Linac Facilities for Single Event Effects Testing

Steve Lidia
Facility for Rare Isotope Beams
lidia@frib.msu.edu

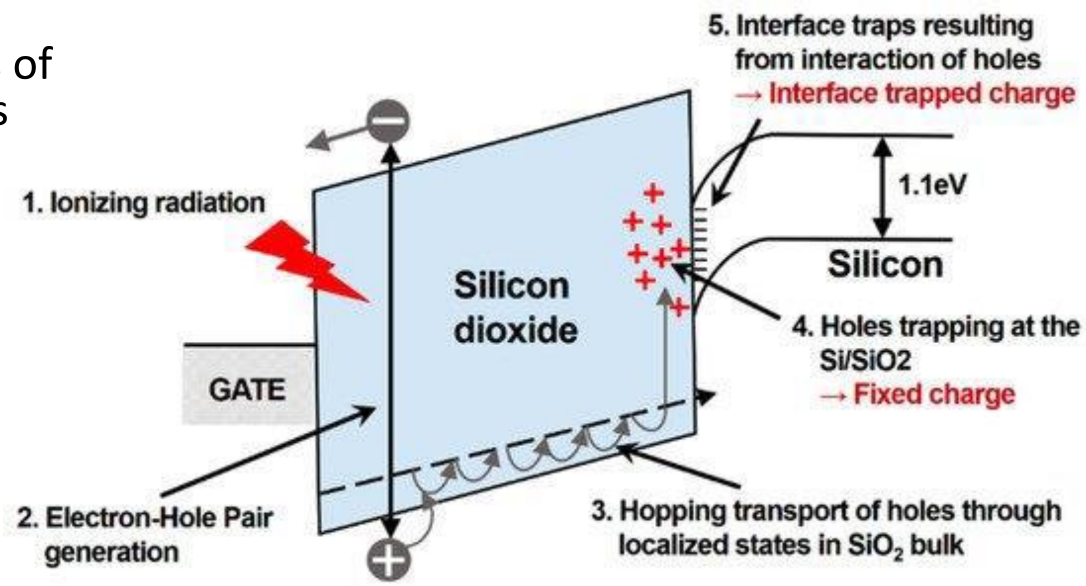
FSEE is operated at full cost recovery and enabled by FRIB, a DOE-SC Office of Science User Facility supporting the mission of the Office of Nuclear Physics, which supported the design and establishment of FRIB under DE-SC0023633. Michigan State University develops Single Event Effect Test Facility Upgrades under award from DOD Test Resource Management Center.

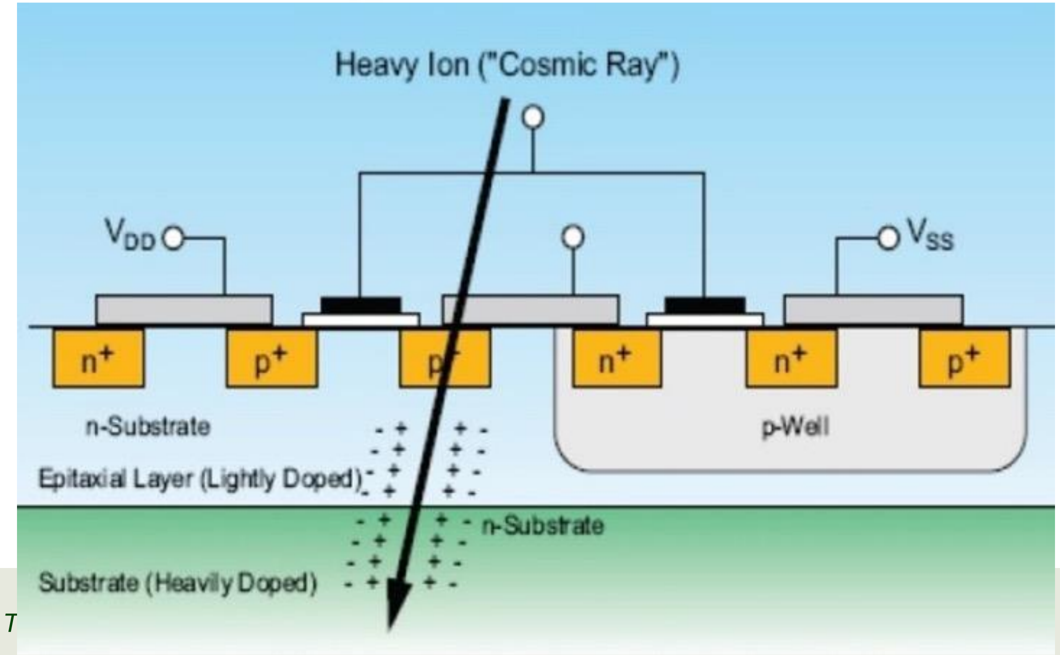
Outline

- Birth of Radiation Effects Studies
- History (so far) of Testing with Accelerators
- Heavy Ion Beams for Single Event Effects Studies
- Architectures and Tradeoffs
- Linac Systems: Injectors, Accelerators, Beam Delivery
- Challenges and Opportunities

Birth of Radiation Effects Studies

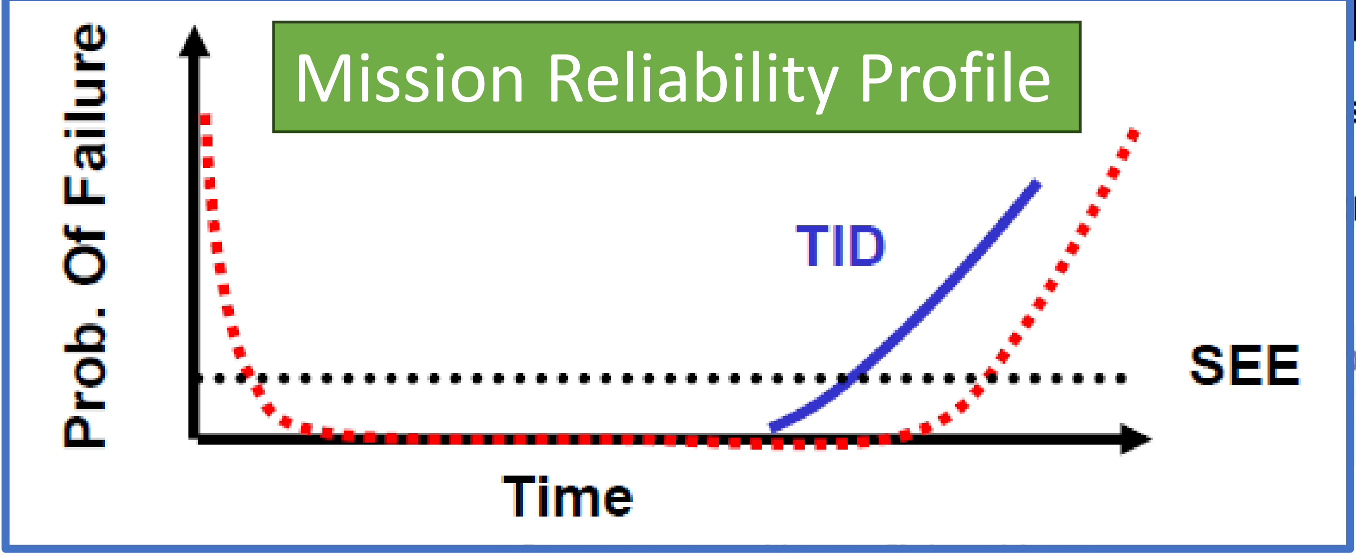
- The birth of the nuclear age in the **1940s** and the beginning of space exploration in the **1950s** ushered in the need to understand the effects of various radiation sources on electronic circuitry, computer components
  - Terrestrial and man-made neutron and gamma-ray sources
  - Solar particle radiation
  - Galactic cosmic rays
- **February 1963**. Telstar 1 (first commercial satellite) suffered complete transistor failure due to radiation damage
- **1960s, 1970s** – problems compounding
  - Transistor densities increase
  - Neutron damage affects BJT gain
  - Observation of Total Ionizing Dose (TID) effects in MOS devices
  - Single Event Upsets (SEUs) observed in satellite systems
  - 1979: observation of sea-level cosmic ray SEU in electronics
- **1980s, 1990s**
  - Basic mechanisms research growing
  - Moore’s Law creating greater densities
- **2000s onward**
  - Rad-hard design importance increasing
  - Satellites, Autonomous vehicles, Medical implants

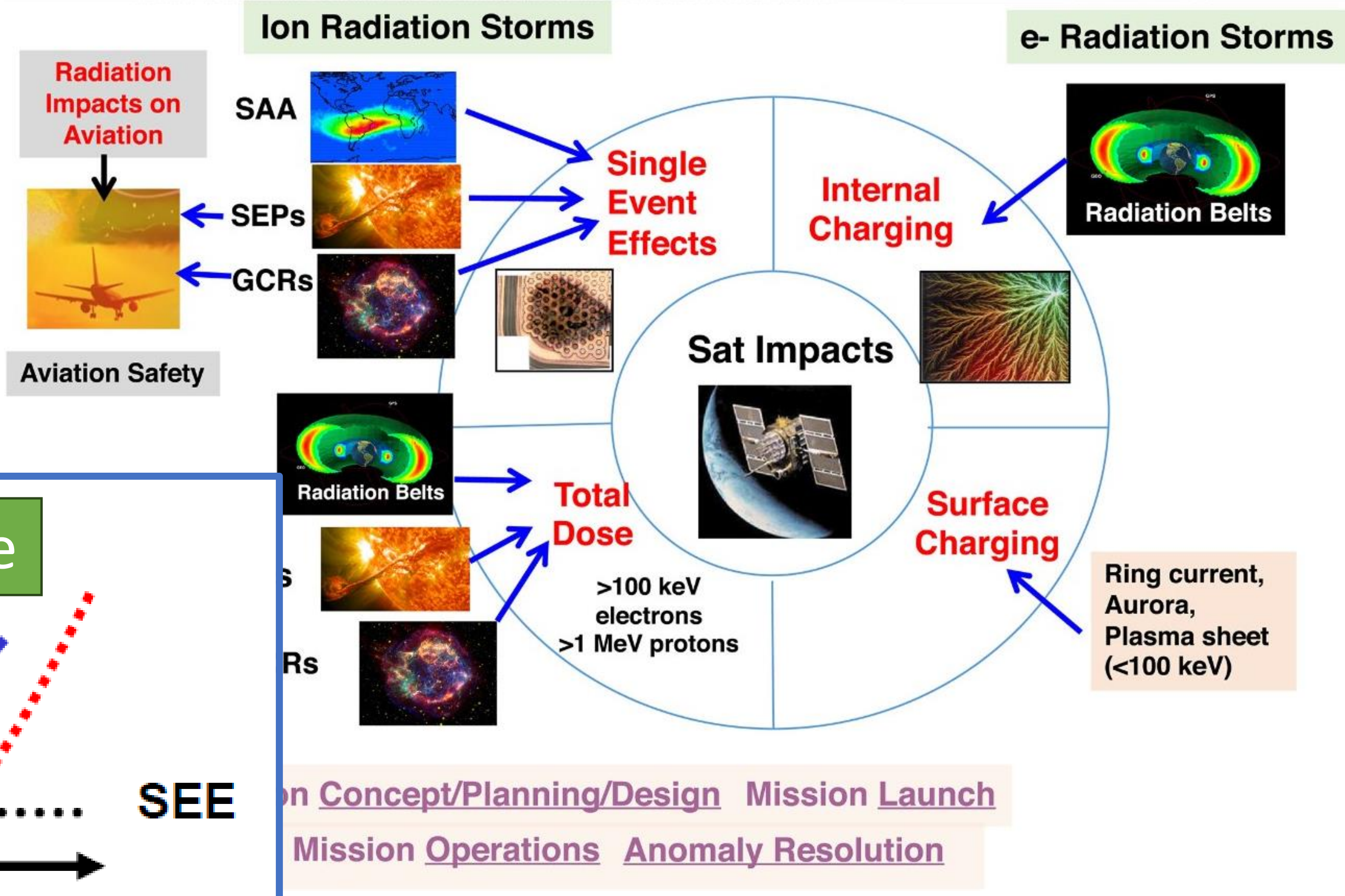




Radiation Effects from the Space Environment

- "Single-event effects from **solar energetic particles** and **galactic cosmic rays** (several MeV to TeV),
- Total dose due to accumulation of doses from electrons (>100 keV) and protons (>1 MeV) in a broad energy range, and
- Radiation effects from solar energetic particles and galactic cosmic rays at aviation altitudes." (Zheng et al., 2019)





(Zheng et al., 2019)

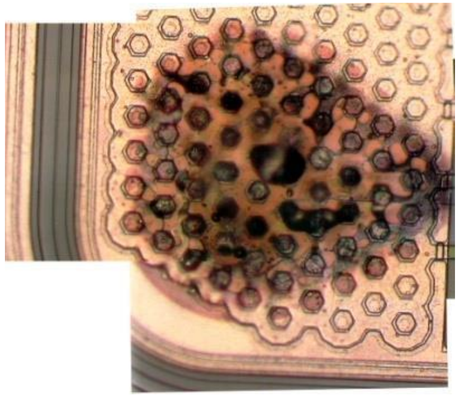
A Short History of Single Event Effects Studies

- The **possibility of single event upsets** was first postulated in 1962 by Wallmark and Marcus.
  - ***J.T. Wallmark****, S.M. Marcus, "Minimum size and maximum packaging density of non-redundant semiconductor devices," Proc. IRE, vol. 50, pp. 286-298, March 1962.*
- The first **actual satellite anomalies** were reported in 1975. SEUs in flip-flops.
  - ***D. Binder****, E.C. Smith, A.B. Holman, "Satellite anomalies from galactic cosmic rays," IEEE Trans. on Nuclear Science, vol. 22, no. 6, pp. 2675-2680, Dec. 1975.*
- First **observation of SEUs on earth** was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors took specific actions to reduce it.
  - ***T. C. May and M. H. Woods****, "A New Physical Mechanism for Soft Errors in Dynamic Memories", Proceedings 16 Int'l Reliability Physics Symposium, p. 33, April, 1978.*
- First report of **SEUs due to cosmic rays on earth** in 1979.
  - ***J. F. Ziegler*** *and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories", Science, 206, 776 (1979).*
- First report of **destructive SEE** (proton induced latch-up) in a memory operating in space in 1992
  - **L. Adams** *et al., "A Verified Proton Induced Latch-up in Space," IEEE TNS vol. 39, No. 6, pp. 1804 – 1808, Dec. 1992.*

J. Pellish, Applied Space Environments Conference, 2017

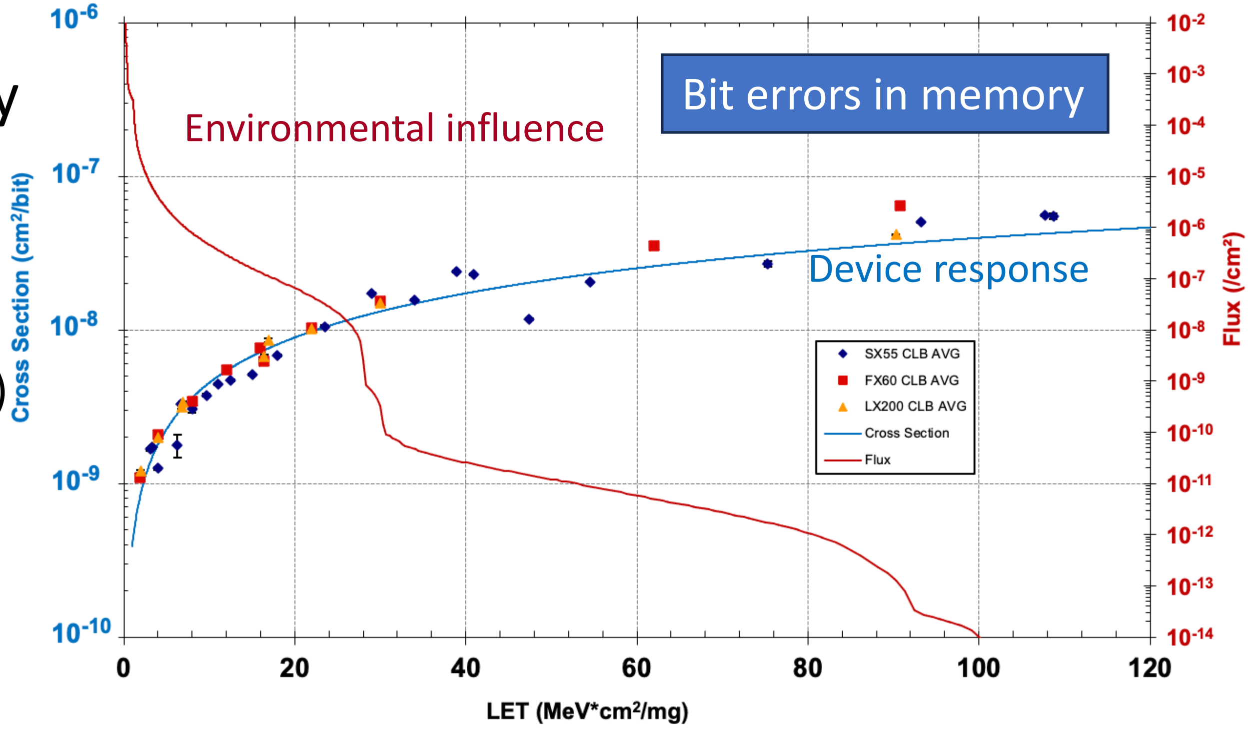
Single Event Effects (SEE)

- Any measureable effect produced by a single particle
  - *Non-destructive* = Single Event Upset (SEU), Single Event Transient (SET)
  - *Destructive* – Single Event Latch-UP (SEL), Single Event Burnout (SEB)
- SEE may be caused by direct ionization (e.g., by heavy ions)
  - Metric is charge collected in sensitive volume Q = C x **LET** x s
    - **Linear Energy Transfer** (LET) = dE/dx (MeV-cm^2/mg)
    - s is path length through volume
- SEE may be caused by nuclear reaction products, typically by protons or neutrons



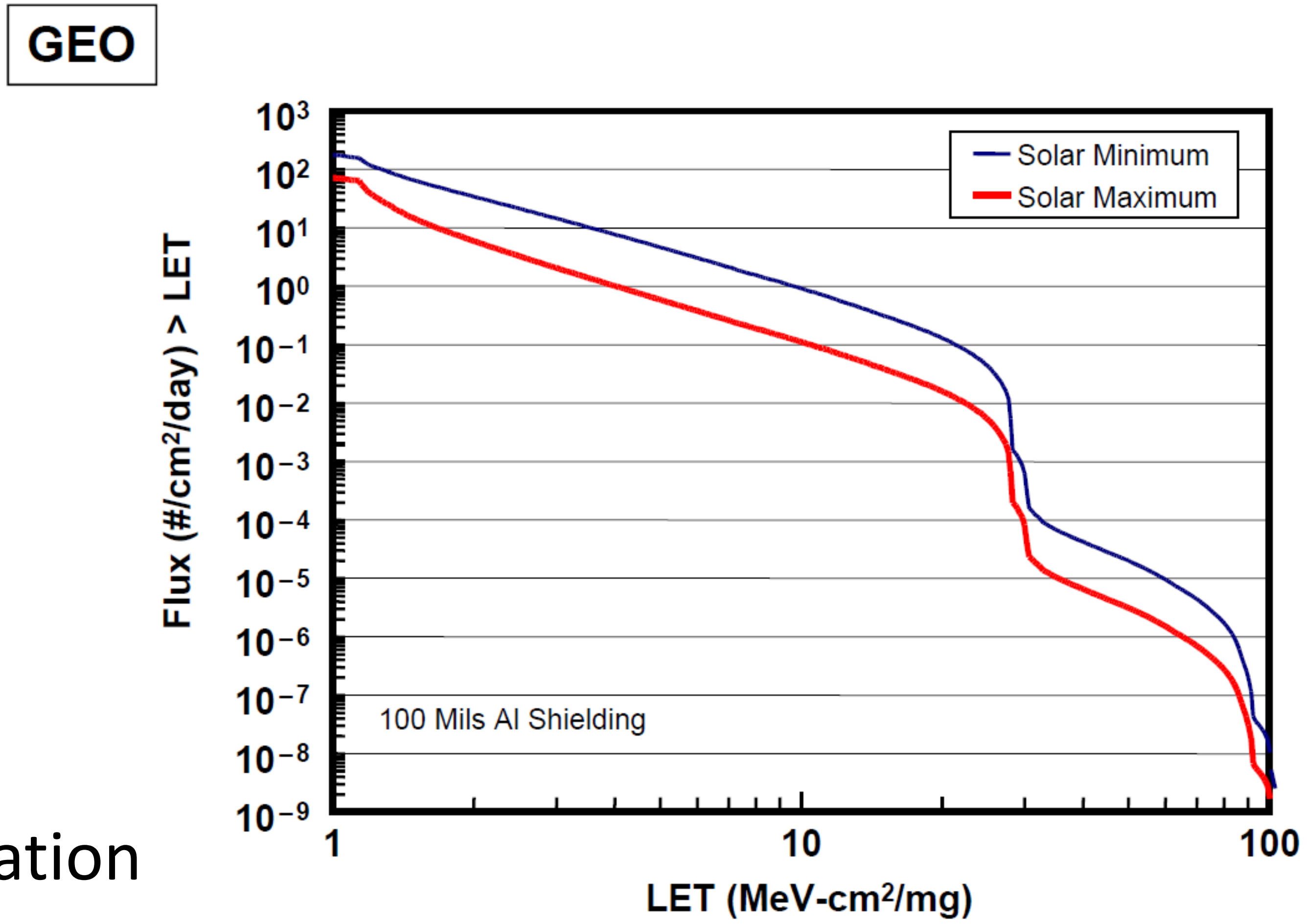
DC-DC Converter showing burnout

NASA Electronics Parts & Packaging Program (NEPPP)



Orbits and compositions – Linear Energy Transfer

- Single Event Effects are characterized by the energy of the incoming particle and the energy deposited in materials (typically referenced to Si).
- Linear Energy Transfer (LET) is **LET = 1/ρ dE/dx**, and energy loss is simply via ionization.
- Nuclear interactions in materials can create charged reaction products (e.g. alphas) that then produce ionization energy transfers.



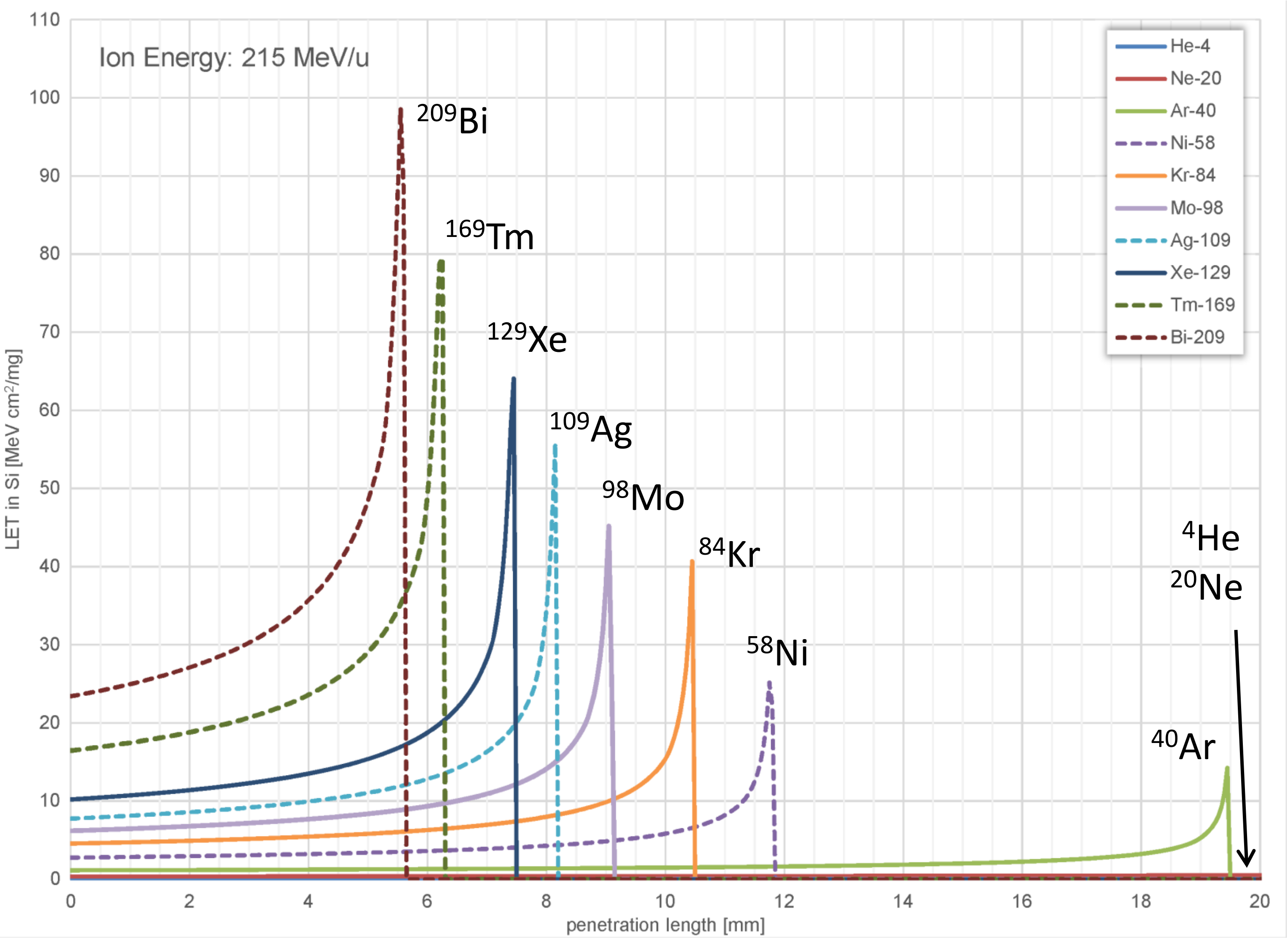
Buchner 2008

- The LET spectrum is dependent on orbit, prevailing ‘space weather’.

Linear Energy Transfer (in SI) vs Ion Species

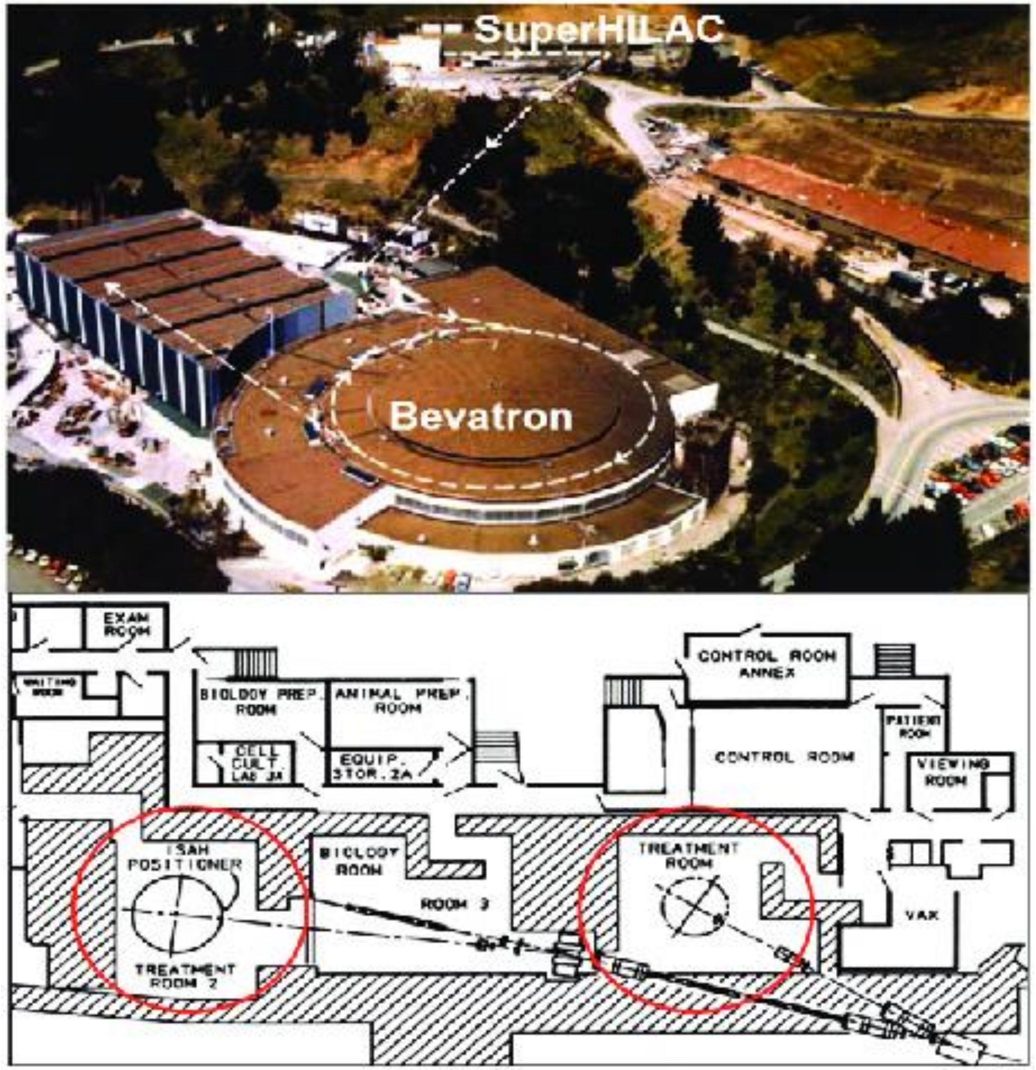
DAEJEON LINAC2026

- The LET spectrum is mapped to energy losses and the Bragg peak of ion species.
- The ion kinetic energy determines the penetration range.
- Penetration through ~mm of Si requires >50 MeV/u for heavy ions.



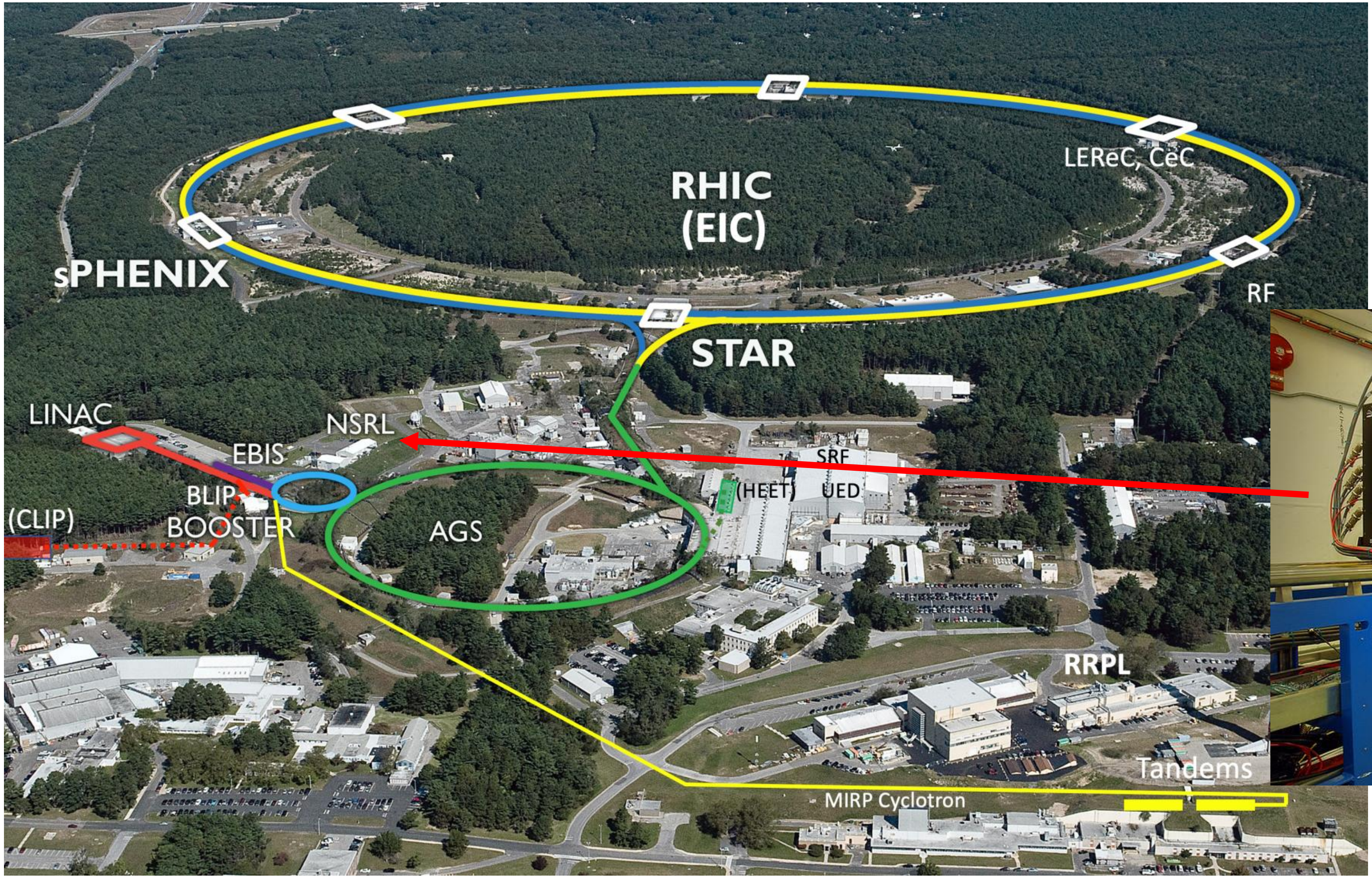
First Tests with Accelerators

- First experiments at Lawrence Berkeley Lab by aerospace engineers (1978)
  - 88” Cyclotron and SuperHILAC driven Bevalac
- Bevalac (SuperHilac + Bevatron) was the first high energy cosmic ray simulator *
  - (SuperHilac) 12 < A < 136, <8.5 MeV/u
  - (Bevatron) A < 40, >200 MeV/u
  - Ran until 1993, the provided the impetus to build NSRL at BNL
- TID and DD effects using high flux sources --- protons, neutrons, ^{60}Co
- NASA, ESA test protocols are established



*Grunder, Selph, Proc. 1976 Proton Linear Accelerator Conference, Chalk River

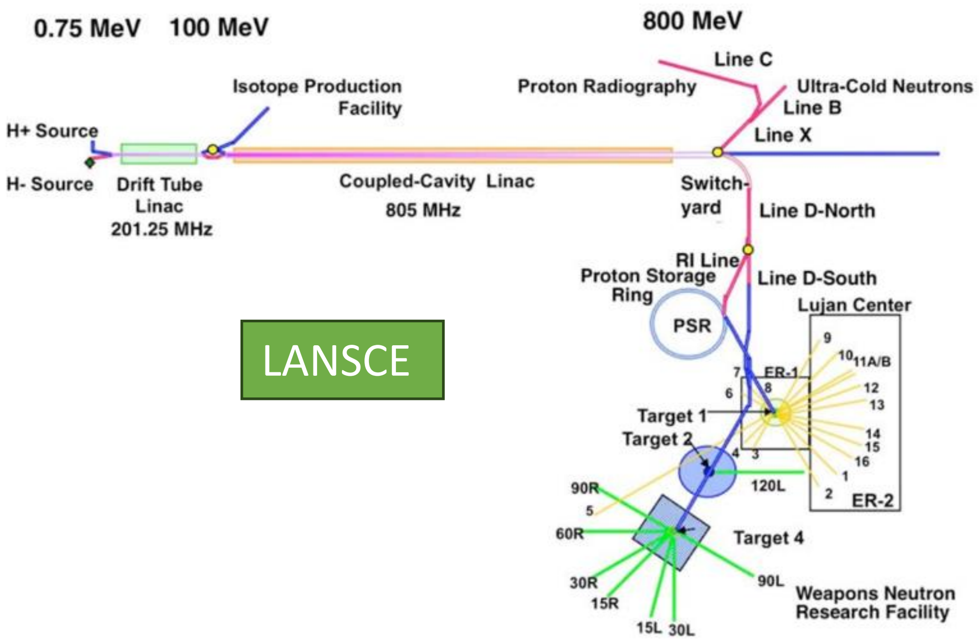
NASA Space Radiation Laboratory (NSRL @BNL)

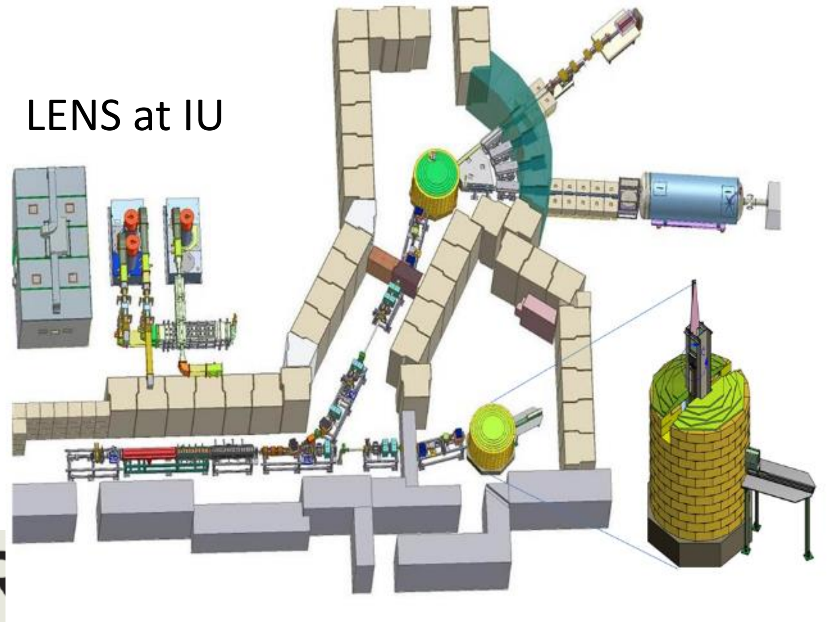


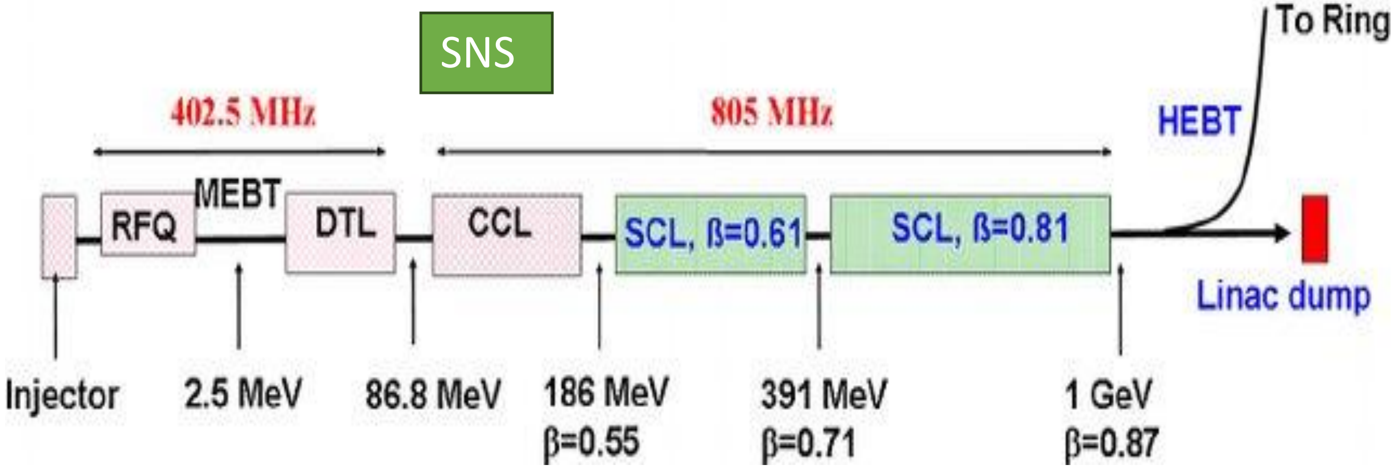
- Operations started 2000
- Protons to ^{209}Bi
- Max energies
  - p 2.2 GeV
  - ^{209}Bi 385 MeV/u

Proton and Neutron Facilities – TID/DD, nSEE

- Proton linac facilities are used for direct radiation with proton beams, or through conversions (p-n in Be targets, eg.) to neutron beams at high flux and energy (~ 1MeV Si equivalent)
- Examples are LENS, ISIS, TRIUMF, LANSCE at LANL (800 MeV), SNS at ORNL (1 GeV)

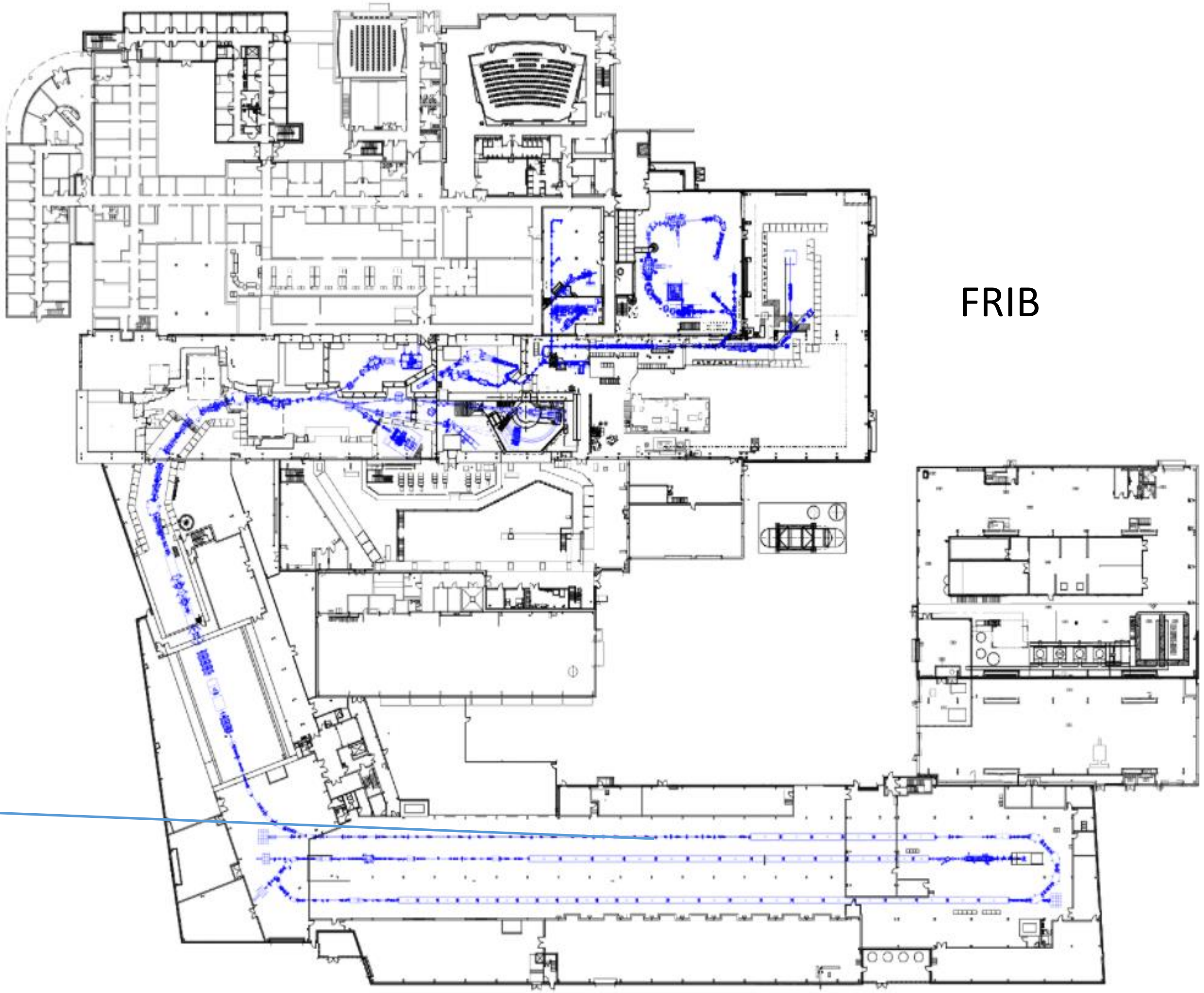






Heavy Ion Facilities – Linacs and Cyclotrons at <500 MeV/u

- Modern heavy ion beam facilities based on high gradient superconducting RF linacs are entering a period of high scientific productivity.
  - ATLAS at Argonne National Laboratory
  - FRIB at Michigan State University
- These provide essential supplementary capability to cyclotron-based heavy ion facilities (e.g. TAMU, Jyväskylä) 10-40 MeV/u



FRIB

Present and Future Community Needs (2018)*

DAEJEON LINAC2026

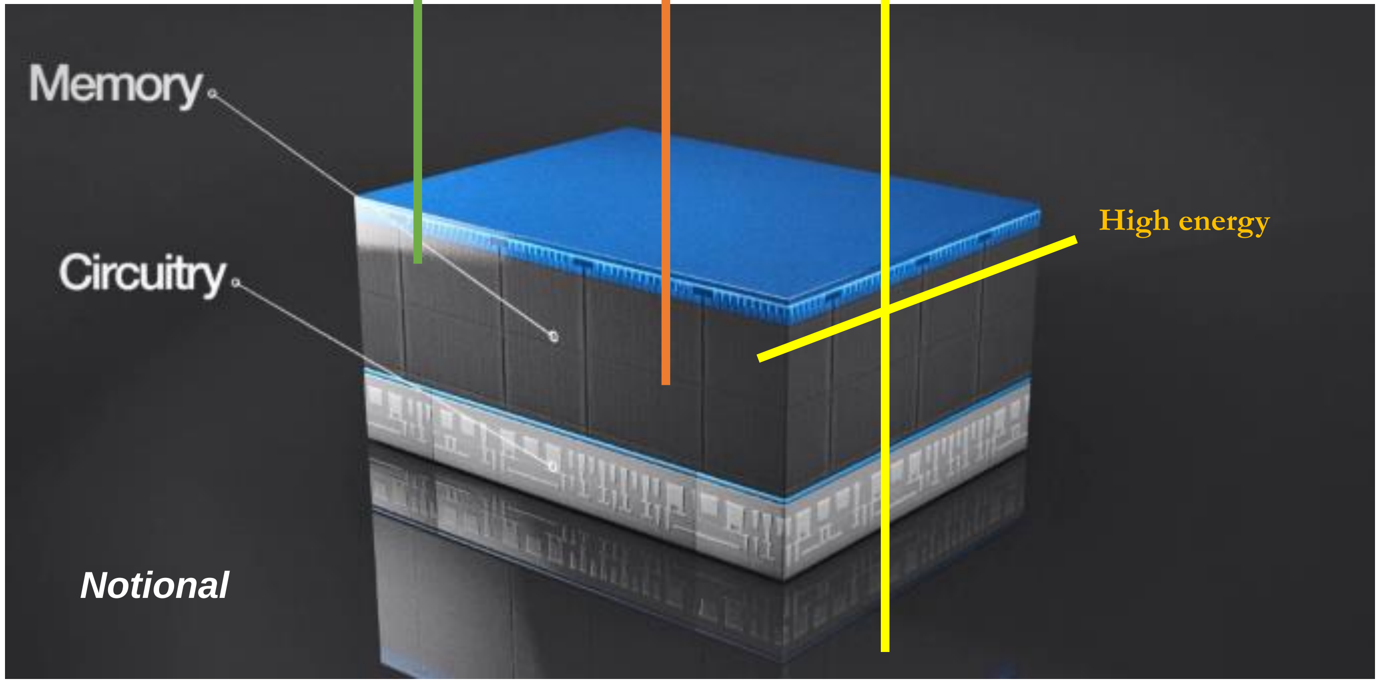
Key System Attributes or Performance Parameter	Description	Threshold Value	Objective Value
Simulation of mission environment	Range of entrance Linear Energy Transfer (LET) in Si [MeV cm^2/mg] at normal incidence	0.7 - 82	0.1 - 120
Provide a range of flux inclusive of target value	Ions/(cm^2-s)	<100, 10^6	10, 10^6
Simulation of mission environment	Kinetic energy [MeV/u]	5 – 40	5 - 400
Variable beam diameter (100% spot size)	cm	0.5 – 2.5	0.5 – 50
Beam uniformity (dosimetry over spot size)	N/A	+/- 10%	+/- 5%
Beam structure	Average flux variance	+/- 15%	+/- 5%
Beam structure	Instantaneous flux variance (no less than 10% duty factor)	+/- 15%	+/- 5%
Homogeneity in ion Species	N/A	>95%	Same as threshold
Homogeneity in ion energy	N/A	>90%	Same as threshold

*National Academies of Sciences, Engineering, and Medicine, Testing at the Speed of Light: The State of U.S. Electronic Parts Radiation Testing Infrastructure., Washington, D.C.: The National Academies Press, 2018.

Update on Community Needs

Technology is evolving to compact, heterogeneous structures

Low energy — **10–15 MeV/u**
Medium energy — **20-50 MeV/u**
High energy — **>100 MeV/u**



Micron's proprietary CMOS-under-Array technique constructs the multilayered stack over the chip's logic, packing more memory into a tighter space and shrinking 176-layer NAND die size, yielding more gigabytes per wafer.

Courtesy of Micron , https://www.eetimes.com/micron-leapfrogs-to-176-layer-3d-nand-flash-memory/#

High Energy SEE Test

2020

- 10% of SEE test is High Energy
  - >100 MeV/n

2030

- 40% of SEE test is High Energy
  - New technology and CCA level testing will demand high energy
  - Economical for new technology
- Access assured by high energy investment
- 40% is ~4000 hours/yr

Current predictions (2025) show a shortfall of
- **4000-5000 hrs/yr low/medium energy**
- **6000-10000 hrs/yr high energy**

Mapping requirements to accelerator architectures

- Energy -> Penetration range
  - 5 - 50 Mev/u — Ok for 2D structures, requires exposing bare Si
  - 50 - 400 MeV/u — Required to penetrate modern 3D packages (multi mm)
- Flux density and variations
  - Low intensity beams (< 1 W peak and average power)
  - Uniform beam profiles
- Temporal distribution and variations
  - CW beams preferred over pulsed (or spilled) for most testing protocols
  - RF structure should be minimized to remove peak flux-dependencies (e.g. error pile-up)
- Ion delivery and switching times, beam purity
  - Short testing periods (hours to few days) need efficient means to vary LET
    - Ion species change at same energy ~10-20 minutes
    - Energy change <2 hours
  - Beam contamination must be as low as possible (<5% to parts per million)

Accelerator architectures and tradeoffs

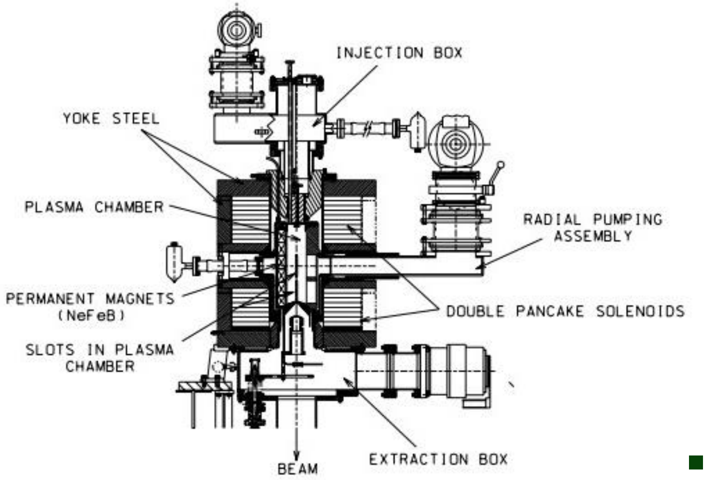
Architecture	Energy (MeV/u)	Flux Density (ions/s/cm^2)	Temporal Distribution	Ion Delivery Switching Times	Species (LET) Purity	Operational Issues
Cyclotron	5 – 40	10 – 10^6	Uniform, RF structure	Minutes @Const. energy <2 hr energy change Can use degraders	Excellent	Single point of failure
Low Energy SRF Linac	15 – 50	10 – 10^7 Supports >>10^{10}	Uniform, RF structure Fine control	Minutes Can use degraders	Good to excellent	Cryoplant needed (4K)
High Energy SRF Linac	>100	10 – 10^7 Supports >>10^{10}	Uniform, RF structure Fine control	Minutes Can use degraders	Good to excellent Fragmentation	Large cryoplant needed (4K, 2K)
Linac + Synchrotron	>1000	10^2 – 10^7 ions/cm^2 per spill	Pulsed, RF structure, Temporal variations >20%	Minutes Can use degraders	Good to excellent Fragmentation	Single point of failure

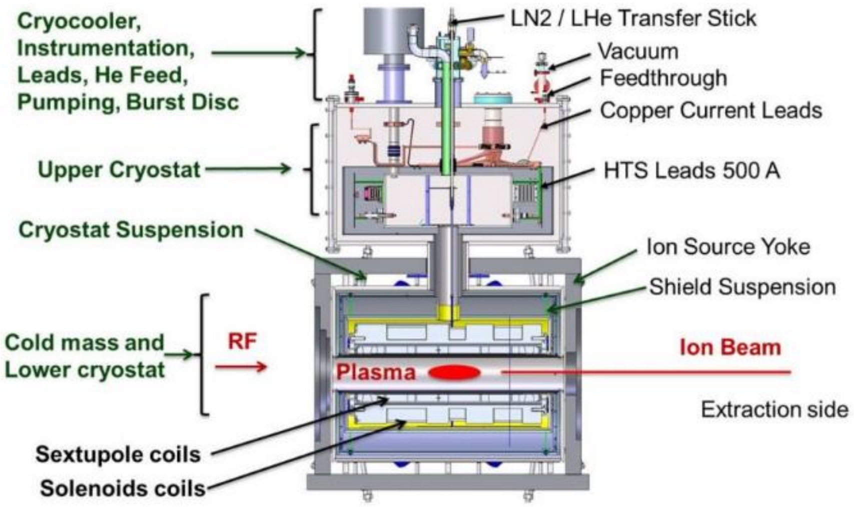
Essential Linac Systems

- **Ion source and injector**
  - ECR chamber can support multiple species simultaneously (A/q 2-7)
  - Species selectivity similar to cyclotron to limit beam contaminants
- **Linear accelerator**
  - CW operation
  - Fast Tuning capabilities – requires high peak current fast acquisition
  - High transmission and intensity flatness over delivery time (seconds to hours)
- **Delivery beamline and targetry/dosimetry controls**
  - Nonlinear optics and collimation. Large beam sizes.
  - Vacuum-air windows (thin for low energy, heavy ions)
  - Intensity and transverse distribution diagnostics in different diagnostic regimes (high rate and very low rate)

Injectors for Heavy Ions

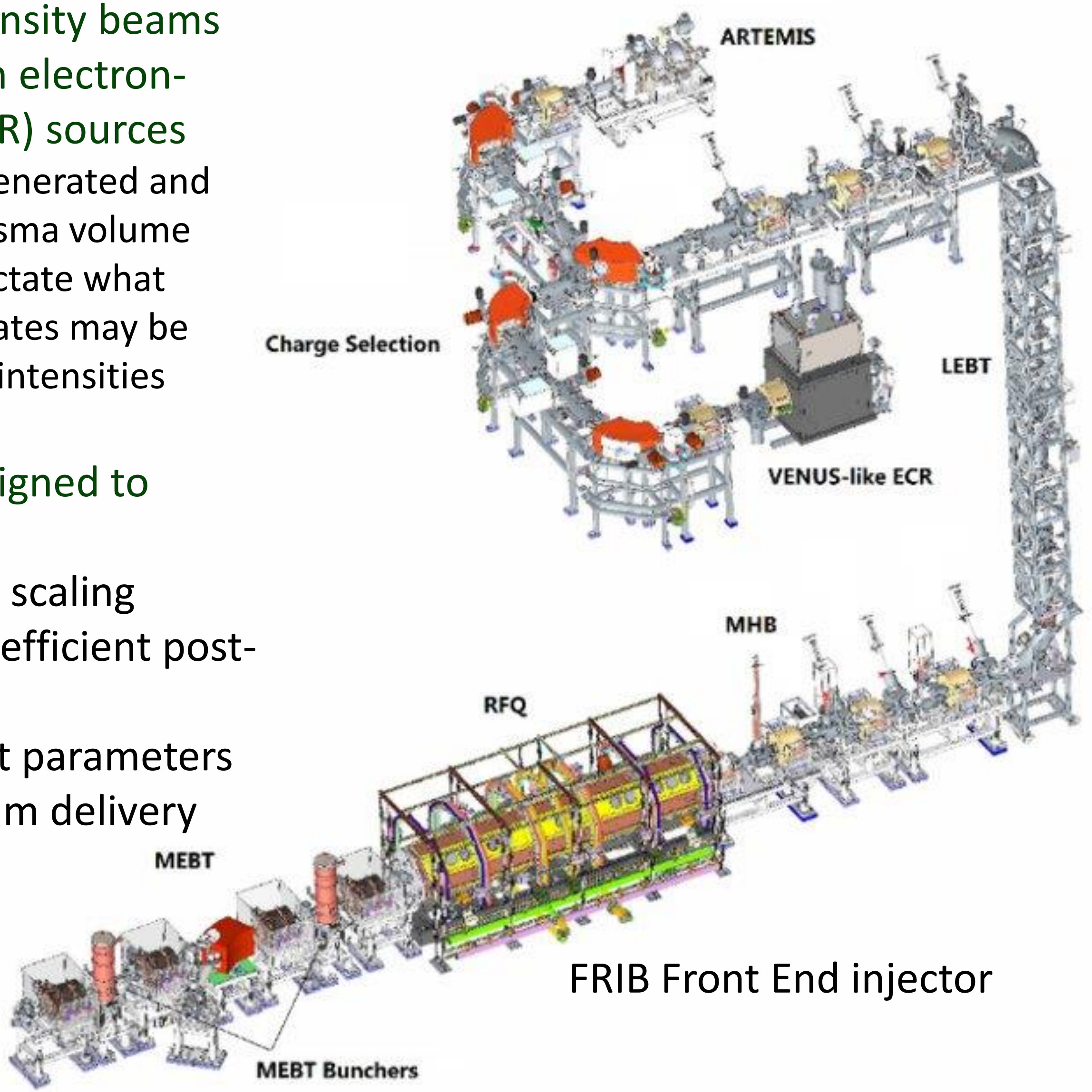
14 GHz ARTEMIS ECR





28 GHz VENUS-like ECR

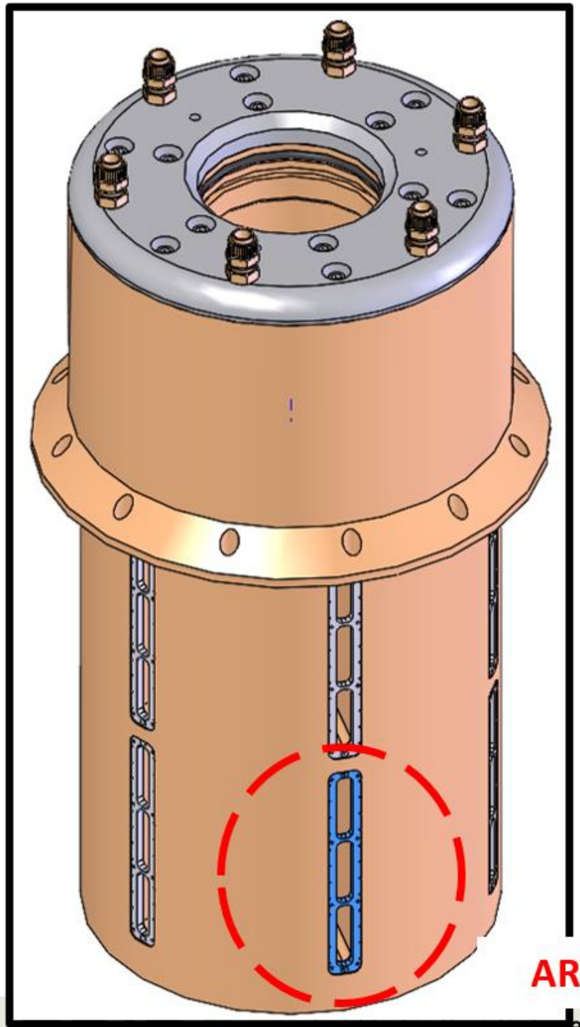
- Ion sources for high intensity beams are typically produced in electron-cyclotron resonance (ECR) sources
  - Ion cocktails can be generated and maintained in the plasma volume
  - ECR characteristics dictate what species and charge states may be generated in useable intensities
- Injector systems are designed to deliver specific ions
  - Use q/A tuning and scaling
  - Package beams for efficient post-acceleration
  - Measure and adjust parameters for high quality beam delivery

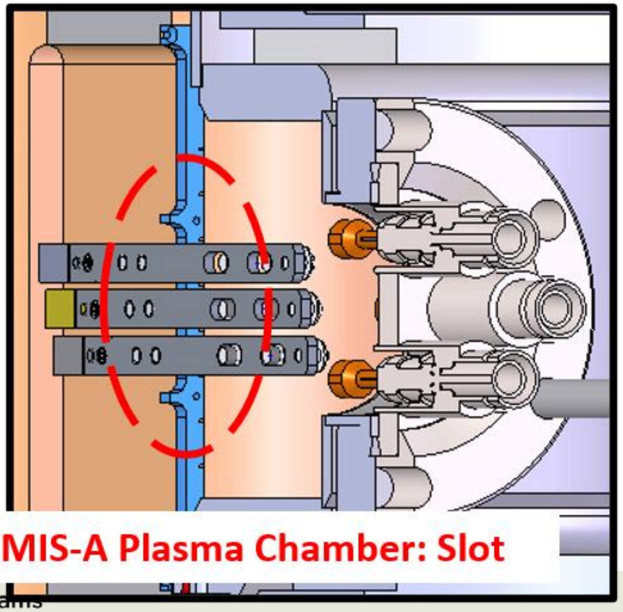


FRIB Front End injector

Adaptations to the 14 GHz ARTEMIS source

Adding on-demand sputtering sources to plasma chamber





ARTEMIS-A Plasma Chamber: Slot

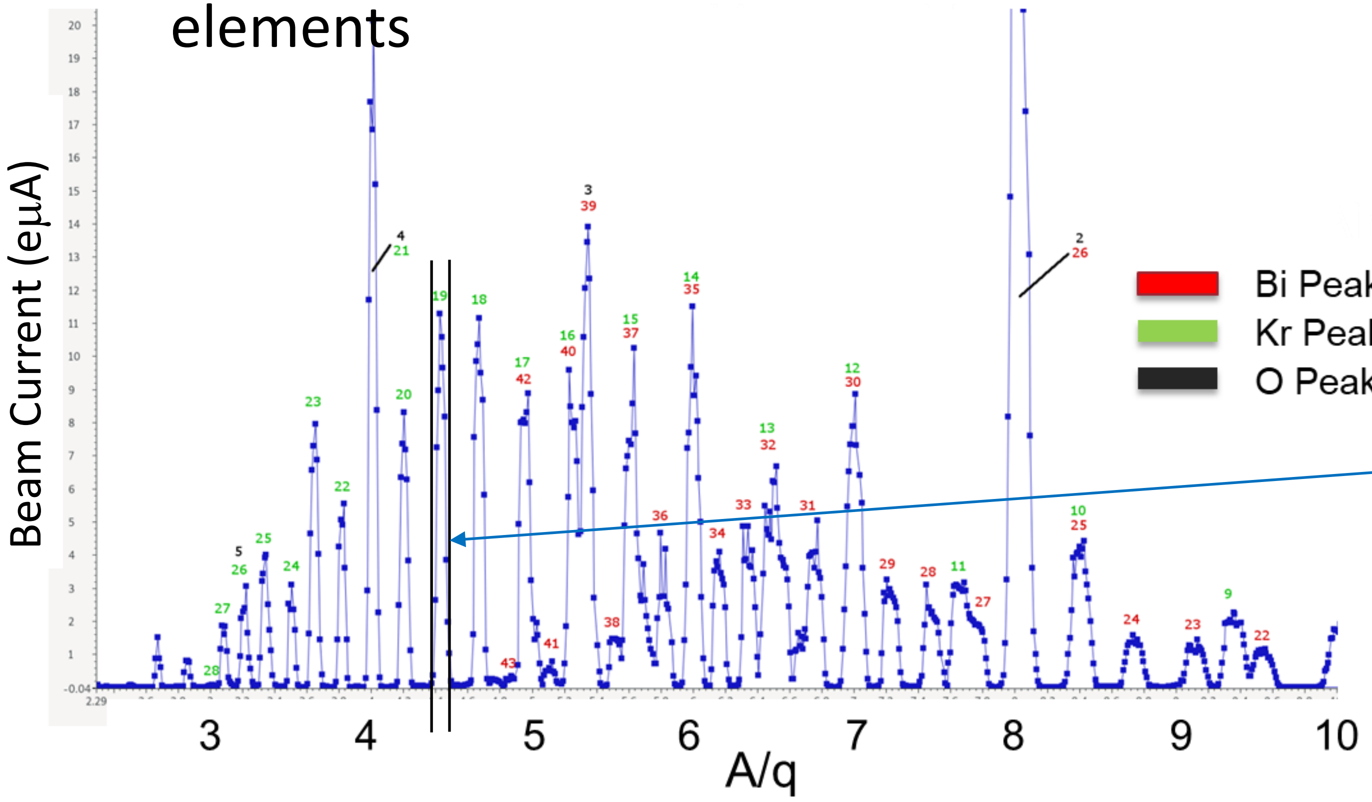
Adding 2nd RF frequency (10 GHz)

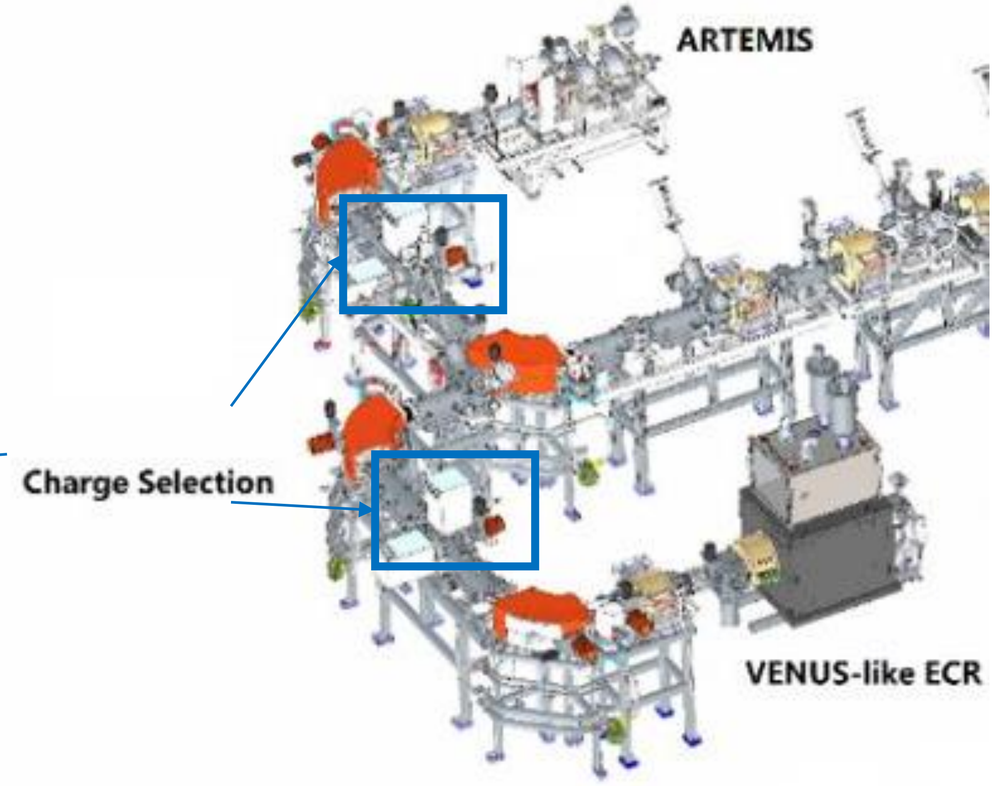
Ion species	Klystron only (eµA)	SSA only (eµA)	Klystron + SSA (eµA)
16O6+	140	145	230
16O7+	42/43	45	100
129Xe28+	4.9	[insufficient RF power alone]	4.5
129Xe29+	3.7	[insufficient RF power alone]	4.2
129Xe33+	0.3	[insufficient RF power alone]	1

- **Light ions see a large intensity increase**
- **Heavy ions see higher intensity in higher charge states**

Example of Cocktail Beam Developed with ARTEMIS

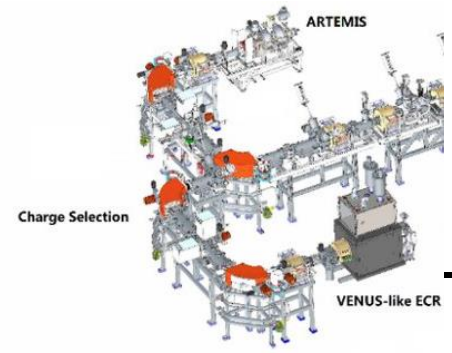
- A cocktail consisting of ^{209}Bi, ^{84}Kr and ^{16}O was produced with the 14 GHz ARTEMIS ion source
  - It takes time to stabilize ion source for cocktail operation but once stable, specific elements and charge states can be selected quickly by scaling the beamline magnetic elements

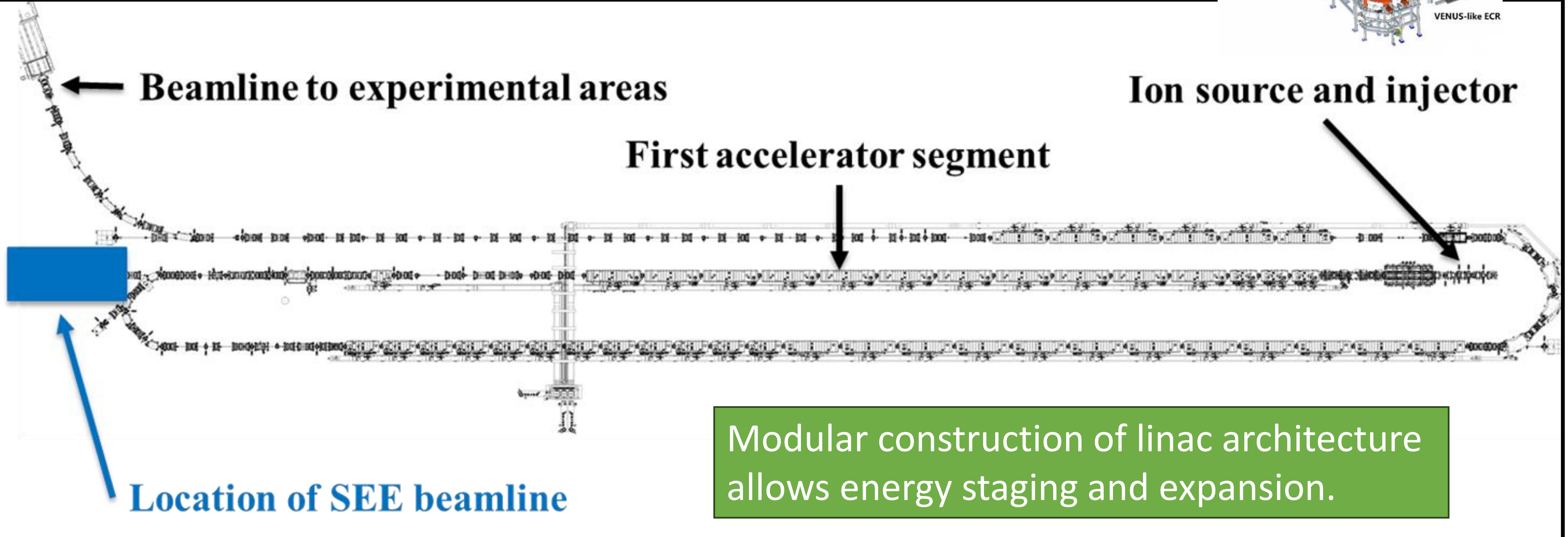




Linac Architecture for SEE Production

- Injector beamline at 12 keV/u
- MHB + RFQ to 500 keV/u → CW operation supported
- SRF Linac to 40 MeV/u, 300 MeV/u → CW operation supported





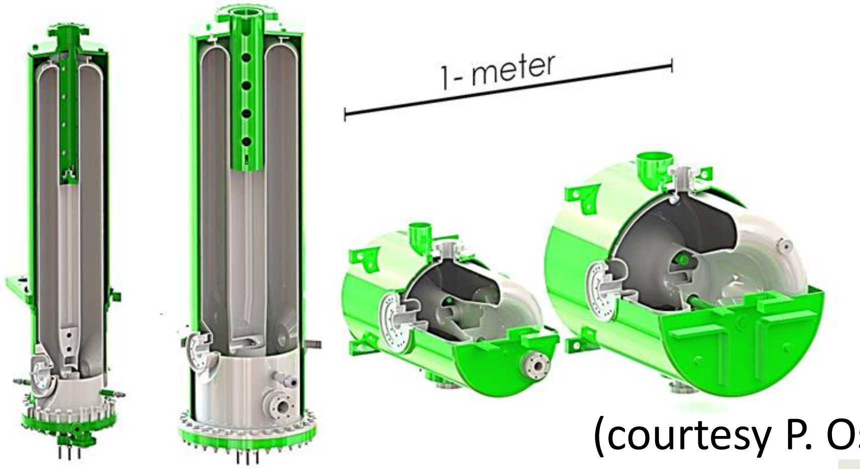
Modular construction of linac architecture allows energy staging and expansion.

Fast Linac Tuning Realized with Automation and Machine Learning

Approach: Model-based re-phasing of 308 SRF cavities in 180 seconds. The model is trained on the measured data of conventional 360 scans of cavity phases using ML tools .

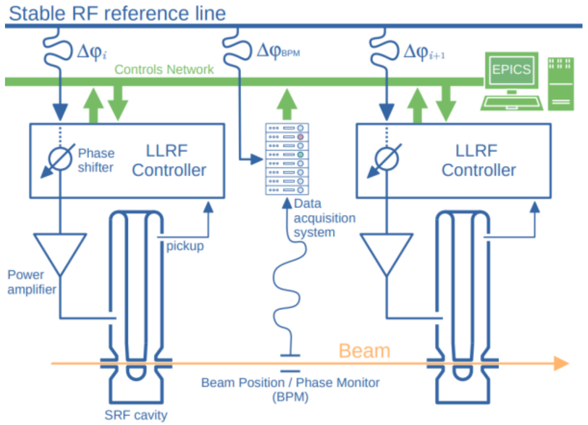
Impact:

- Linac re-phasing time reduced from 20 hours to 180 seconds.
- Total PDT duration decreased by a factor 25-50%
- Cavity failure or performance degradation can be mitigated in 180 seconds, reducing downtime to maintain high availability for user operations.

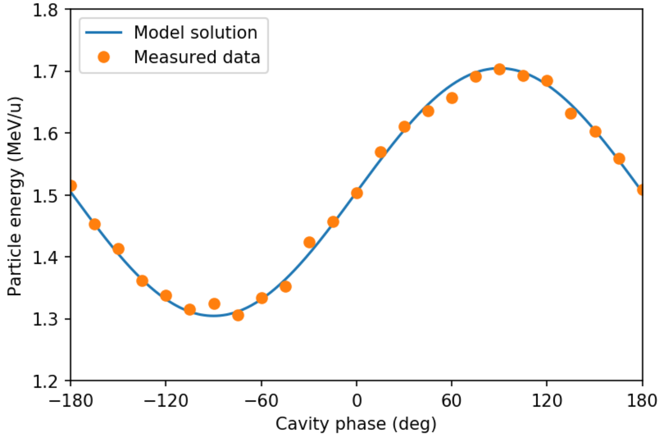


(courtesy P. Ostroumov)

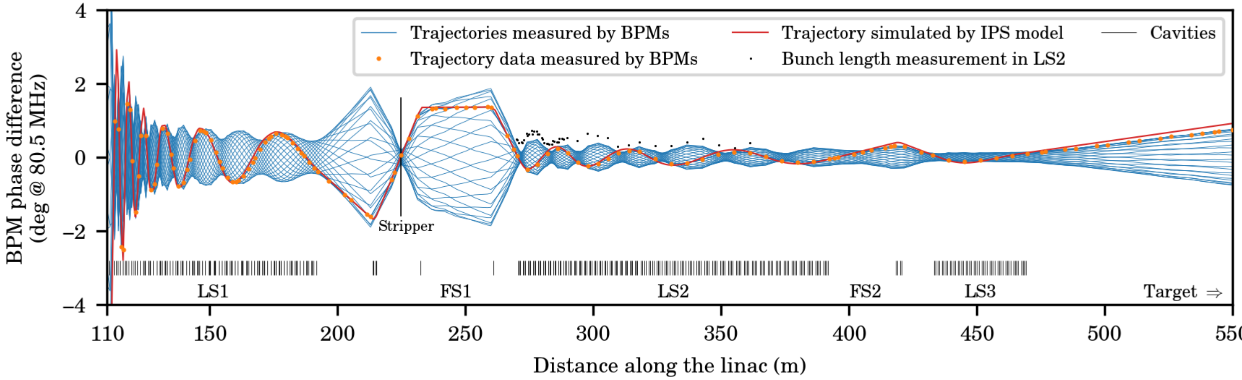
Motivation: Reduce the time required to retune the FRIB SRF linac, allowing more time for science. The linac consists of over 300 individually phased cavities.



Physics-informed model based on the integrated RF control system and beam instrumentation

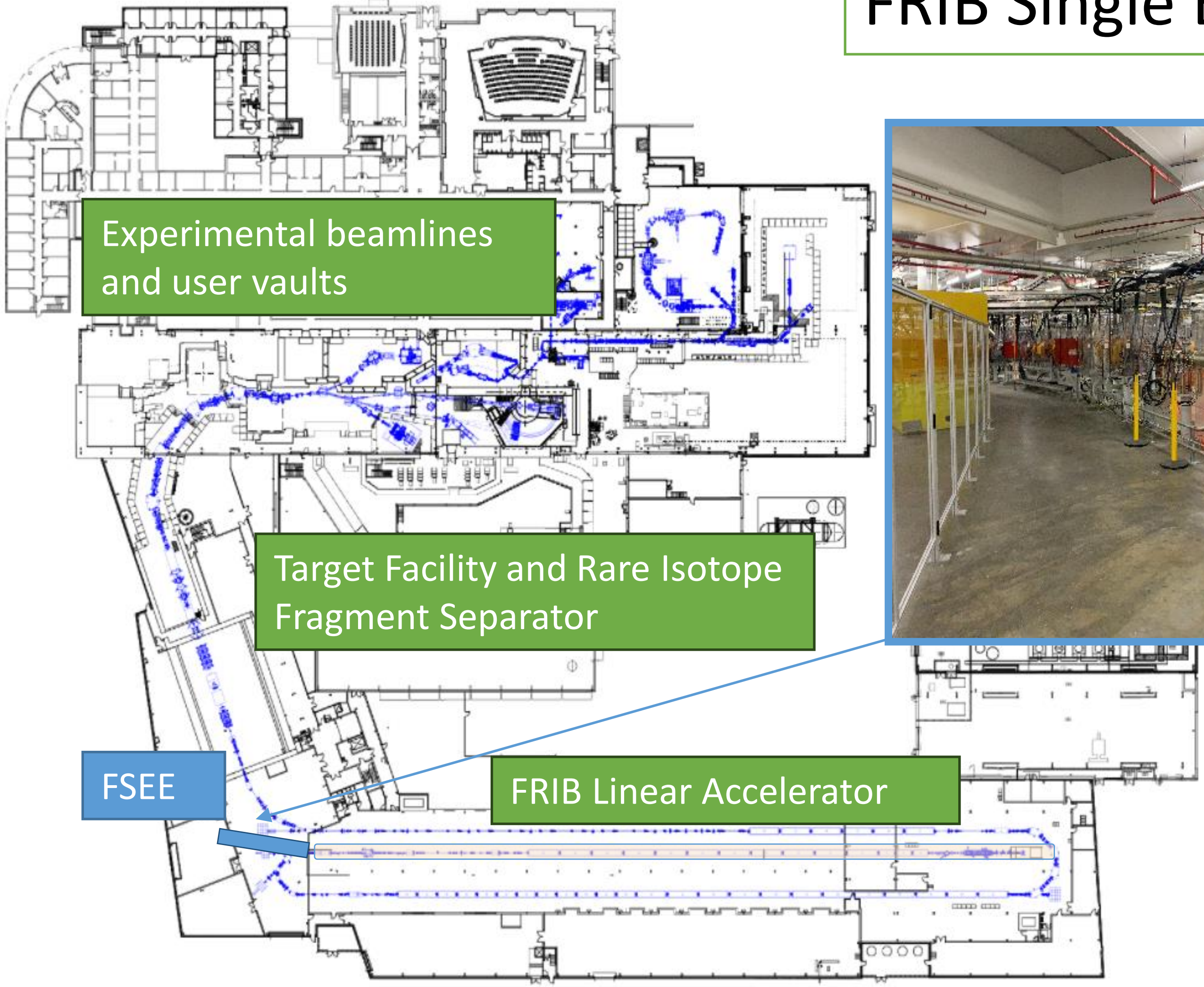


Model trained on measured 360-degree phase scan data

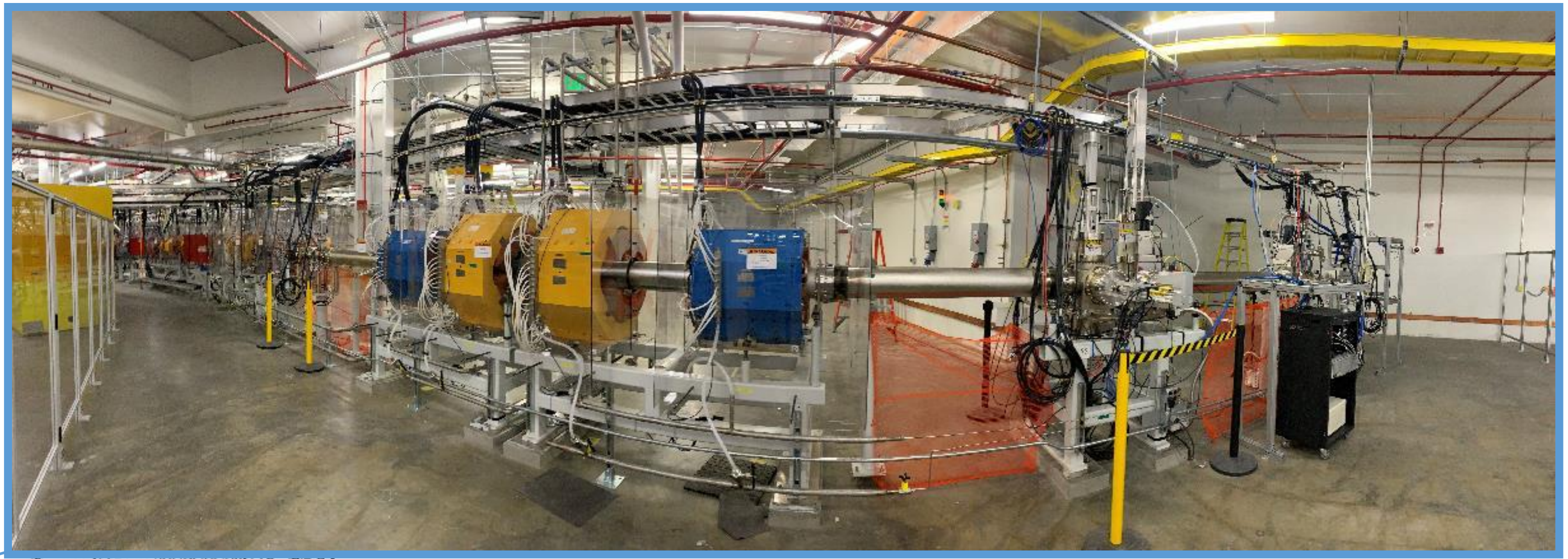


Envelope mapping technique developed to validate the model and verify the quality of predicted tunes

FSEE is Built on the FRIB Linac Infrastructure

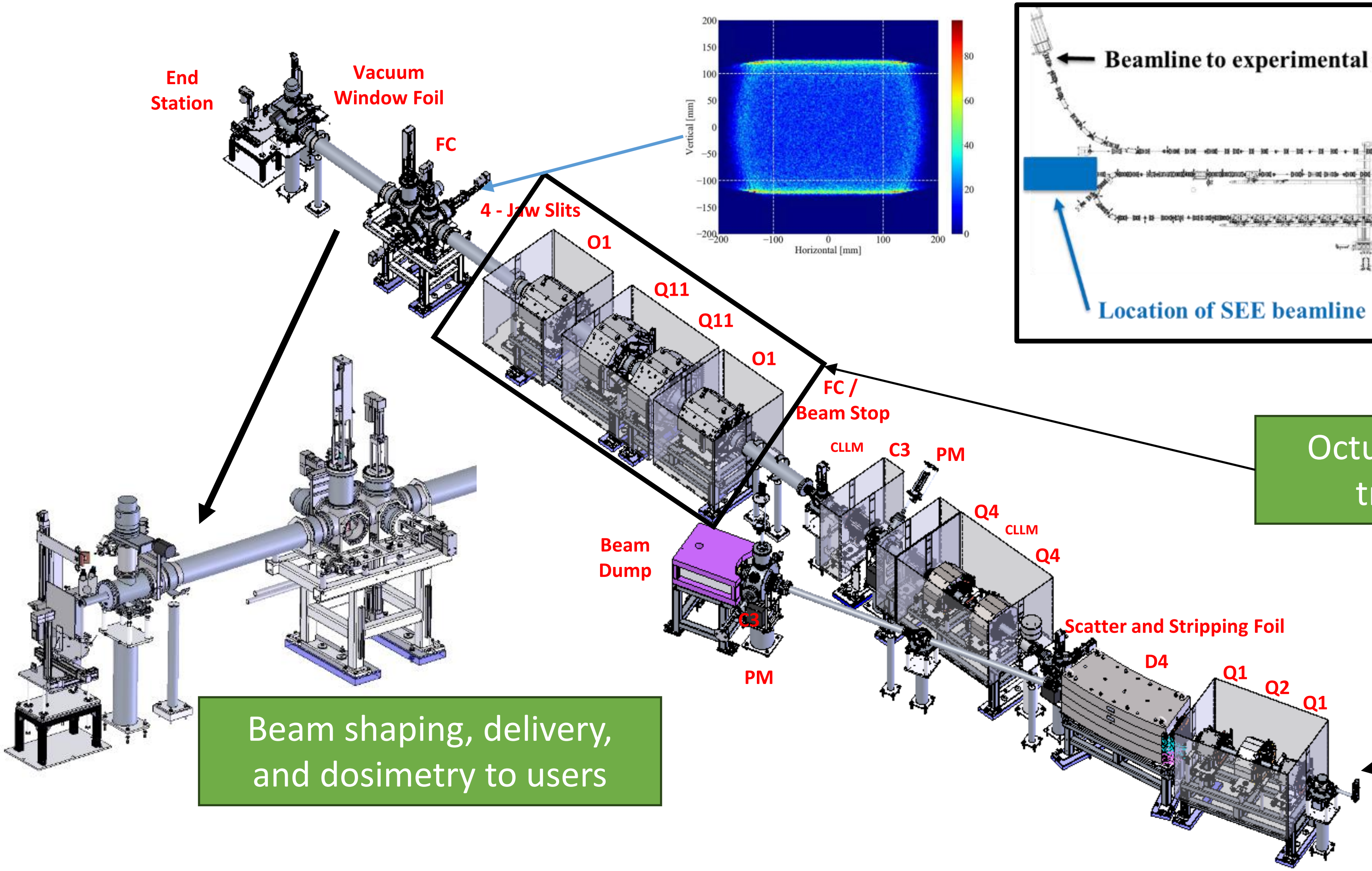


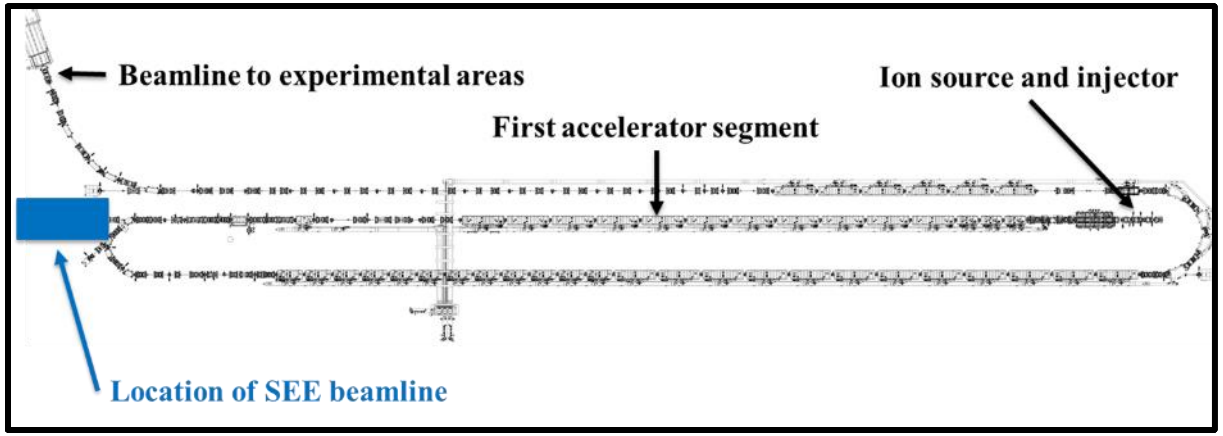
FRIB Single Event Effects (FSEE) Facility



FSEE uses the ion source, Front End, and first segment of the FRIB linac.

FSEE Beamline Layout





Octupole-quadrupole beam transformation optics

Upstream Interface to linac

Beam shaping, delivery, and dosimetry to users

Challenges for linacs

Beam purity and ion switching time

Linac injectors are less capable mass discriminators, and high linac acceptance permits entraining of contaminant species.

Time structure

Efficient acceleration requires tight RF bunching. Debunching at high energy requires high energy spreads, long drift lengths, or very high field dipoles.

Diagnostics for high dynamic range

Linacs built for high intensity require additional diagnostics beyond the intended dynamic range.

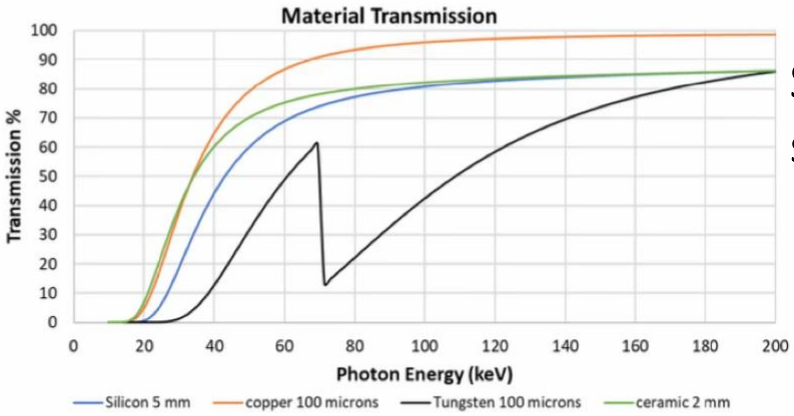
High energy fragmentation effects

Beam interactions with degraders, windows, slit collimators generate additional fragments with a spread of energy/mass and LET.

Bypassing the Heavy Ion Linac – LET simulators

- DARPA ASSERT program seeks to develop means for screening semiconductor devices at the foundries.
  - Small footprint facility
  - Provide go/no-go discrimination for further testing with heavy ions

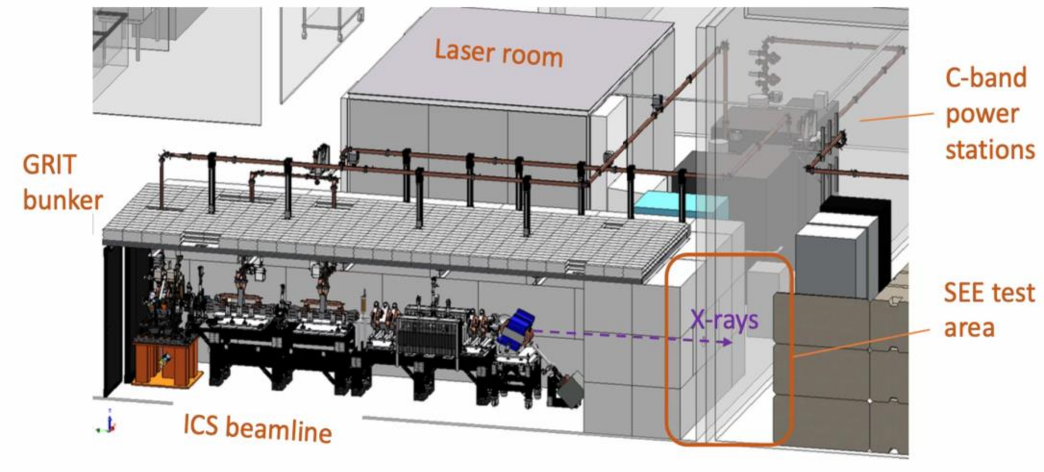
Radiabeam/Radiasoft/Aerospace Corp/SLAC Proposal

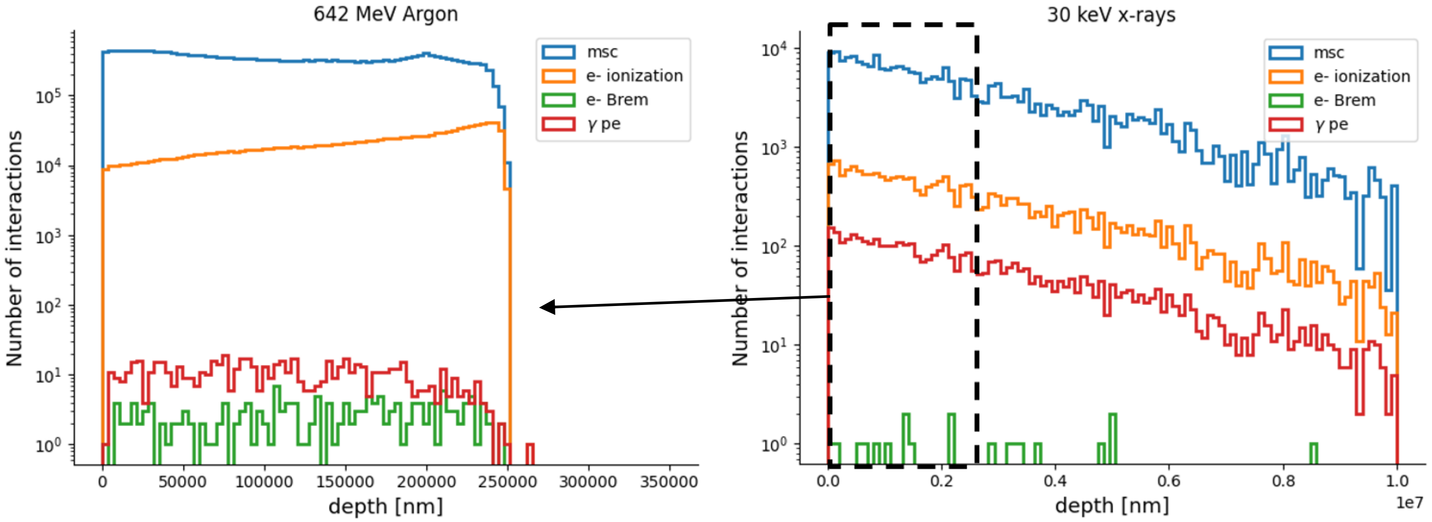


Synchrotron pulsed x-ray research shows promising results

- Higher x-ray energy emulates heavy ion LETs for charge
- Also correlates to transients

Inverse Compton Scattering X-ray Source





Courtesy G. Andonian (Radiabeam), S. Coleman (Radiasoft)

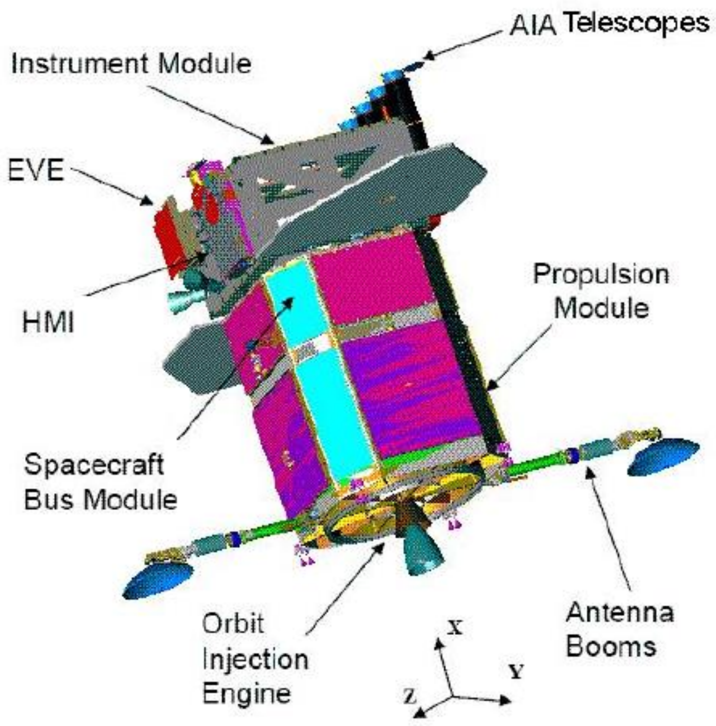
Outlook

- Current efforts focused on new cyclotron facilities; expanding existing heavy ion accelerator support for SEE users
  - Michigan State University FSEE (<40 MeV/u), KSEE (K500 cyclotron <40 MeV/u), FSEE3 (<350 MeV/u)
  - Brookhaven National Lab HEET (GeV)
  - CERN HEART (multi-GeV)
  - Additional utilization of medical synchrotrons (HIMAC, MedAustron)
- Testing protocols are shifting towards higher energy beams
  - Demand signal is strong with uncertainties – is demand elastic ?
  - Parasitic operations are expanding. New beamlines at existing facilities.
  - Multiple regions are exploring needs for dedicated high energy ion beam facilities.
- SRF Linacs provide modular, expandable system for full characterization
- Compact accelerators may provide initial radiation hardness assurances

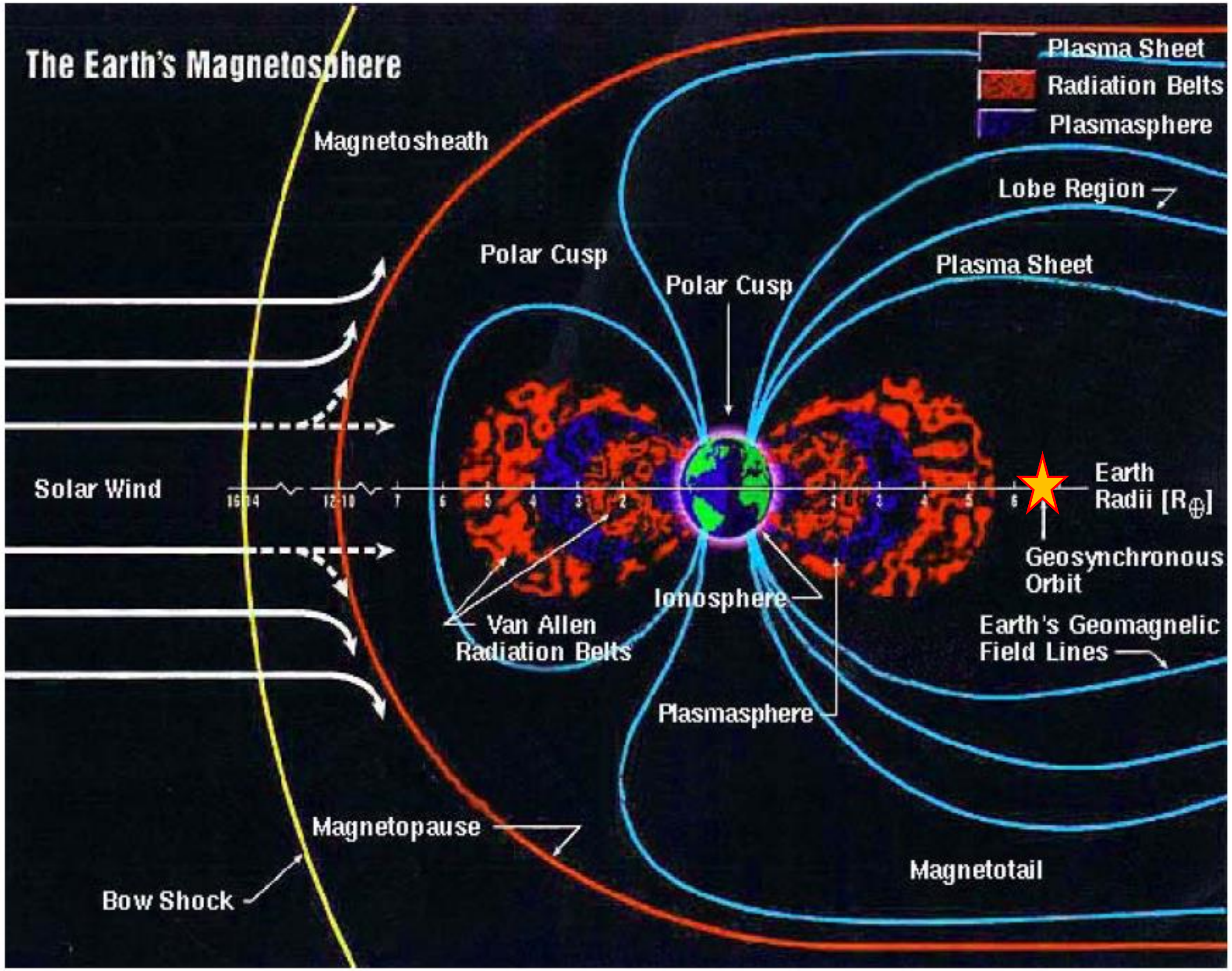
Thank you for your attention

Acknowledgments
- G. Andonian (Radiabeam)
- S. Coleman (Radiasoft)
- K. LaBel (TSS)
- BNL NSRL
- DARPA ASSERT

Example Mission: Solar Dynamic Observatory (2008)



Buchner 2008



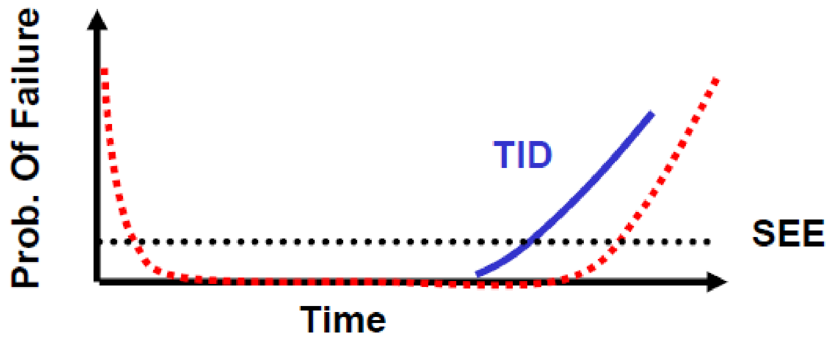
Mission Requirements Set Testing Needs

1. **Mission launch date and duration:**
   a) Launch date is November 2008 - increased solar activity.
   b) 5-year mission (10-year option).
   c) Geosynchronous orbit.
2. **Operation Requirement:**
   a) Must be operational 95% of the time.
3. **Data Requirement:**
   a) Data downlink at 150 MBPS (250 DVDs per day).
   b) Data integrity must be 99.99% valid.
4. **Radiation Requirement:**
   a) Continue functioning reliably for five years in radiation environment at geosynchronous orbit.
   b) Single event effects – non-destructive and destructive.
   c) Cumulative radiation effects – TID and DD.

Buchner 2008

SDO Part Level Requirements

- ***Cumulative***
  - **Total Ionizing Dose** (TID = 60 Mrad(Si) – free field)
  - **Displacement Damage** (DD = $2x10^{10}$ MeV/gm – field free)
- ***Single Event***
  - **Non-Destructive** (LET_{th} > 36 $MeV.cm^2/mg$)
    - Single Event Upset (SEU),
    - Single Event Transient (SET),
    - Single Event Functional Interrupt (SEFI).
  - **Destructive** (LET_{th} > 80 $MeV.cm^2/mg$)
    - Single Event Latchup (SEL)
    - Single Event Burnout (SEB)
    - Single Event Gate Rupture (SEGR)



Non-Destructive SEE rates are incorporated into planned down times

Destructive SEE events are NOT ALLOWED