Johns Hopkins Applied Physics Laboratory

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The role of radiation testing in modern space flight missions

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Acronyms

Artificial Intelligence (AI)
Complementary Metal Oxide Semiconductor (CMOS)
Creating Helpful Incentives to Produce Semiconductors (CHIPS)
Displacement Damage Dose (DDD)
Electronic Design Automation (EDA)
Electromagnetic Interference (EMI)
Electrostatic Discharges (ESD)
Enhanced Low Dose Rate Sensitivity (ELDRS)
Gate All Around (GAA)
Galactic Cosmic Ray (GCR)
Heavy Ion (HI)
Integrated Circuit (IC)
Internet Of Things (IOT)

Linear Energy Transfer (LET)
Microelectronics (ME)
National Institute of Standards and Technology (NIST)
Natural Space Environment (NSE)
National Advanced Packaging Manufacturing Program (NAPMP)
National Semiconductor Technology Center (NSTC)
Radiation Design Margin (RDM)
Radiation Hardness Assurance (RHA)
Radiation Lot Acceptance Testing (RLAT)
Single Event Effects (SEE)
Single Event Functional Interrupt (SEFI)
Solar Energetic Particles (SEP)
Solar Particle Event (SPE)

South Atlantic Anomaly (SAA)
State Of The Art (SOTA)
Strategic Radiation Hardened (SRH)
Strategic Radiation Hardened Electronics Council (SRHEC)
Test and Evaluation (T&E)
Test Resource Management Center (TRMC)
Trusted & Assured Microelectronics (T&AM)
Total Ionizing Dose (TID)
Total Non-Ionizing Dose (TNID)
United States Government (USG)
Venture Capital (VC)
Wide Bandgap (WBG)
Workforce Development (WFD)

Natural Space Environment (NSE) hazards

General categorization:

- Cumulative (dose) effects
- Single Event Effects (SEE)
- Spacecraft charging
- Other or combined effect
- Ignoring hostile threats

Displacement Damage (DD) dose in solar cells (power decrease)
- Degraded transmission in CG
- Degraded performance in detectors
- Degraded performance in lenses, opto-couplers, LEDs, fiber, …

Charging induced Electrostatic Discharges (ESD & Electromagnetic Interference (EMI)
- EM pulse (radiation emissions)
- External to / internal to spacecraft

Plasma effects on solar array
- Collection current (losses)
- Electrostatic discharges

Surface charging & spacecraft floating potential fluctuations

Deep / internal charging of dielectrics & ungrounded metal
- Discharges & EM pluses

Single Event Effects in microelectronics
- Destructive and / or non-destructive
- Event rates & fault propagation

Total Ionizing Dose (TID) & Total Non-Ionizing Dose (TNID) on microelectronics & materials
- System performance degradation against predicts (e.g. WCCA)

Combined surface dose, UV, AO & MMOD degrades materials properties
- Thermo-optical, electrical & mechanical
- Also results from EP plumes, outgassing, …

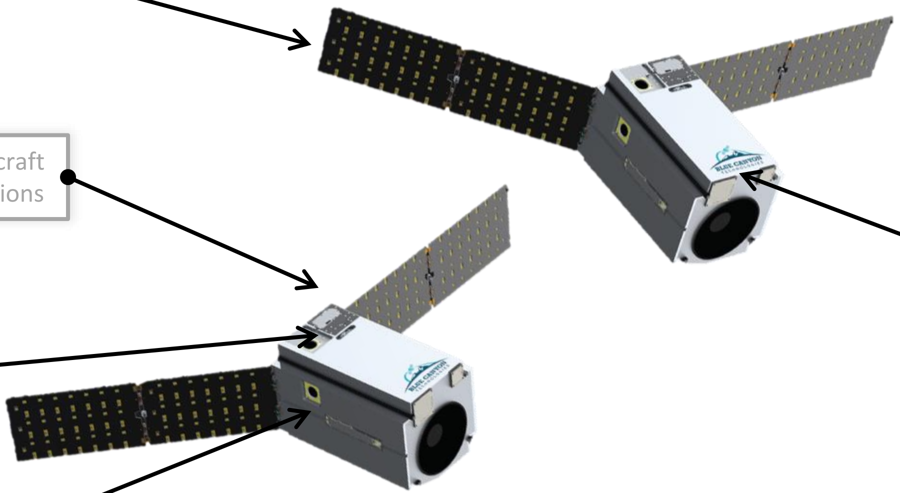


Image credit: https://www.bluecanyontech.com/

NSE overview (magnetosphere)

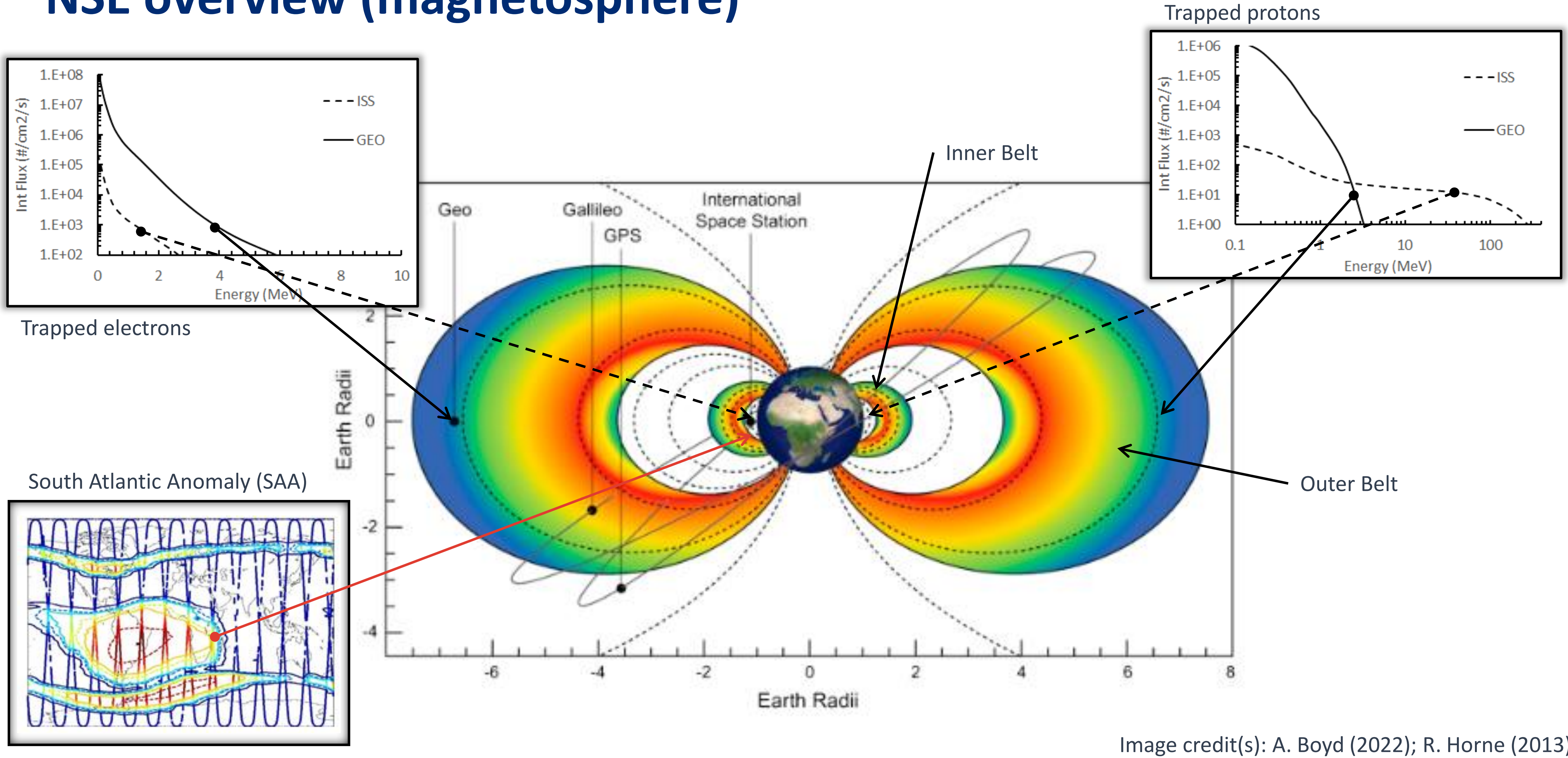
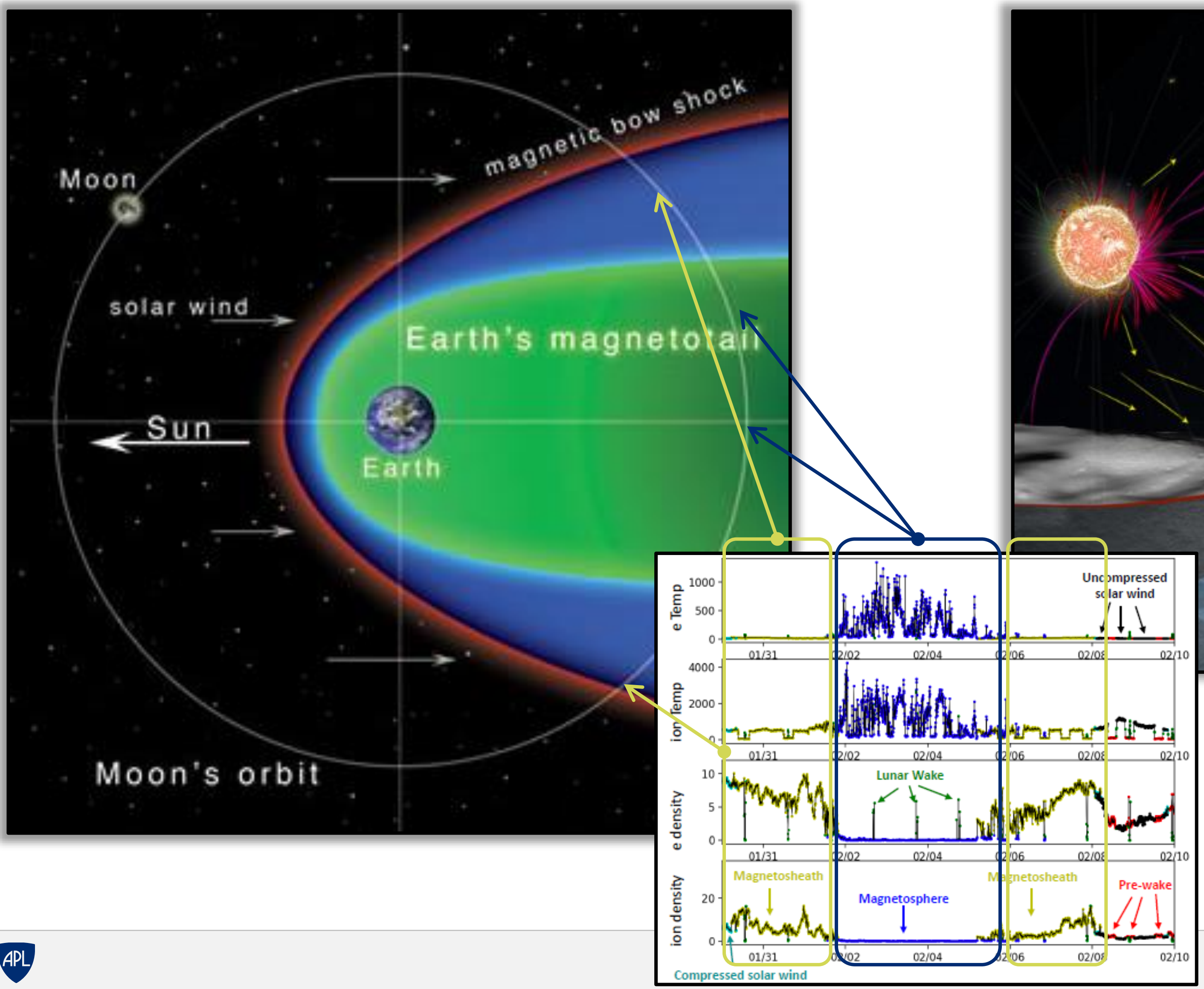


Image credit(s): A. Boyd (2022); R. Horne (2013)

NSE overview (inner heliosphere, cis-lunar and lunar surface)



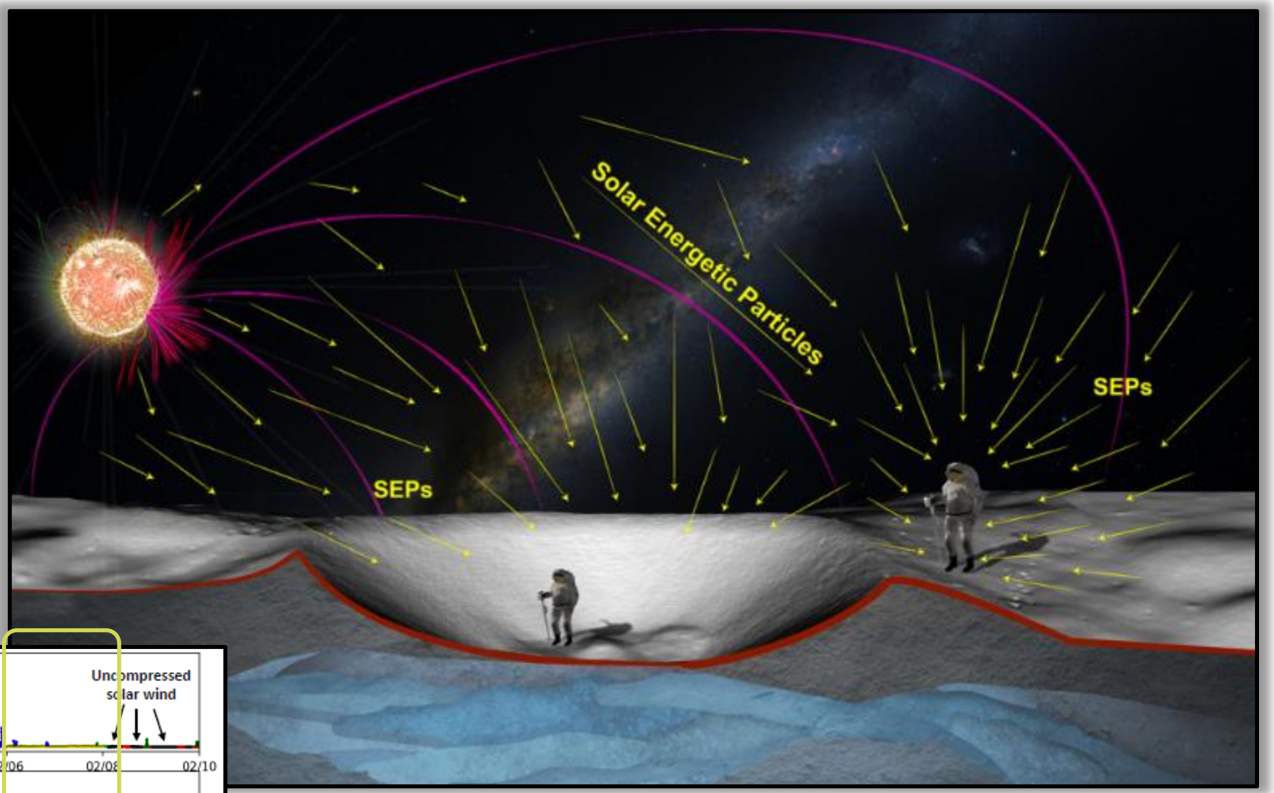


Image credit(s): USRA; L. Parker (2023)

RHA and mission classifications / sliding scale

NASA (NPR 8705.4A); also TOR-2011 (8591)				
Characteristic	Class A	Class B	Class C	Class D
Risk acceptance	Minimum practical	Low	Moderate	High(er)
Priority	Very high	High	Medium	Low
Acquisition costs	High	Med to High	Medium	Med to Low
Complexity	Very high	High	Medium	Med to Low
Mission life	Long (>5 yr)	Medium (3-5 yr)	Short (1-3 yr)	Brief (<1 yr)
Examples	Flagship missions (JWST)	Discovery missions	Explorer / MIDEX missions	SMEX missions
Part quality	Level 1	Level 2	Level 3	Per PMP
RHA levels	RDM 2x[1] – 4x[2] SEE LET_{th} <75[3]	RDM 2x[1] – 4x[2] SEE LET_{th} <75[3]	RDM 2x SEE LET_{th} <37[3]	Tailored for criticality
Radiation transport	Slant rays M-C	Tailorable	Tailorable	Tailorable
RLAT	Margin	Margin	Data evaluation	Tailored for criticality

ESA (ECSS)					
Class I	Class II	Class III	Class IV	Class V	Characteristic
Extremely high priority	High priority	Med priority	Low priority	Educational purposes	Mission objectives
Extremely high	High	Medium	Low	Educational purposes	Criticality to agency strategy
>700 M€	200-700 M€	50-200 M€	1-50 M€	<1 M€	Cost
High	High to Med	Medium	Med to Low	Low	Mission complexity
>10 yr	5-10 yr	2-5 yr	2 yr to 3 mo	<3 mo	Mission lifetime
JUICE	PROBA III, FLEX	FORUM, CHEOPS	AWS, SCOUTS		Examples
Class 1	Class 2 fully acceptable	Class 3 fully acceptable	Lower grade acceptable	N/A	Part quality
Fully applicable	Fully applicable	>1x[5]	>1[5]	N/A	RDM
Fully applicable	Fully applicable	Fully applicable	Limited; criticality based	Limited; criticality based	Radiation analysis
Fully applicable	Fully applicable	Rec. for <5 krad Req >5 krad	Rec. for <5 krad Req >5 krad	<5 krad not req >5 krad rec	TID testing (RLAT)

Notes

[1]Lot specific RLAT.
[2]Non-lot specific data.
[3]Units on LET MeV-cm2/mg.
[4]Refers to ECSS parts quality levels (Class 1 = Space; Class 2 = Mil Active; Class 3 = Mil Active & Hybrid).
[5]RDM between 1.0x and 2.0x depending on lot-to-lot traceability.

J. Likar (2023)

CHIPS Act | Introduction

- Addresses roadblocks to domestic ME production(s) –
  - Viability and marketability of new microelectronics technologies
  - Access to facilities for innovators (to explore, prototype, and demonstrate leap-ahead technological advancements)

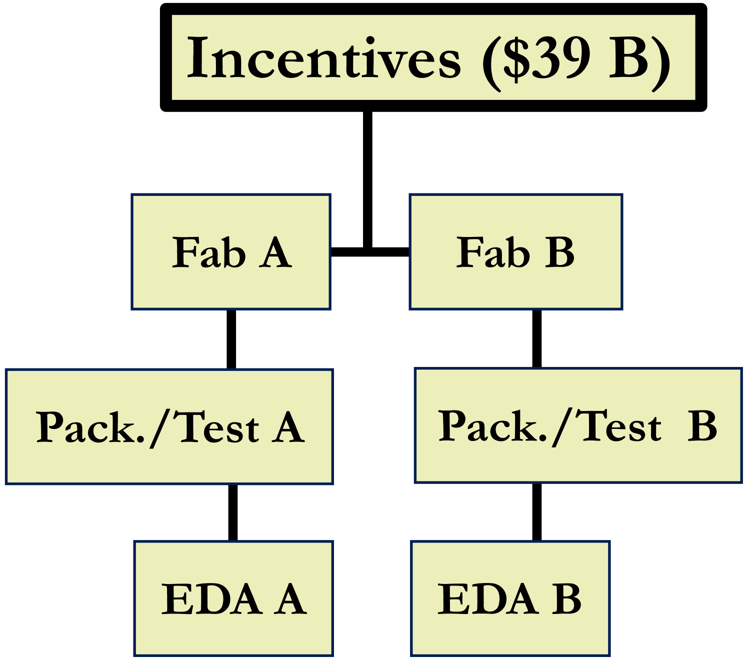
Research Universities, **Start-ups** have facilities for Lab prototyping but face barriers to Technology Demonstration.

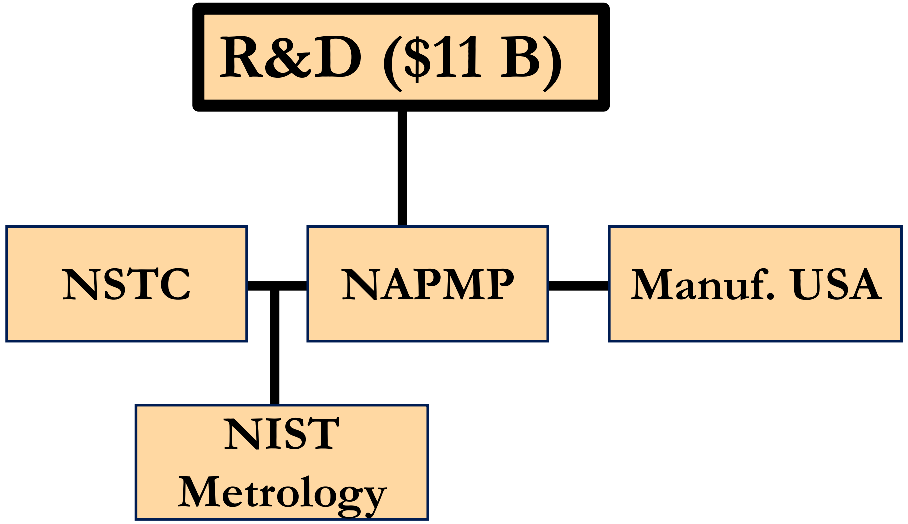
Core Facilities or Foundries/Fabs provide access to early stage Fab prototyping.

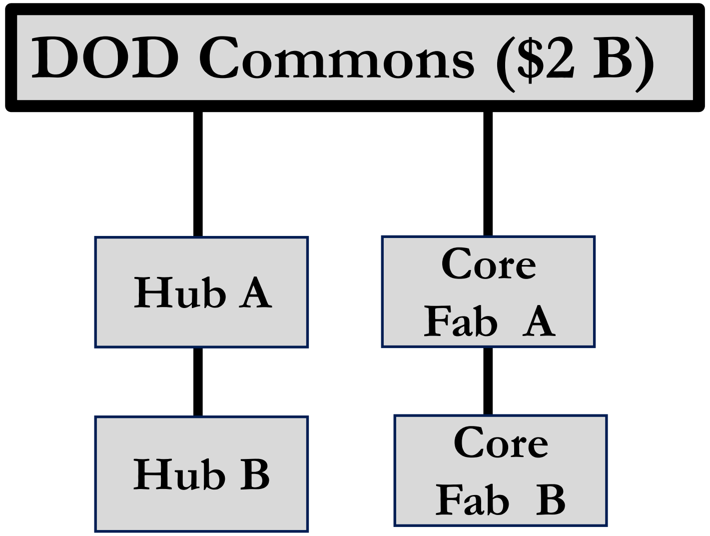
Microelectronics Commons aims to enable lab-to-fab prototyping– evolve microelectronics laboratory prototyping to fabrication prototyping – in domestic facilities

Image credit: https://www.cto.mil/wp-content/uploads/2022/11/DoD_Microelectronics_Commons.pdf

CHIPS appropriations (5 year period FY23 – FY27)







Incentives intended to develop domestic manufacturing capabilities

EDA = Electronic Design Automation. EDA providers usually license certain parts of the fundamental chip design so that they do not need to recreate it, saving time and cost.

DOC describes the NSTC as the focal point for R&D. The NSTC is to be a public-private consortium that will serve as an innovation hub to advance semiconductor technology and seed new industries built on the capabilities of a wide range of advanced chips.

National Advanced Packaging Manufacturing Program (NAPMP), led by the Director of NIST to strengthen semiconductor advanced test, assembly, and packaging capability in US.

M. Fritze (2023)

CHIPS Act | Radiation Hardening & radiation testing

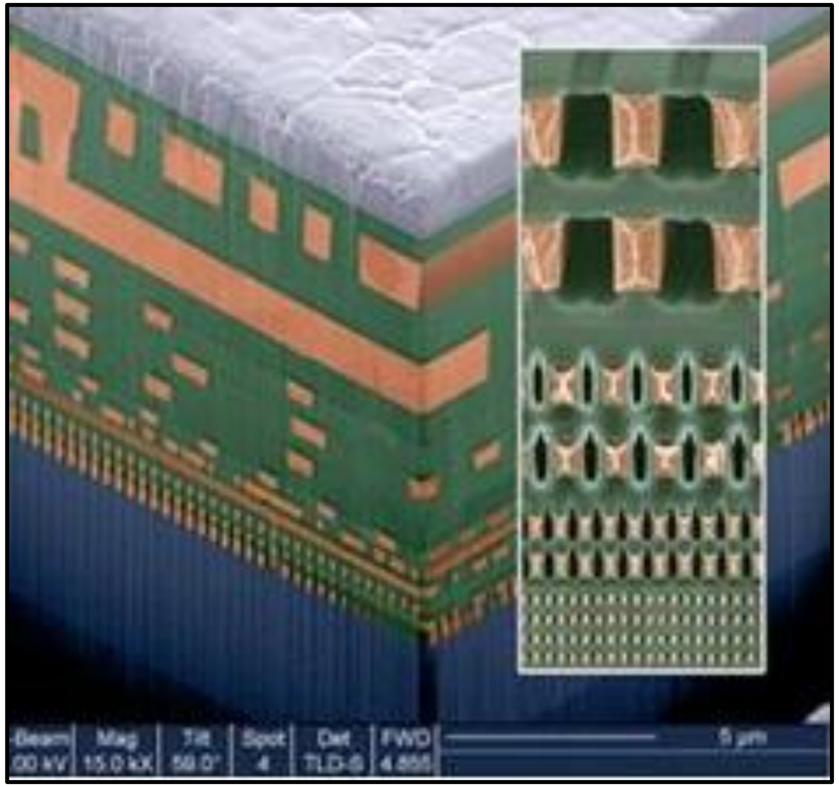
DOD Commons

- During the Industry Days kickoff each of the *technical areas* noted a need for radiation hardened microelectronics
- Radiation testing and facilities a key portion of that equation

DOC portion of CHIPS

- SOTA semiconductors are often evaluated for their radiation characteristics for aerospace and military usage
- Reliability of terrestrial and aeronautic electronics is often driven by radiation Soft Error Rate (SER)
  - Also applies to medical, automotive (self-driving vehicle reliability) and other areas

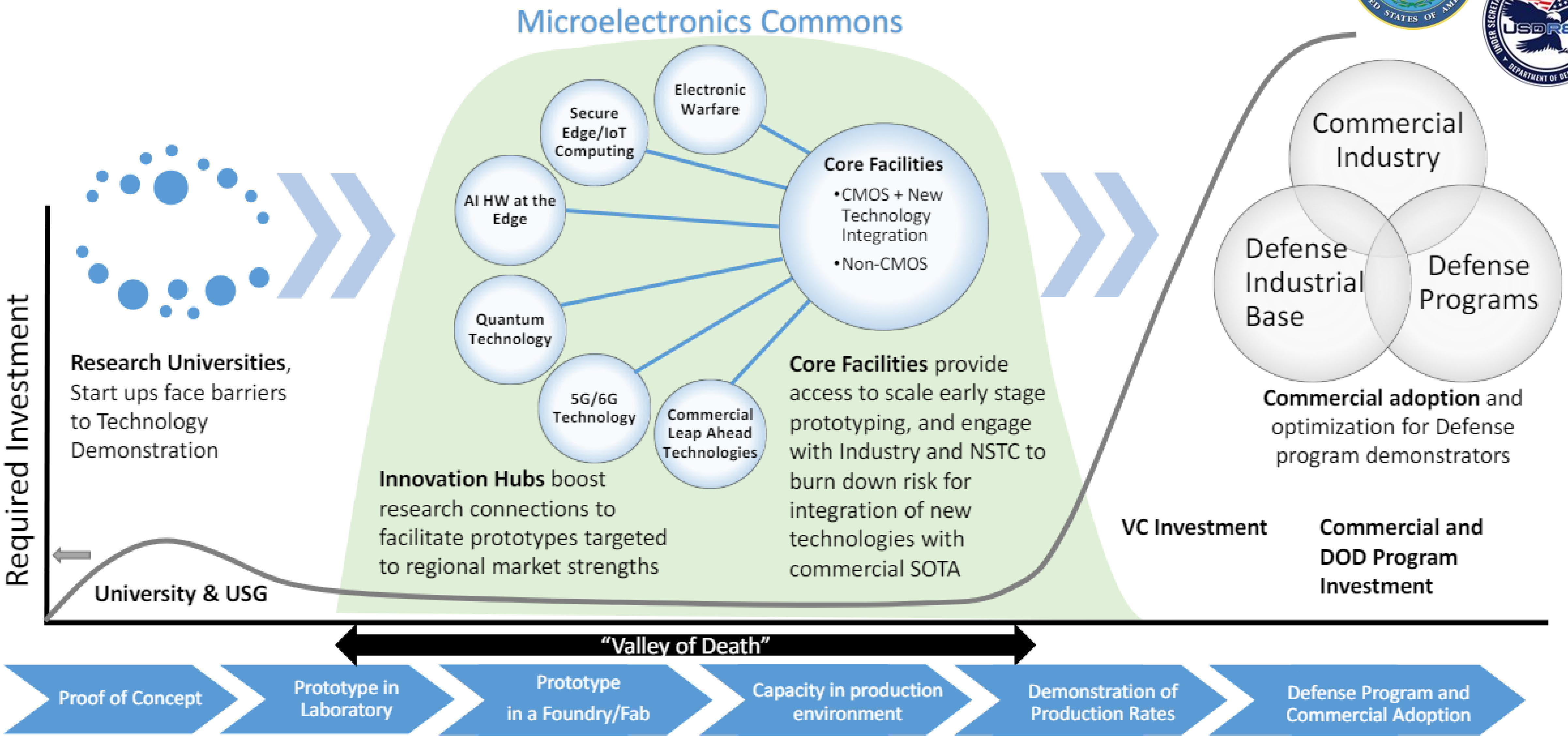
CHIPS Act | T&E BLUF



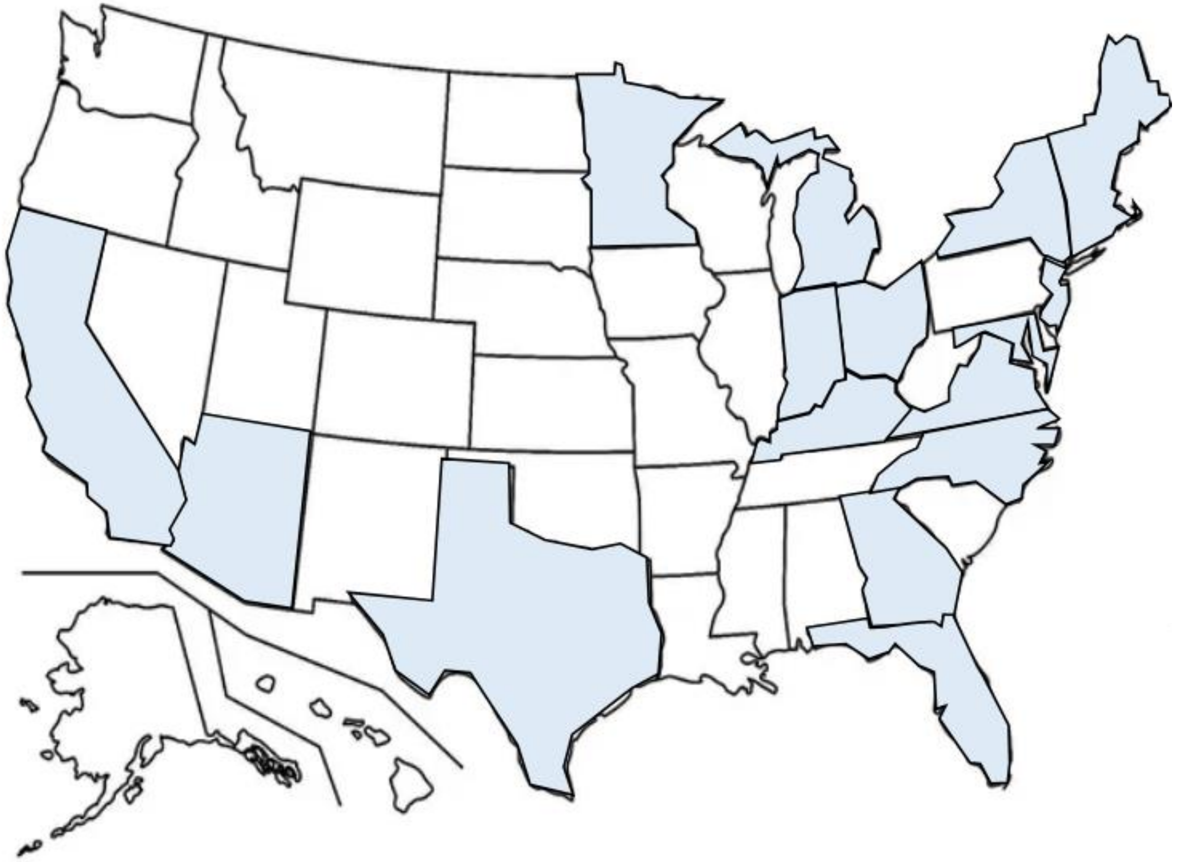
- The DOD portion of ME Commons is focused on the “lab to fab” of ME technologies and concepts
  - No direct discussion of T&E has been included to ensure end products meet DOD availability, reliability and RH requirements
    - Modeling / tools / standards are included in T&E
    - Ties with other DOD programs / entities (T&AM, SRHEC, Nuc Matters, …) are critical
- This talk promotes the idea of the national network required to support the ME Commons efforts as well as the DOC plans for commercial technologies in the area of DOD specific T&E
- Intent is to mirror the ME Commons concepts of regional hubs, core facilities and projects / roadmaps to meet DOD unique needs

While nuclear / radiation is focused herein, reliability aspects should also be considered

Microelectronics Commons addresses "Valley of Death"



ME Commons | HUBS



Applied Research Institute	AZ Board of Regents on behalf of Arizona State University	The Board of Trustees of the Leland Stanford Junior University	Massachusetts Technology Collaborative
Silicon Crossroads Microelectronics Commons (SCMC) Hub	Southwest Advanced Prototyping (SWAP) Hub	California-Pacific-Northwest AI Hardware Hub (Northwest-AI-Hub)	Northeast Microelectronics Coalition (NEMC) Hub
Midwest Microelectronics Consortium	**North Carolina State University**	**The Research Foundation for The State University of New York (SUNY), on behalf of The SUNY Center for Economic Development**	**University of Southern California**
The Midwest Microelectronics Consortium (MMEC)	Commercial Leap Ahead for Wide-bandgap Semiconductors (CLAWS)	Northeast Regional Defense Technology Hub (NORDTECH)	California Defense Ready Electronics and Microdevices Superhub (California DREAMS)

☐ **States Representing Organizations Responding to Microelectronics Commons RFI (Notice ID: N0016422SNB42)**

Image credit: https://microelectronicscommons.org/connect/

ME Commons technologies – attributes require T&E consideration

- Devices are –
  - Multi-technology (integrated optics, quantum, …)
  - New architectures (GAA, nanowires, …)
  - Projections for increased integration (AI, IoT, Edge computing, …)
  - Heterogeneous
  - Ultra-high frequencies
- Technologies (Silicon & ??)
  - A few electrons only needed to switch states
  - Use of SiGe, graphene, carbon nanotubes
  - Wide bandgap, Ultra Wide bandgap
- Device packaging
  - Integration, integration, integration, …
  - Heterogeneous integration of materials, architectures, …

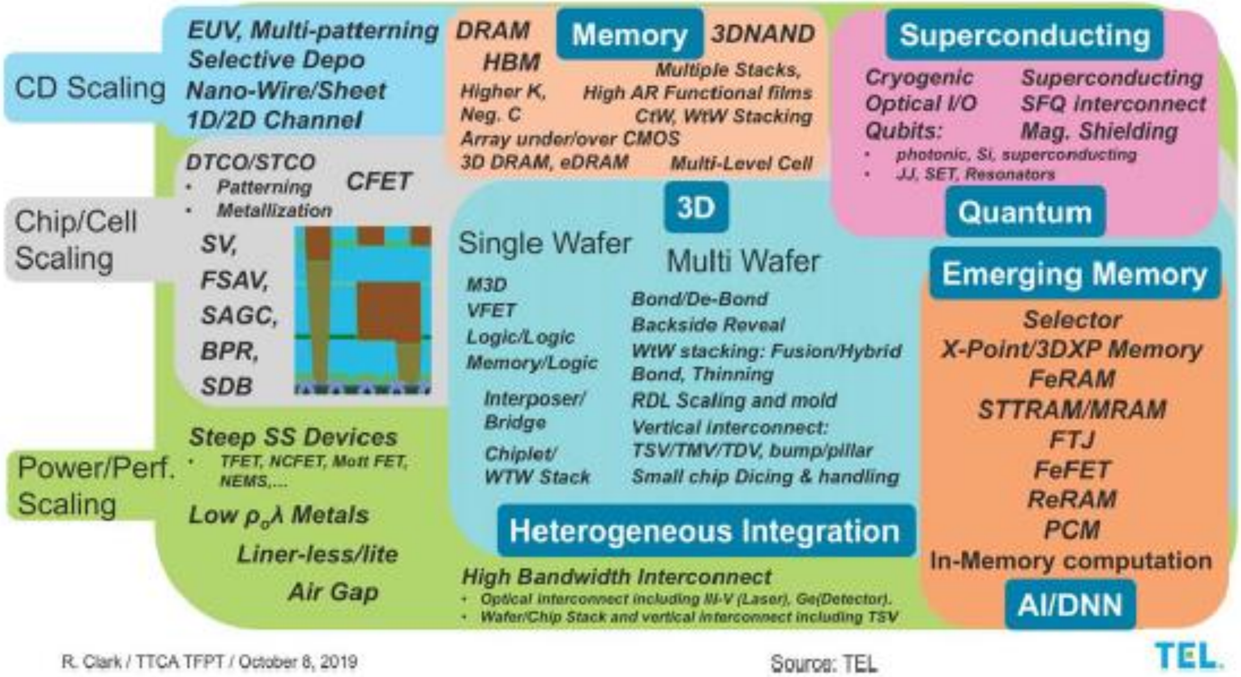


Figure 5.9: Drivers and technologies for better power, performance, area, and cost Scaling[34] (courtesy of Robert Clark, Tokyo Electron)

Coordination between ME Commons Technologies and T&E needs to happen for mission success

Mapping ME Commons to representative needs areas for T&E

Technology Areas Supported by the Microelectronics Commons

- 5G/6G Technology
- Artificial Intelligence/Hardware
- Commercial Leap-Ahead Technologies
- Electromagnetic Warfare
- Secure Edge/IoT Computing
- Quantum Technology

6.1 / 6.2 (Lab)	Basic mechanisms research (materials, structures, transistors and similar); physics based modeling; new effects & concerns
6.3 / 6.4 (Fab)	Device / architecture characterization; guideline(s) development; risk based tool / methodology development
Post-Commons (P&Q)	Qualification standards and tests
Workforce Development (WFD)	University, vocational, certification and radiation simulators

Qualified workforce needed at every step

Two-fold plan to map to T&E

DOC portion of CHIPS Act can also be considered for dual-use nature of commercial technologies by DOD and related assurance areas (terrestrial soft error rates,…) and architectural lessons

Roadmap Development

- Survey existing capabilities
- Determine gaps for ME Commons technologies
- Create Roadmap and Funding Requirements

Mirror ME Commons Format

- Create Regional Hubs
- Identify Core Facilities for Hubs
- Identify Projects Needed
  - Upgrades, new facilities, models/tools, guidelines/standards,…

Cumulative dose (TID / TNID) overview

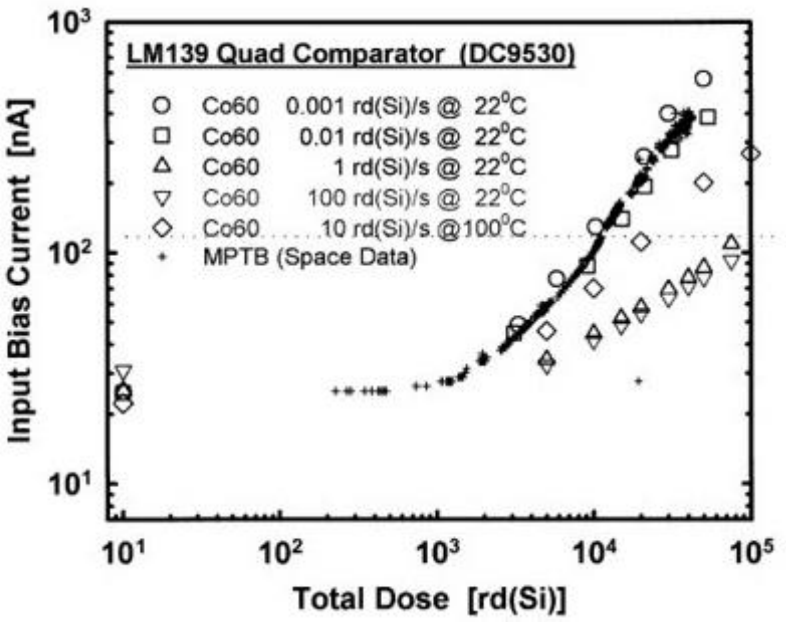
Total Ionizing Dose (TID)

- Creation of electron-hole pairs (ionization)
- Energy lost to target material (dE/dx)
- Electron-hole movement depends on local fields, …
- Cumulative effects include gain degradation, leakage current increases, reduced noise margin, timing (rise / fall / signal propagation), …

Total Non Ionizing Dose (TNID)

- Disruption to lattice structure; defect creation
  - Primary particle may dislocate target atom or stop in interstitial location

- TID & TNID cause parametric (electrical) degradation in Integrated Circuits (IC)
- Bipolar devices subject to Enhanced Low Dose Rate Sensitivity (ELDRS), below



A. Johnston (1995)

Total Ionizing Dose (TID) testing

- Qualification testing predominately performed per –
  - MIL-STD-883 Test Method (TM) 1019 in US (below)
  - ESA ESCC Basic Specification No. 22900 in Europe
- TM 1019 includes multi-phase approach to CMOS testing
- TM 1019 includes ELDRS & mission specific provision(s)
- DLA-certified Commercial services available (VPT Rad at top left)
  - Many performers / suppliers have incorporated in-house systems (APL at lower left)

3.6.1 Condition A. For condition A (standard condition) the dose rate shall be between 50 and 300 rad(Si)/s [0.5 and 3 Gy(Si)/s] ^{60}Co 2/ The dose rates may be different for each radiation dose level in a series; however, the dose rate shall not vary by more than ±10 percent during each irradiation.

3.6.2 Condition B. For condition B, for MOS devices only, if the maximum dose rate is < 50 rad(Si)/s in the intended application, the parties to the test may agree to perform the test at a dose rate ≥ the maximum dose rate of the intended application. Unless the exclusions in 3.12.1b are met, the accelerated annealing test of 3.12.2 shall be performed.

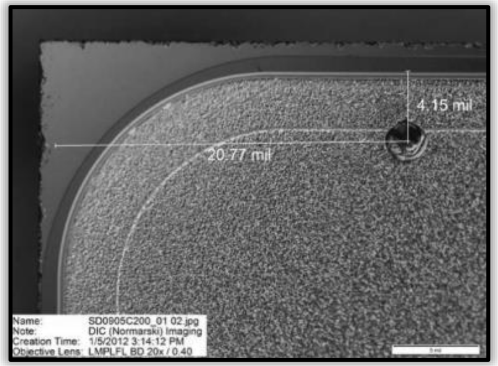
3.6.3 Condition C. For condition C, (as an alternative) the test may be performed at the dose rate agreed to by the parties to the test. Where the final user is not known, the test conditions and results shall be made available in the test report with each purchase order.

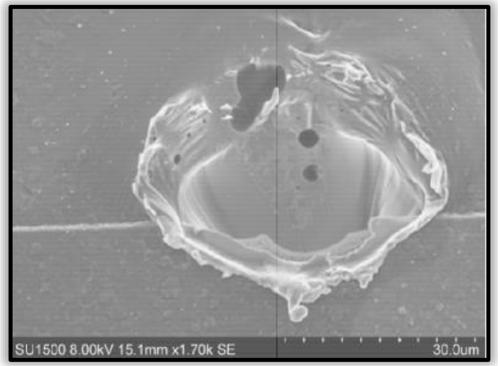
3.6.4 Condition D. For condition D, for bipolar or BiCMOS linear or mixed-signal devices only, the parts shall be irradiated at ≤10 mrad(Si)/s.

3.6.5 Condition E. For condition E, for bipolar or BiCMOS linear or mixed-signal devices only, the parts shall be irradiated with the accelerated test conditions determined by characterization testing as discussed in paragraph 3.13.2. The accelerated test may include irradiation at an elevated temperature.

Single Event Effects (SEE) overview

- Impacts range from catastrophic to nuisance (imperceptible)
- Direct ionization (primary particle)
  - Primary mechanism for $Z \geq 2$
  - Possible with protons
- Indirect ionization resulting from primary induced secondaries
  - Lighter particles produce less charge





Destructive SEE

- Includes (non all inclusive list) –
  - Latchup in CMOS devices (parasitic PNP / NPN)
  - Burnout (left) / Gate Rupture in power transistors
- As effects may be (often) non-recoverable mitigation is required

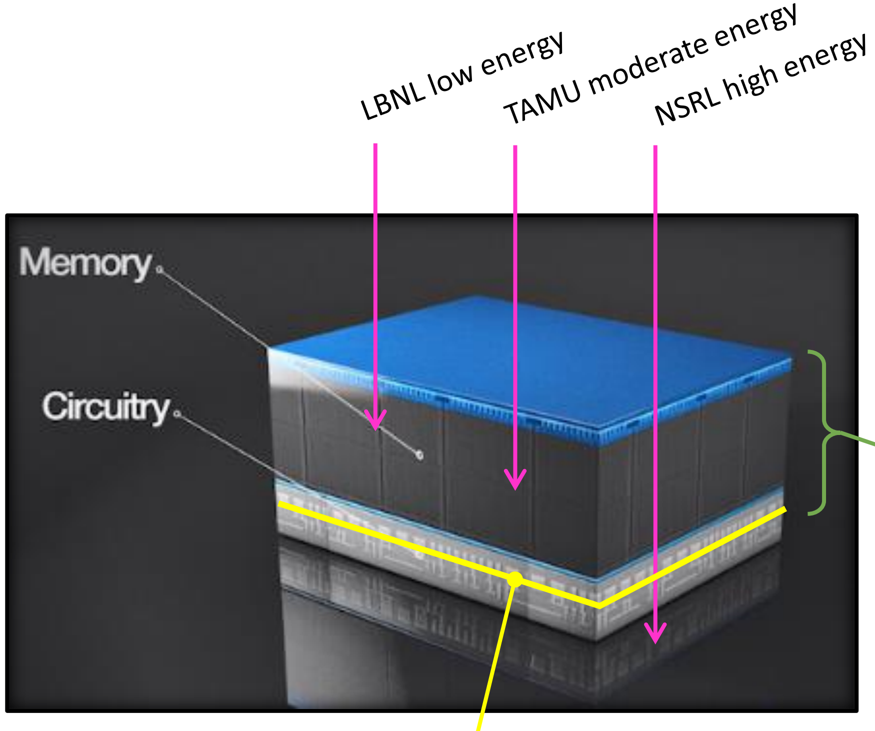
Non Destructive SEE

- Includes (non all inclusive list) –
  - Bit Errors (Single & Multiple)
  - Transients (Analog & Digital)
- Functional Interrupts (SEFI) prioritized for highly scaled devices & Class C/D projects

J. George (2013)

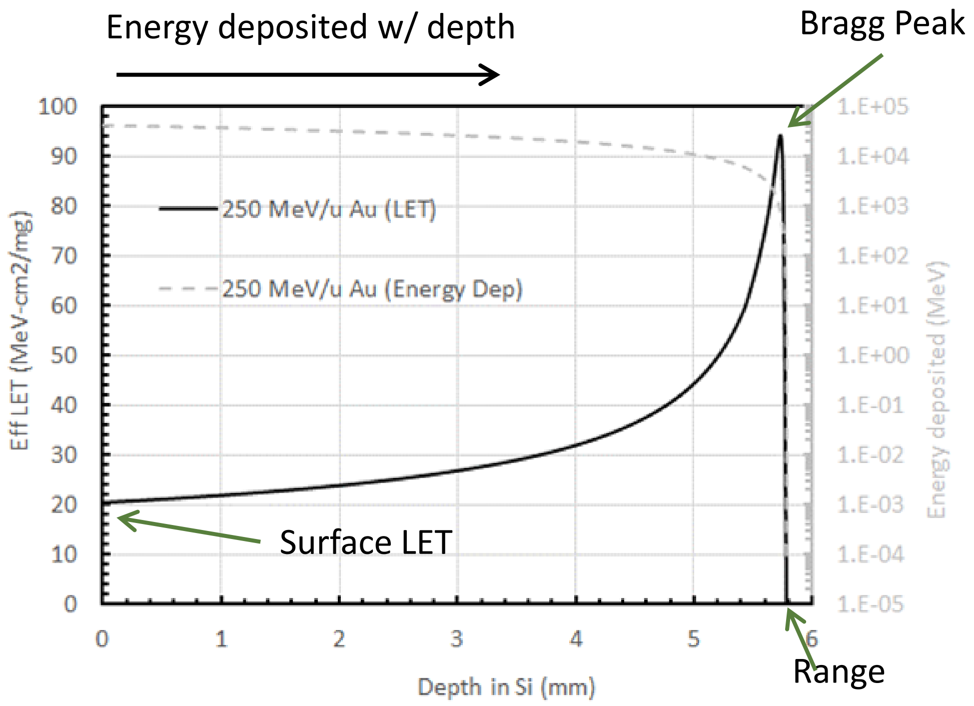
SEE (HI) testing

- Performed for number of reasons
  - Generic (datasheet), Mission Application, Go / No-Go, …
- Testing is at small number of accelerator laboratories (right)
- Availability deficits persist but addressed by DOD / TRMC

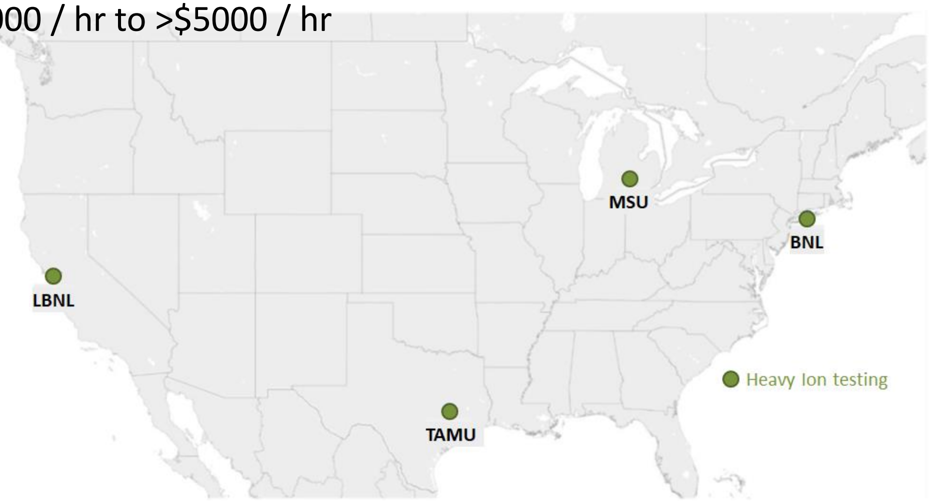


Deep Sensitive Volume (SV)

Low energy ions cannot penetrate into stacked microelectronics and 3DHI systems. Deep SV requires penetrating lots of material before the SV. Testers need to know the LET at the SV and need to minimize variability in LET across the SV. This implies a Bragg Peak deeper than the SV.



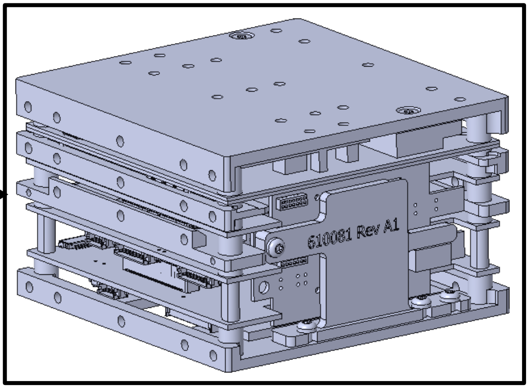
$1000 / hr to >$5000 / hr



Role of protons

- Suitable for –
  - Direct ionization SEE (20 MeV – 50 MeV energy regime)
  - Indirect ionization SEE (100 MeV to >200 MeV energy)
  - TID & TNID (DD)
    - 50 MeV to 75 MeV is “go to” for testing optics / sensors
  - Go / No-Go testing at system (box / board) level
- The customer base is more than space
- Look aheads – outlook uncertain
  - MGH shutting down for 2 years in mid / late 2024
  - ProNova / Covenant situation still fluid
  - Go / No-Go testing of Commercial & Alternate Grade devices / systems will add to demand
  - Commercial, RH & SRH optics and sensors will add to demand

Unibap iX5 DPU



Commercial non-RH (here 12.3 Mpx Sony) CMOS Global Shutter sensor module; attractive for LEO & lunar surface missions

$1000 / hr to $2500 / hr

Challenges and future looking

- Predominant current trends –
  - Tailored RHA (including V&V) for Class C/D projects
  - nSEE needs
  - Growth of Go / No-Go & System level testing
- Robust T&E Hubs, core facilities and projects / roadmaps required to meet DOD-unique needs
  - National network which mirrors ME Commons concepts of regional hubs, core facilities and projects / roadmaps
- 3DHI (3D Heterogeneous Integration) will complicate all manner of SEE testing (beyond 2D / 2.5D)
  - Higher energies, beam uniformity, beam diameter, …
- Embedded AI likely to (should) drive TLYF & demand
- TID not really a driver for many (some) operational regions (cis-lunar, lunar surface, inner heliosphere, pLEO, VLEO, …) but we cannot lose lock on TID needs (standards, WFD, …)
- Users looking for –
  - Sponsor dictated requirements for HI SEE; else target derived range from 0.1-100 MeV-cm^2/mg
    - Energies >300 MeV/u
  - High energy protons (125 MeV to >200 MeV) to large fluences (>10^{11} #/cm^2) over large areas

Continuous / effective WFD and communications / coordination critical