavy ion microbeam; Protons to uranium ions at typically 5 MeV/amu; specific energy LETs from 13 keV/um to 27000 keV/µm in silicon
RADEF / University of Jyväskylä (JYFL)	University of Jyväskylä, Finland / University	Jyväskylä, Finland	Proton & heavy ion cyclotron (K130); Protons: 0 to 60 MeV; High energy cocktail 9.3 MeV/amu: 15N, 20Ne, 30Si, 40Ar, 56Fe, 82Kr, 131Xe. Low energy Cocktail 3.6 MeV/amu: 12C, 30Si, 54Fe, 84Kr, 132Xe. Other ions/energies
Centre de Ressources du Cyclotron Université Catholique De Louvain (UCL)	UCL / University	Louvain la Neuve, Belgium	Protons (62 MeV primary beam on DUT, down to 14 MeV using plastic degraders), neutrons (broad spectra mean E at 23 MeV, energy filter for n lower than 1 MeV, max E 50 MeV; quasi-monoenergetic beams between 20 and 65 MeV), heavy ions (low-energy cocktail 3.7 MeV/amu; high-energy cocktail 9.3 MeV/amu), and pulsed laser (1064 nm, 50 ps single shot up to 1 MHz).

Heavy Ion Sources - Microbeam

- Microbeams are used to deterministically inject a single ion (or simulated ion) to a single transistor
  - Think of it as a single particle sent at a target
    - We know where the particle has gone
    - Only one US facility
  - LASER simulation is also an option
    - Has its own challenges



Preparing an INTEL processor for test at TAMU.
When we see an error at a macrobeam source, how do we identify what the cause was within the device?
Photo by Ken LaBel, NASA

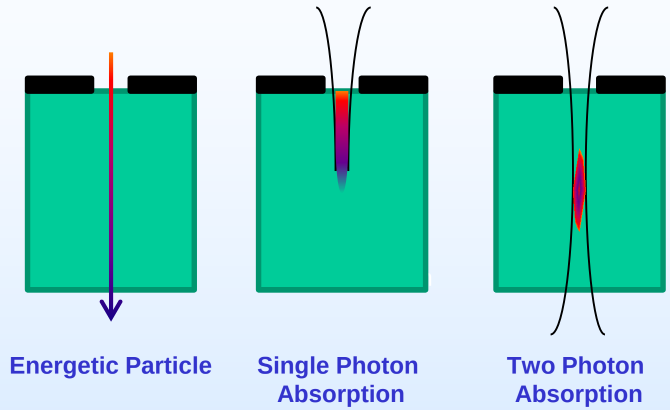
Used in collaboration with standard heavy ion tests and does not replace

Heavy Ion Microbeam Facility – Sandia National Labs

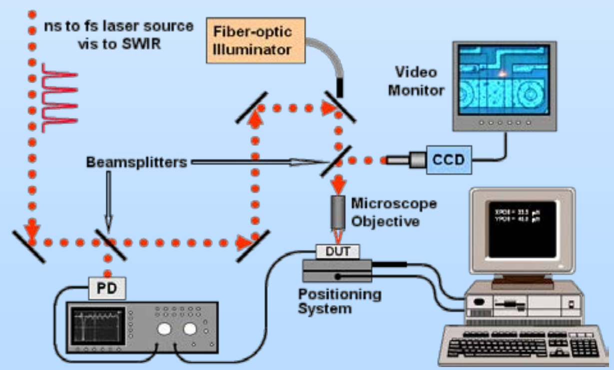
- Type of Source: TBs
- Energies: Very Low
  - Can penetrate almost NOTHING
- Test constraint: Vacuum w/small area
  - Increases thermal, power, cabling constraints
- Accessibility: Fair
  - Contract w/DOE/SNL required
  - Normally ~3 months
- Good for:
  - Test structures that are sensitive at low LETs only
- Not good for:
  - Anything complex
  - Any need above single digit LETs
- Comments
  - Fairly high. ~ $TBs/hr

LASER-Induced Simulations of SEE

- Type of Source: LASER
- Energies: Not applicable, but various wavelengths can be available
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: Good
  - Naval Research Labs (NRL), Vanderbilt University, and The Aerospace Corporation have most widely used U.S. facilities
  - JPL also has options
  - Normally <1 month
- Good for:
  - Simple devices with die access and few metal layers or through two-photon backside tests
  - Precision localization of sensitive nodes
- Not good for:
  - Some modern higher performance devices
  - Space event rate prediction
- Comments
  - Does not replace standard heavy ion testing



Excitation modes
Courtesy The Aerospace Corporation

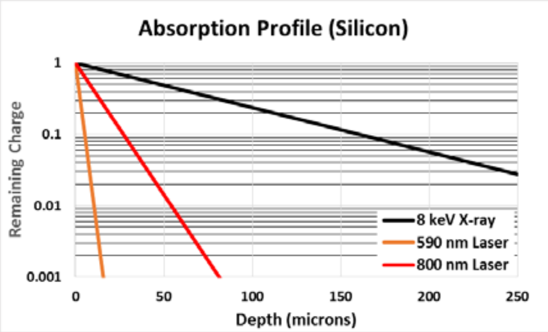


Experimental laser test set-up
Courtesy The Aerospace Corporation

Synchrotron Pulsed X-ray Test Facility - Advanced Photon Source (APS)

- Type of Source: Synchrotron w focusable pulsed X-rays
- Energies: Nominally 8-12 keV; other photon energies (4.3 – 27 keV) available upon request
- Test constraint: Air
  - Decreases thermal, power, cabling constraints
- Accessibility: 3-6 Weeks/year
  - Test dates are in March, July and November
  - Access via open proposal process or mediated by Aerospace Corporation
- Good for:
  - Simple to medium complexity devices regardless of metal coverage
  - Precision localization of sensitive nodes (2 μm spot)
  - Focused TID testing
- Not good for:
  - Basic exploration of very large devices
  - Space event rate prediction
- Comments
  - Smaller spot sizes (300nm – 1 μm) available via planned upgrades

The Advanced Photon Source is an Office of Science User Facility operated for the U.S. DOE Office of Science by Argonne National Laboratory.
https://www1.aps.anl.gov/



Short pulsed x-rays generate charge tracks similar to those produced by energetic particles.
Courtesy, The Aerospace Corporation

Summary

- In this talk, we've presented a brief overview of whys and whats related to NASA's interest in using TAMU Cyclotrons for SEE testing.
  - We see this interest increasing due to many factors related to both technology and applications (even more terrestrial!)
- This talk was far from complete, however, we hope you gained an appreciation of why the "space folks" care so much about access.

Questions?