Accelerator Test Facility (ATF)
Users' Meeting

Novel Application of a Pulsed Electron Linear Accelerator as a Single Event Effects Simulator

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In collaboration with Aerospace Corp.
Proposal ID: 312807
Funding Source: NASA
Funding Status: Received

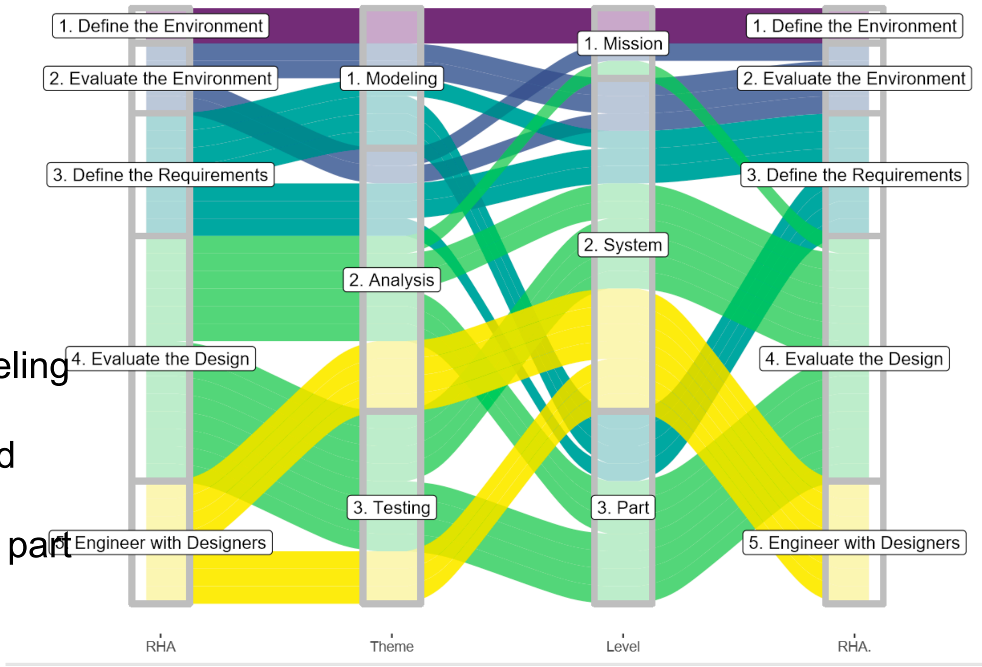
Jet Propulsion Laboratory
California Institute of Technology

RHA Philosophy

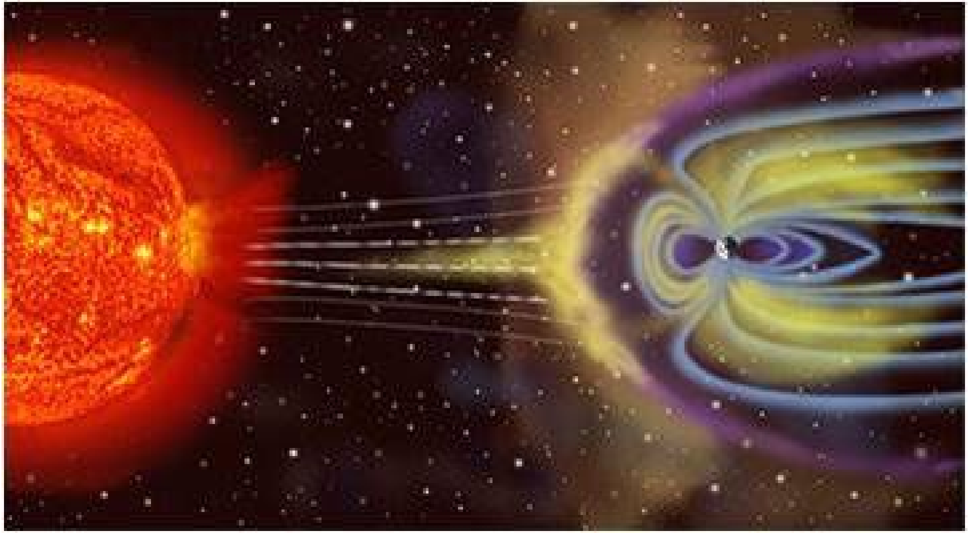
M.E.A.L. – Mission. Environment. Application. Lifetime.

The RHA process is laid out with interdependent activities. It may help to group these activities by the type or “theme” of work (e.g., modeling, analysis, or testing), or to examine the “level” or scope to which these activities can address information (e.g., mission, system, or part level).

- Defining radiation requirements relies on modeling and model fidelity.
- Radiation requirements exist at the system and part levels.
- Testing and analysis may be conducted at the part level, but outcomes and engineering are most prevalent and defined at the system level.

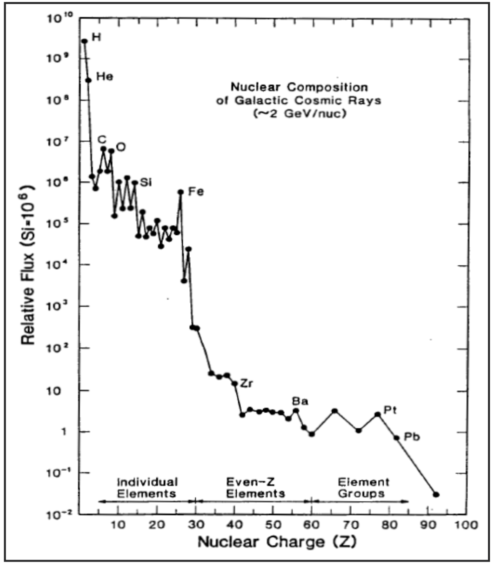


Natural Space Environment Overview



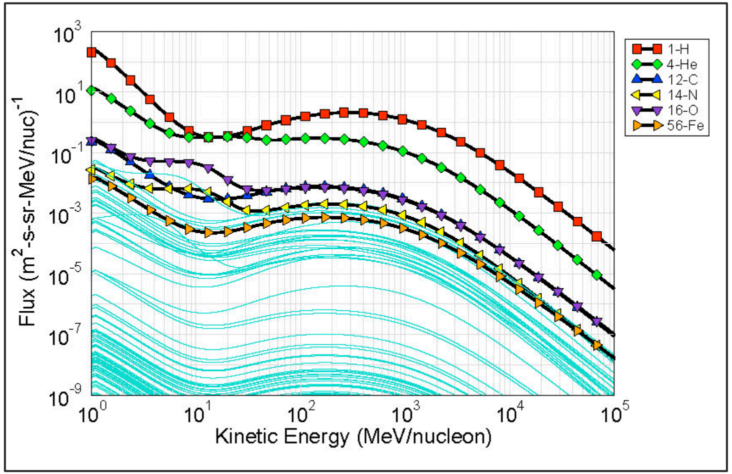
- Particle radiation – High-energy electrons, protons & heavy ions
  - Solar
  - Galactic cosmic rays (GCR)
  - Trapped in magnetospheres
- Plasma
  - Ionosphere
  - Plasmasphere – Magnetosphere
  - Solar wind
- Neutral gas particles
  - Lower – atomic oxygen (AO)
  - Higher – hydrogen & helium
- Ultraviolet and X-ray
- Micrometeoroids & orbital debris

Natural Space Environment: GCR



R. A. Mewaldt, *Adv. in Space Res.*, 1994.

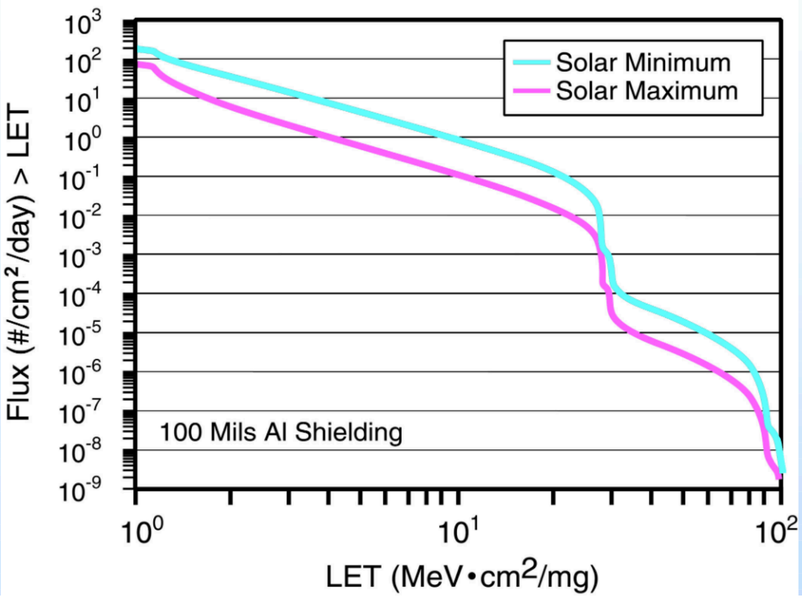
Nymmik



https://creme.isde.vanderbilt.edu/

- Originate outside the solar system (*e.g.*, supernovae)
- Include all naturally-occurring elements
  - Drops off rapidly for $Z > 26$ (iron)
- Most energetic of all space environment radiation

Application of LET



Ion	Cocktail (AMeV)	Energy (MeV)	Z	A	Chg. State	LET (Entrance) (MeV/mg/cm2)	LET (Bragg) (MeV/mg/cm2)	Range (Bragg) Vacuum (µm)	Range (Bragg) Window/Air (µm)
B	10	108.01	5	11	+3	0.89	4.19	307.0	---
O	10	183.47	8	18	+5	2.19	7.16	239.2	---
Ne	10	216.28	10	22	+6	3.49	8.95	174.1	---
Si	10	291.77	14	29	+8	6.09	13.99	134.2	---
Ar	10	400.00	18	40	+11	9.74	18.65	116.6	---
V	10	508.27	23	51	+14	14.59	25.59	93.9	---
Cu	10	659.19	29	65	+18	21.17	33.95	85.4	---
Kr	10	885.59	36	86	+24	30.86	40.91	84.3	---
Y	10	928.49	39	89	+25	34.73	47.42	68.9	---
Ag	10	1039.42	47	107	+29	48.15	59.27	53.9	---
Xe	10	1232.55	54	124	+34	58.78	69.24	48.6	---
Au*	10	1955.87	79	197	+54	85.76	94.18	55.0	---
He*	16	43.46	2	3	+1	0.11	1.45	836.0	795.5
B	16	190.22	5	11	+4	0.56	4.19		796.2
N	16	233.75	7	14	+5	1.16	6.04	503.0	464.0
O	16	277.33	8	17	+6	1.54	7.16	478.5	439.3
Ne	16	321.00	10	20	+7	2.39	8.95	337.5	299.2
Si	16	452.10	14	29	+10	4.56	13.99	269.5	230.7
Cl	16	539.51	17	35	+12	6.61	17.35	219.6	180.1
Ar	16	642.36	18	40	+14	7.27	18.65	242.2	203.1
V	16	832.84	23	51	+18	10.90	25.59	206.3	167.6
Cu	16	1007.34	29	63	+22	16.53	33.95	166.5	127.6
Kr	16	1317.18	36	78	+28	23.97	40.90		97.1
Ag	16	1768.61	47	107	+38	38.17			
Xe*	16	1954.71	54	124	+43	49.29	69.24	105.4	66.0
O	20	374.89	8	18	+7	1.28	7.16	800.5	763.2
Ne	20	440.56	10	20	+8	1.85	8.95	583.4	545.1
Al	20	510.89	13	27	+10	3.50	12.49	382.3	342.1
Cl	20	730.57	17	37	+14	5.61	17.35	357.2	319.6
Ca**	20	905.53	20	44	+17	7.33	21.53	348.7	312.0
V**	20	976.69	23	51	+19	9.88	25.59	266.2	227.4
Cu	20	1260.99	29	63	+24	14.53	33.95	237.2	199.3
Kr	20	1487.67	36	78	+29	22.26	40.91	182.1	142.9
Ag	20	2062.70	47	107	+40	35.29	59.27	161.6	124.1
Xe*	20	2354.00	54	124	+46	45.22	69.24	141.1	101.5

Breaking down radiation effects

Ionizing Radiation Effects

Total Ionizing Dose (TID)

Total Non-Ionizing Dose (TNID)

Single-Event Effects (SEE)

Non-Destructive

Destructive

Primarily high-energy protons and heavy ions

SEE Mechanisms

- **When an ion passes through a conductor or semiconductor e.g. Si:**
  - Most charge deposition is compensated quickly through recombination, drift and diffusion.
  - This is what causes SEE
  - BUT, from a TID perspective charge isn't accumulated or stored.

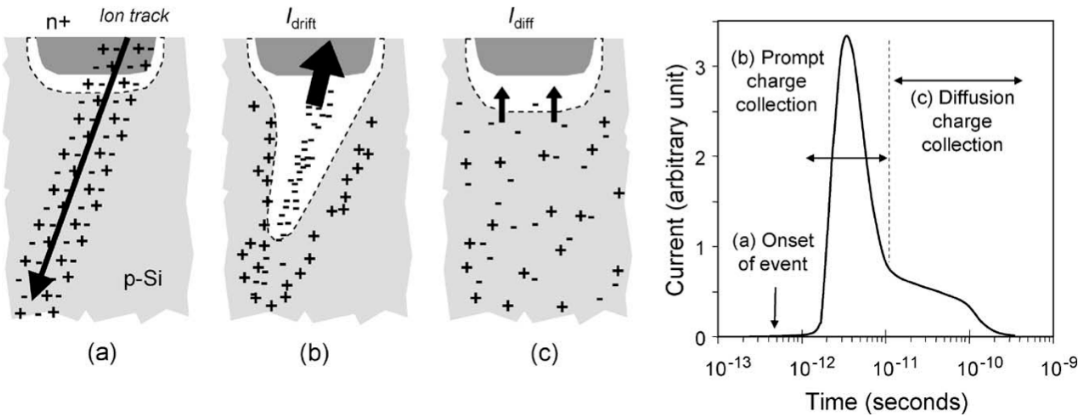


Image reproduced from Baumann: [Radiation-Induced Soft Errors in Advanced Semiconductor Technologies]

Putting it all Together

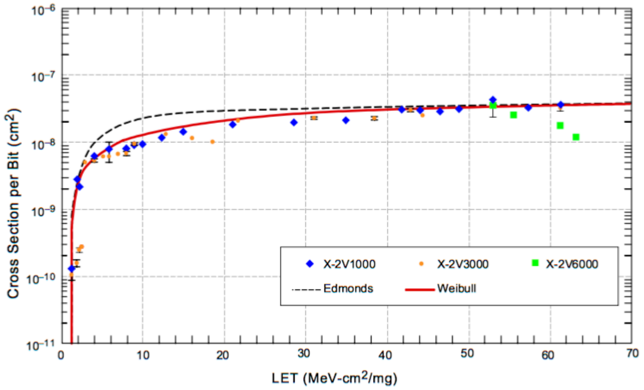
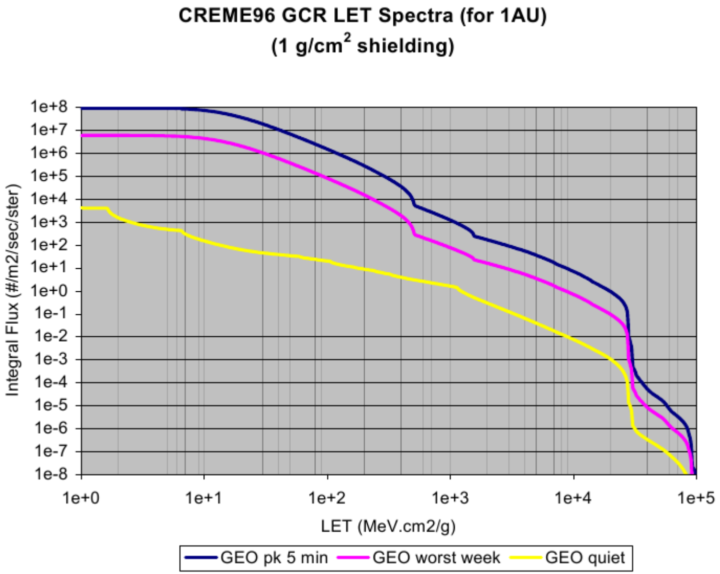
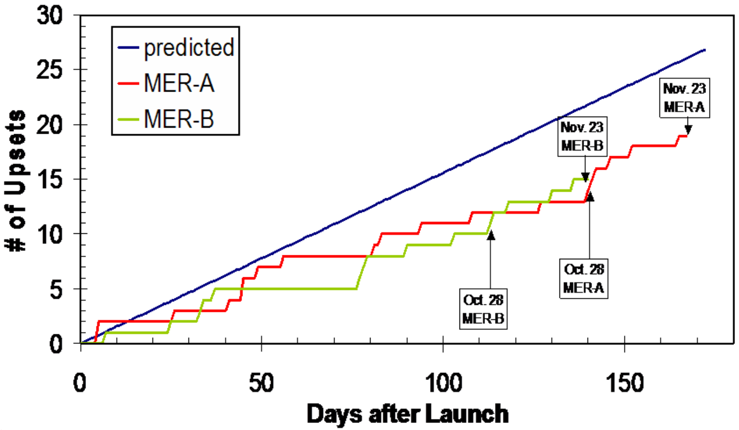


Figure 4. Virtex-II Configuration Memory Cells (Texas A&M)
Heavy Ion SEU Cross Sections for the X-2V1000, X-2V3000, and X-2V6000





SINGLE EVENT EFFECTS

RECENT ASSESSMENTS AND RESPONSES

NASEM 2017-2018

Key findings
- Growing use and tightening supply
- Infrastructure showing signs of strain
- Aging workforce in a domain that requires specialized training and skills
- Fast-moving technology

Points to / needs
- More organizational coordination
- Test facility sustainment & new investments
- Coupled with appropriate research & development
- Workforce development

AOA 2019

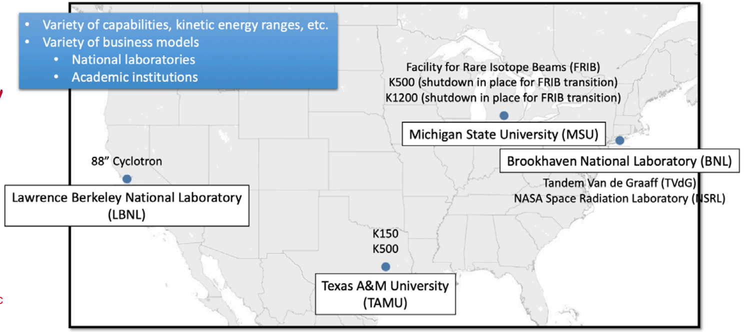
- Existing heavy ion SEE test facilities cannot meet current or future SEE test demand (~5000 hour/year gap)
- Department of Defense efforts as well as U.S. Government and commercial space are driving significant increases in SEE testing demand
- Current heavy ion accelerators for SEE testing at U.S. universities and Department of Energy labs have limited capacity and capability

COLLABORATION IS NECESSARY

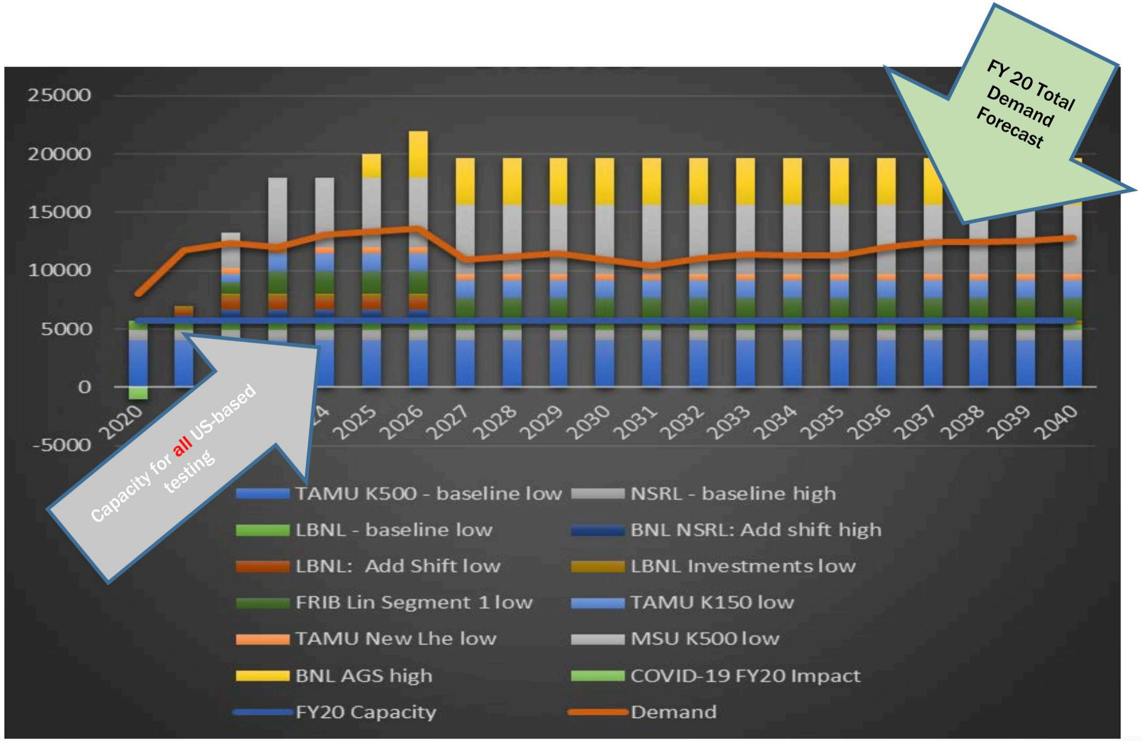
Agency-wide facility block buys

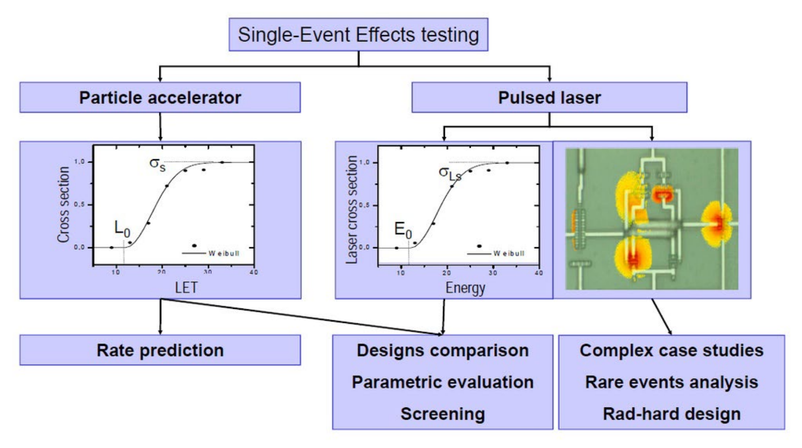
NASA-DoD Collaborations:
Workforce Development
SEE Testing Advisement
Data Sharing
Common Part Testing
New Facility Shakeouts

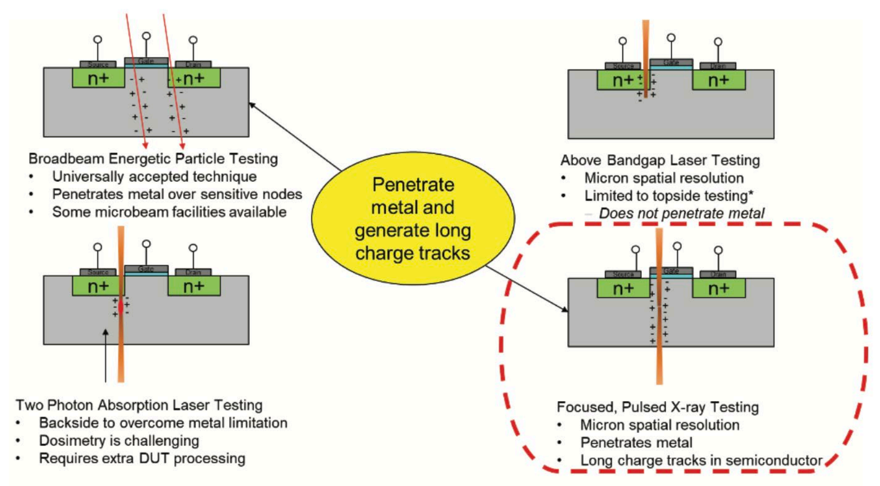
U.S. Heavy Ion Test Facilities (*currently*)



Accelerator Supply and Demand







Alternative Test Techniques

The Radiation Effects Community has developed a few alternative approaches to generate SEE

Pulsed Laser

Pros:

- Provides spatial correlation
- Can be productized

Cons:

- Charge track structure
- Cannot penetrate through overlayers/packaging

Pulsed X-Ray

Pros:

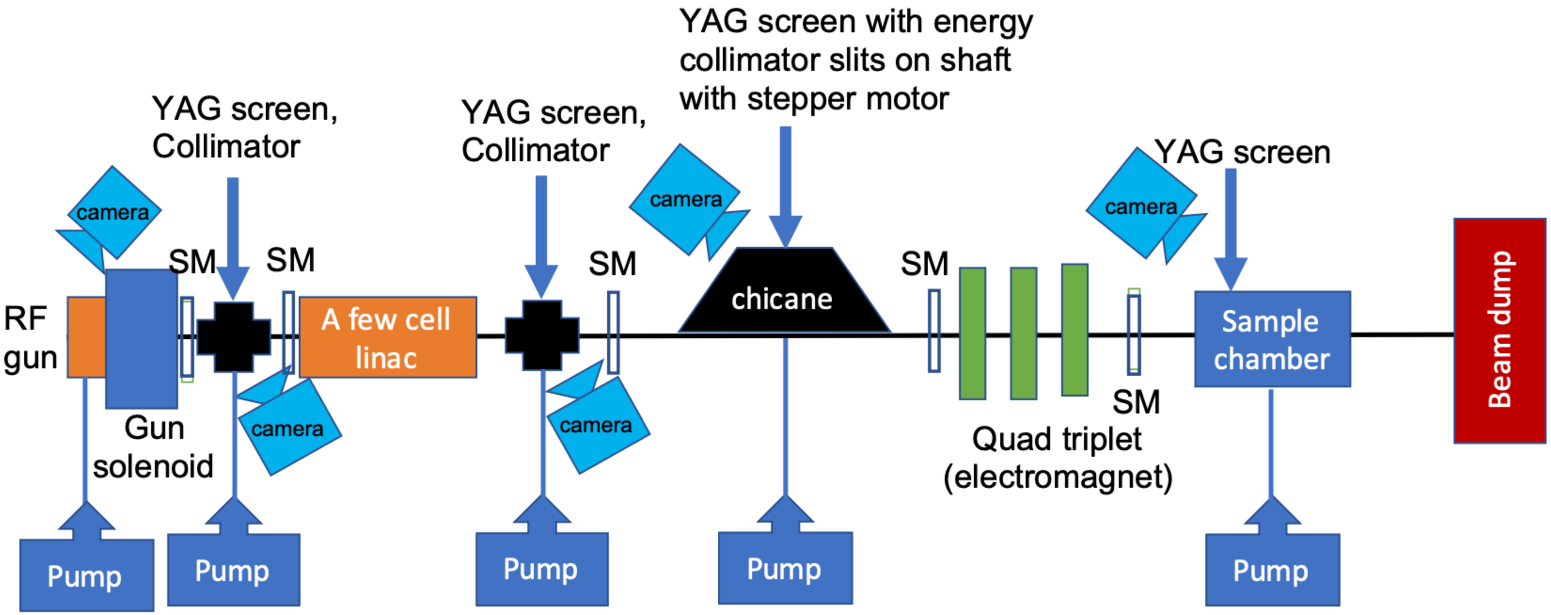
- Similar ranges to terrestrial heavy ion facilities
- Provides spatial correlation

Cons:

- Dose effects

Proposed Alternative

Pulsed Electron Beam



Requirements

Duration

Sub-picosecond

- A relativistic particle travels a 1-micron distance in several femtoseconds
- For either case (electron pulse or heavy ion), there is virtually no charge collection or charge-carrier recombination during this time, so all charge liberated at the beginning of the process is still present at the end .

Energy/Range

The 3-30 MeV electrons have ranges much longer than most heavy ions used for SEE tests.

Equivalent LET

A short bunch allows us to consider the energy deposition to scale linearly with n number of electrons. The number of electrons in a pulse can be adjusted to produce an equivalent LET for a pulse having any value up to a value at least as large as 100 MeV-cm^2/mg and beyond

Track Radius

1 micron diameter

Large lateral dimensions of the semiconductor allow a track to expand by radial diffusion without being inhibited by dielectric structures.

Such radial diffusion expands an initially very narrow track (e.g. from a heavy ion) into a track having a 1-micron diameter in a few tens of picoseconds.

Next Steps

Energy/Dosimetry Calibration

Proof of concept study - target beam structure & dosimetry

- Sample Chamber installation (BNL supplied)
- Compact permanent magnet quadrupoles (PMQ) mounted inside the sample chamber
- Installation and test of diamond detectors (BNL Instrument Division – existing technology)
- Target spot size measurement

Correlated Testing

Test simple devices in increasing complexity: Photodiode, linear devices, scaled memory, etc. Compare with existing heavy ion measurements characterized over LET

Request: 80-120 Hours Setup Time
80-120 Hours Facility Beam Time

Impact

Near-term

Inform a DARPA backed BAA

Long-term

Productization of the technology

Partners

Aerospace
BNL
UCLA

Relevant Publications:

National Academies of Sciences, Engineering, and Medicine. 2018. Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure. Washington, DC: The National Academies Press. https://doi.org/10.17226/24993.

John Franco, DTRA Jim Ross, NSWC Crane Strategic Radiation-Hardened (SRH) Electronics Council (SRHEC) Public Summary from Analysis of Alternatives (AoA) for Domestic Single- Event Effects (SEE) Test Facilities. https://nepp.nasa.gov/workshops/dhesee2021/talks/6a_SEE%20AoA%20summary%20Nov%202020%20approved%20for%20release.pdf

L. D. Flesner, R. Zuleeg and W. A. Kolasinski, "Comparison of heavy ion and electron-beam upset data for GaAs SRAMs," in IEEE Transactions on Nuclear Science, vol. 35, no. 6, pp. 1670-1672, Dec. 1988, doi: 10.1109/23.25519.

Buchner, Stephen & Miller, Florent & Pouget, Vincent & McMorrow, Dale. (2013). Pulsed-Laser Testing for Single-Event Effects Investigations. Nuclear Science, IEEE Transactions on. 60. 1852-1875. 10.1109/TNS.2013.2255312.

Cardoza, David & LaLumondiere, Stephen & Tockstein, Michael & Brewe, Dale & Wells, Nathan & Koga, R. & Gaab, Kevin & Lotshaw, William & Moss, Steven. (2014). Comparison of Single Event Transients Generated by Short Pulsed X-Rays, Lasers and Heavy Ions. IEEE Transactions on Nuclear Science. 61. 3154-3162. 10.1109/TNS.2014.2368057.

DEIA - @ JPL

About

Inclusion is a JPL core value, and fostering a diverse and equitable work environment is mission-critical for the Lab. Just as we are fearless in doing the impossible, we must also be fearless in taking action, respecting our employees' experiences, creating an inclusive environment where differing perspectives are valued and respected, and being a catalyst for positive change.

What We Do

The Office of Inclusion (OOI) develops, implements, evaluates, and informs the matrix of activities and efforts that involve Diversity, Equity, Inclusion, and Accessibility (DEIA) at JPL. Examples of this work include:

•Developing and implementing a DEIA strategic plan for the Lab

•Driving mechanisms and partnerships to cultivate the growth an inclusive, welcoming environment for all employees and the communities with which we engage

•Collaborating with the Communities of Inclusion to ensure issues affecting marginalized communities are heard by senior leadership

•Working with HR, senior leadership, managers, and other stakeholders to ensure our business practices are equitable and inclusive

•Partnering with NASA and Caltech to help ensure DEIA efforts are aligned with both NASA and Caltech’s goals

DEIA – Personal Activities

JPL Activities

- Member of the Office of Safety and Mission Success DEIA advisory counsel
- Have lead multiple listening sessions for our section

Community Activities

- Initiated the first ever IEEE Nuclear and Space Radiation Effects Conference DEIA session

Electron Beam Requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	***3-30***
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	***<1 pC***
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	***<1 ps***
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	***1 um***
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	***1 um***
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	***any***
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	***Single***

CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2*
	Peak Power	GW	~3		*~3*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2 ps*
	Pulse Energy	mJ	6		*6 mJ*
	M^2	---	~1.5		*1.5*
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	*1.5*
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	*Linear*
CO_2 CPA Beam	Wavelength	µm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2*
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	5	*~5 TW operation will become available shortly into this year's experimental run period. A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	*~5*
	M^2	---	~2		*~2*
	Repetition Rate	Hz	0.05		*.05*
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*	*Linear*

Other Experimental Laser Requirements

Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments	Requested Values
Central Wavelength	nm	800	800	*Stage I parameters are presently available and setup to deliver Stage II parameters should be complete during FY22*	*800*
FWHM Bandwidth	nm	20	13		
Compressed FWHM Pulse Width	fs	<50	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.*	
Chirped FWHM Pulse Width	ps	≥50	≥50		
Chirped Energy	mJ	10	200		
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.*	
Energy to Experiments	mJ	>4.9	>80		
Power to Experiments	GW	>98	>1067		

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	
Energy	mJ	5		
Pulse Width	ps	14		
Wavelength	nm	532	*Frequency doubled*	
Energy	mJ	0.5		
Pulse Width	ps	10		

Experimental Time Request

CY2023 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)		
Laser* + Electron Beam		

Total Time Request for the 3-year Experiment (including CY2023-25)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)		
Laser* + Electron Beam		

* Laser = Near-IR or LWIR (CO_2) Laser