Single-Event Effects
Part 2 – SEE Facilities and Practical Considerations for Measuring SEE

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Luddy School of Informatics, Computing, and Engineering
Indiana University

Module 3: Objective and Outcomes

- This module will
  - Introduce the basic principles of accelerator facilities used for SEE testing
  - Describe the properties of ground test facilities related to microelectronics test requirements
  - Outline the necessary measurements for obtaining accurate SEE models
  - Provide a practical guide for preparing for an SEE experiment

- Student Outcomes
  - 1. Students will demonstrate an understanding of critical ground test properties and variables and how they influence test performance requirements.
  - 2. Students will be able to describe the beam structure, method of delivery, and the beam's influence on an experiment.

Outline

- SEE Radiation Facility Basics
  - Accelerators
  - Beam basics
  - Properties of ground test parameters
  - Available beams
- Measuring SEE
  - SEE Cross Section and LET Threshold
  - Modeling SEE Cross Section
  - Sensitive Volume
  - From Experiment to On-orbit Rate Estimate
- Practical Considerations

04

SEE Radiation Facility Basics

Accelerators for SEE: Testing procedures are dependent on the chosen facility!

- The main types of facilities used for SEE testing are:
  - Linear accelerator (LINAC)
  - Cyclotron
  - Synchrotron
  - Other:
    - Tandem Van der Graff (TvdG)
    - Pulsed laser
    - Short-pulse X-ray

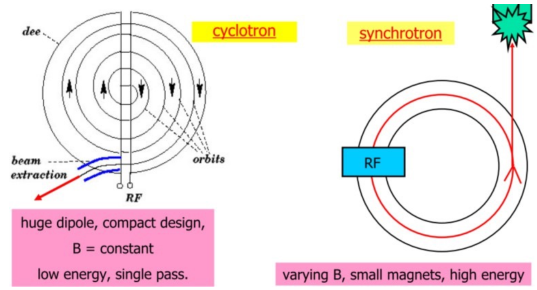
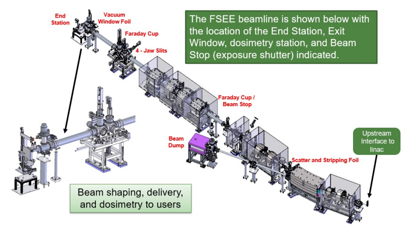


Image Credit: T. Olson, 2021



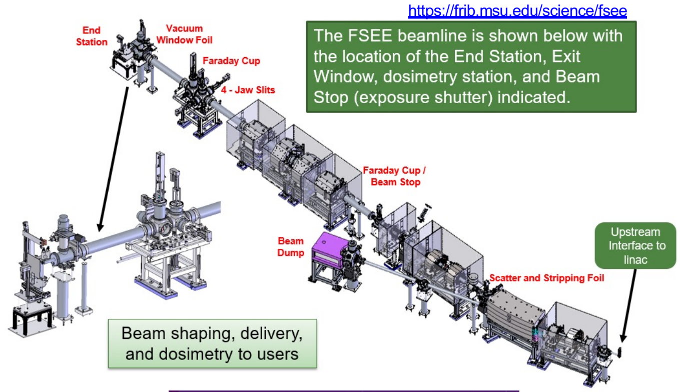
https://frib.msu.edu/science/fsee

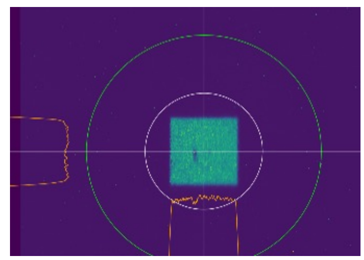
Linear Accelerator (LINAC)

- LINACs include a series of RF cavities that use electromagnetic fields to accelerate particles and magnets to focus the beam through transport.
- Benefits:
  - Higher energy requires more stages and doesn't rely on magnetic field constraints
  - Good beam control and stabilization
- Limitations:
  - Higher energies require longer distances; e.g. , the FRIB is approximately 450 ft long!
- Example: Michigan State University's (MSU) Facility for Rare Isotopes Beam (FRIB)

https://frib.msu.edu/science/fsee

The FSEE beamline is shown below with the location of the End Station, Exit Window, dosimetry station, and Beam Stop (exposure shutter) indicated.

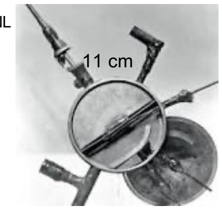




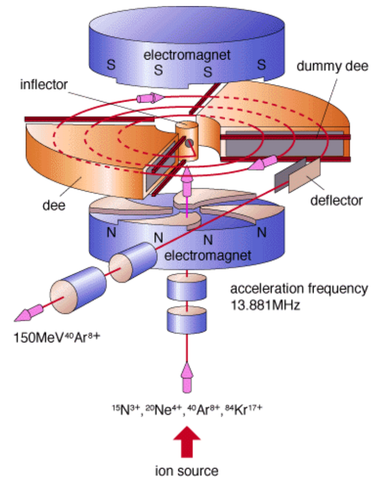
https://frib.msu.edu/science/fsee/facility-details

Cyclotrons

Image credit: LBNL

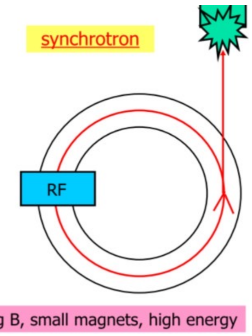


- Cyclotrons use a constant magnetic field and an alternating electric field, resulting in a "nearly" constant particle flux and are the most common for SEE testing
- Benefits:
  - Compact design and more cost effective (for low to moderate energies)
  - Continuous beam
- Limitations:
  - Large magnets required; higher energies require larger and stronger magnetic fields
- Examples:
  - Lawrence Berkeley National Laboratories (LBNL) 88": Heavy ion "cocktail" with 10, 16, & 20 MeV/amu
  - Texas A&M University's (TAMU) K500: 15-40 MeV/amu
  - TAMU K150: 15 MeV/amu
  - TRIUMF 520 MeV



Synchrotrons

- Synchrotrons allow for higher energy beams than LINACs and Cyclotrons. Particles are compressed into separate bunches spaced on a scale of RF wavelength. Bunches are contained in a ring and pass through RF cavities that provide successive energy increases.
- Limitations:
  - High cost and space requirements
  - Pulses or "bunches" of particles can complicate SEE testing
- Example
  - NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL):
    30 MeV/amu to > 1 GeV/amu



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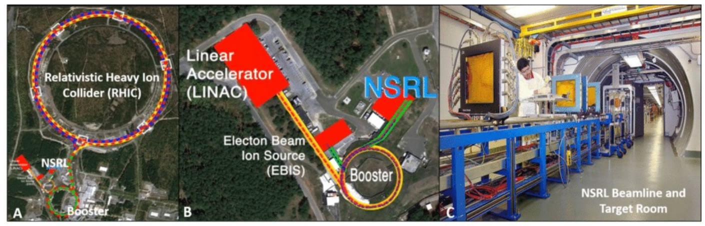


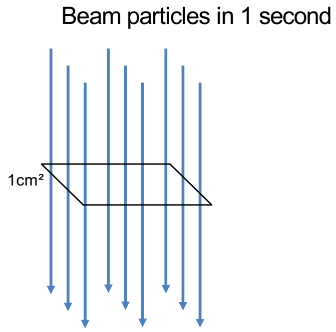
At NSRL:

The ions are delivered to the target room in 300 ms spills approximately every 3.7 s!

Beam Basics - Flux and Fluence

Flux: The rate of beam particles passing through a unit area

Question: *Is flux always constant?*



Flux = 9 /cm²/s

Pause, ask question to connect to accel type

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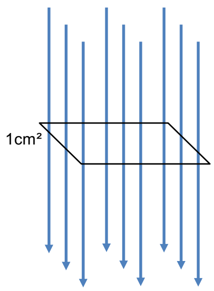
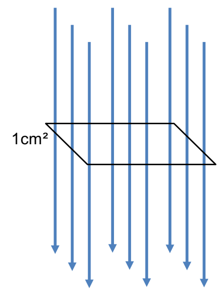
Beam particles in 1 second

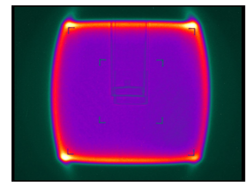


Flux = 9 /cm²/s

Fluence: The total number of beam particles passing through a unit area in over some period of time

Beam particles during an entire run





https://www.bnl.gov/nsrl/docs/pdf/nsrl-electronics-testing.pdf

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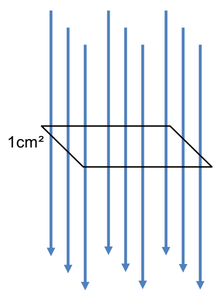

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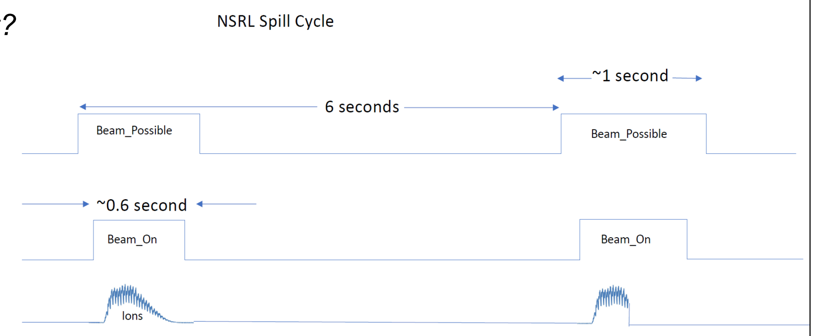
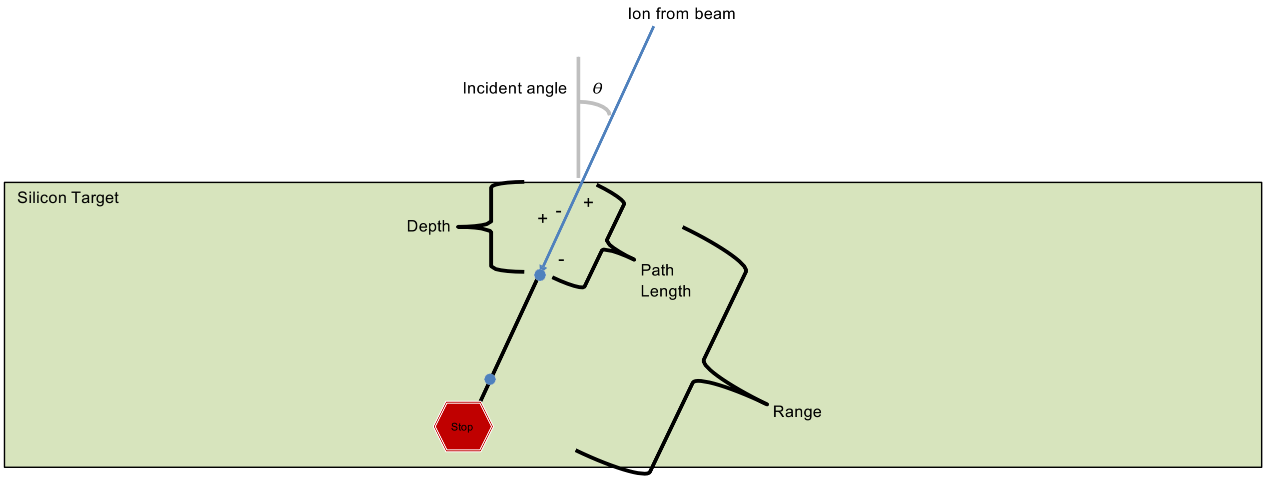
Synchrotrons release radiation in "spills"



BNL/NSRL User Guide

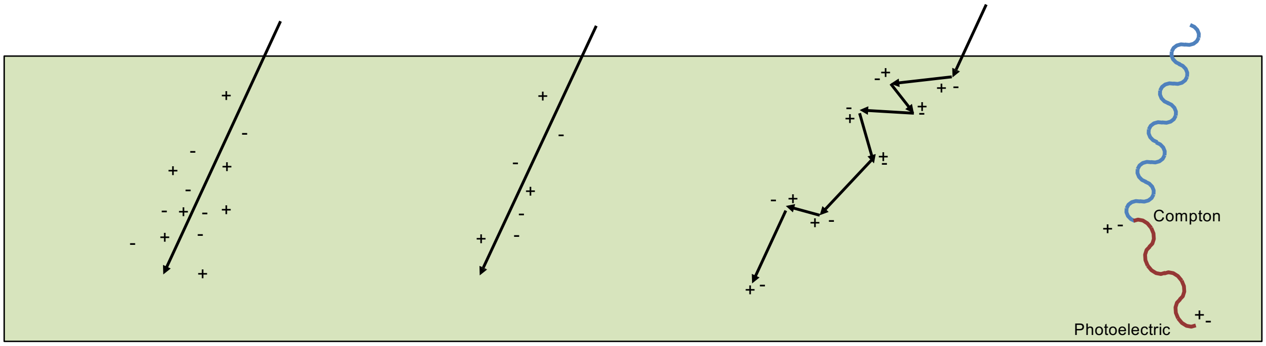
Pause, ask question to connect to accel type

Beam Basics - Geometry



Particle Track

- Heavy Ion (Z≥2)
- Proton (Z=1)
- Electron
- Photon



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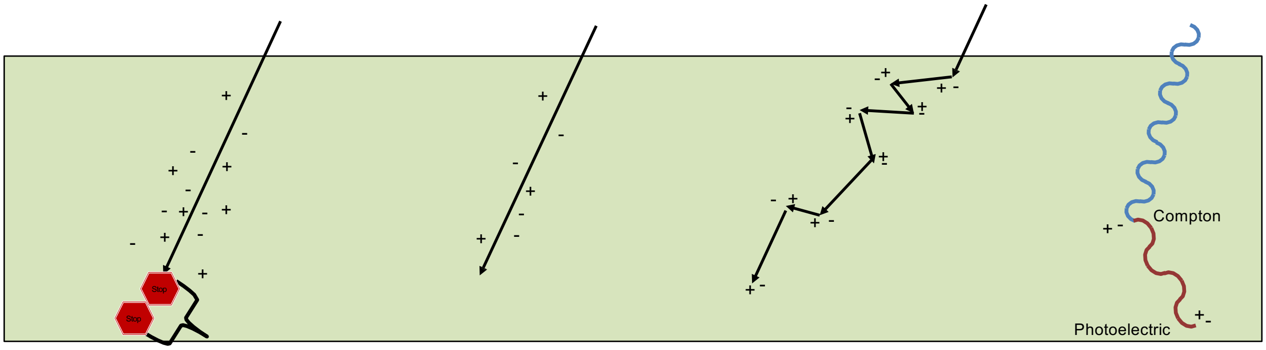


Straggling: variation in total range of individual beam particles due to probabilistic nature of interactions. Thus, the “Range” of a beam is not exact.

Mean free path: average distance travelled by a beam particle between interactions that change its path or energy.

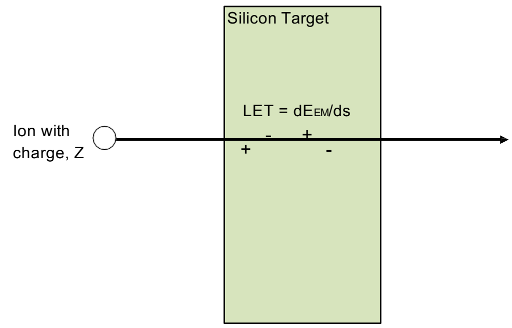
LET – Linear Energy Transfer

- The rate of ionization energy deposition per unit of path length

$$LET = dE_{EM}/ds$$

- s is along the path of the particle

- LET is a critical metric for beams used in SEE testing because it quantifies the density of charge generated inside the target material



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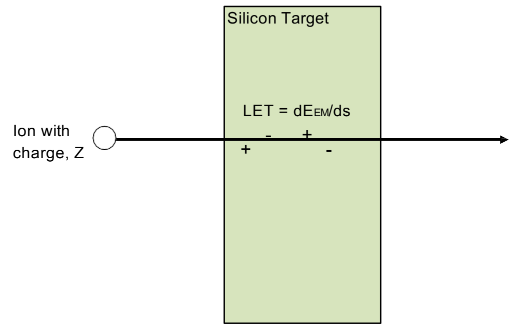
- What influences LET?



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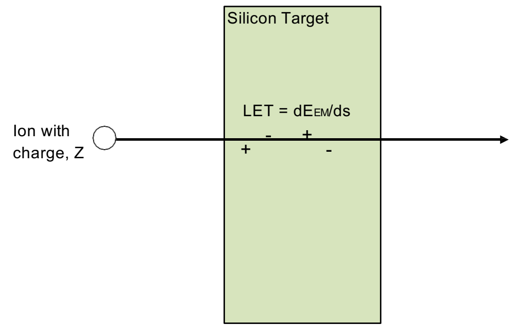
- What influences LET?
  - Charge of ion, Z
  - Target Material
  - Energy of ion
    - » Initial ➔ "Initial LET"
    - » At each location along the ion's path ➔ Instantaneous LET



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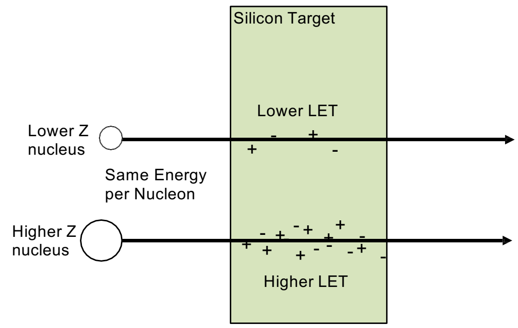

- Higher Z ions are more stressing from an SEE test standpoint, *i.e.,* they have higher LET (everything else being the same)

LET – Linear Energy Transfer

- The rate of ionization energy deposition per unit of path length

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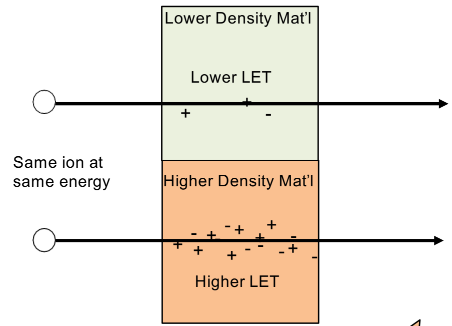
- LET is a critical metric for beams used in SEE testing because it quantifies the density of charge generated inside the target material.



- LET is dependent on the target material!!

Caution: "What is the LET of the beam?" … in silicon(?)

LET – Units

- The rate of ionization energy deposition per unit of path length

$$LET = dE_{EM}/ds$$

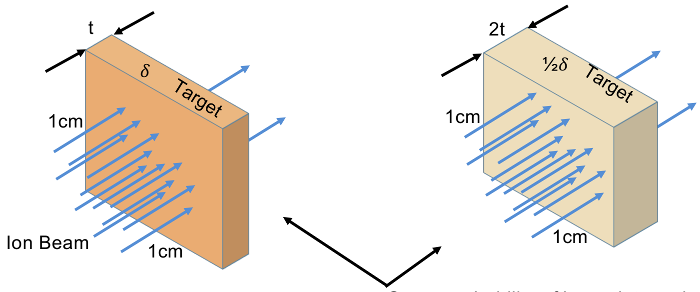
- s is along the path of the particle

- LET is a critical metric for beams used in SEE testing because it quantifies the density of charge generated inside the target material.

- LET units
  - MeV·cm²/mg
  - Think of it as:
    - MeV/(mg/cm²)
    - MeV/(cm · mg/cm³) ➔ dE/(ds*δ)
    - Energy deposited per unit of length normalized by density of the target material

Target Density

- Just as chance of interaction can be increased by increasing t, it can similarly be increased by **increasing density**



Same probability of beam interaction

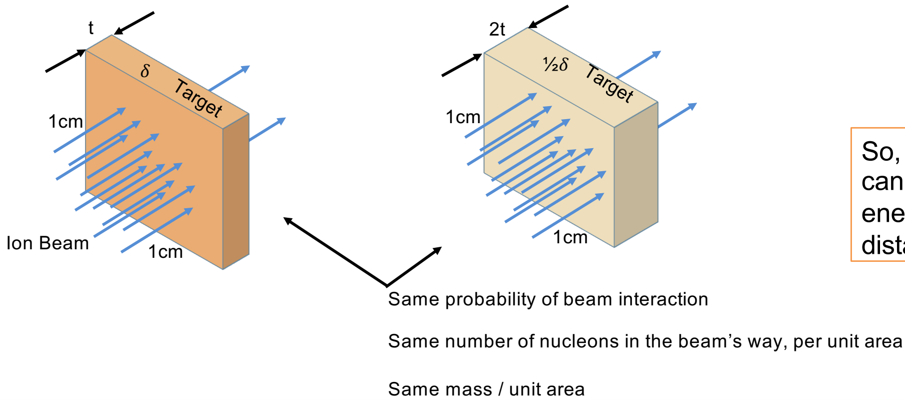
Same number of nucleons in the beam's way, per unit area

Same mass / unit area

"Thickness" can be thought of as mass per unit area of the target

Target Density

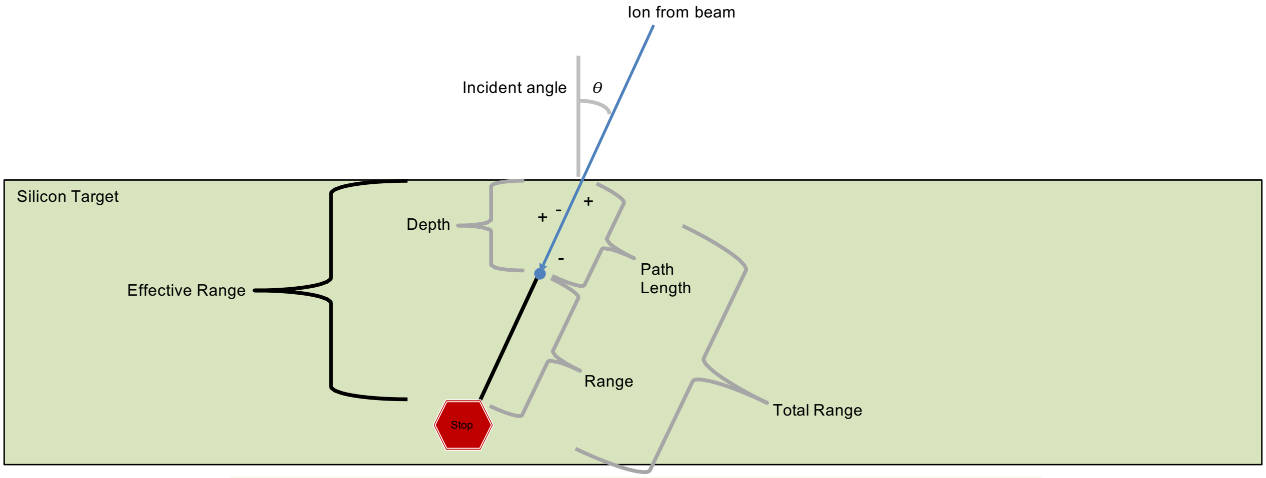
- Just as chance of interaction can be increased by increasing t, it can similarly be increased by **increasing density**



So, MeV/(mg/cm²) can be thought of as energy per unit of distance

“Thickness” can be thought of as mass per unit area of the target

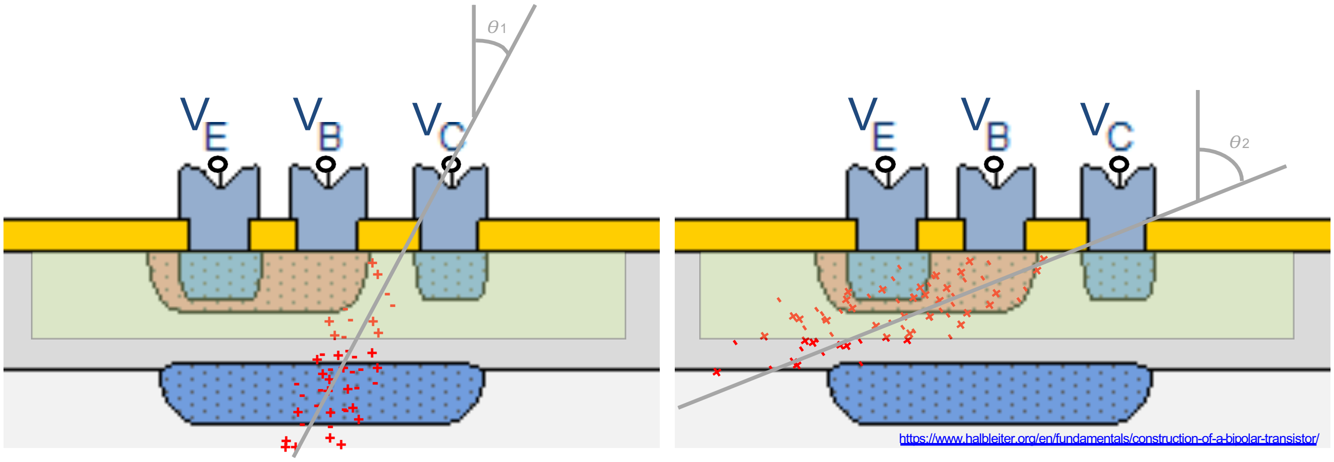
Beam Basics – Orientation



Effective LET ➔ LET as if the beam were normally incident

Effective Range ➔ Range as if the beam were normally incident

Influence of Angle of Incidence



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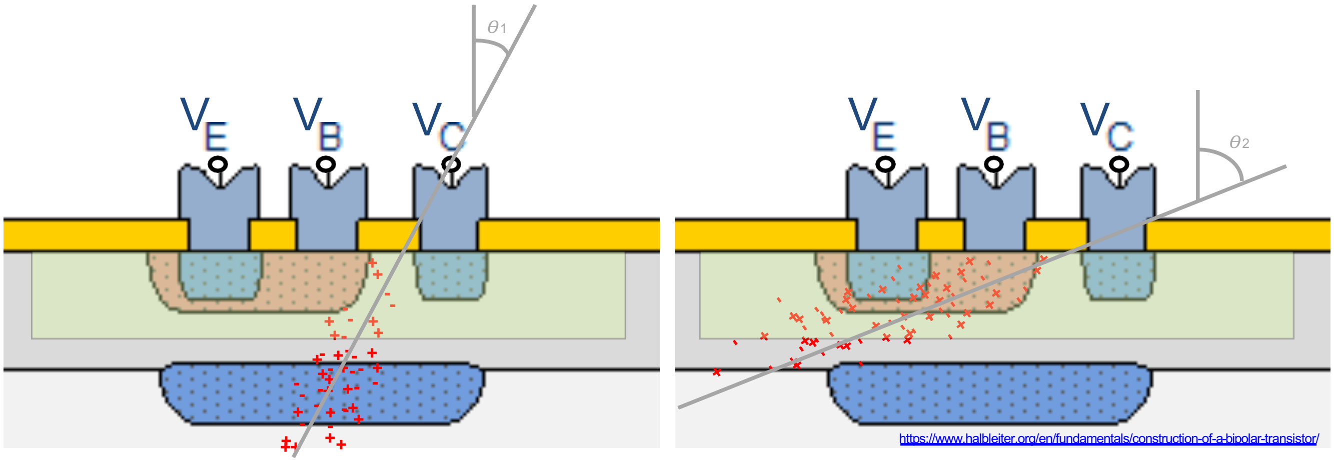
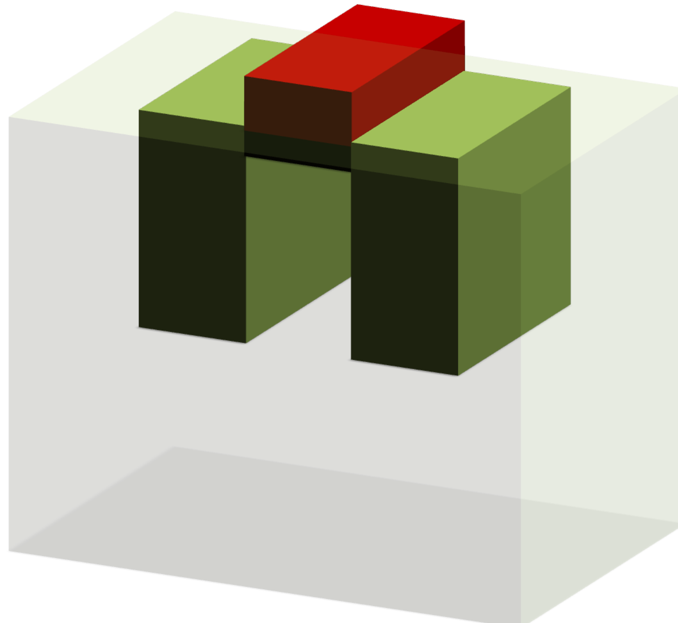


- Larger angle of incidence deposits greater charge in ”sensitive volume (SV)”
- **True or false:** Larger angle of incidence is comparable to being hit with a higher LET ion? Why or why not?

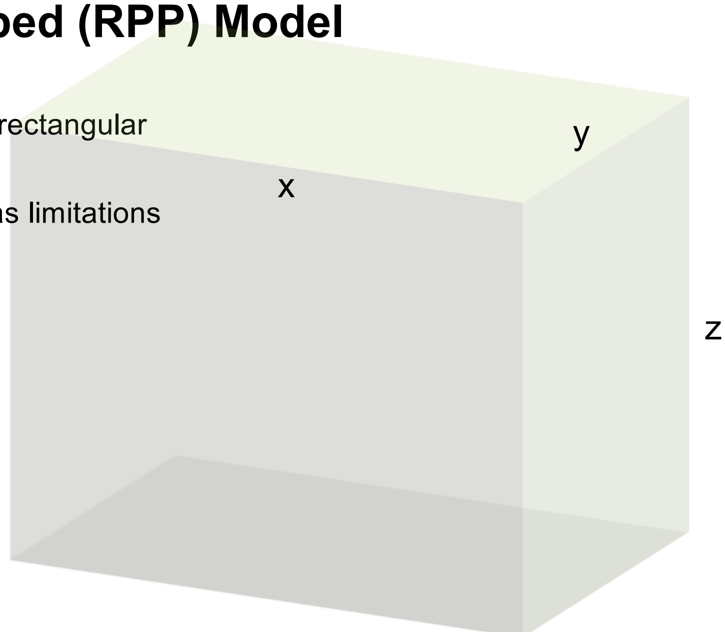
Sensitive Volume (SV)

- SV = Region of a device within which charge can contribute to SEE
- Critical Charge (Q_{CRIT}) = The threshold of charge in the SV that will result in an SEE of interest



Rectangular Parallel Piped (RPP) Model

- RPP is an abstraction as if the SV truly is rectangular
- Useful conceptually, but be careful as it has limitations



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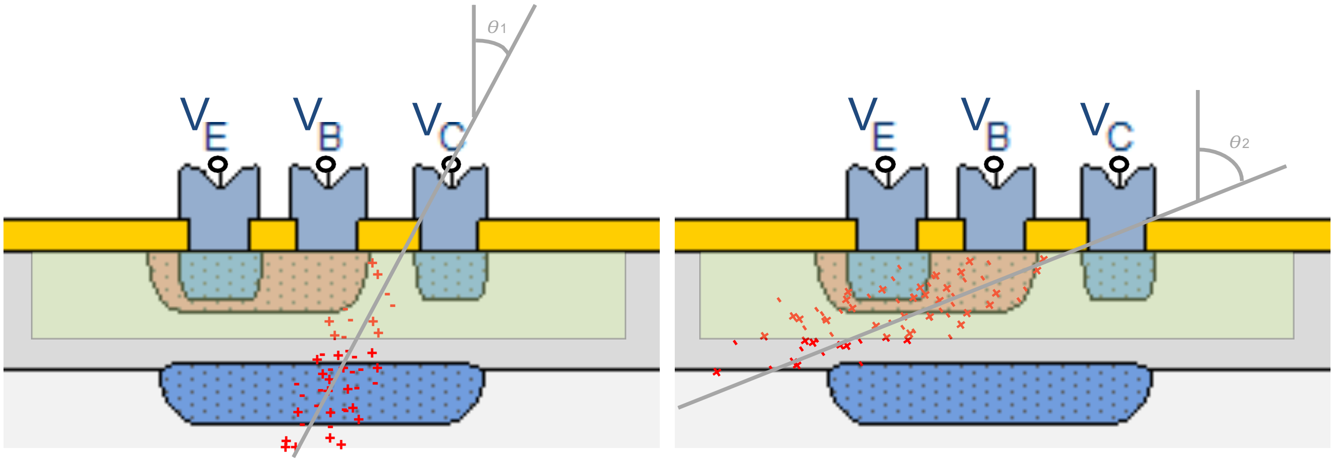
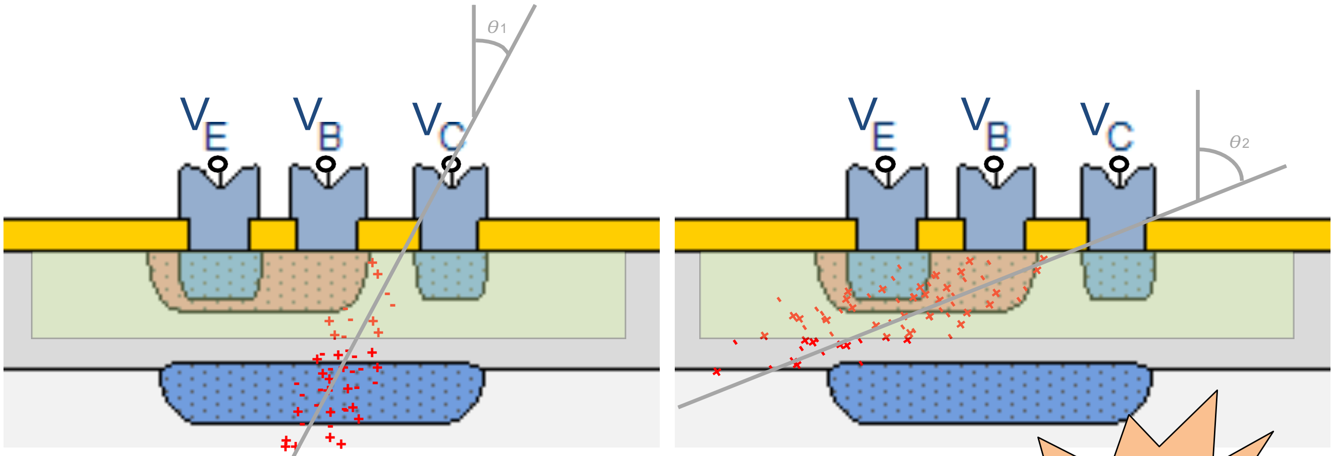


- Larger angle of incidence deposits greater charge in SV
- Comparable to being hit with a higher LET ion
- Effective LET: $LET_{eff} = LET / \cos(\theta)$

Influence of Angle of Incidence



- Larger angle of incidence deposits greater charge in SV
- Comparable to being hit with a higher LET ion
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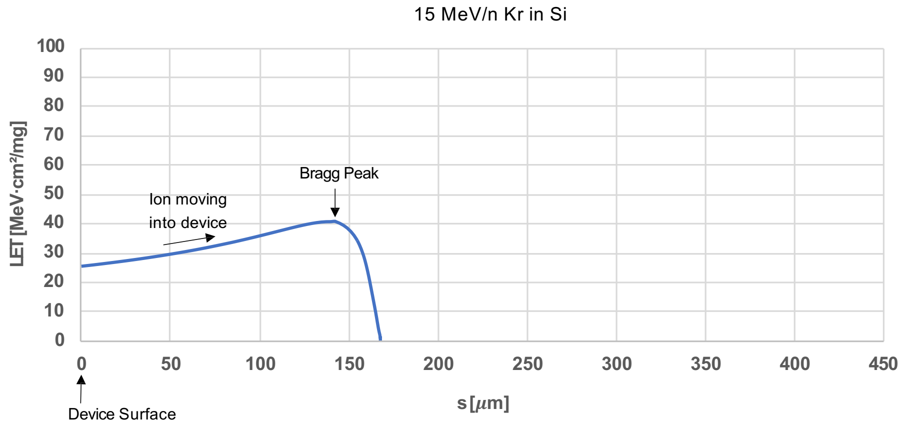
Caution: Not all SEE follow $1/\cos(\theta)$

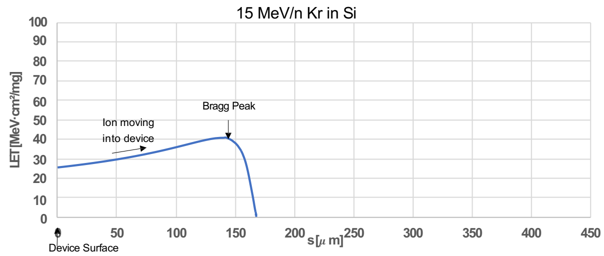
LET as Ion Moves through Material

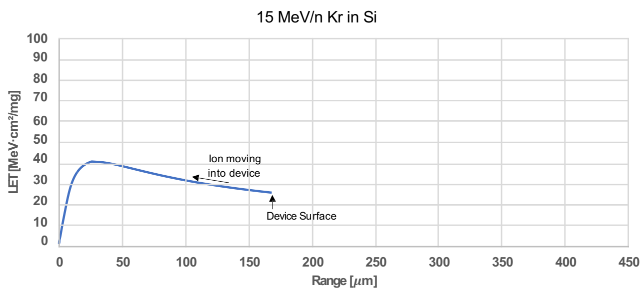


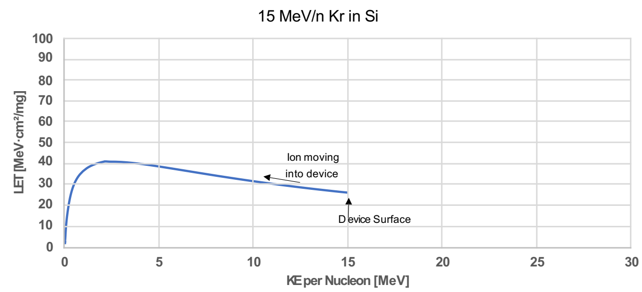
- Bragg Peak = maximum rate of energy deposition
  - Before peak, LET increases as ion slows, increasing the probability of EM interaction
  - After peak, LET decreases as ion picks up electrons, decreasing charge

LET as Ion Moves through Material

- 3 common ways to view the same information







LET as Ion Moves through Material

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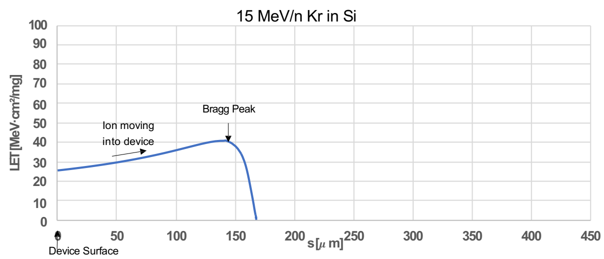
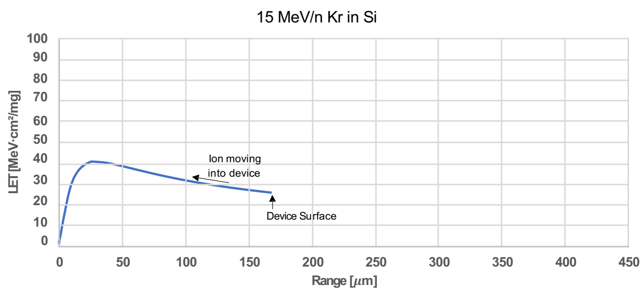
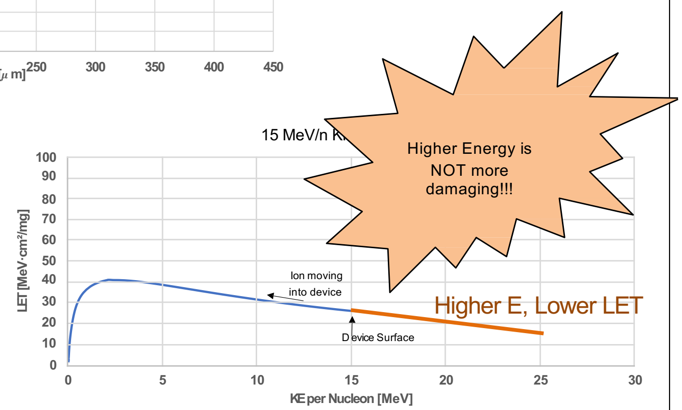
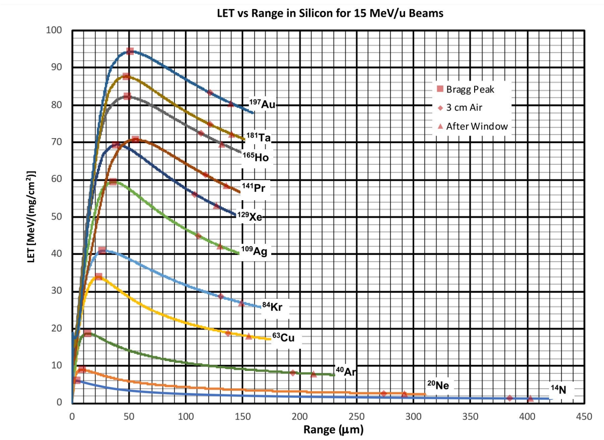






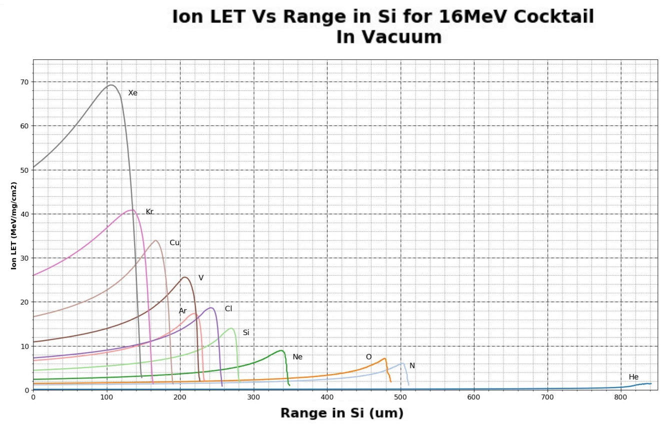
Some Available Beams

TAMU 15 MeV/n Heavy Ions



https://cyclotron.tamu.edu/ref/images/let_vs_range_plots.pdf

LBNL 16 MeV/n Heavy Ions



https://cyclotron.lbl.gov/base-rad-effects/heavy-ions

Remember the type of beam?

Some Available Beams

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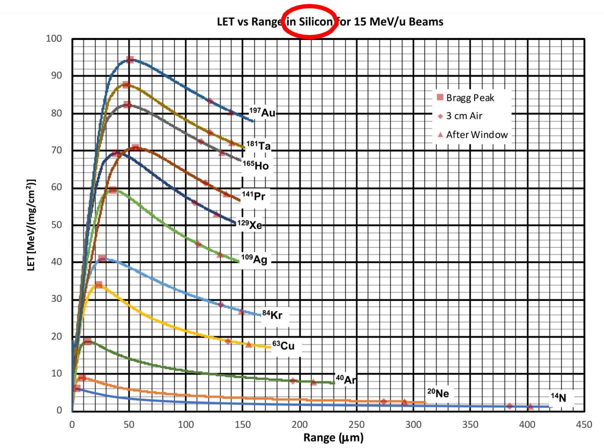

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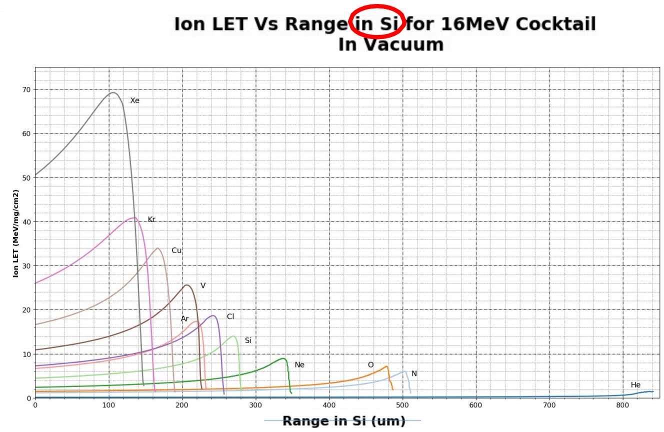

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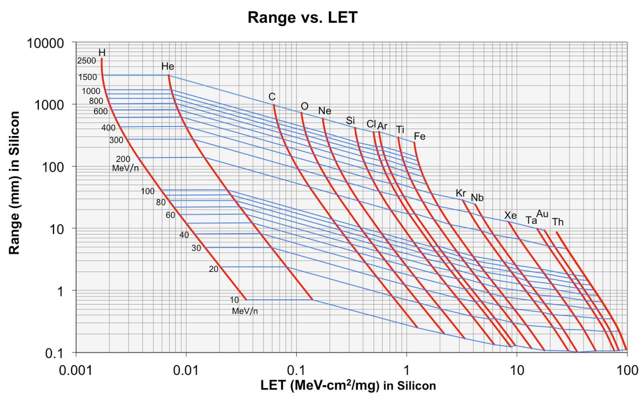
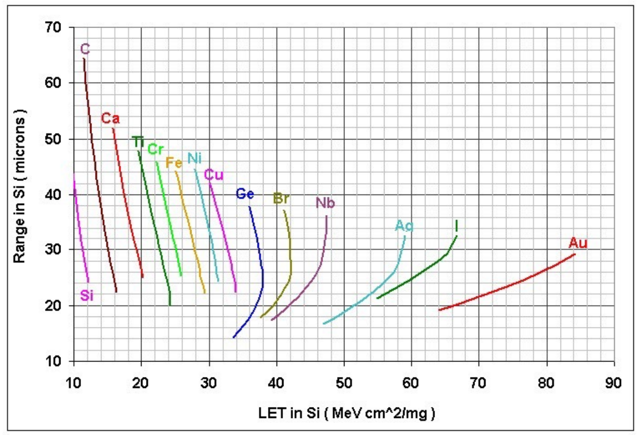
Some Available Beams

NASA Space Radiation Lab (NSRL)



https://www.bnl.gov/nsrl/userguide/let-range-plots.php

BNL Tandem VdeG SEU Facility



https://www.bnl.gov/tandem/capabilities/ions.php

Step 1: use charts
Step 2: follow up with SRIM , SUESS, etc

Facility Flux Capabilities and Other Details

- LBNL 88” BASE Facility, TAMU K500, and MSU FRIB all can provide flux levels of between 1E2 and 1E7 ions/cm^2-sec (though, in general, 1E4 to 1E5 ions/cm^2-sec is typical)
  - https://cyclotron.lbl.gov/base-rad-effects
  - https://cyclotron.tamu.edu/ref/downloads.html#forms
  - https://frib.msu.edu/science/fsee/fsee-downloads

- **Question:** How do these flux levels compare to near-Earth space environments?

Facility Flux Capabilities and Other Details

- LBNL 88” BASE Facility, TAMU K!
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  - https://frib.msu.edu/science/fsee/

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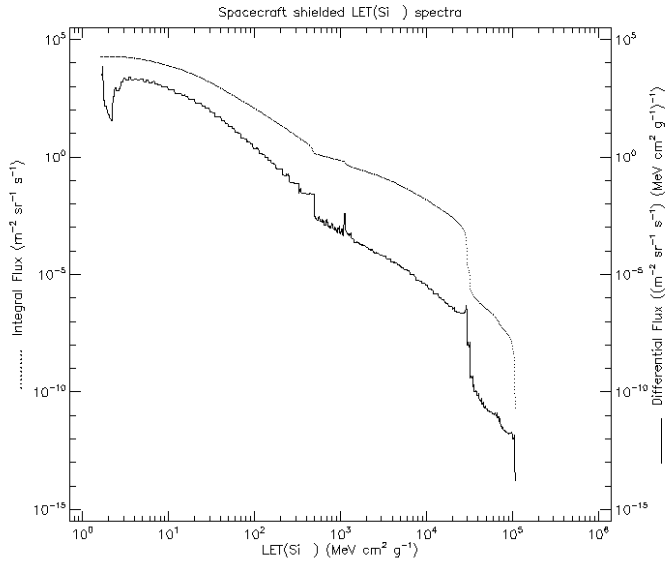

Facility Flux Capabilities and Other Details

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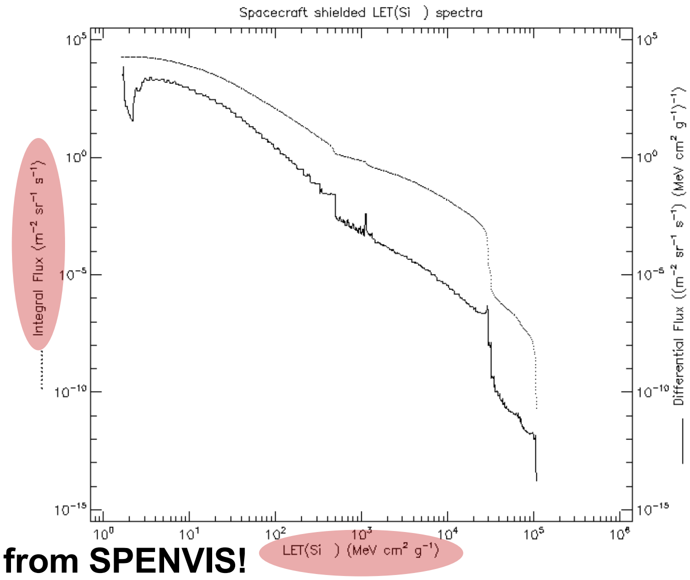
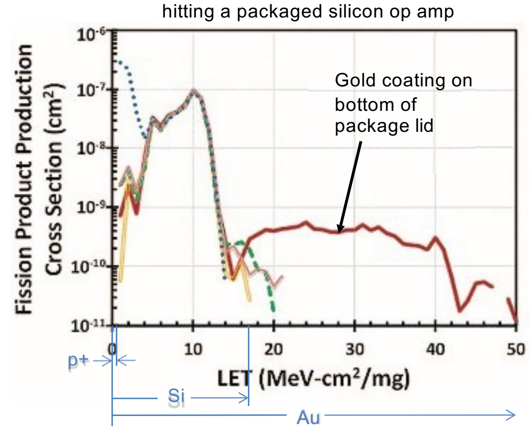


Careful of units from SPENVIS!

Note: Nuclear Interactions are Important

- Examples of protons leading to significantly higher LET than is possible with Direct Ionization:
  - Silicon nucleus in device
  - Gold-coated package lids
  - Tungsten plugs

LETs resulting from 200 MeV p+ beam hitting a packaged silicon op amp

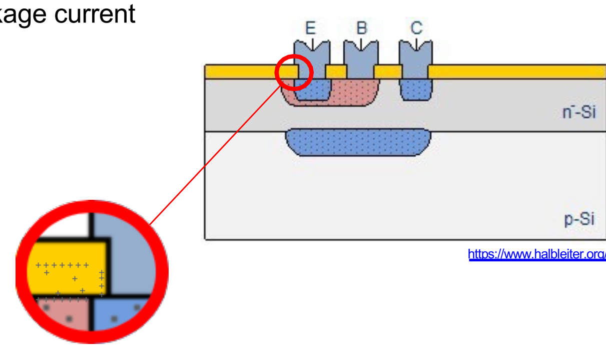


T.L.Turflinger,D.A.P.Clymer,L.W.Mason,S.Stone,J.S.George, M. Savage, R. Koga, E. Beach, and K. Huntington, *"RHA implications of proton on gold-plated package structures in SEE evaluations,"* IEEE Trans. Nucl. Sci., vol. 62, no. 6, pp. 2468–2475, Dec. 2015.

What tools help with this??
GEANT4, CREMEMC, e.g.

Note: Keep Track of Total Ionizing Dose (TID)!

- After the radiation dose, holes trapped in the dielectrics modify the electric fields in the device, leading to
  - Threshold voltage shifts
  - Leakage current



$$\mathrm{TID} = \Phi k(\mathrm{LET})$$

$$\mathrm{TID} = \text{total ionizing dose in rad}(\mathrm{SiO_2})$$

$$k = \text{conversion factor equal to } 1.602 \times 10^{-5} \frac{\mathrm{rad}}{\mathrm{MeV/mg}}$$

https://www.halbleiter.org/en/fundamentals/construction-of-a-bipolar-transistor/

- This is “TID damage” - eventually the device will fail to operate
- Even during SEE testing, you must track TID!

Add tid calculation

Useful Tools and Resources

- LET-Range Charts – **start here to get an estimate**
  - LBNL 88” Cyclotron BASE: https://cyclotron.lbl.gov/base-rad-effects/heavy-ions/cocktails-and-ions
  - NSRL: https://www.bnl.gov/nsrl/userguide/let-range-plots.php
  - TAMU: https://cyclotron.tamu.edu/ref/downloads.html
- SRIM – **follow up with analysis of LET**
  - SRIM: http://www.srim.org
  - NSRL Stack-Up Tool: https://www.bnl.gov/nsrl/stackup/
  - IU web-SRIM (in development)
  - IU web-SRIM on nanoHUB (in development)
- SUESS: https://mare.cyclotron.tamu.edu/vladimir/SeussW.htm