Single-Event Effects
Part 1 - General Principles

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**Special thanks to R. Davies and M. Casey*

Module 3: Objective and Outcomes

- This module will
  - Review SEE
  - 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

- Charge Generation due to Single-Events (Review of Module 2)
- Charge Collection
- Summary of SEE Charge Generation and Collection
- 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

Motivation

A Little Single-Event History

1962 Prediction of space-system upsets from ionizing particles
Wallmark and Marcus, RCA

1975 Cosmic-ray-induced upsets observed in spacecraft BJT flip-flop circuits
Binder and Smith, Hughes

1978 Upsets in 16k DRAMs observed and attributed to alpha particles from packaging contaminants
May and Woods, Intel

1978 Cosmic-ray-induced upsets observed in spacecraft RAM circuits
Pickel and Blandford, Rockwell

1979 Heavy-ion-induced latchup in SRAMs discovered

1983 Galileo refit

1989 Solar Flare Event:

INTELSAT 46 pitch glitches, potential orbit disruption

TDRS-A 53 hits in 3 days, near catastrophic loss of attitude control

Bottom Line

- Single event effects (SEEs) are taking a prominent position in the mainstream integrated circuit industry
- Many commercial manufacturers are coming to grips with the problem as a key reliability issue
- The problem is of growing importance as noise margins diminish with scaling
- GHz logic, terabyte RAM, low-power circuits are leading to new upset scenarios
- Clearly, there is a recognized need for SEE analysis integrated into accepted design flows

Definitions

Single Event (SE) or Single Event Phenomena (SEP) -

interaction of a single ionizing particle with a semiconductor device - localized interaction - event occurrence does not depend on flux or total exposure - event is spatially and temporally random - event seems (though not scientifically verified) to perfectly implement Murphy's Law

Single Event Effect (SEE) -

a circuit or system response to a SE

Single Event Upset (SEU) -

a bit flip or other *corruption* of stored information due to an SEE (usually applied to memory circuits)

Single Event Error or Soft Error-

the observable, measurable *manifestation* of an SEE as a incorrect circuit operation (usually a system response)

Definitions (cont)

Single Event Transient (SET)

- a signal glitch caused by an SE

ASET - analog single event transient

DSET - digital single event transient

Single Event Error Rate or Soft Error Rate (SER) -

the frequency of errors in a particular environment (e.g. an orbit, mission trajectory, etc) -- can be related to FITs

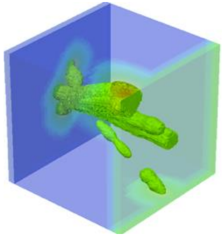
01

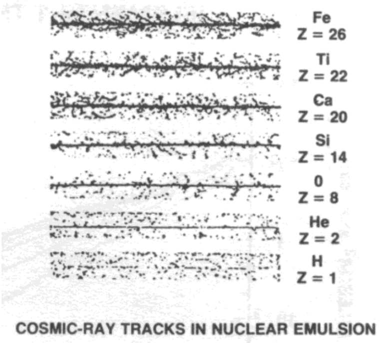
CHARGE GENERATION DUE TO SINGLE EVENTS

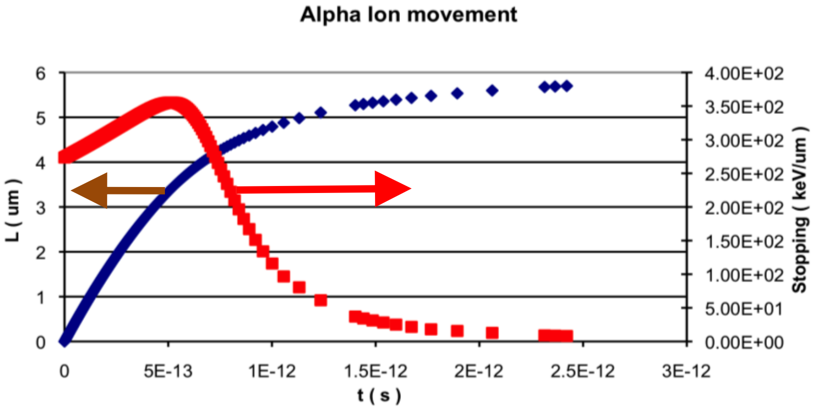
Interactions of the Particles with Semiconductors

Energy Loss or Stopping Power

- Charged particle passes through a material
- Loses energy by Rutherford scattering with the lattice nuclei
- Energy transferred to bound electrons -- ionized into the conduction band
- Imparts a dense track of electron hole pairs (EHPs)







Interactions of the Particles with Semiconductors

Energy Loss or Stopping Power

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Incremental rate of energy loss along the ion's path
= stopping power (dE/dx)
units of energy per unit length (typical: MeV/cm)

Interactions of the Particles with Semiconductors

LET and the Amount of Charge Liberated

Stopping power: Depends on mass, energy of particle and density of material

Linear energy transfer (LET) normalizes out the density of the target material (units = $MeV/mg/cm^2$)

LET ($MeV/mg/cm^2$) * Target Density (mg/cm^3) = Energy deposition (MeV/cm)

Charge creation: 3.6 eV needed to create one EHP in silicon

Amount of charge liberated (pC/μm) = LET ($MeV/mg/cm^2$) * 0.01035
(approximately 100 to 1 conversion factor)
(e.g. Particle of LET=100 $MeV/mg/cm^2$ --> 1 pC/μm)

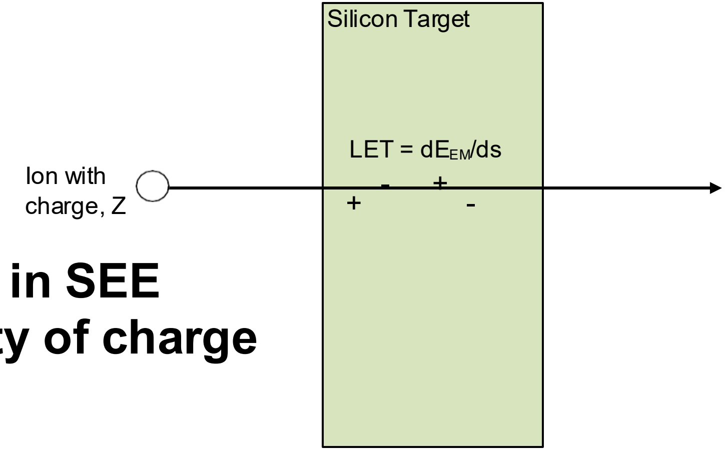
Stopping powers and LETs for various ions, energies, and target material are tabulated, or can be calculated using SRIM code (www.srim.org)

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**
- **LET depends on**
  - Charge of ion, Z
  - Target Material
  - Energy of ion
    - Initial ➔ "Surface LET"
    - At each location along the ion's path ➔ Instantaneous LET



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 is dependent on the target material!!**

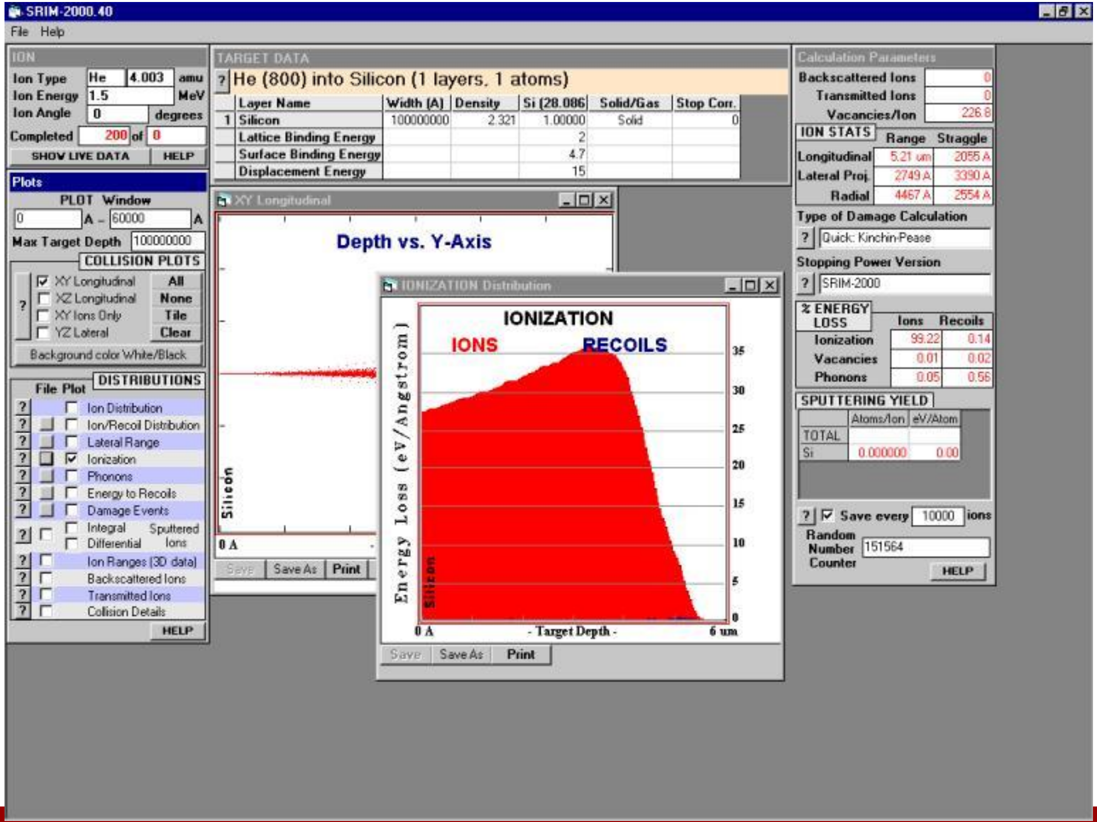
- **LET units**
  - MeV·cm²/mg
  - Think of it as:
    - MeV/(mg/cm²)
    - MeV/(cm · mg/cm³) ➔ dE/(ds*δ)
    - Energy deposited per unit of length normalized by density of the target material

Caution: "What is the LET of the beam?"

… in silicon(?)

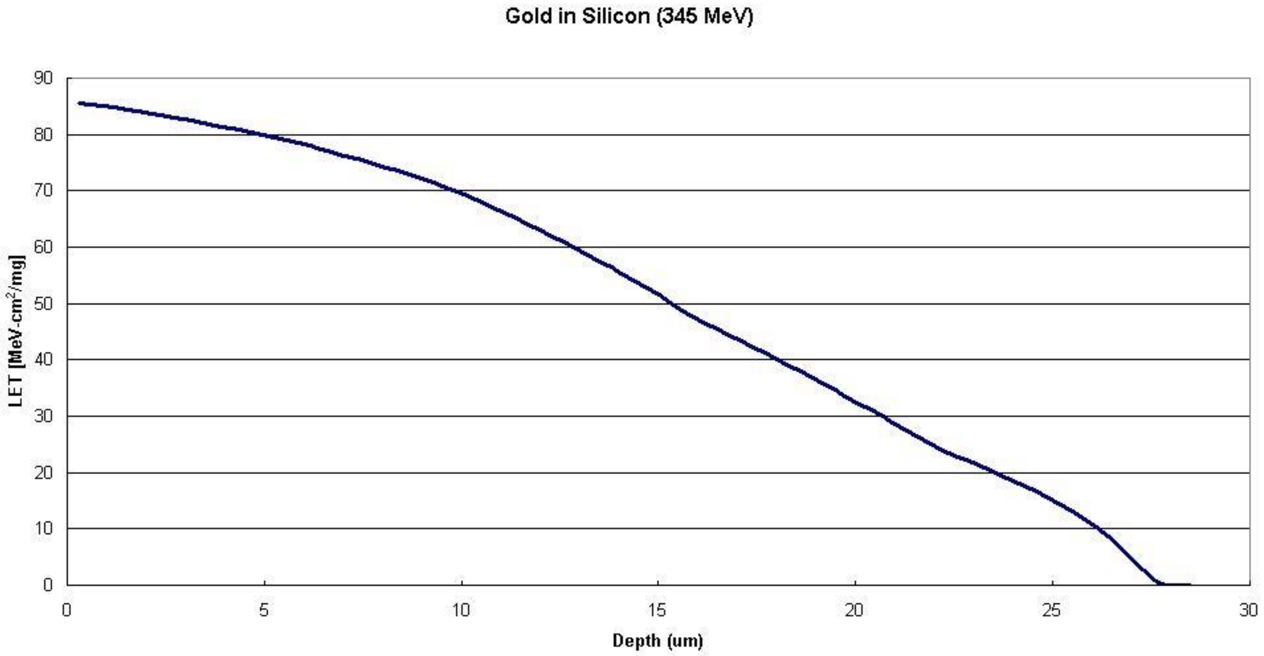
Interactions of the Particles with Semiconductors

SRIM Calculations



LET Curves for Typical Ions

Heavy-Ion Beam Examples (Brookhaven)



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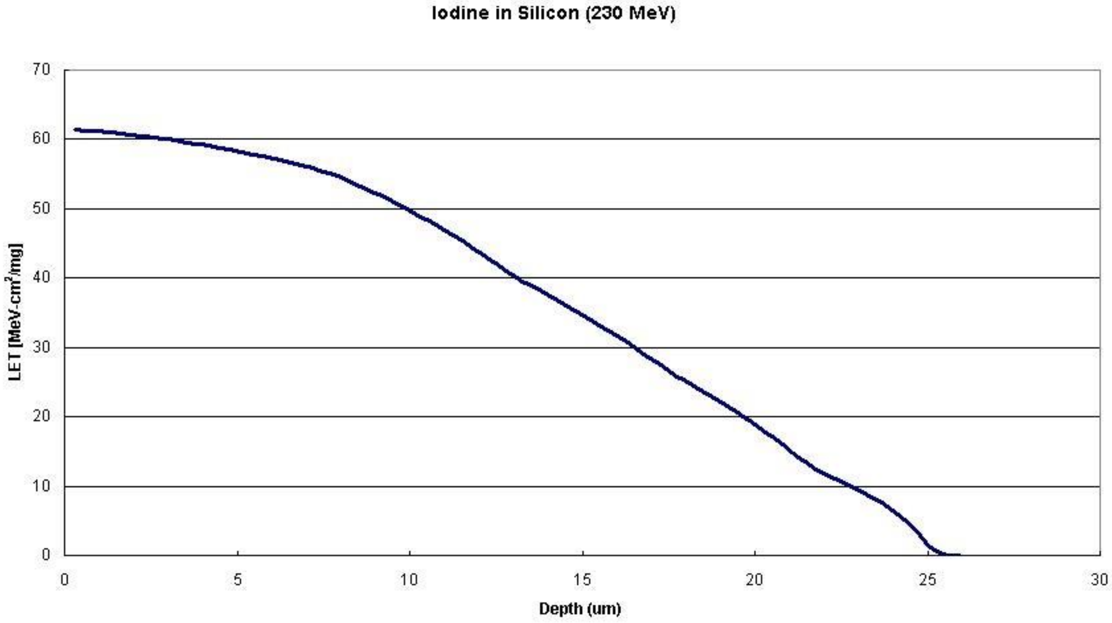

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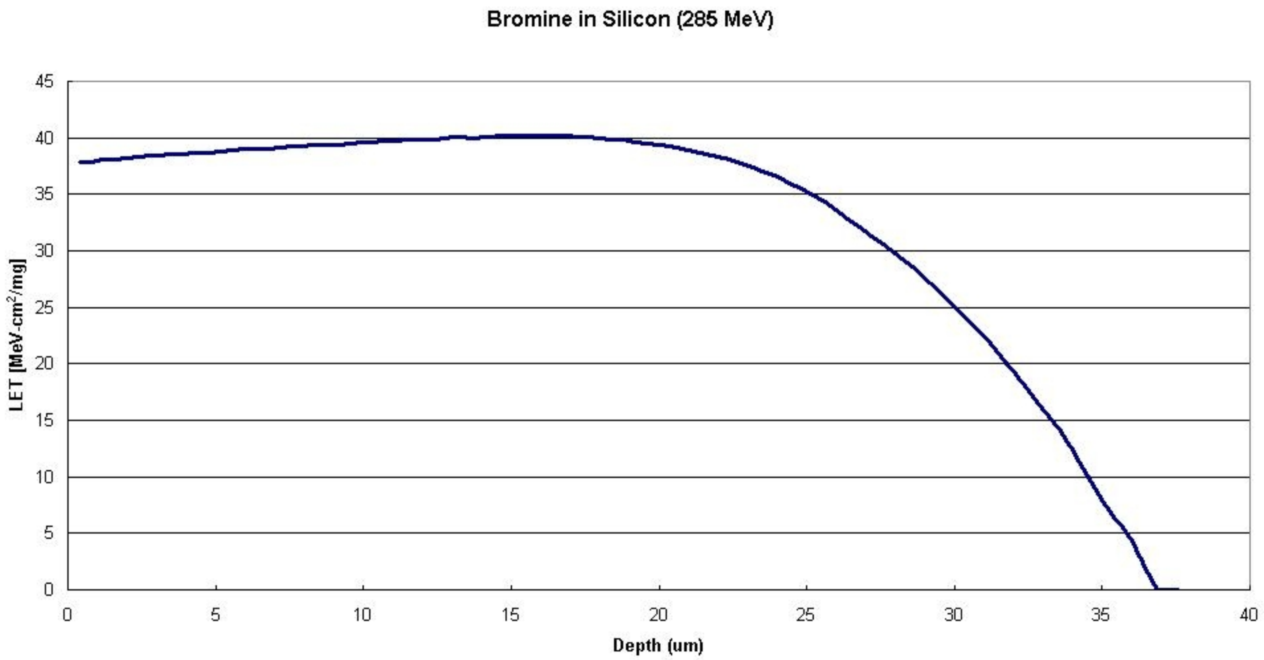

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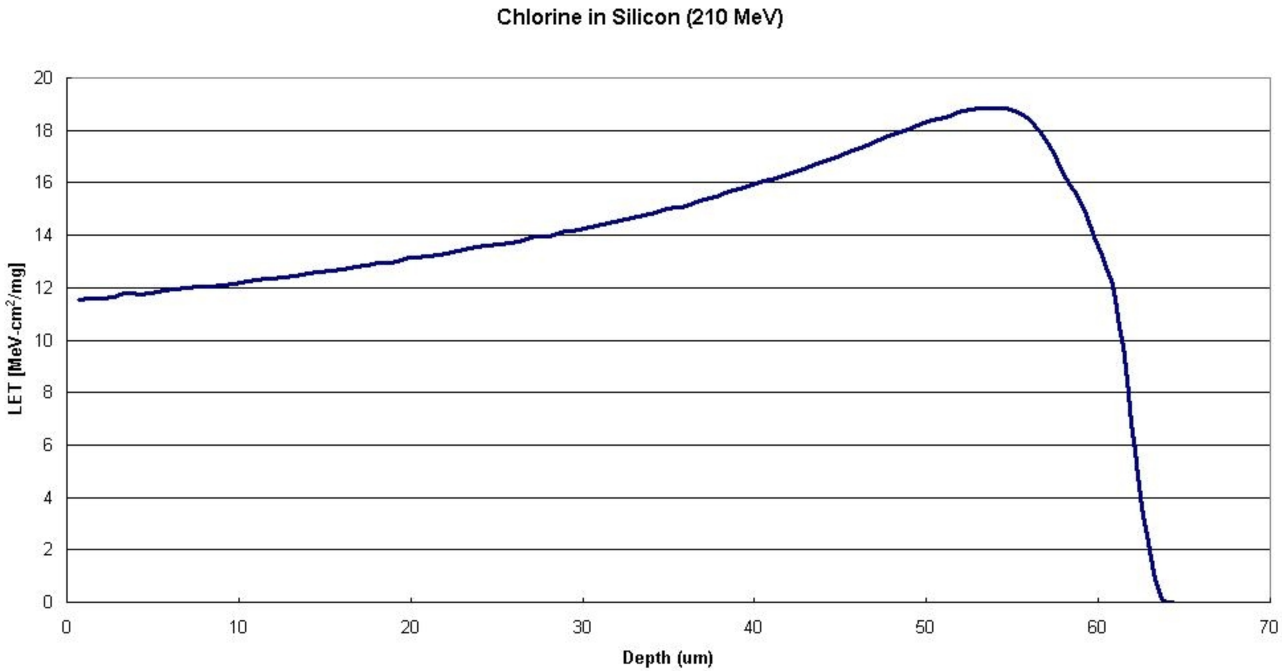

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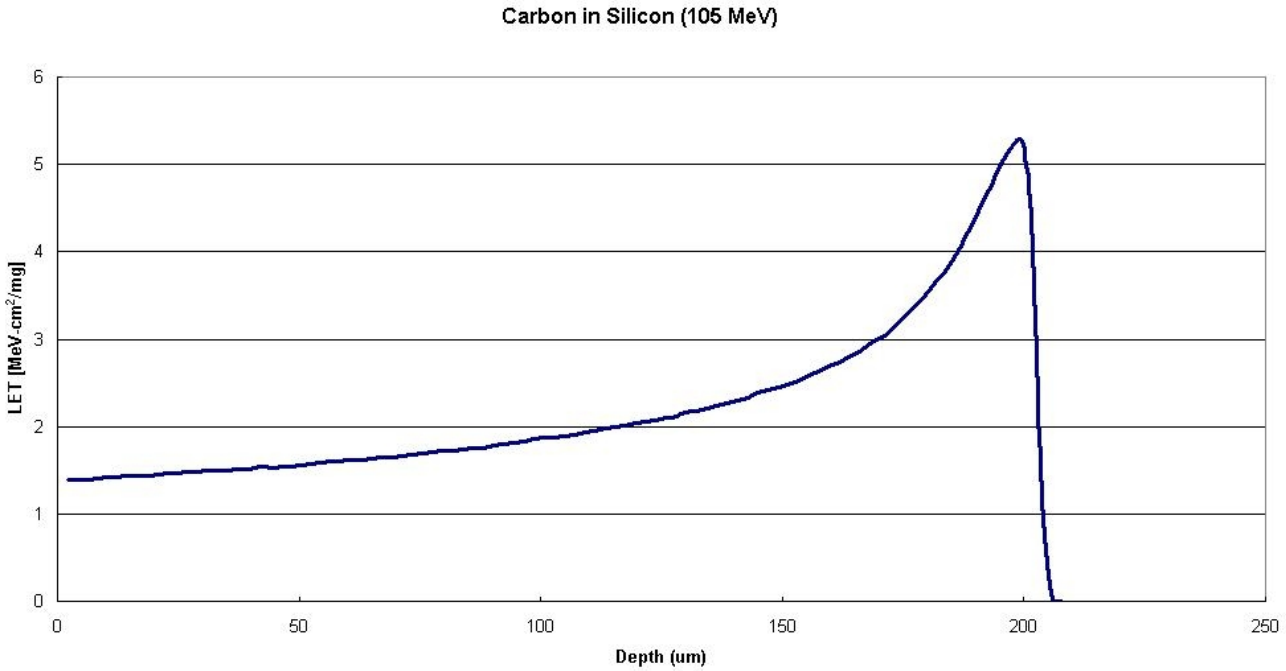
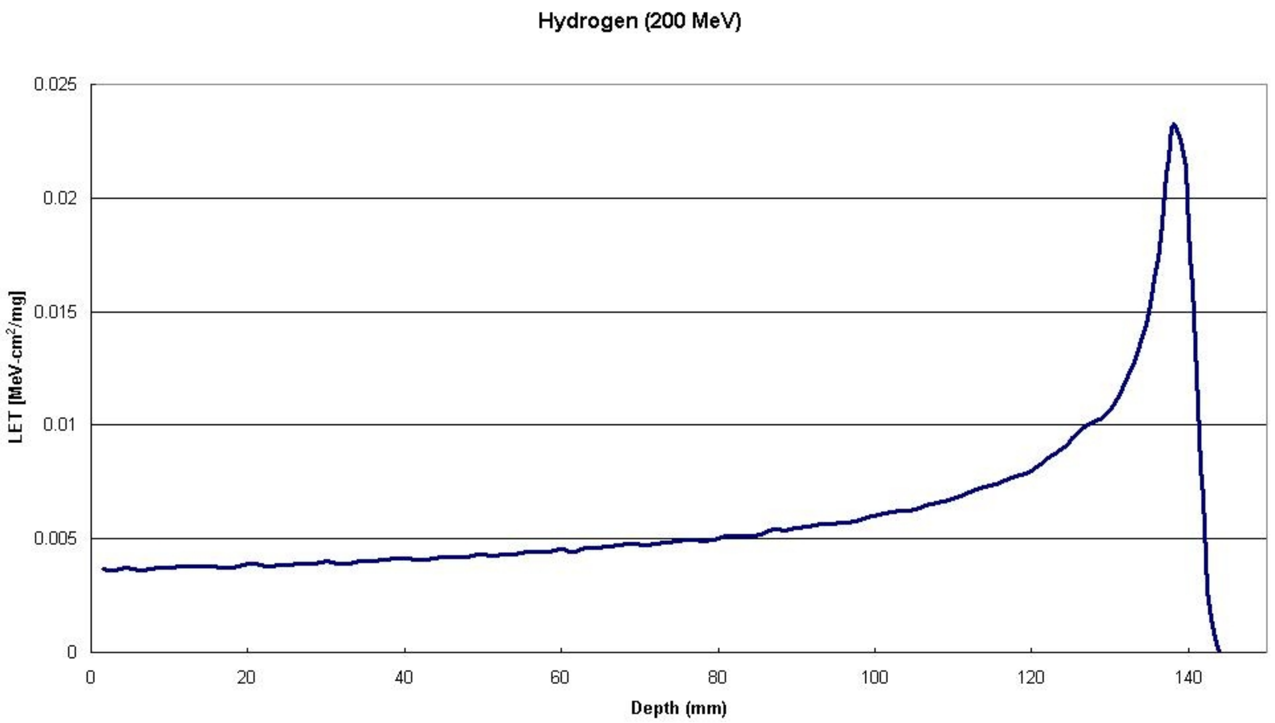


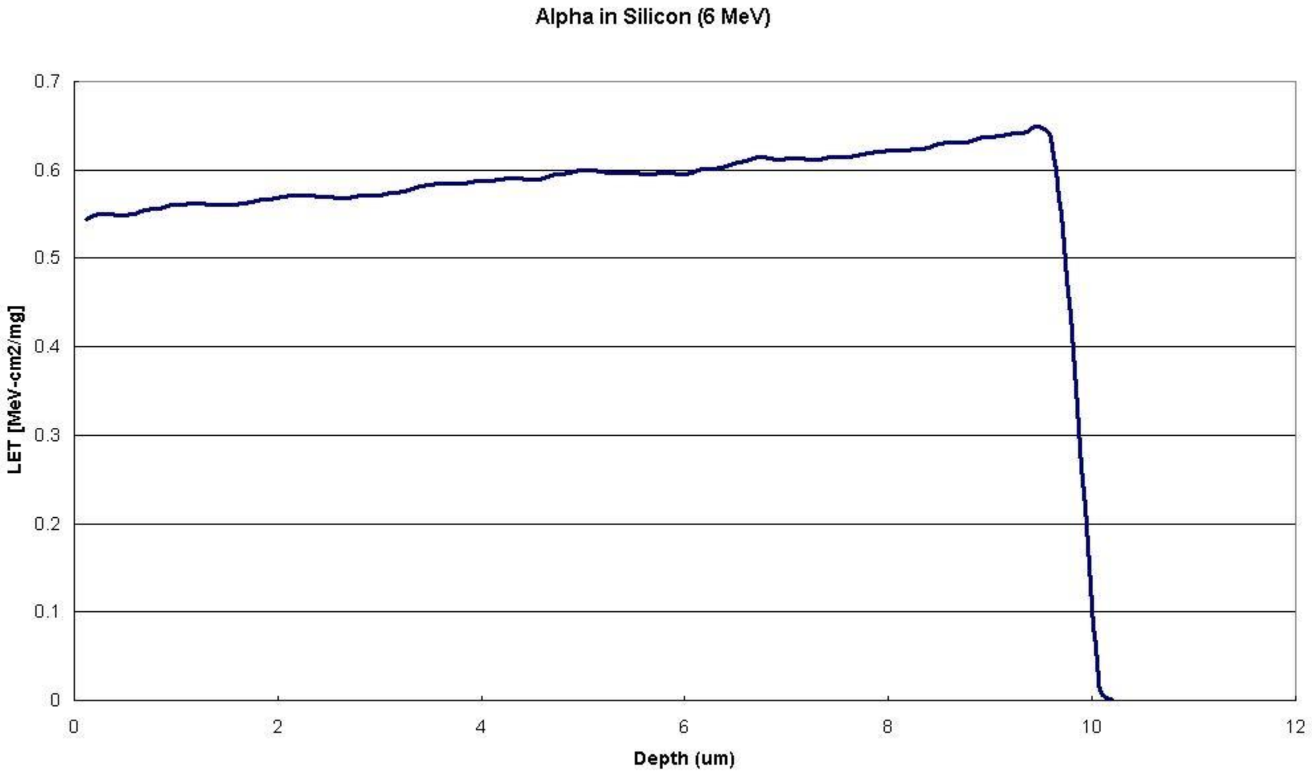
LET Curves for Typical Ions

Proton Beam Examples (Indiana University)



LET Curves for Typical Ions

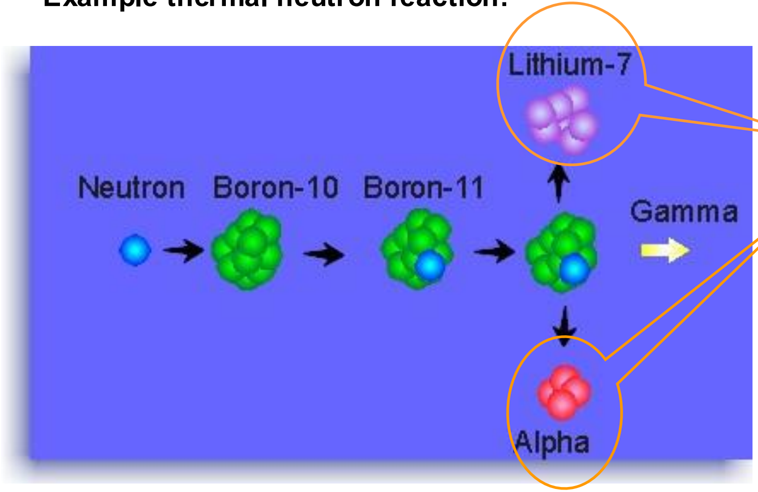
Packaging/Impurity Alpha Example



Terrestrial Neutrons

Created by cosmic ion interactions with oxygen and nitrogen in the upper atmosphere

Example thermal neutron reaction:

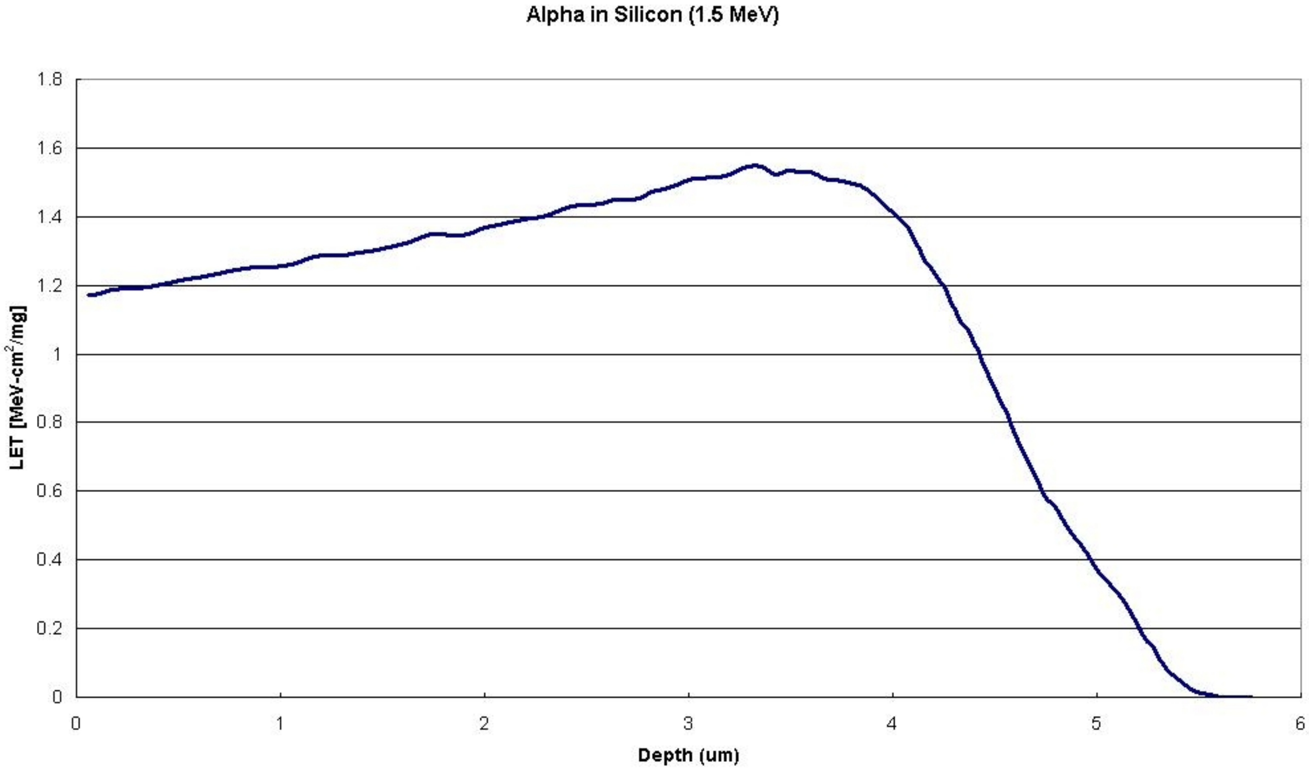


Energy; Range;
Time of Flight; Total Charge
0.8 MeV; 2.4µm; 1.5ps; 36fC

1.5 MeV; 5.2µm; 2.4ps; 67fC

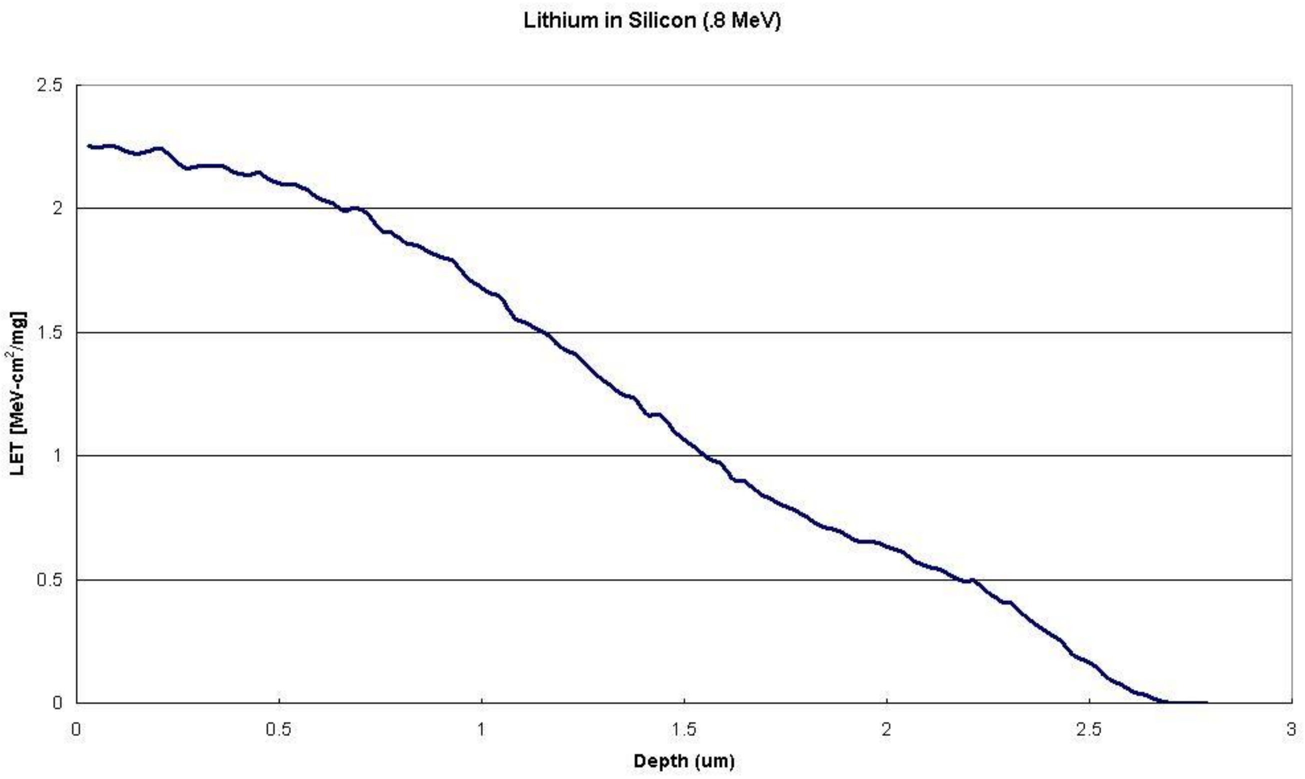
LET Curves for Typical Ions

Terrestrial Neutron Product Examples

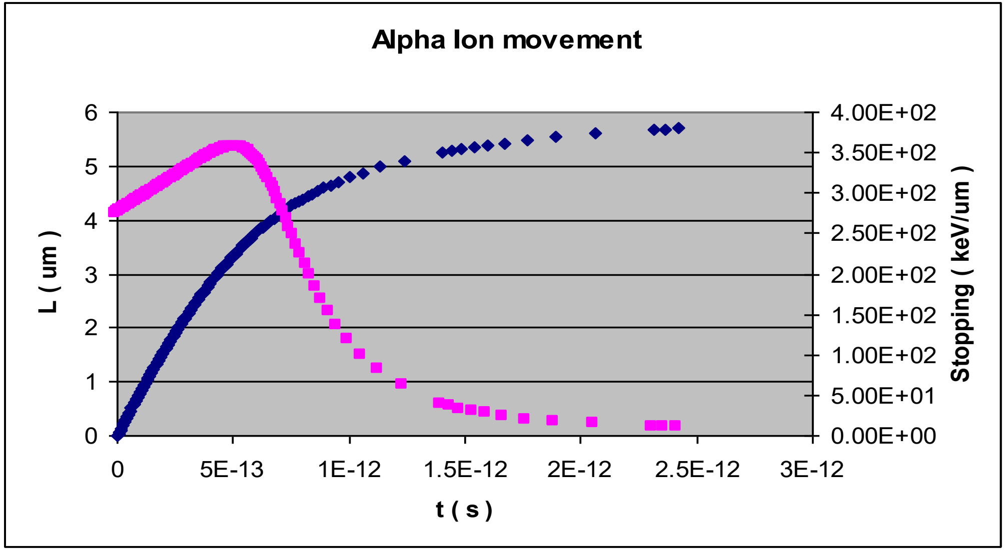


LET Curves for Typical Ions

Terrestrial Neutron Product Examples



Further Information from Stopping Power Data

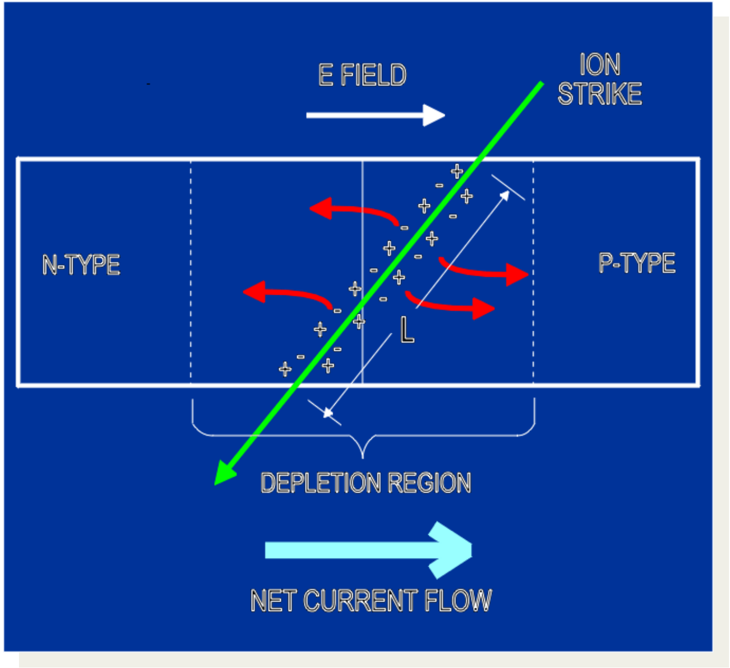


02

CHARGE COLLECTION

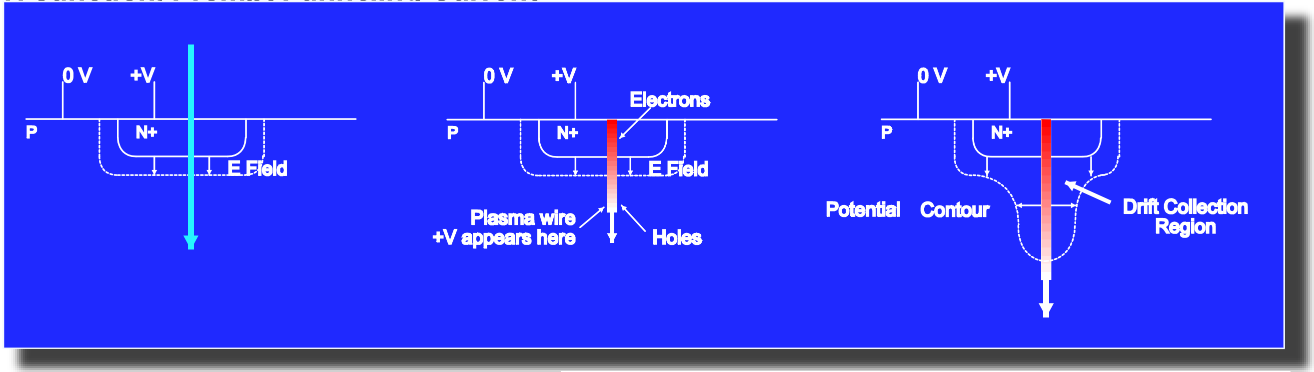
Depletion Region (Drift) Charge Collection

Simple P-N Junction, Prompt Current

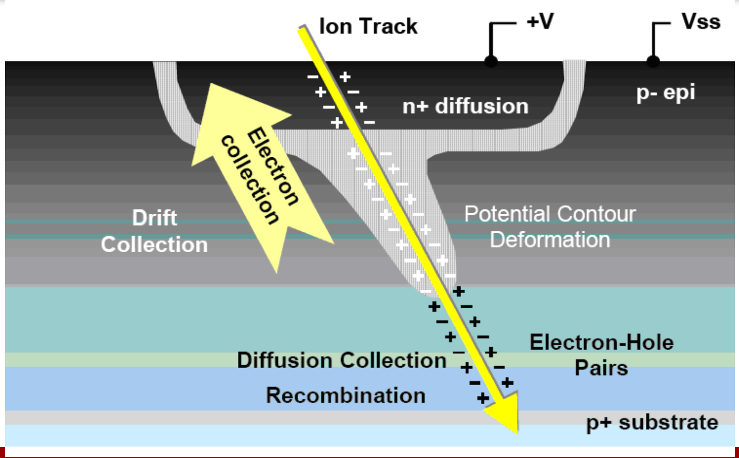


Enhanced Drift Charge Collection (Field Funneling)

Simple P-N Junction, Prompt Funneling Current

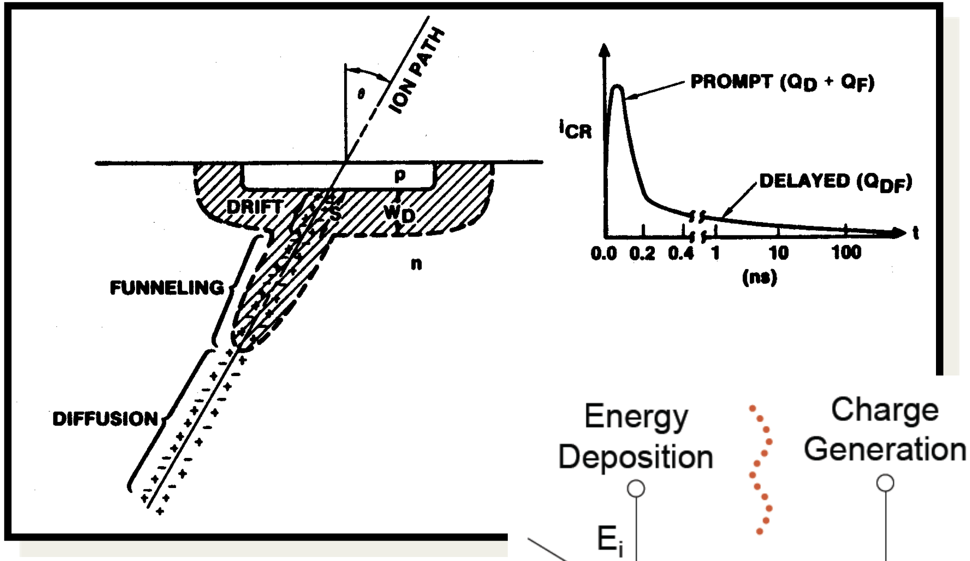


The track of ionized carriers can perturb the depletion region traversed by the path, leading to enhanced collection via drift processes

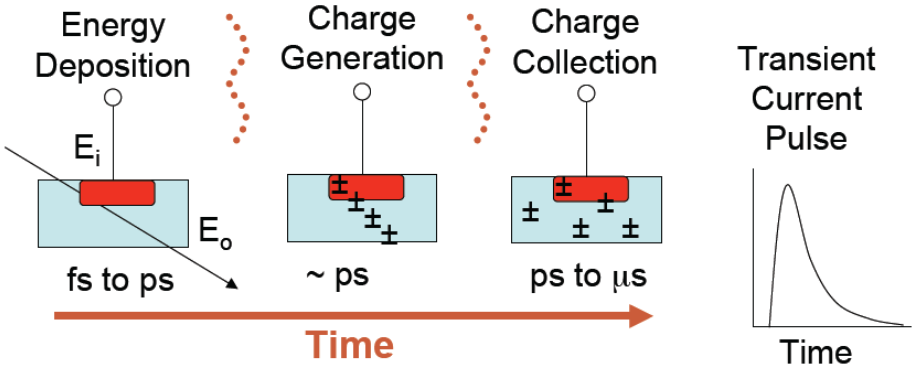


Diffusion Collection

Simple P-N Junction, Delayed Current



McLean 82



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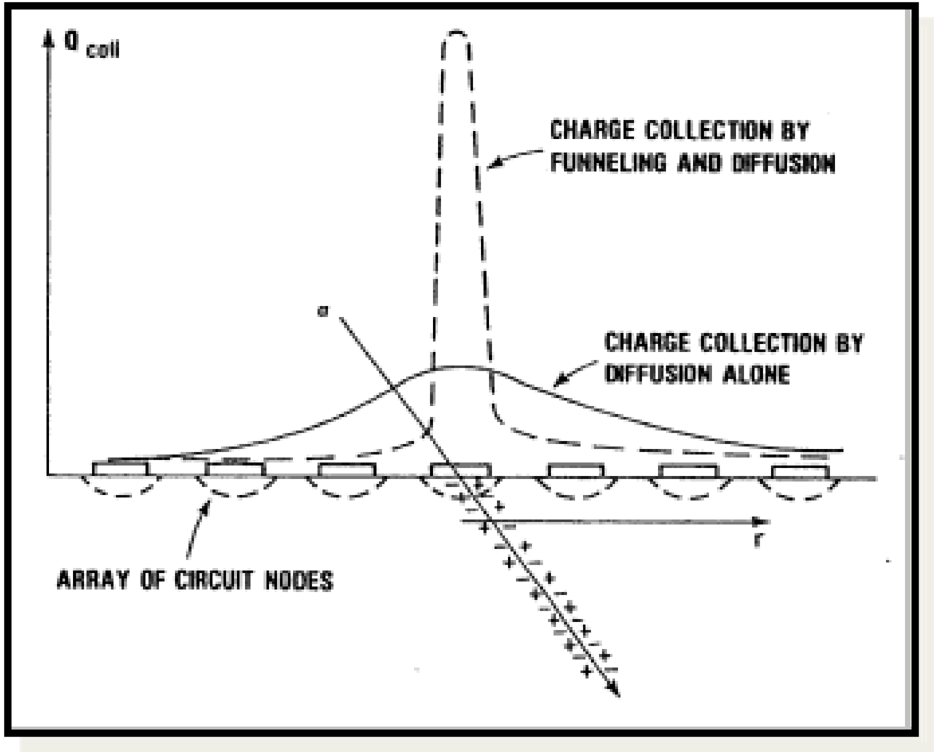
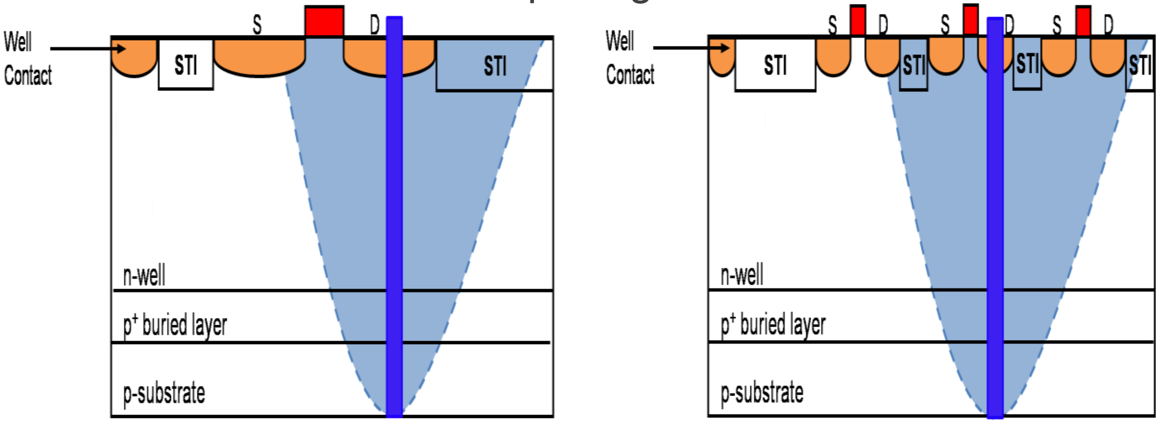


Pickel 83

Charge Sharing

- Single-event (SE) generated charge may be “shared” between the device directly penetrated by the ionizing particle (hit device) and proximal devices

- Scaling technology increases the probability of charge sharing due to decreased device sizes and decreased device spacing

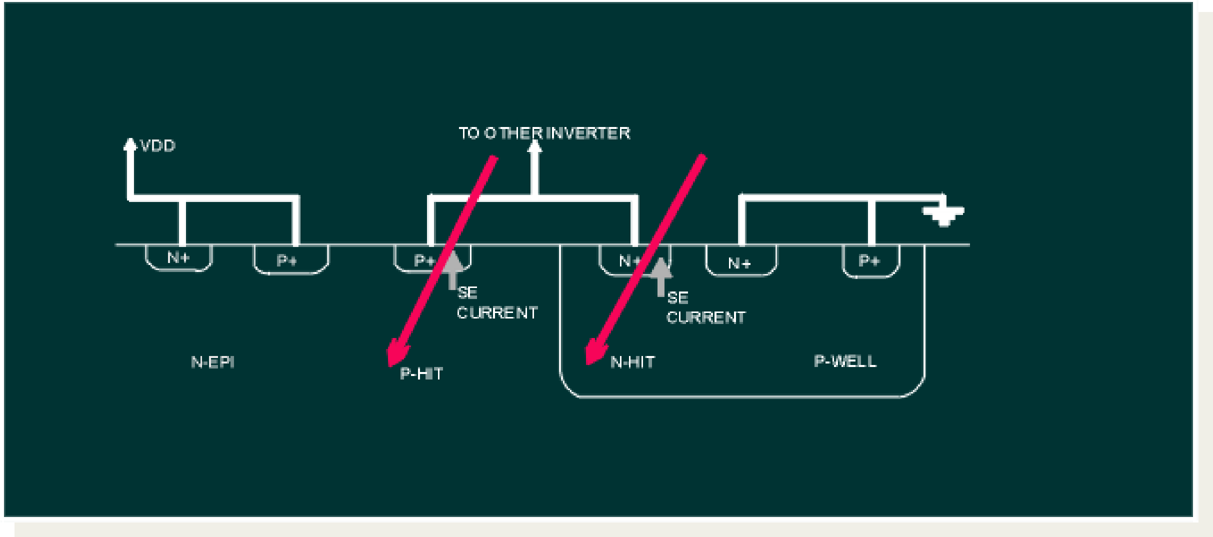


Older CMOS technology **Sub-100 nm CMOS Technology**

Complex Geometries

CMOS Structure

Charge collection influenced by neighboring junctions or boundary conditions

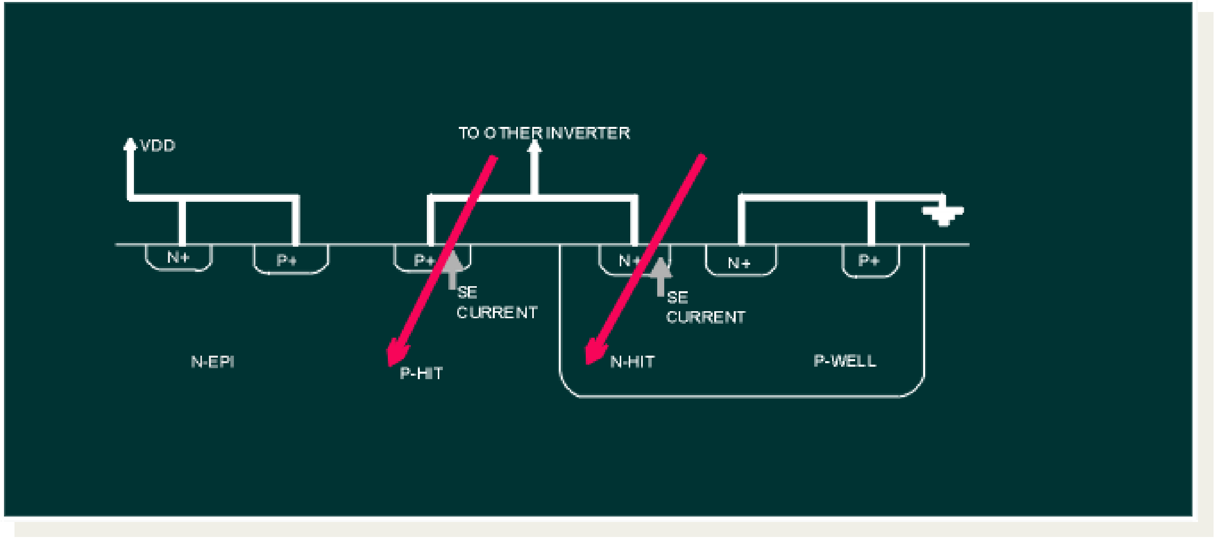


Complex Geometries

CMOS Structure

Charge collection influenced by neighboring junctions or boundary conditions

Junctions are vulnerable when reversed biased



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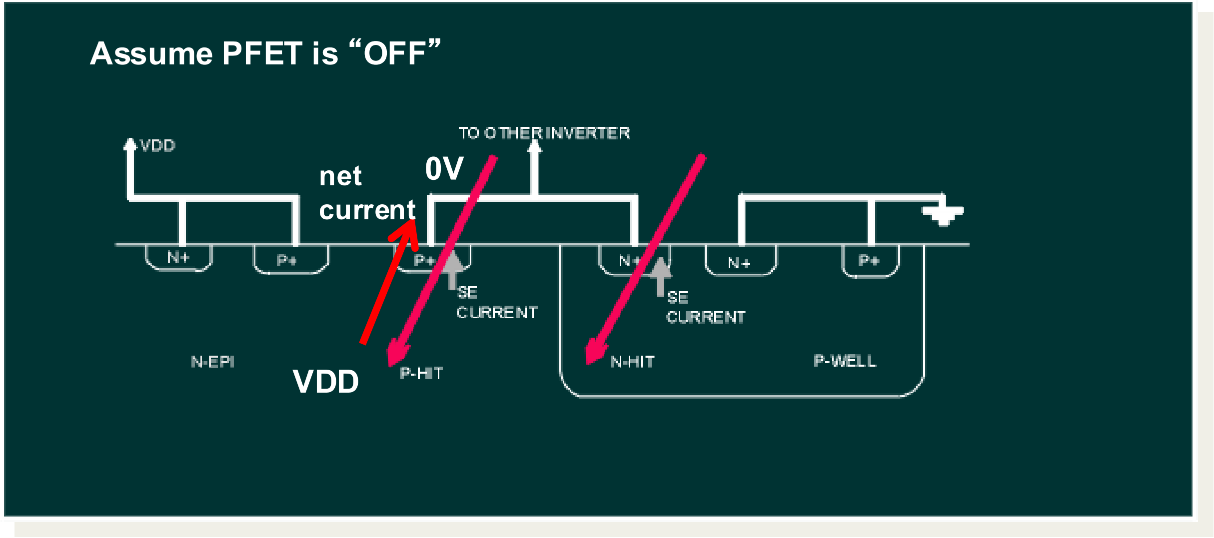

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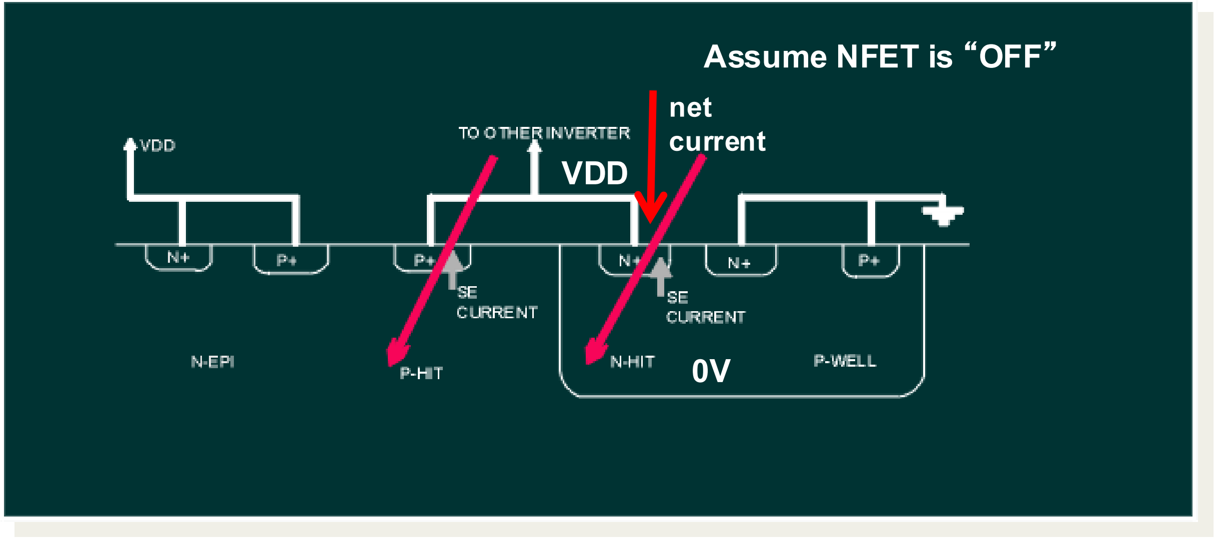

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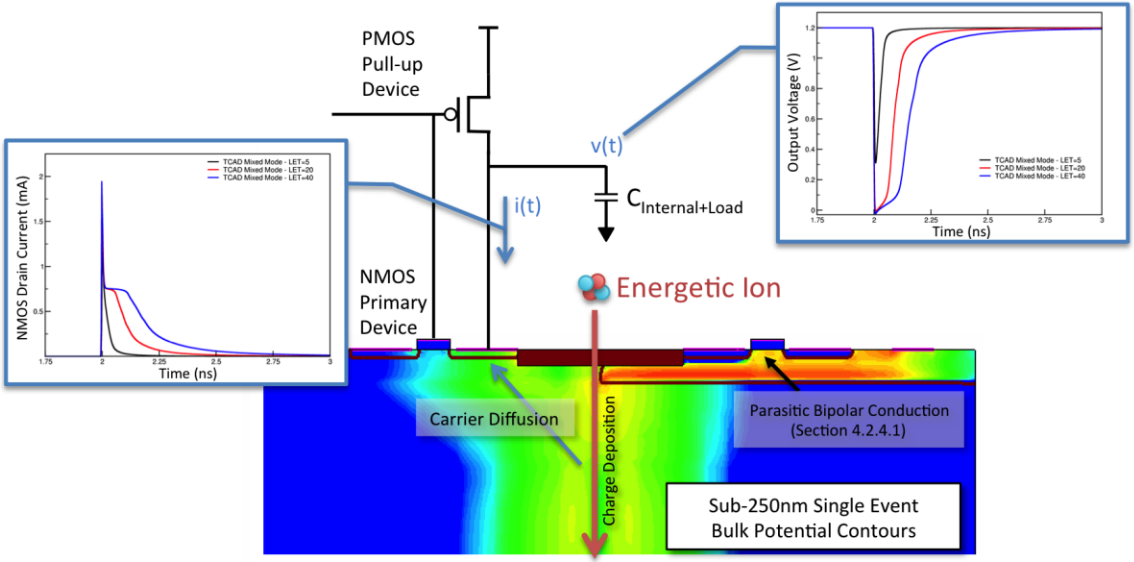

Massengill 2012

Complex Geometries

CMOS Structure

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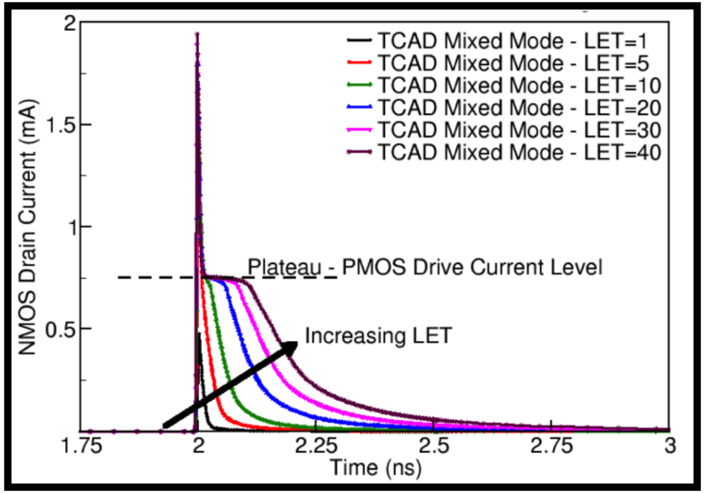
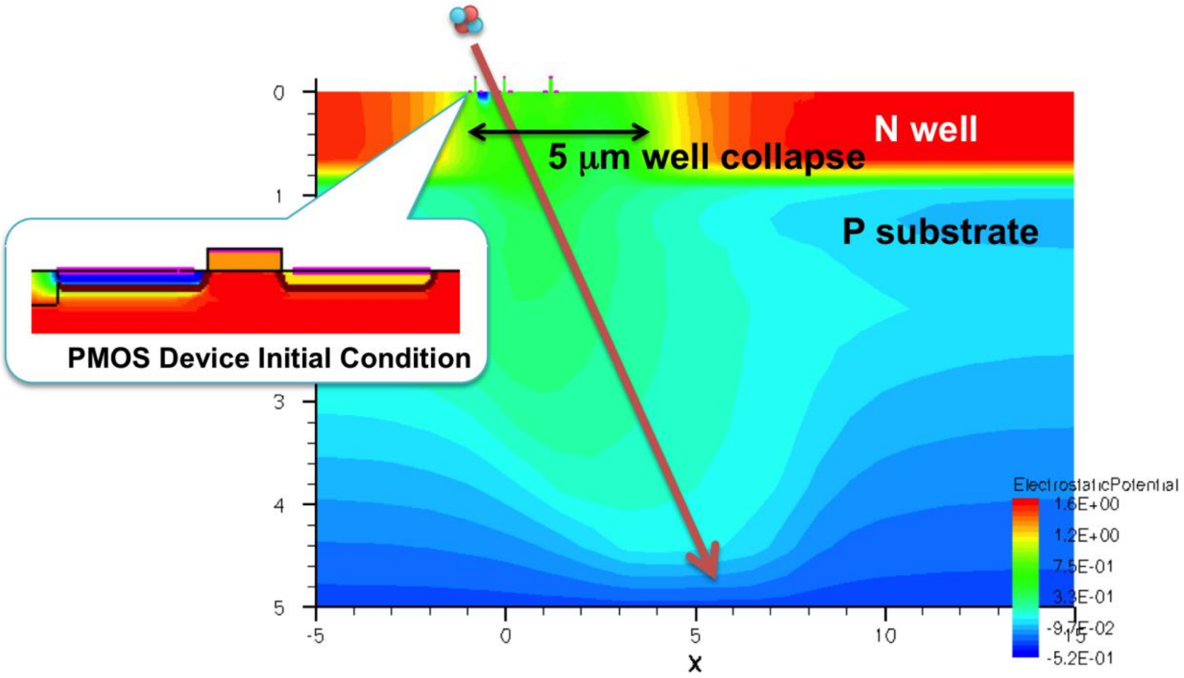


Kauppila 2009

The plateau region, caused by the collapse of the device depletion region, is the induced balance of charge collection current and resupply current)

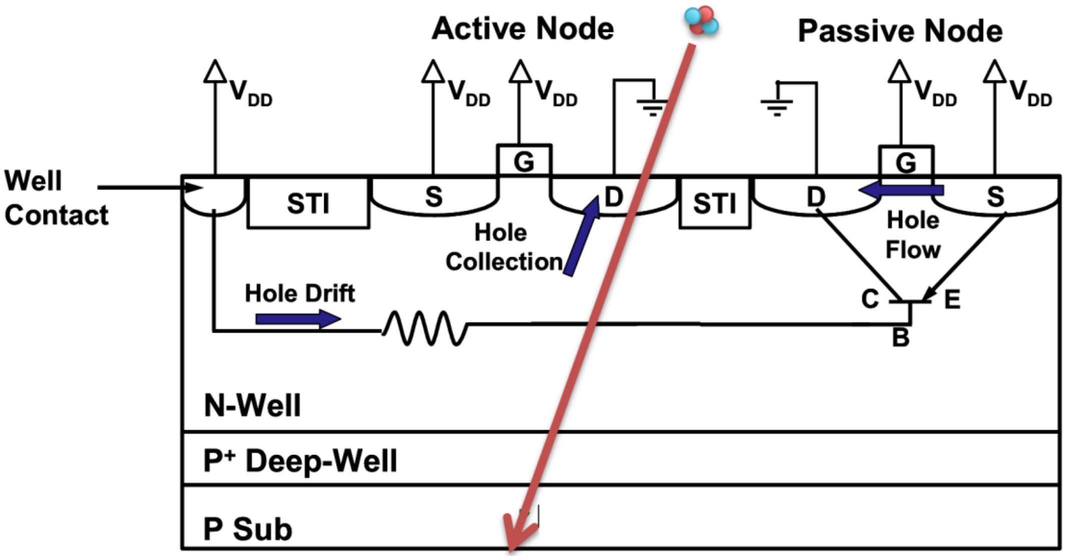
Complex Geometries

Well Potential Collapse



Olson 2007

Parasitic Bipolar Action Due to Well Potential Collapse

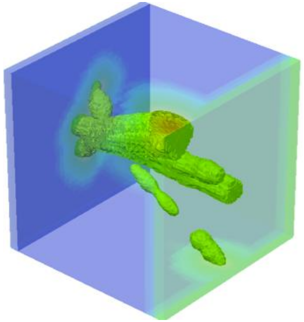


Olson 2005

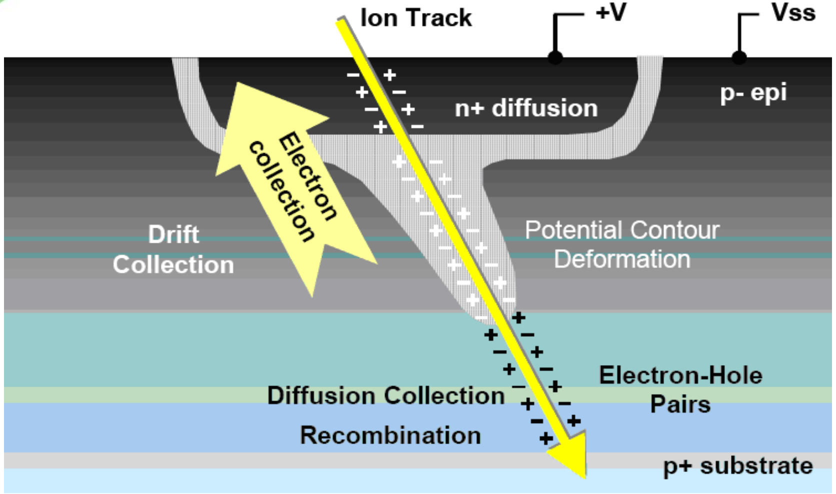
03

Summary of SEE Charge Generation and Collection

REMINDER: Single-Event Effects In Microelectronics



- Single-Event Effects (SEE):
  - Caused by the interaction of a single energetic particle



Ionizing Particles:

Heavy ions from deep space (galactic cosmic rays)

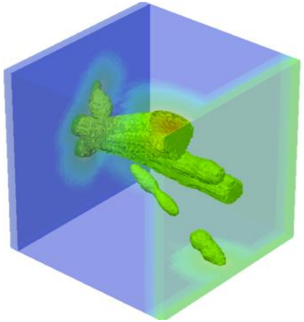
Energetic protons (trapped in the Van Allen belts)

Neutron products (terrestrial)

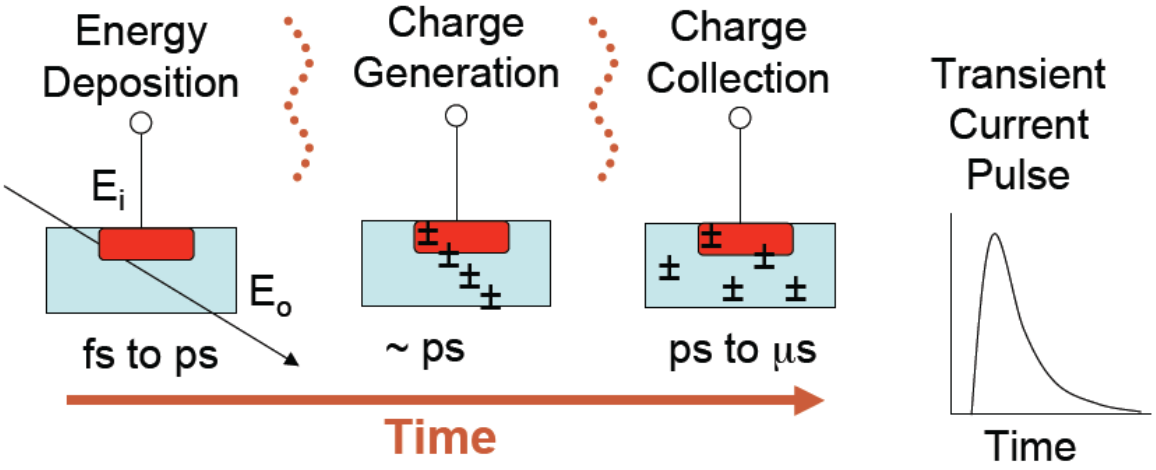
Alpha particles (from contaminants)

Example of Ion Penetrating Reverse-Biased p-n Junction

REMINDER: Single-Event Effects In Microelectronics



- Single-Event Effects (SEE):
  - Caused by the interaction of a single energetic particle
  - SEE are determined by:
    - Charge generation
    - Charge collection
    - Circuit response



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

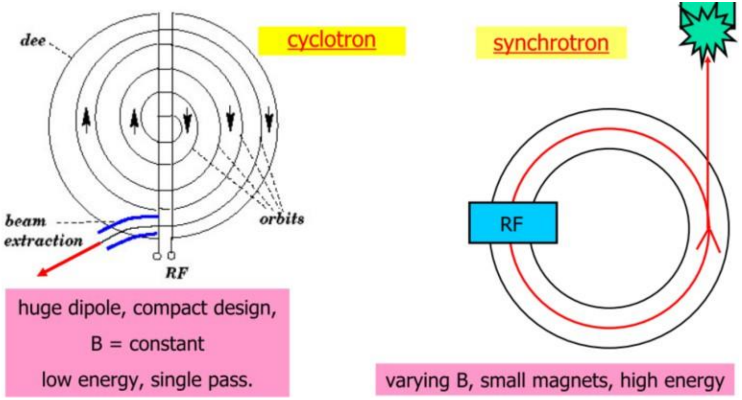
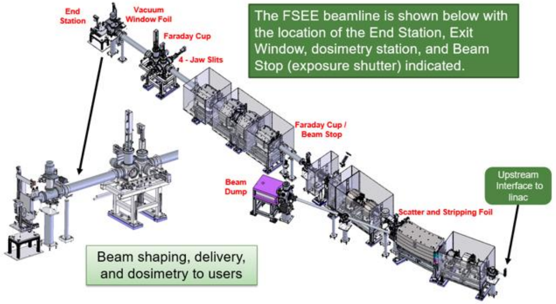


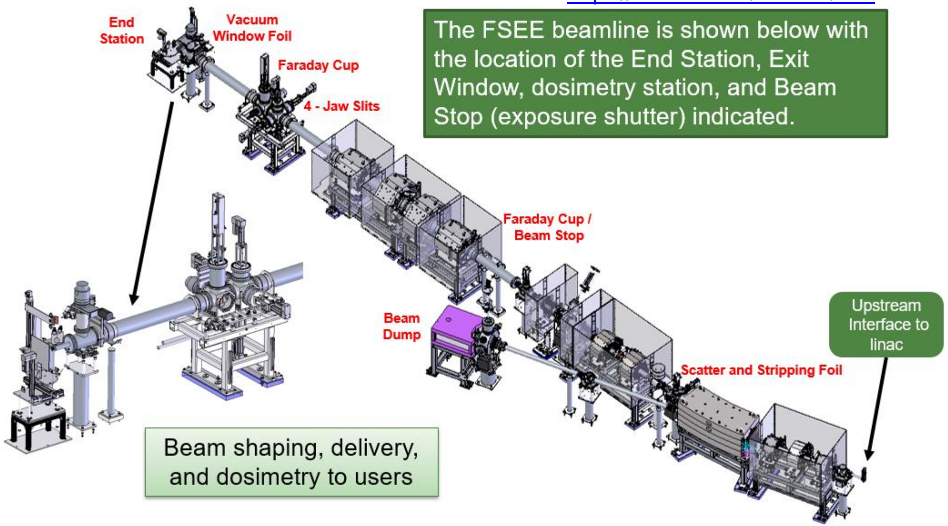
Image Credit: T. Olson, 2021



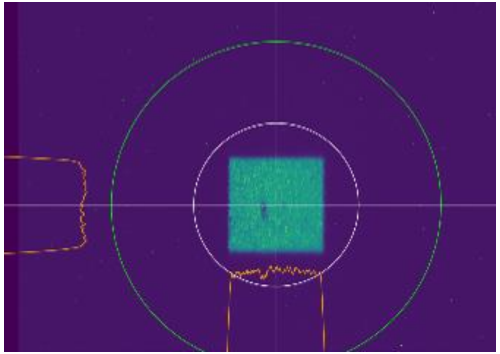
https://frib.msu.edu/science/fsee

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

Linear Accelerator (LINAC)



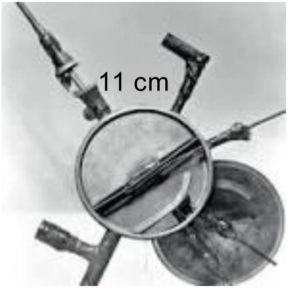
- LINACs include a series of RF cavities that use electromagnetic fields to accelerate particles and magnets to focus the beam through transport.
- Benefits:
  - Higher energy requires more stages and doesn't rely on magnetic field constraints
  - Good beam control and stabilization
- Limitations:
  - 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)



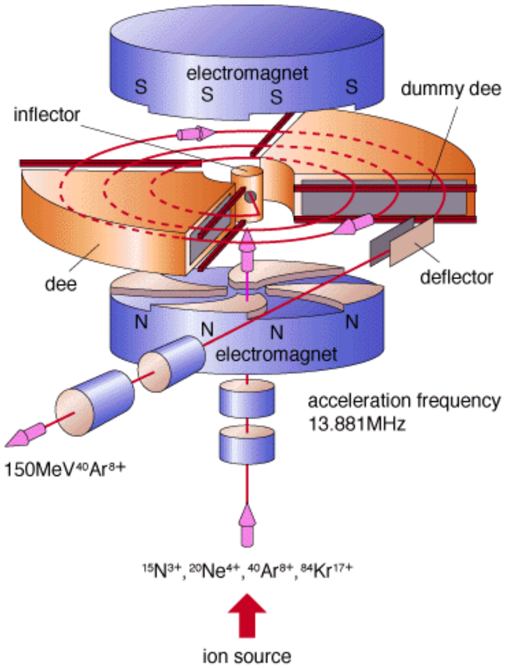
https://frib.msu.edu/science/fsee/facility-details

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

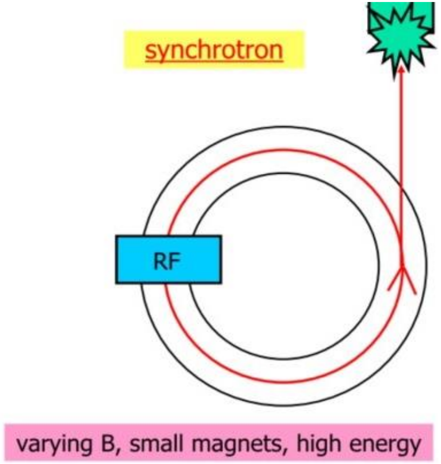
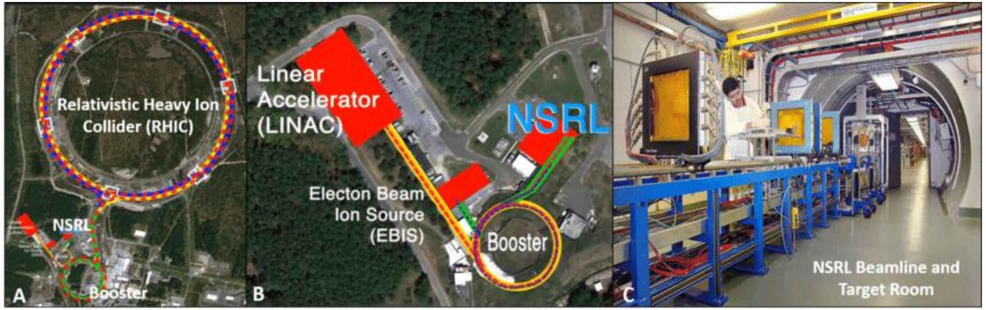


Image Credit: T. Olson, 2021

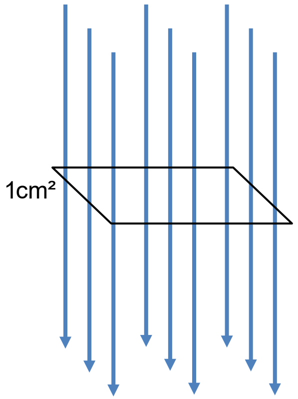


Beam Basics - Flux and Fluence

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

Question: *Is flux always constant?*

Beam particles in 1 second



Flux = 9 /cm²/s

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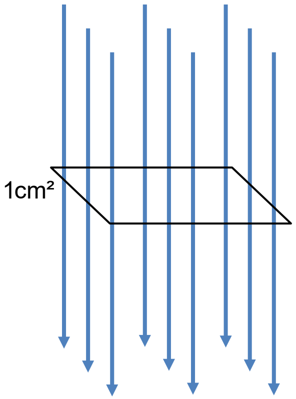
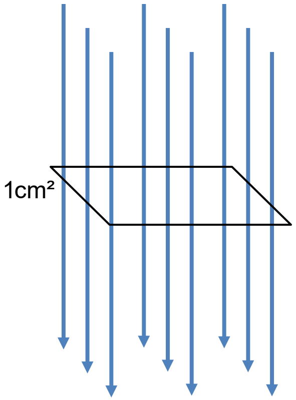
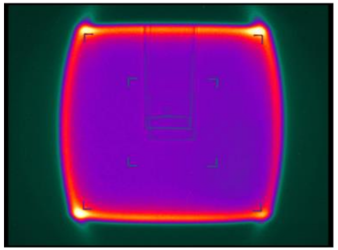


Flux = 9 /cm²/s

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

Beam particles during an entire run





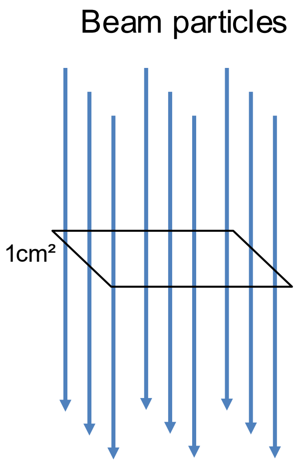
https://www.bnl.gov/nsrl/docs/pdf/nsrl-electronics-testing.pdf

Fluence = 9 /cm²

Beam Basics - Flux and Fluence

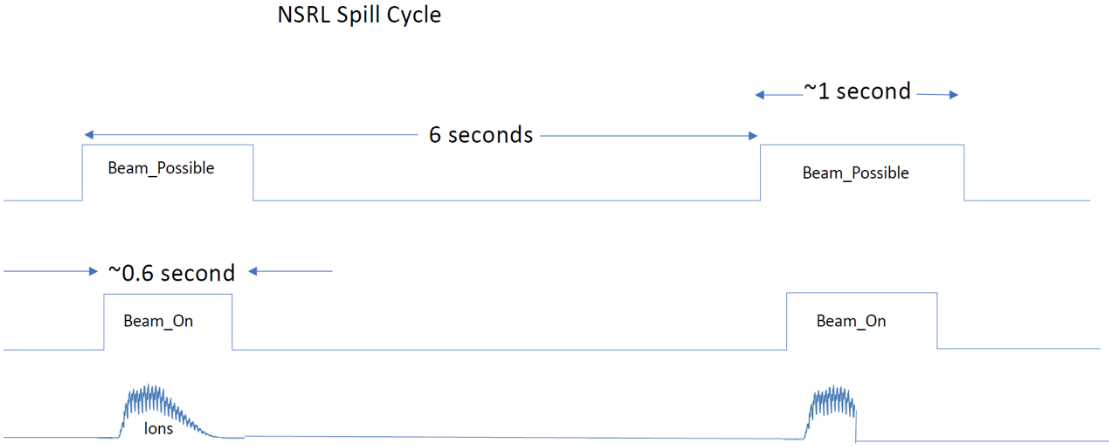
Flux: The rate of beam particles passing through a unit area

Question: *Is flux always constant?*



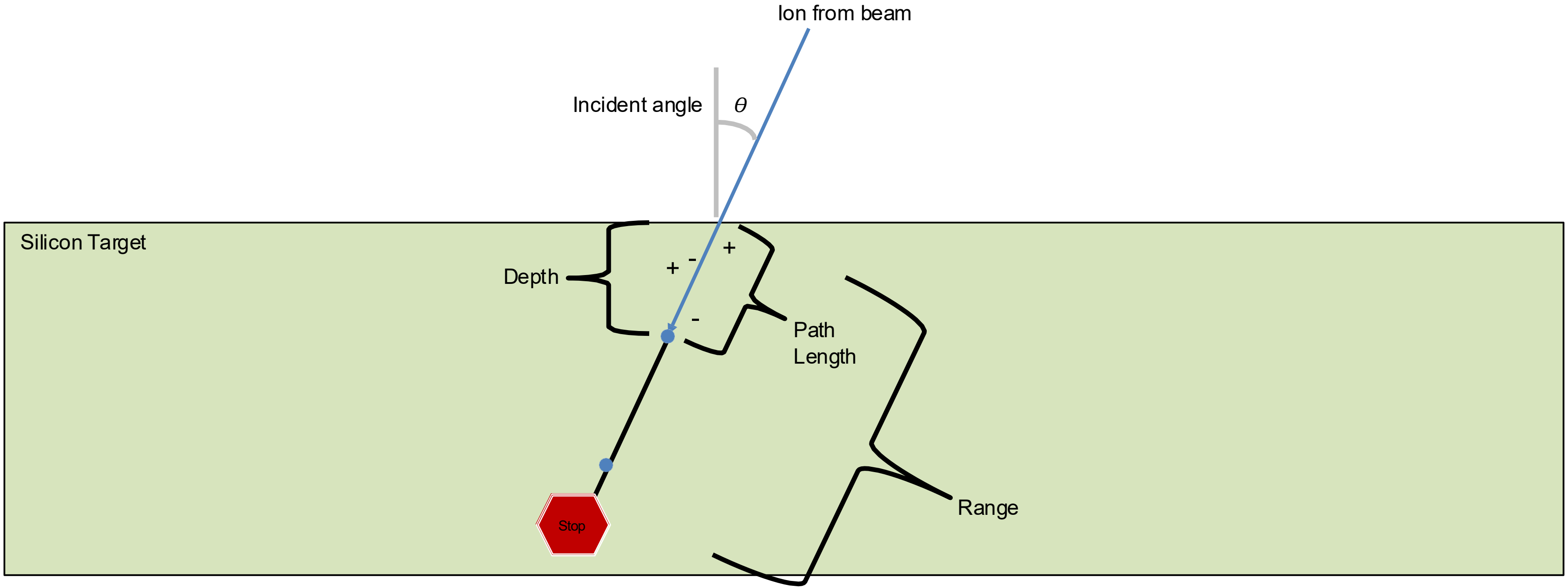
Flux = 9 /cm²/s

Synchrotrons release radiation in "spills"



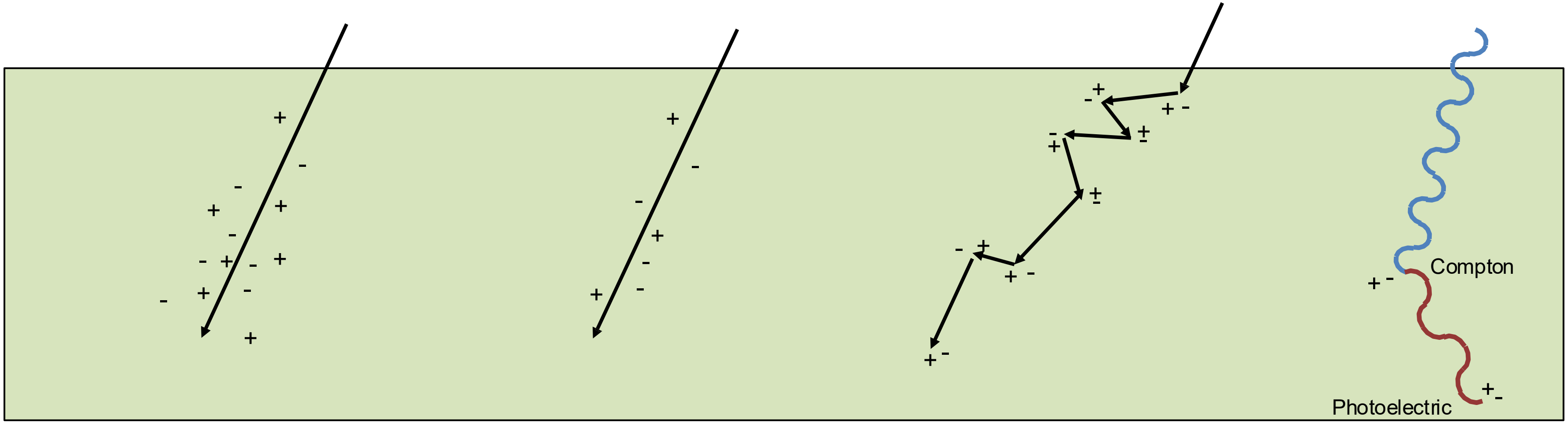
BNL/NSRL User Guide

Beam Basics - Geometry



Particle Track

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



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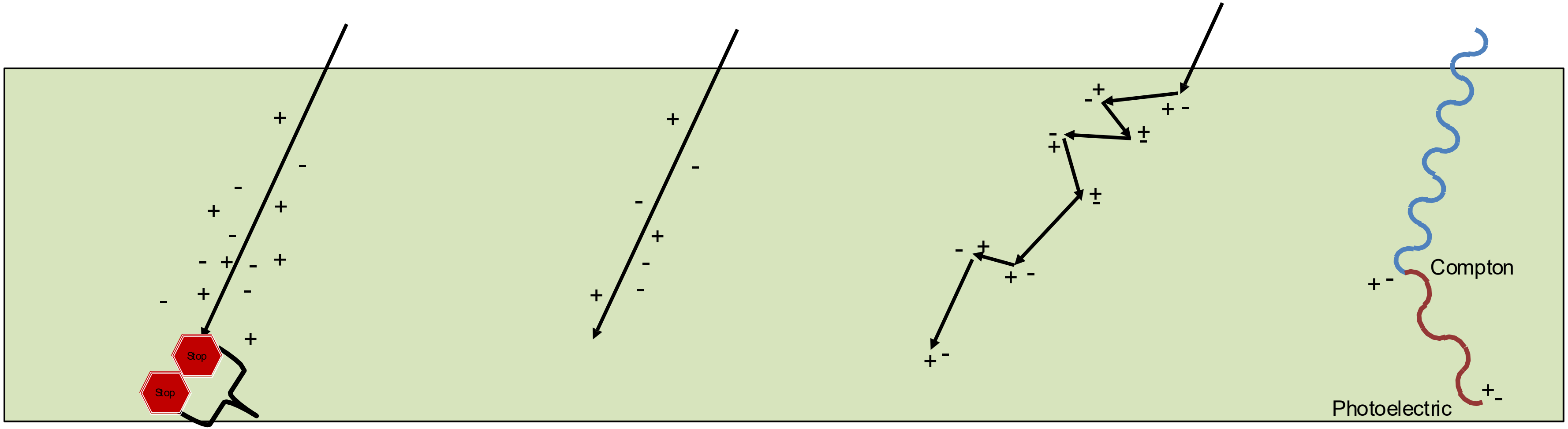


Straggling: variation in total range of individual beam particles due to probabilistic nature of interactions. Thus, the “Range” of a beam is not exact.

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

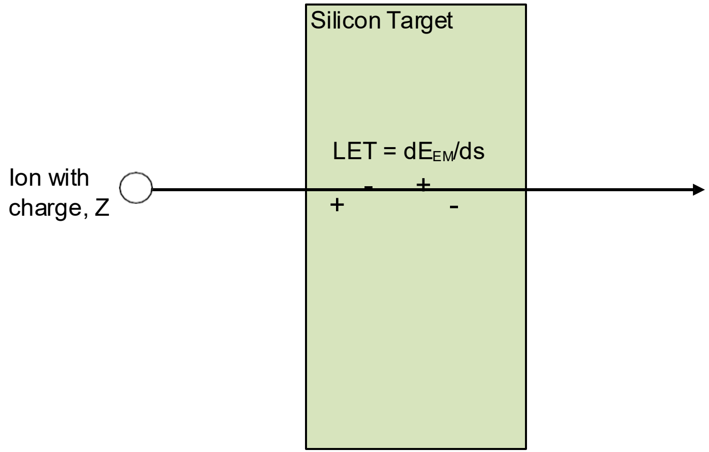
LET – Linear Energy Transfer

- 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

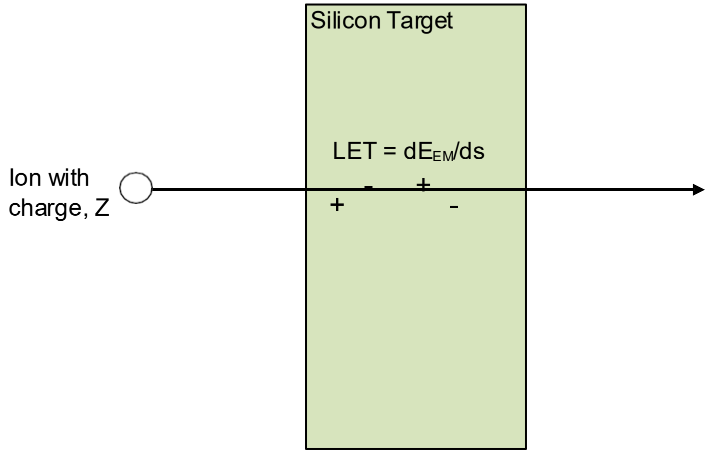


LET – Linear Energy Transfer

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

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

- What influences LET?

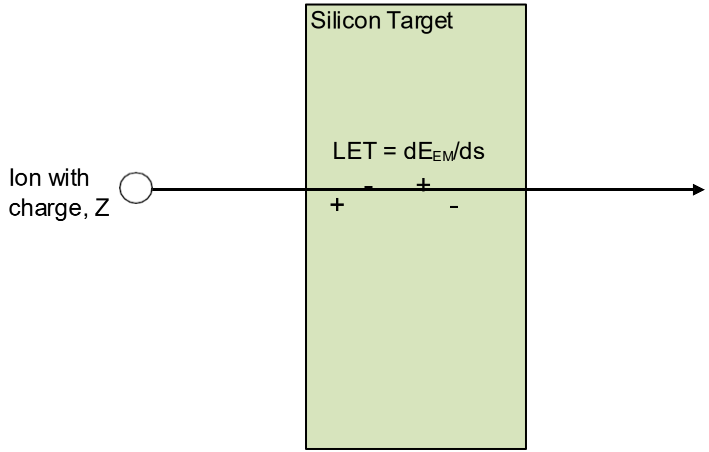


LET – Linear Energy Transfer

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

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

- 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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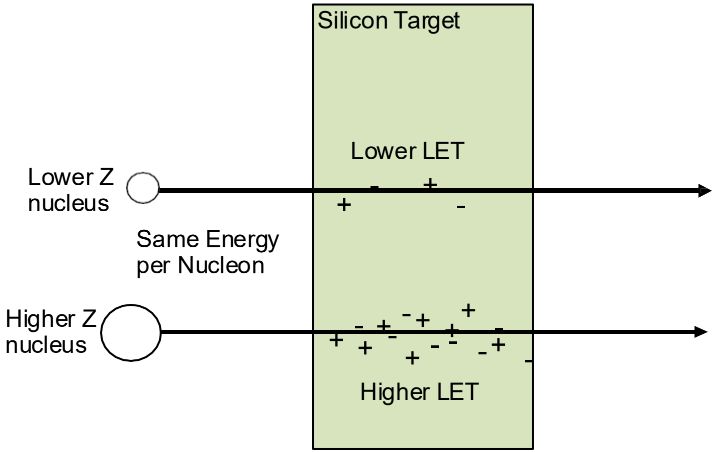


- Higher Z ions are more stressing from an SEE test standpoint, *i.e.*, they have higher LET (everything else being the same)

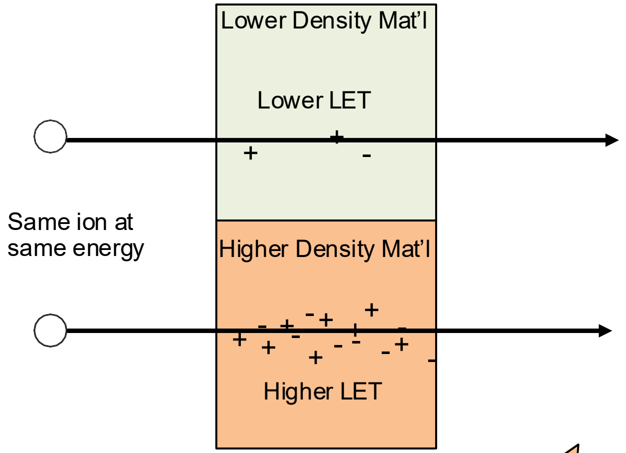
LET – Linear Energy Transfer

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

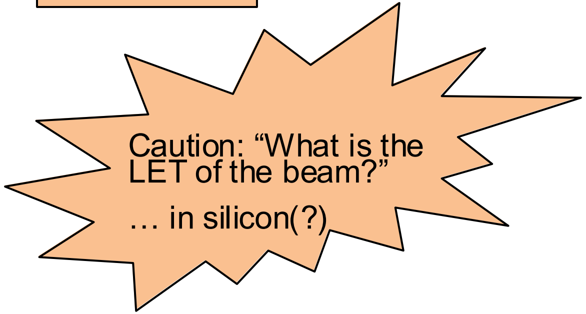
$$LET = dE_{EM}/ds$$

- 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 is dependent on the target material!!



LET – Units

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

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

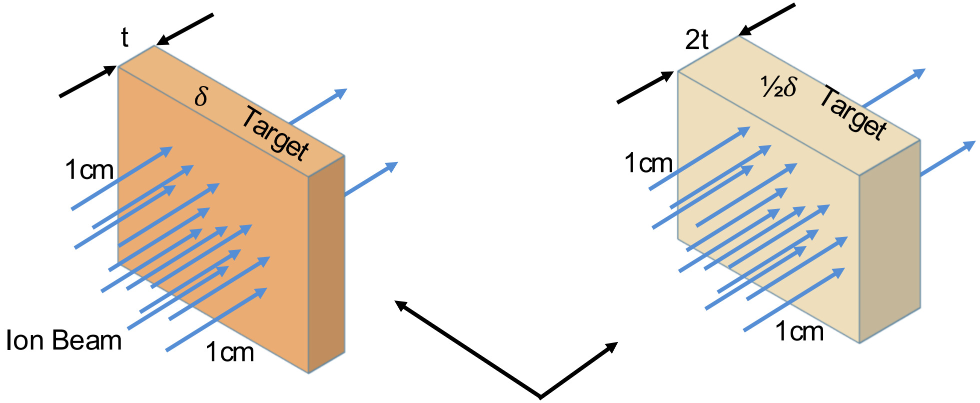
- s is along the path of the particle

- 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
  - $MeV \cdot cm^2/mg$
  - Think of it as:
    - $MeV/(mg/cm^2)$
    - $MeV/(cm \cdot mg/cm^3) \rightarrow dE/(ds*\delta)$
    - 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

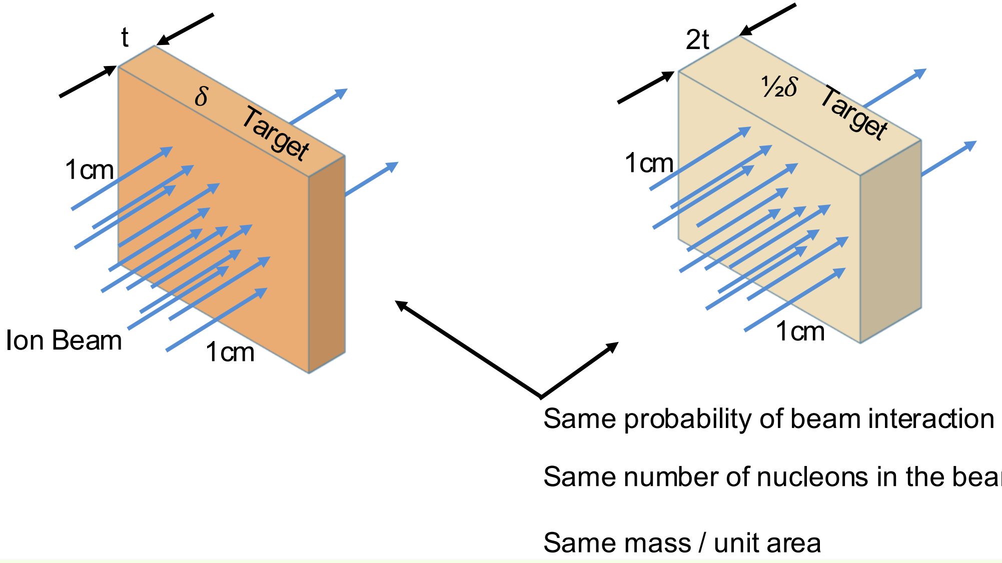
Same number of nucleons in the beam’s way, per unit area

Same mass / unit area

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

Target Density

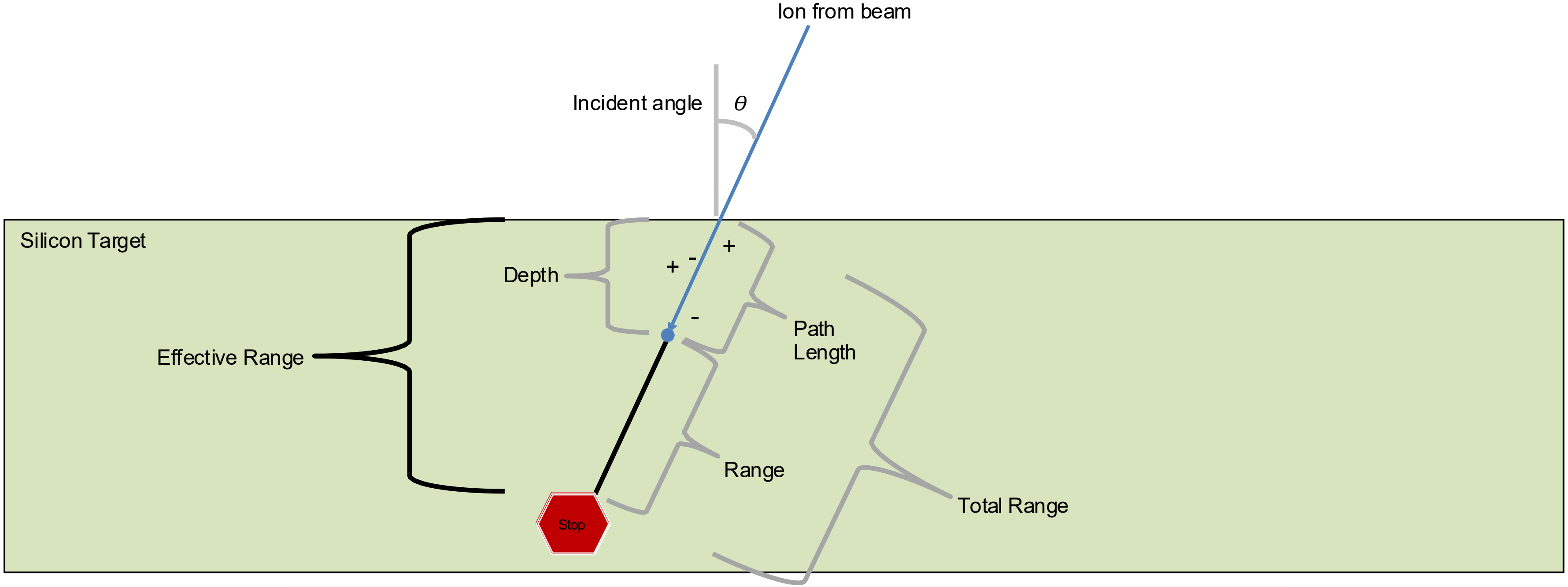
- Just as chance of interaction can be increased by increasing t, it can similarly be increased by **increasing density**



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

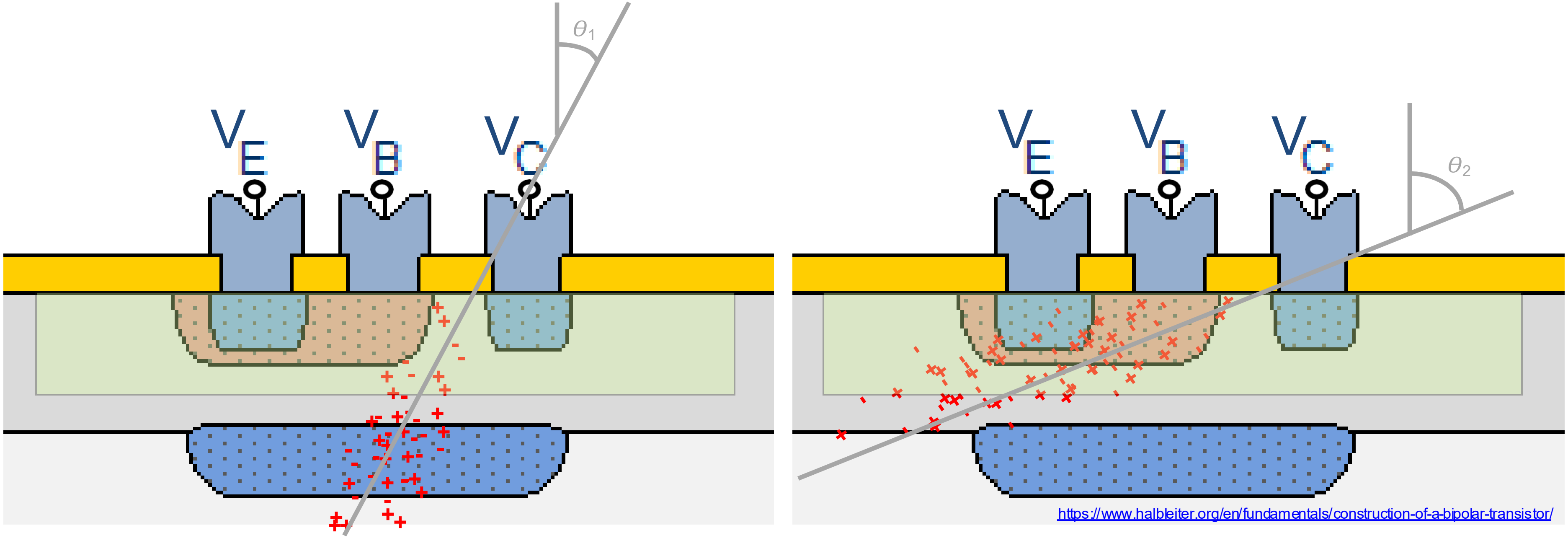
Beam Basics – Orientation



Effective LET ➔ LET as if the beam were normally incident

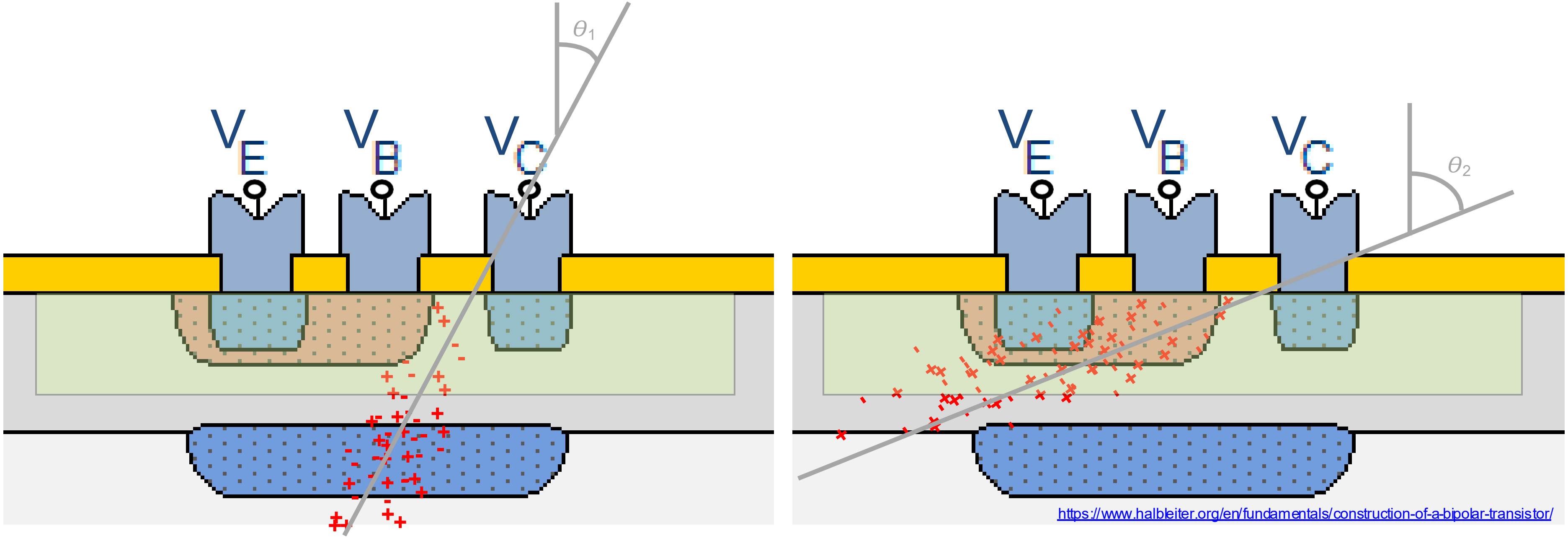
Effective Range ➔ Range as if the beam were normally incident

Influence of Angle of Incidence



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

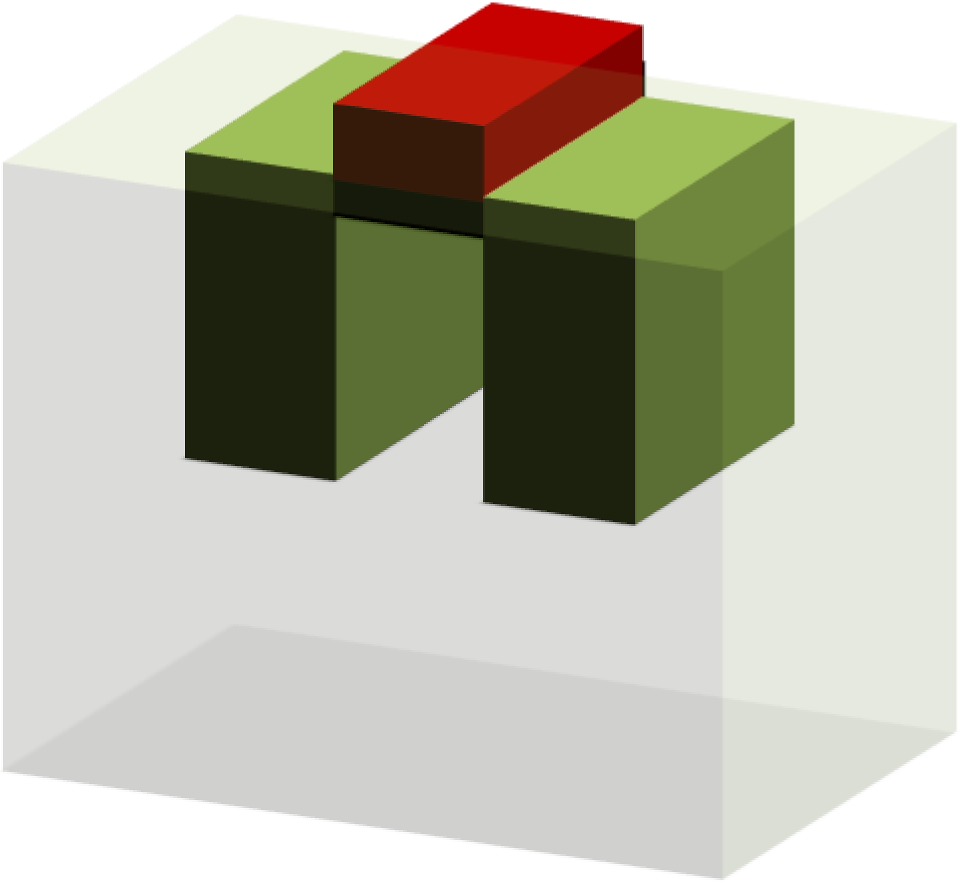
Influence of Angle of Incidence



- 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?

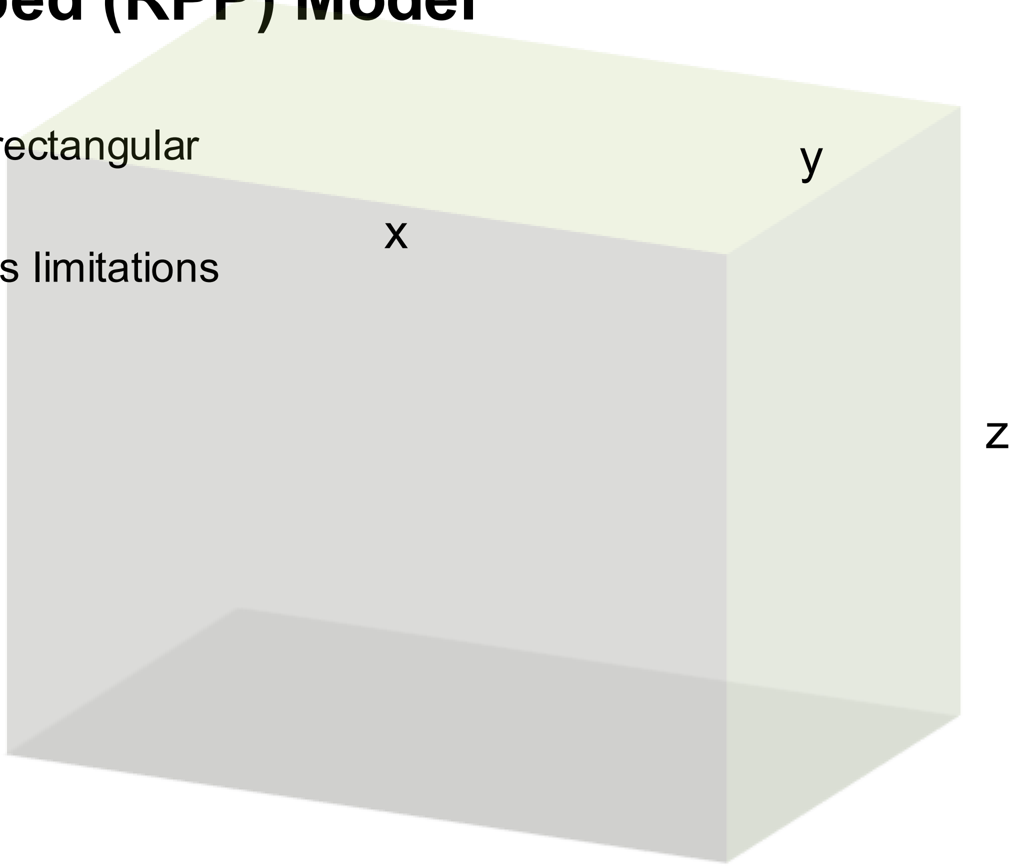
Sensitive Volume (SV)

- 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

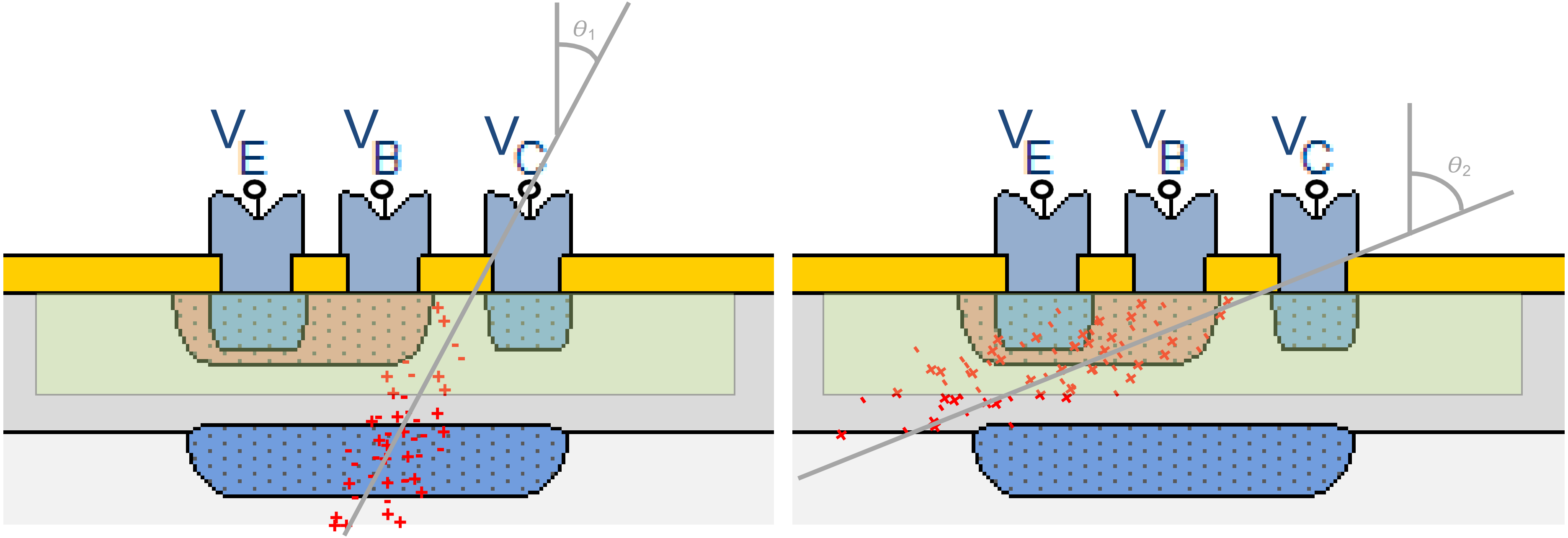


Rectangular Parallel Piped (RPP) Model

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

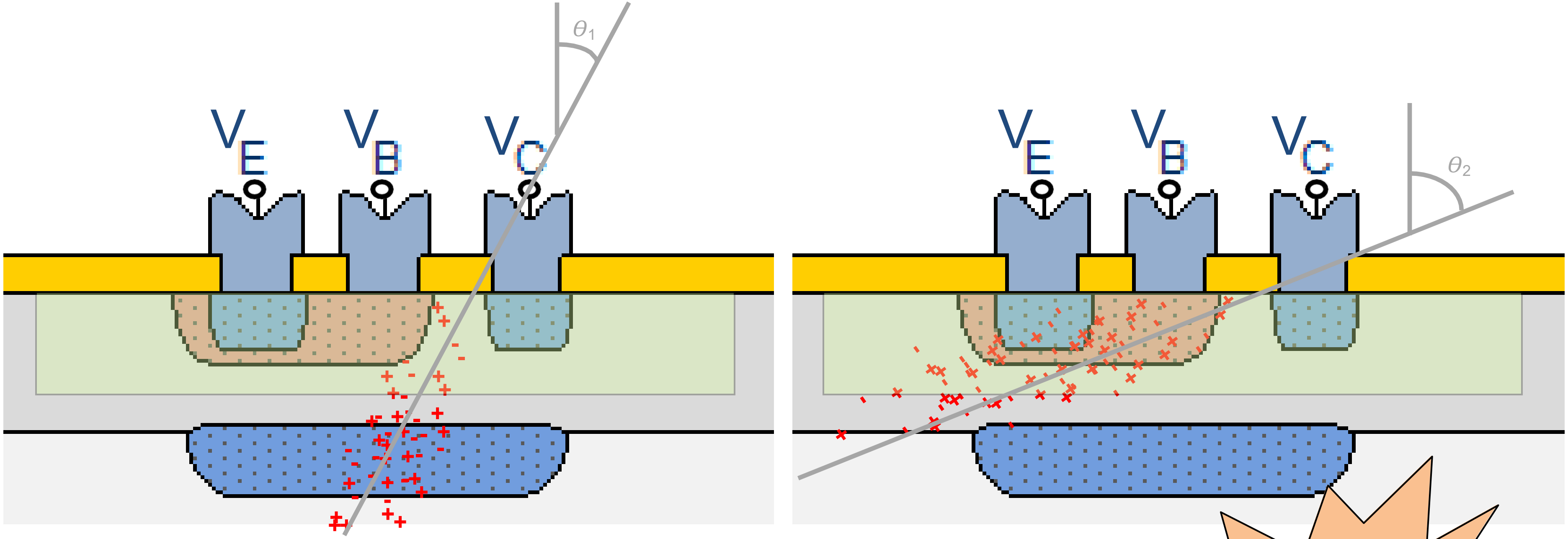


Influence of Angle of Incidence



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

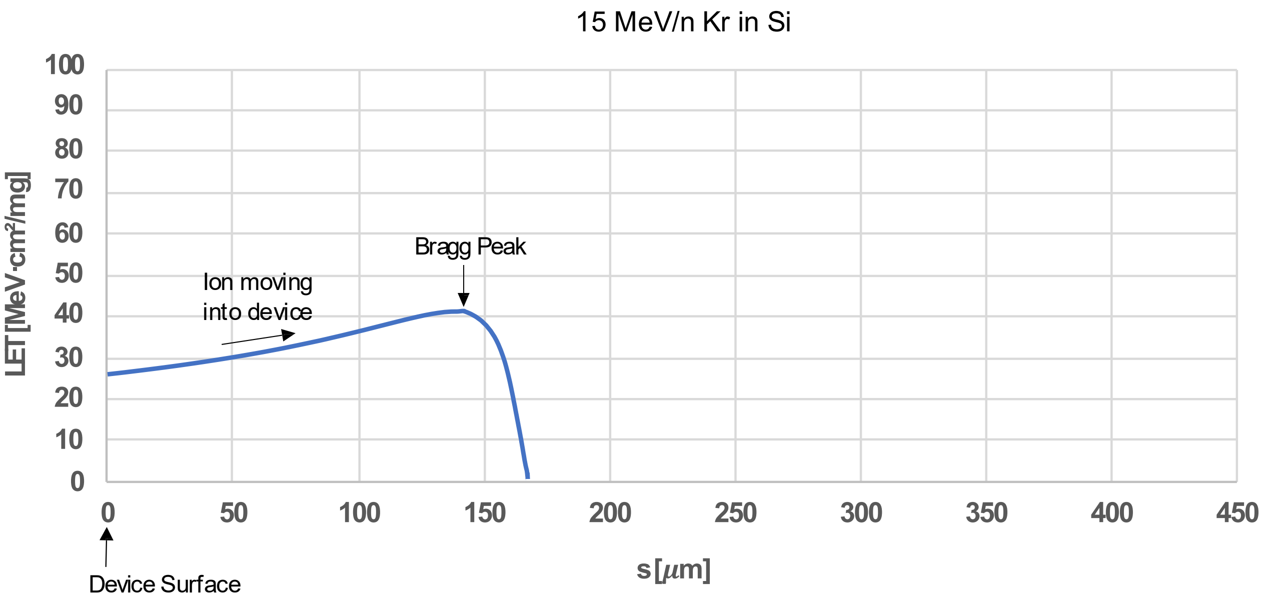
Influence of Angle of Incidence



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

Caution: Not all SEE follow $1/\cos(\theta)$

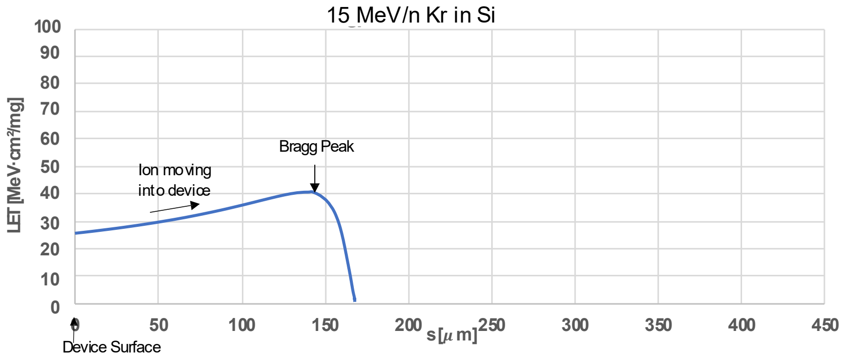
LET as Ion Moves through Material

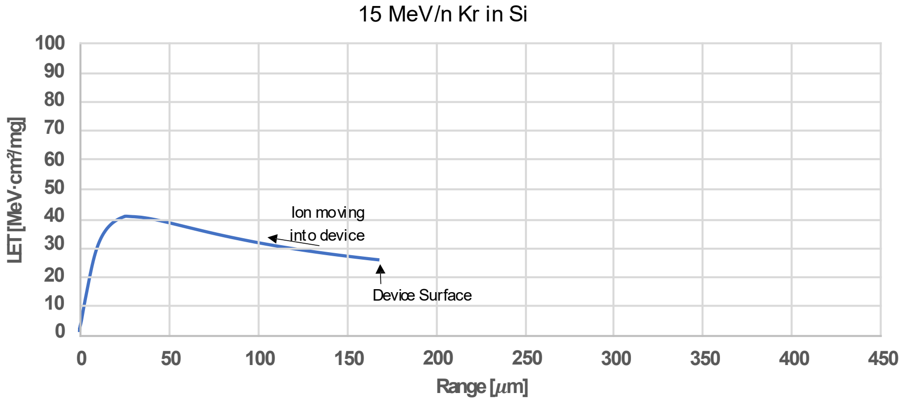


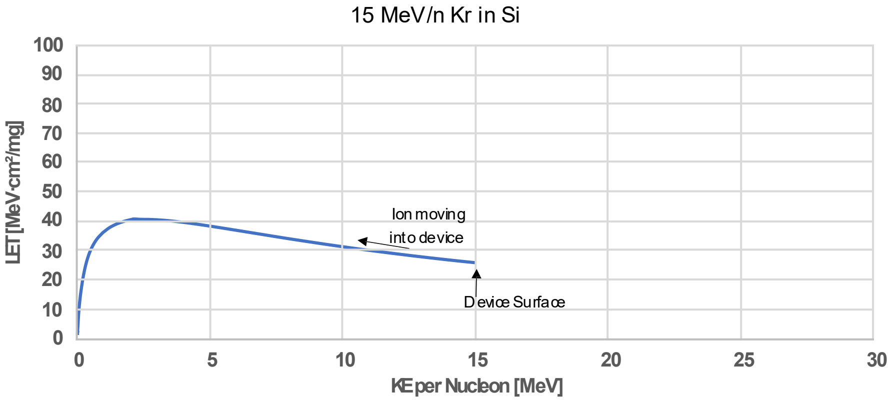
- Bragg Peak = maximum rate of energy deposition
  - Before peak, LET increases as ion slows, increasing the probability of EM interaction
  - After peak, LET decreases as ion picks up electrons, decreasing charge

LET as Ion Moves through Material

- 3 common ways to view the same information







LET as Ion Moves through Material

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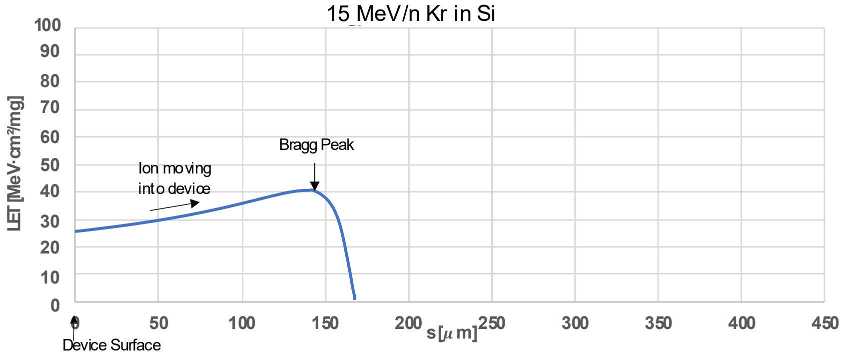
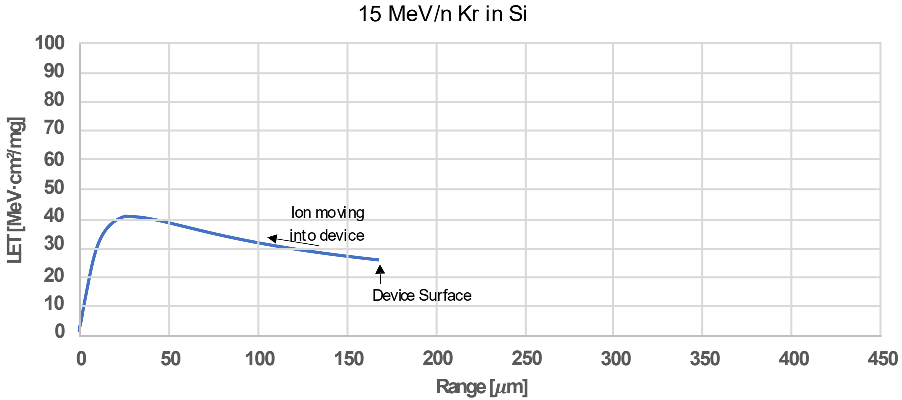
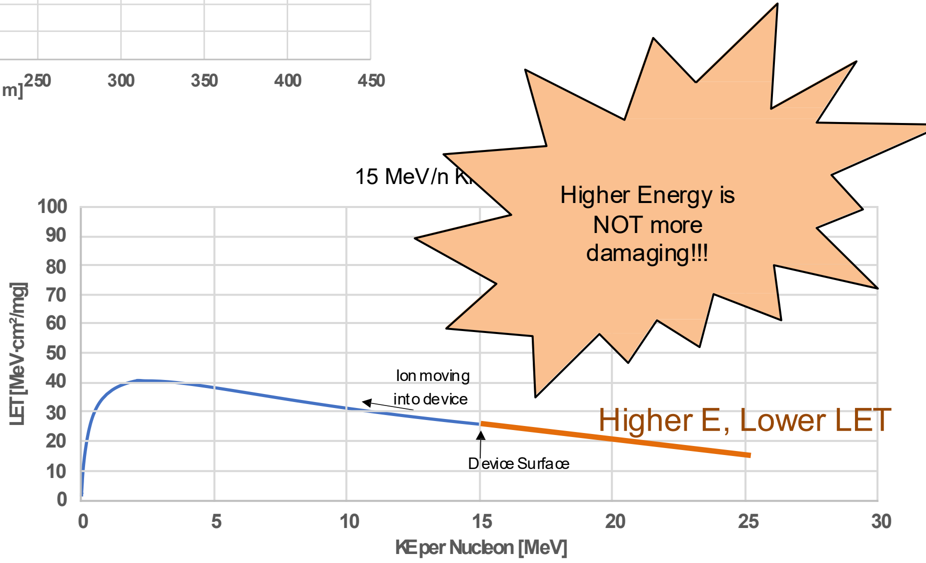
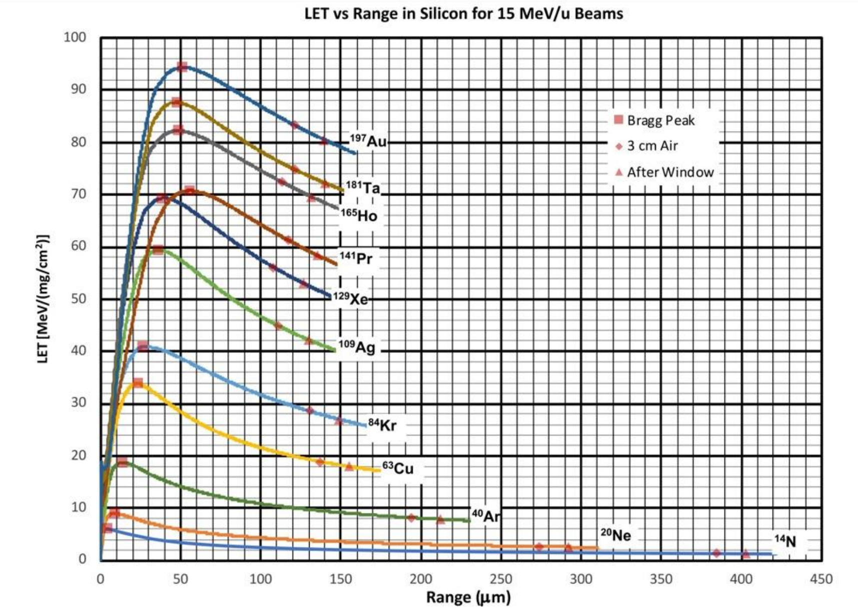






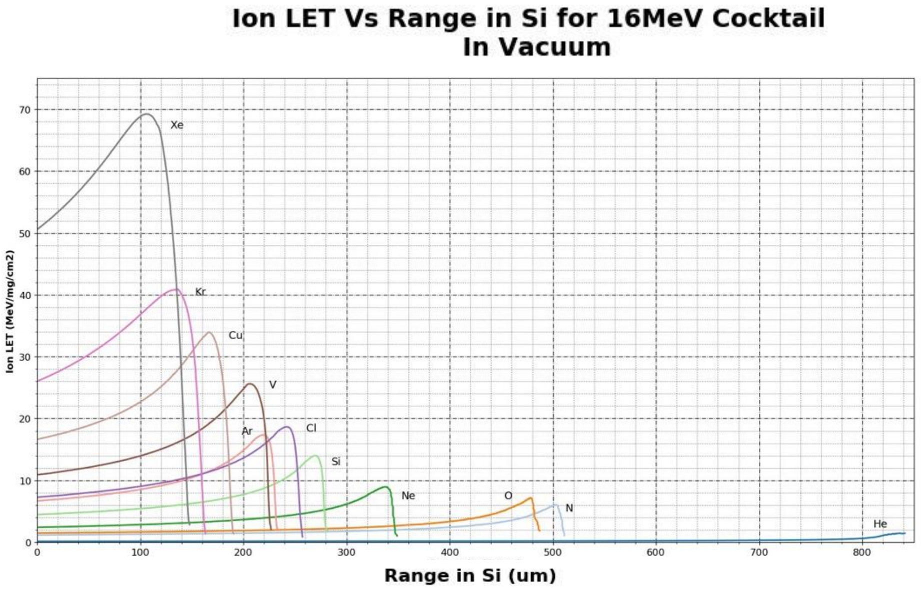
Some Available Beams

TAMU 15 MeV/n Heavy Ions



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

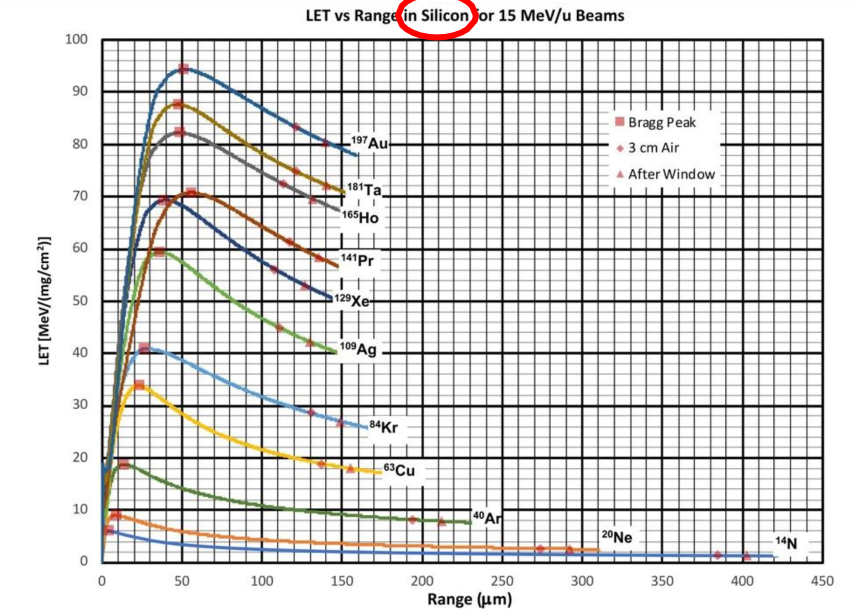
LBNL 16 MeV/n Heavy Ions



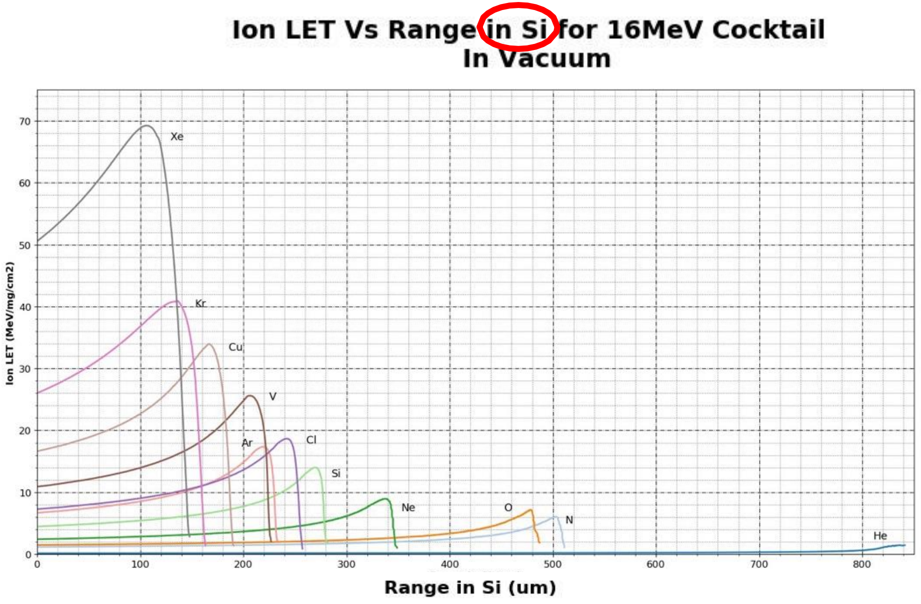
https://cyclotron.lbl.gov/base-rad-effects/heavy-ions

Some Available Beams

TAMU 15 MeV/n Heavy Ions



LBNL 16 MeV/n Heavy Ions

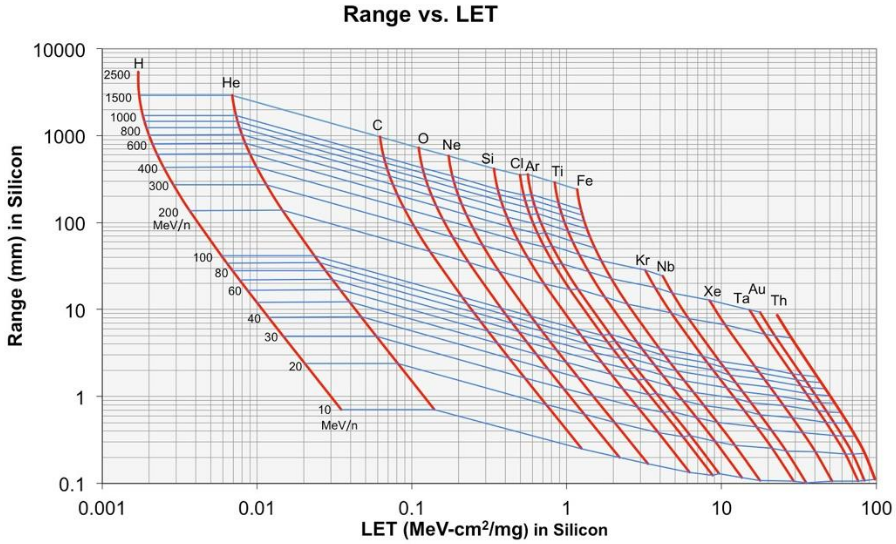


https://cyclotron.tamu.edu/ref/images/let_vs_range_plots.pdf

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

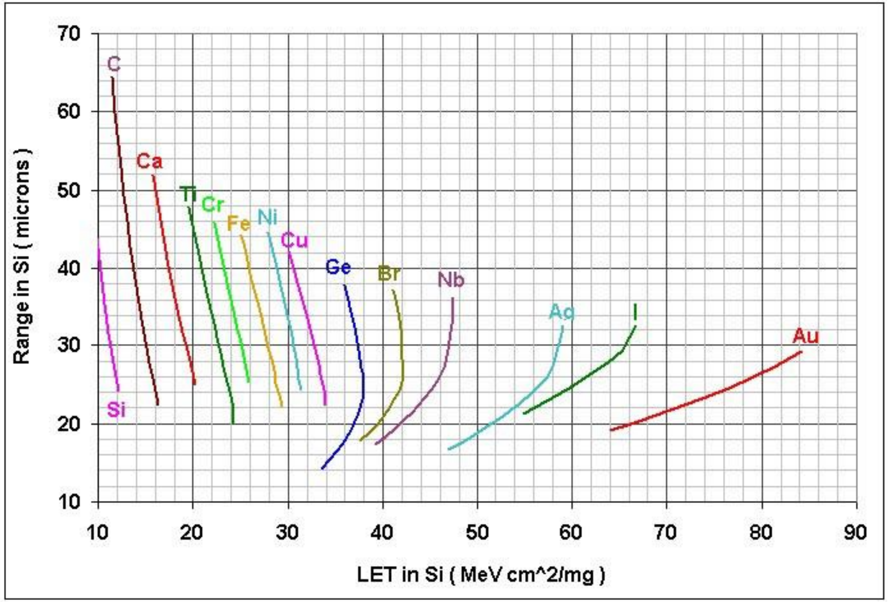
Some Available Beams

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

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 K5
between 1E2 and 1E7 ions/cm^2-s
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  - https://cyclotron.lbl.gov/base-rad-
  - https://cyclotron.tamu.edu/ref/dow
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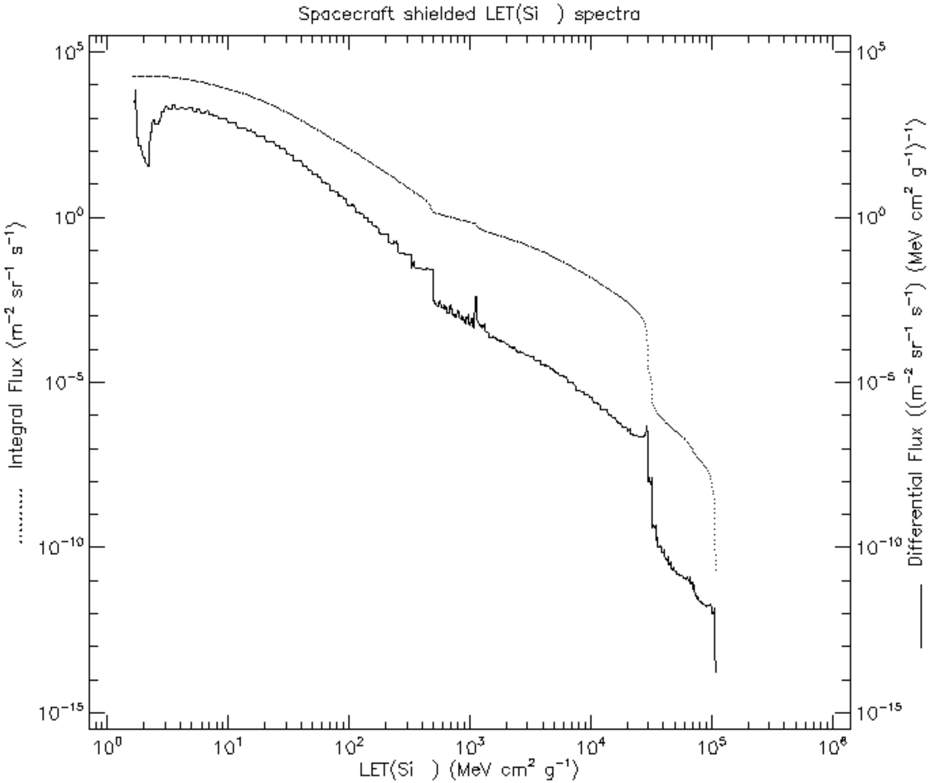

Facility Flux Capabilities and Other Details

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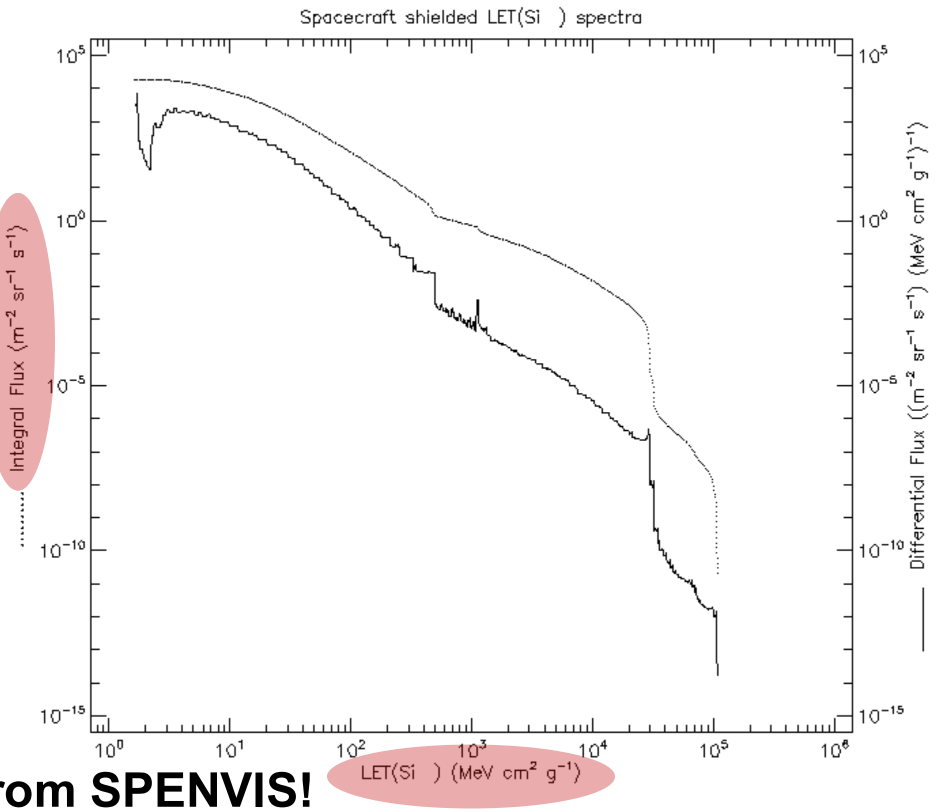
  - https://frib.msu.edu/science/fsee/f

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

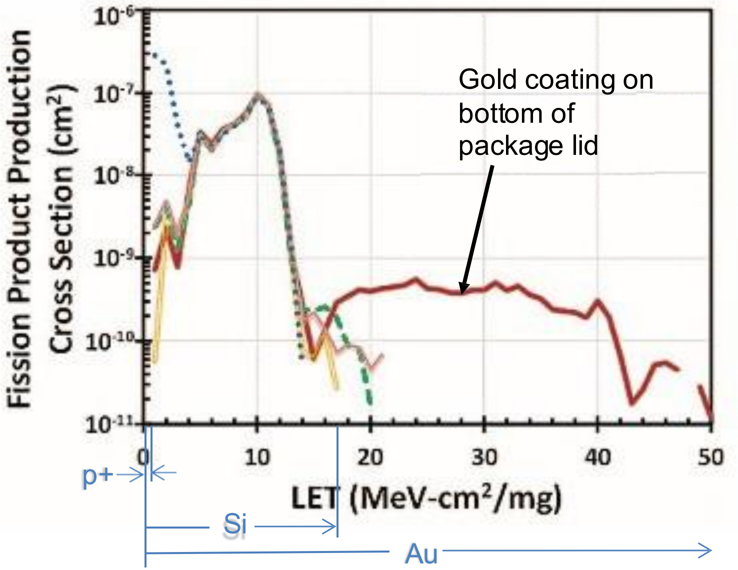


Careful of units from SPENVIS!

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

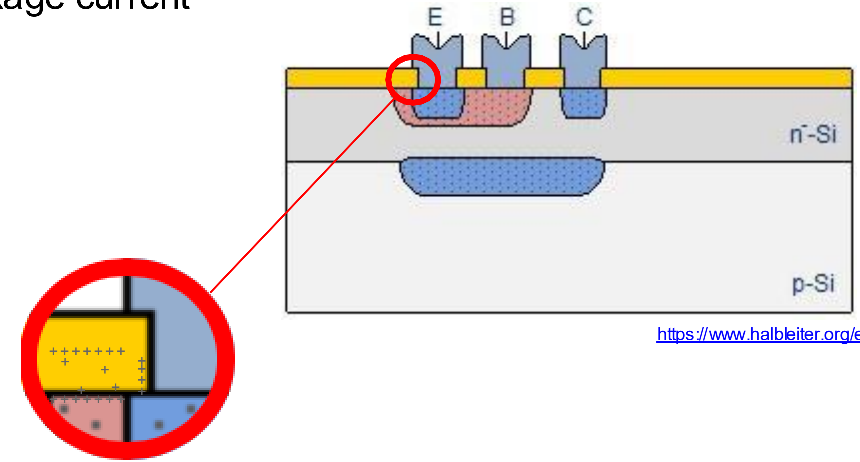
LETs resulting from 200 MeV p+ beam hitting a packaged silicon op amp



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.

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!

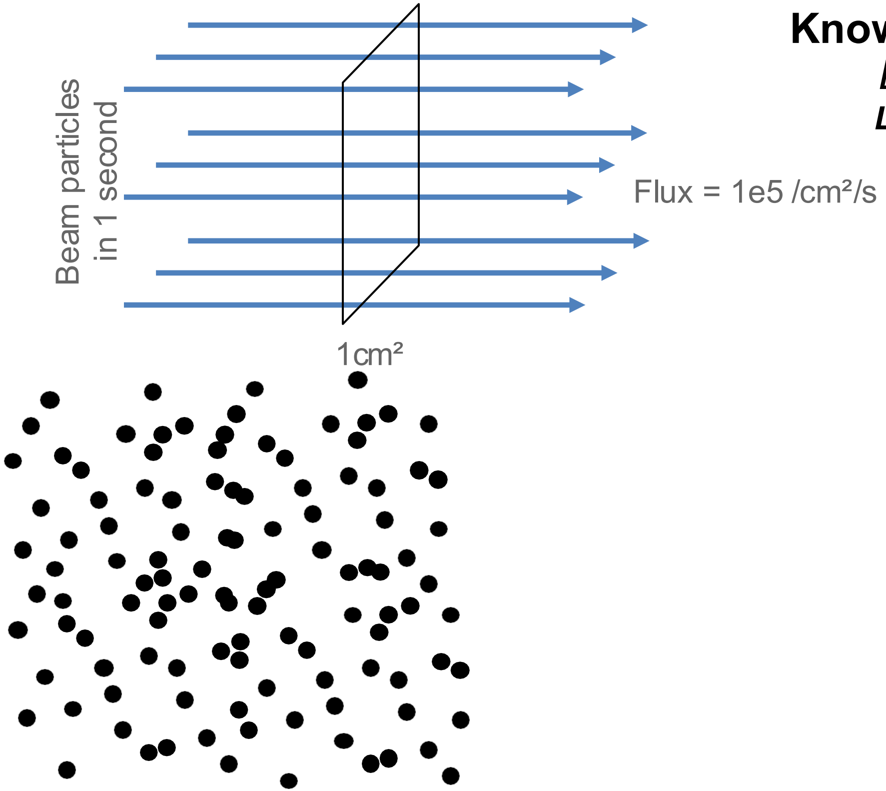
Useful Tools and Resources

- 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

05

MEASURING SEE

SEE Cross Section



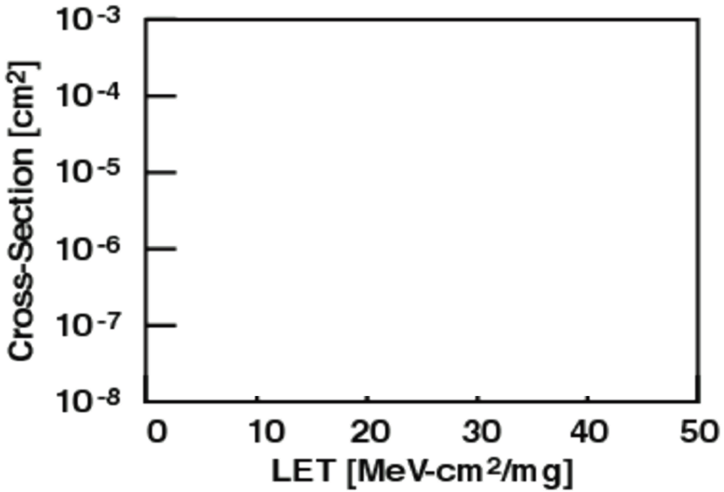
Calculation of Cross-Section

Known Fluence (Ions), LET

Ex. 1000 sec of irradiation to 1e8 ions/cm²

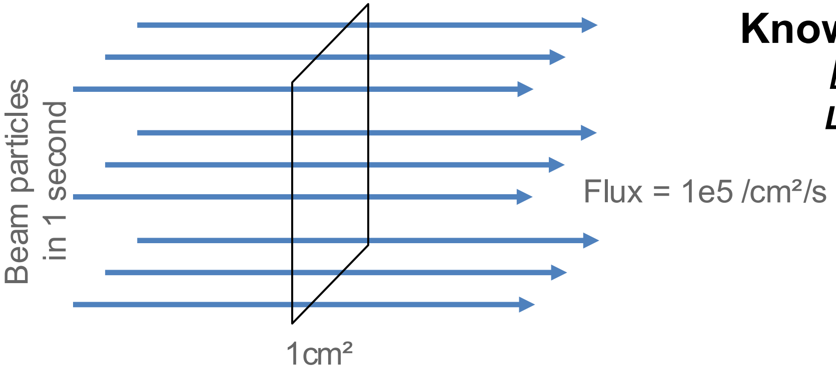
LET = 11, 12, 13 … 38 MeV-cm²/mg

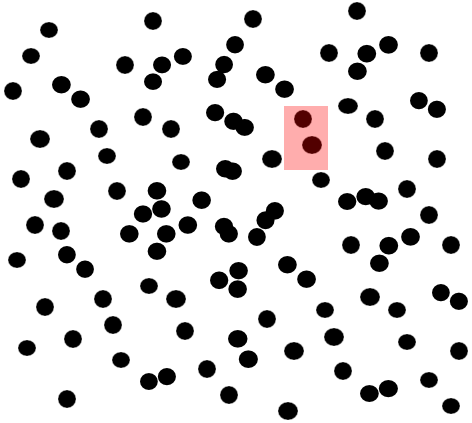
Sensitive Area vs. LET



LET = Linear Energy Transfer

SEE Cross Section





Calculation of Cross-Section

Known Fluence (Ions), LET

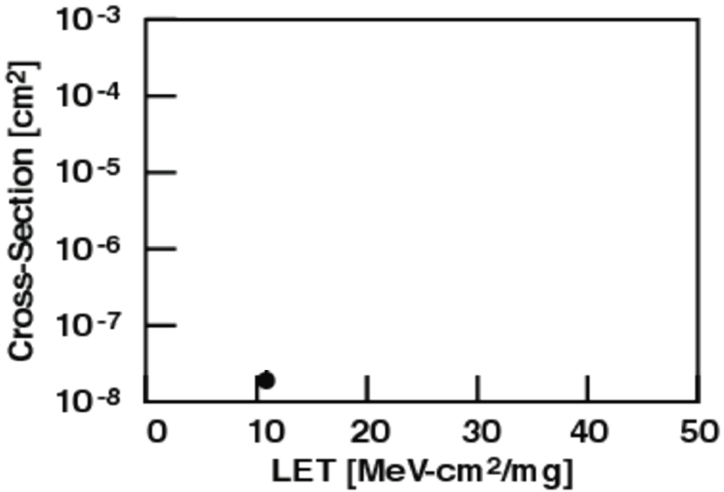
Ex. 1000 sec of irradiation to 1e8 ions/cm²

LET = 11, 12, 13 … 38 MeV-cm²/mg

$$\text{Cross-section} = \frac{\text{2 upsets/device}}{\text{1e8 ions/cm}^2}$$

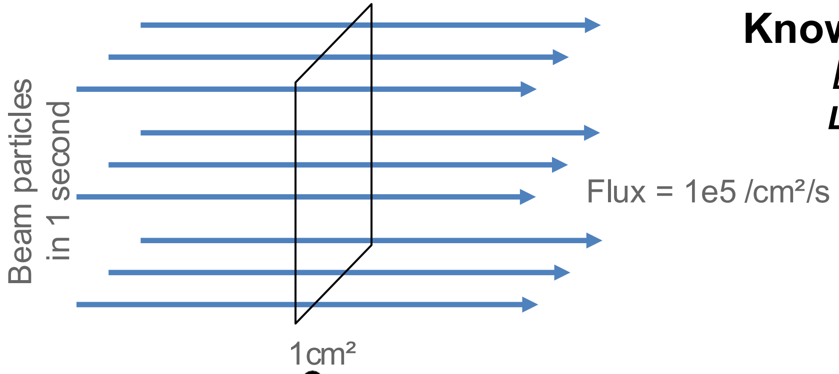
= 2e-8 cm²/device

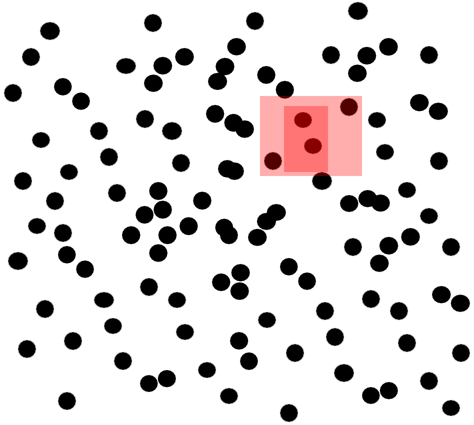
Sensitive Area vs. LET



LET = Linear Energy Transfer

SEE Cross Section





Calculation of Cross-Section

Known Fluence (Ions), LET

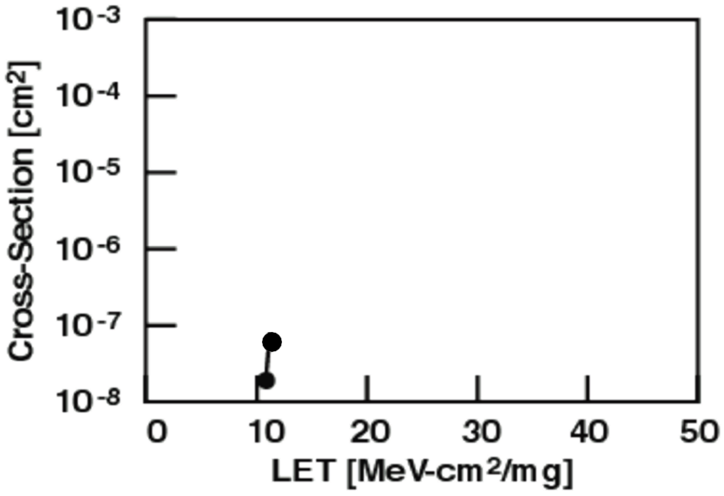
Ex. 1000 sec of irradiation to 1e8 ions/cm²

LET = 11, 12, 13 … 38 MeV-cm²/mg

Cross-section = $\frac{\text{4 upsets/device}}{\text{1e8 ions/cm}^2}$

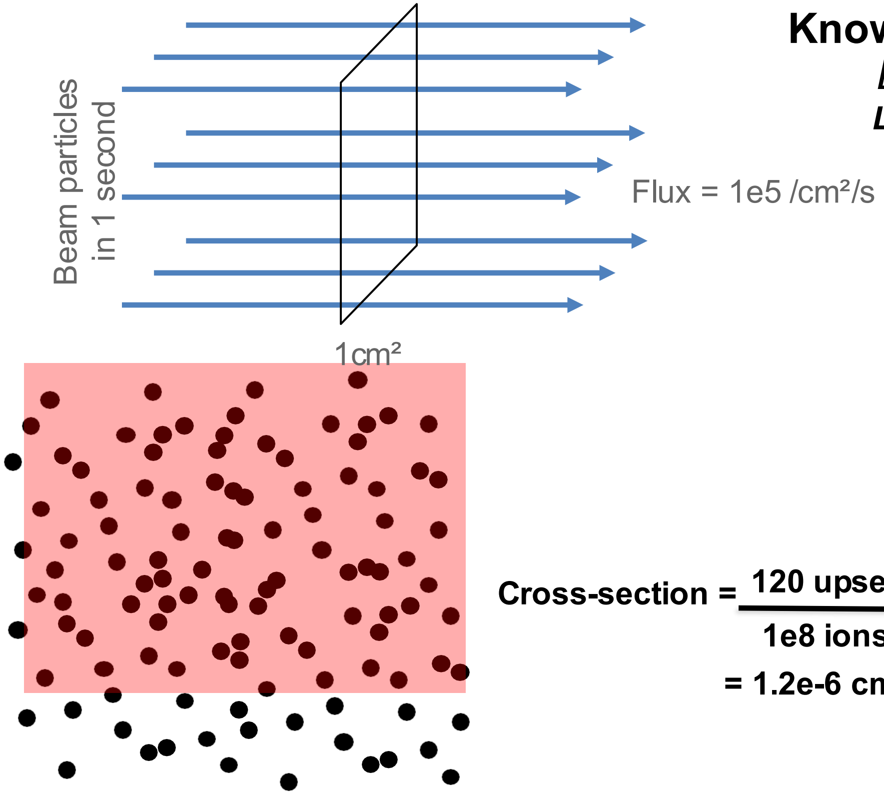
= 4e-8 cm²/device

Sensitive Area vs. LET



LET = Linear Energy Transfer

SEE Cross Section



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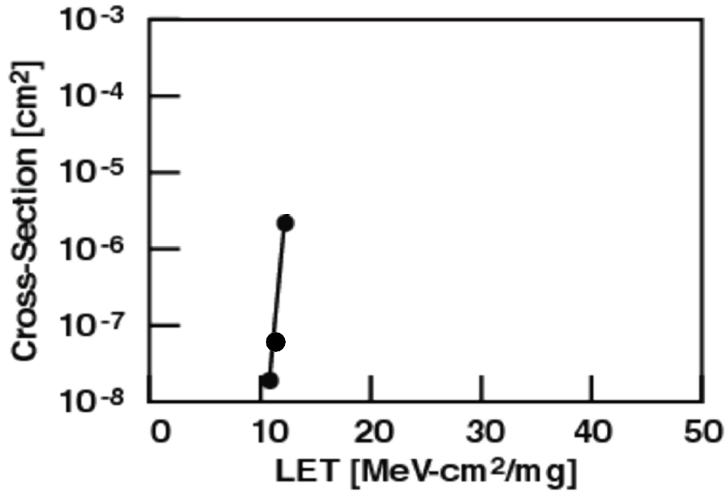
Sensitive Area vs. LET

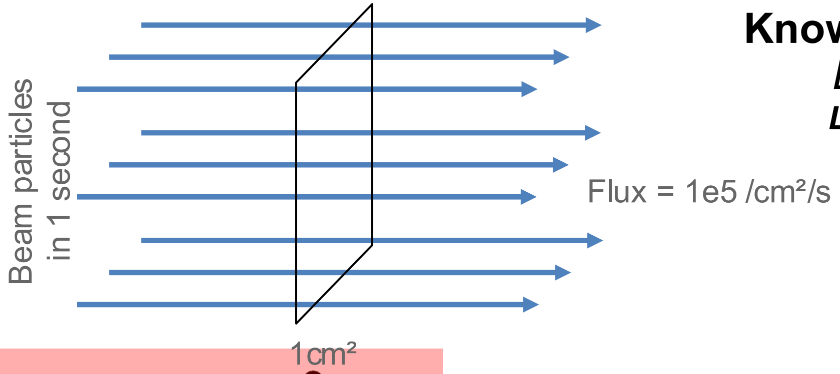


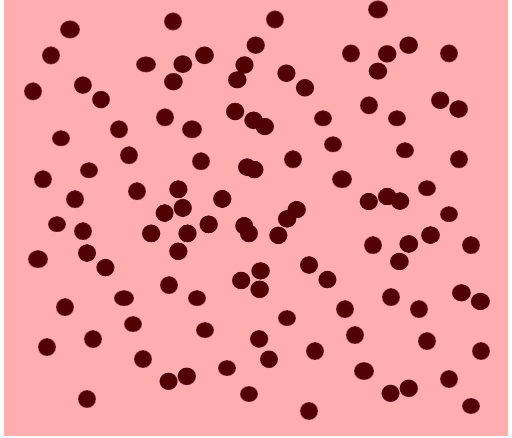
Cross-section = $\dfrac{\textbf{120 upsets/device}}{\textbf{1e8 ions/cm}^2}$

= 1.2e-6 cm²/device

LET = Linear Energy Transfer

SEE Cross Section





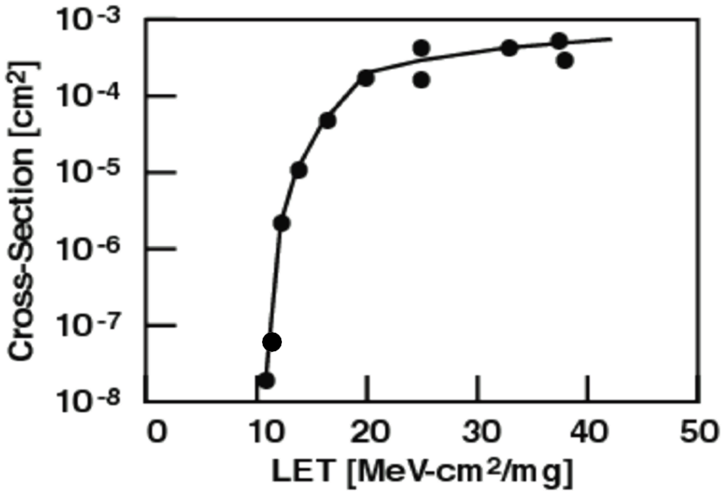
Calculation of Cross-Section

Known Fluence (Ions), LET

Ex. 1000 sec of irradiation to 1e8 ions/cm²

LET = 11, 12, 13 … 38 MeV-cm²/mg

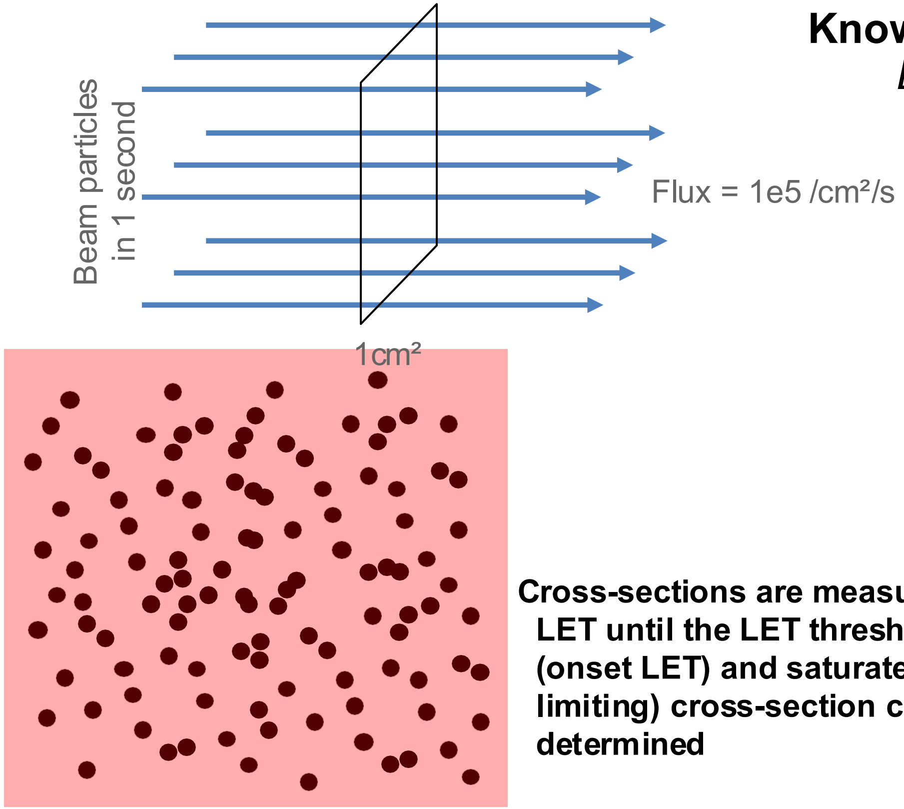
Sensitive Area vs. LET



Cross-sections are measured vs. LET until the LET threshold (onset LET) and saturated (or limiting) cross-section can be determined

LET = Linear Energy Transfer

SEE Cross Section



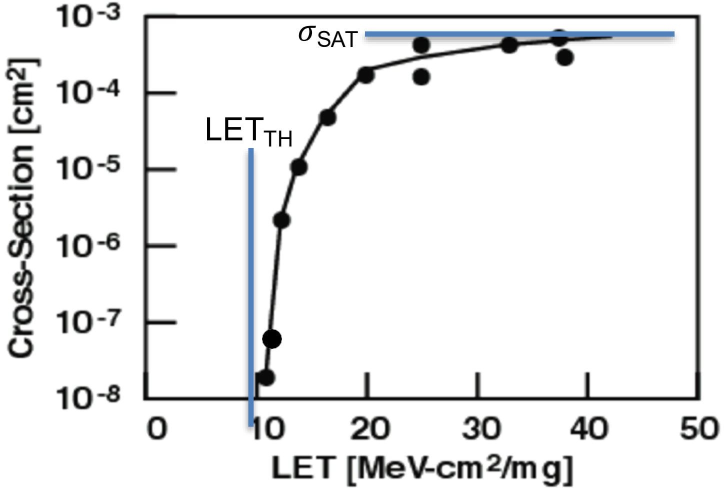
Calculation of Cross-Section

Known Fluence (Ions), LET

Ex. 1000 sec of irradiation to 1e8 ions/cm²

Cross-sections are measured vs. LET until the LET threshold (onset LET) and saturated (or limiting) cross-section can be determined

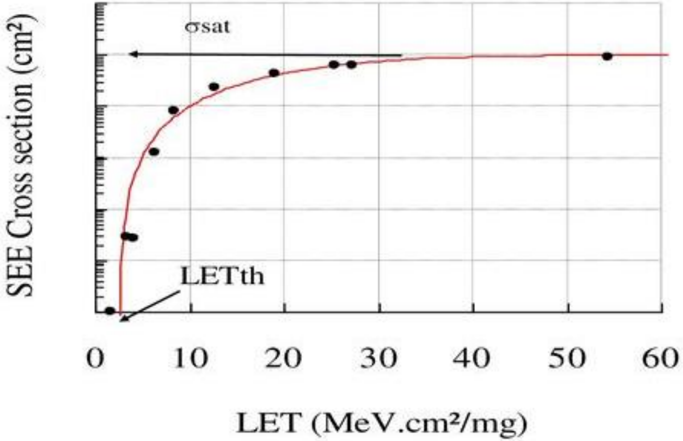
Sensitive Area vs. LET



LET = Linear Energy Transfer

Modeling the SEE Cross Section – more in Module 12

- Model cross-section data with a Weibull curve (use a semi-log y scale)
- Fit the model by minimizing the sum of the squared residuals



Source: [ESA presentation by C. B. Polo]

$$[\mathrm{cm}^2] \longrightarrow \sigma = \frac{N_{events}}{\mathrm{Fluence}} \longleftarrow [N_{particules}/\mathrm{cm}^2]$$

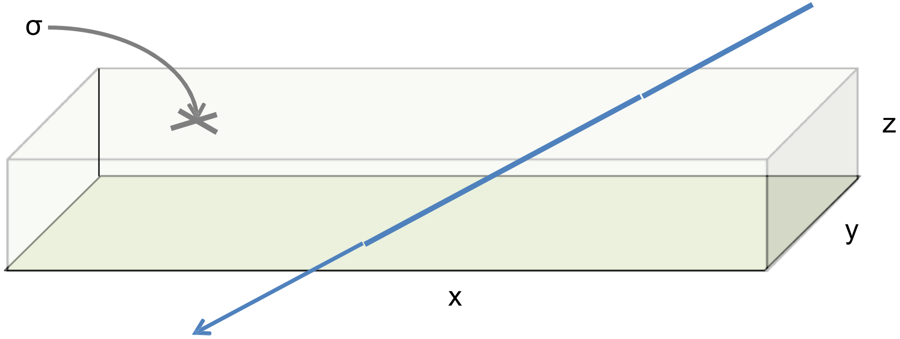
Fit with Weibull (integral form)

$$\sigma = \sigma_{sat}\left(1 - \exp\left(\frac{LET - LET_{th}}{W}\right)^{S}\right)$$

W and S are fitting parameters

SEE cross-section is a crucial input for in-orbit SEE rate prediction.

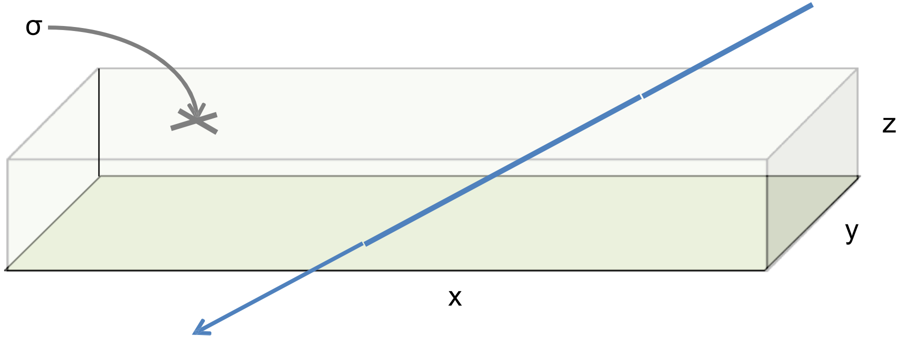
Rectangular Parallel Piped (RPP) Model



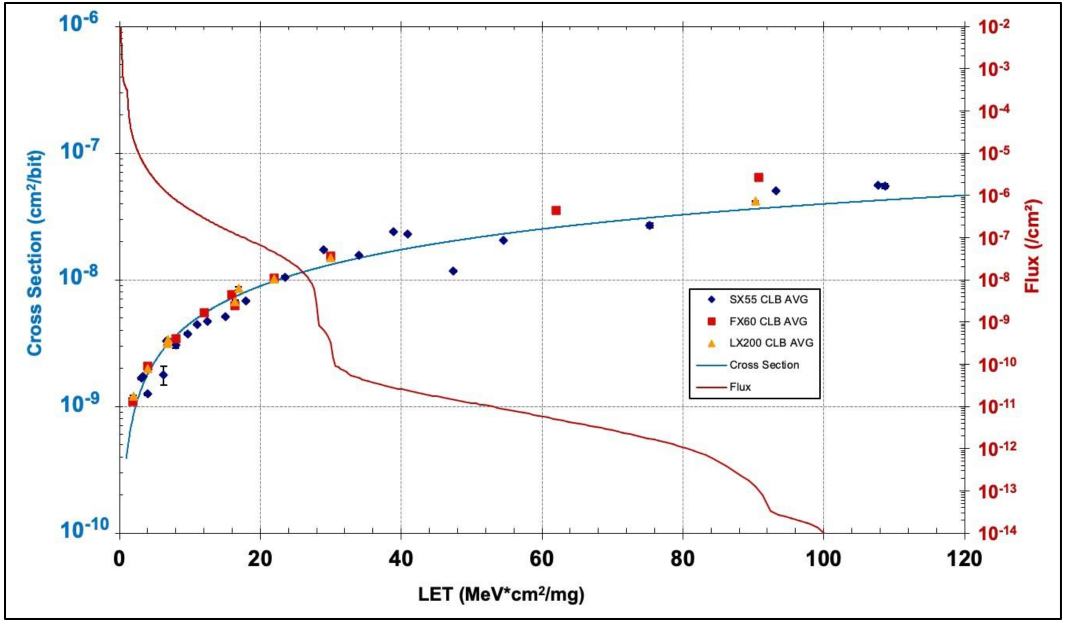
- Cross-Section:
  - $\sigma = x * y$
  - The top-down area of the SV (or sensitive area)
- Depth of sensitive volume, z
- Path Length, distance traveled by ion through the SV (———)

Measuring SV?

- You may need to estimate the SV to use error rate modeling tools
- Experimentally:
  - Measure N, the number of SEE, during a run to fluence, Calculate:
    - $\sigma = N/\Phi$
    - $x = y = \sqrt{\sigma}$
    - z
- Many organizations use a "rule of thumb" for determining z
  - Example
    - Typical: z = x/5
    - Worst-case: z = x/100



From Experiment to On-orbit Rate Estimate
more on this in 3.1



$$Rate = \int \underbrace{\frac{dflux(LET,\Theta)}{dLET}}_{\text{environment}} \times \underbrace{\sigma(LET,\Theta)}_{\text{device response}} d\Theta\, dLET$$

06

PRACTICAL CONSIDERATIONS

Example: LBNL 88” Cyclotron BASE Facility

About the facility

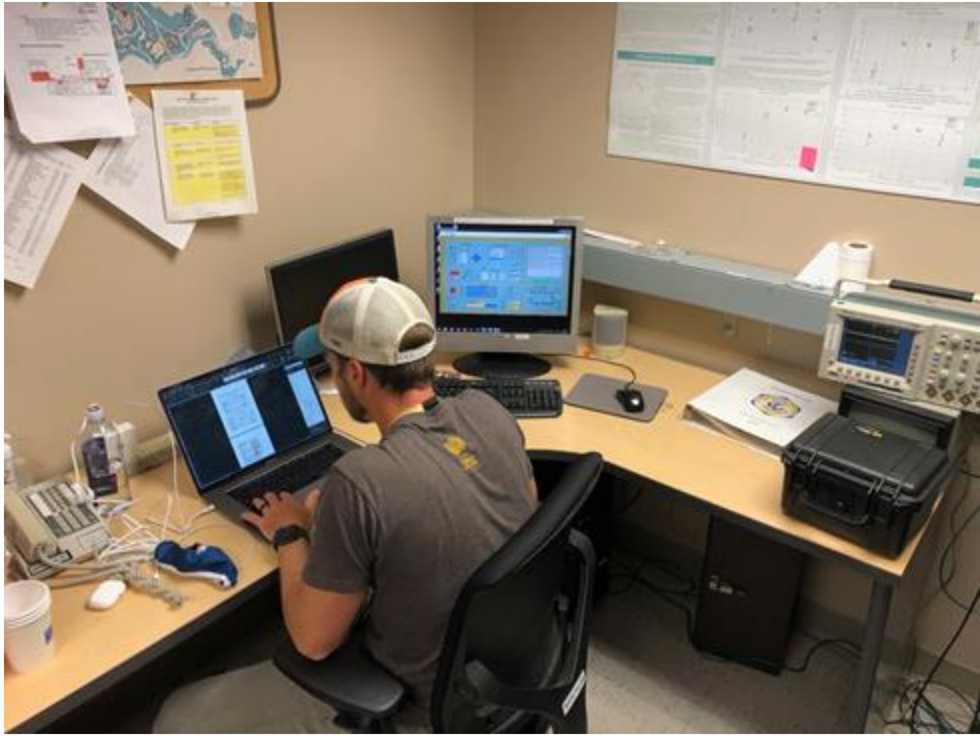
- 88” Cyclotron built in the 60s
- Heavy ions available in “cocktails”
- Example 16 MeV/amu cocktail below – don’t rely on quoted LET values!

Ion	Cocktail (AMeV)	Energy (MeV)	Z	A	Chg. State	% Nat. Abund.	LET (Entrance) (MeV/mg/cm2)
He*	16	43.46	2	3	+1	0.000137	**0.11**
N	16	233.75	7	14	+5	99.63	**1.16**
O	16	277.33	8	17	+6	0.04	**1.54**
Ne	16	321.00	10	20	+7	90.48	**2.39**
Si	16	452.10	14	29	+10	4.67	**4.56**
Cl	16	539.51	17	35	+12	75.77	**6.61**
Ar	16	642.36	18	40	+14	99.600	**7.27**
V	16	832.84	23	51	+18	99.750	**10.90**
Cu	16	1007.34	29	63	+22	69.17	**16.53**
Kr	16	1225.54	36	78	+27	0.35	**24.98**
Xe*	16	1954.71	54	124	+43	0.1	**49.29**

Source: [LBNL Cyclotron Ion Cocktails]

About the facility

- Advantages
  - Changing ions (LET) is fast and easy
    - Usually just a few minutes
    - Not the case at other facilities!
  - Flux can be tuned with attenuators
  - They have a sparkling water machine

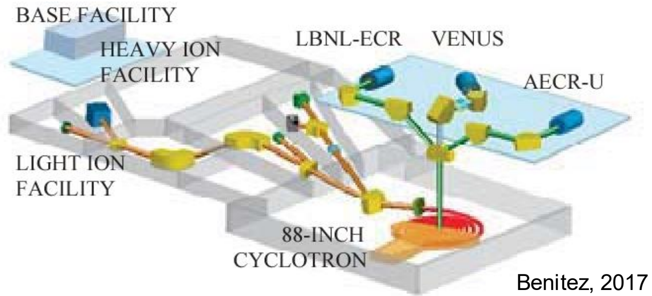


About the facility

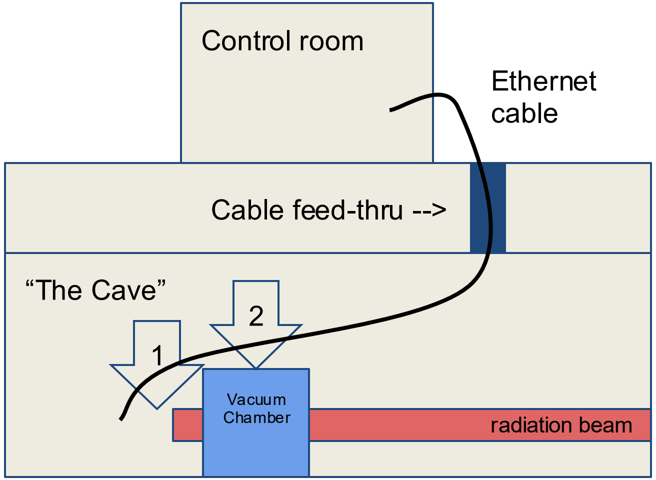
- Disadvantages
  - The beam goes down often for hours at a time
  - The beam runs 24 hours/day so you lose a lot of sleep

Setting up your system

- The control room sits directly above the beam chamber
- There is a tube into the chamber where you can run cables
- 60 feet of cables will be plenty to reach your test system
- Outside the vacuum chamber (position 1) you do not need to worry about bulkhead connectors
- Using the vacuum chamber (position 2) you need to know what connections will be available and will need extra cables
- Some cocktails (such as 10 MeV/amu) require the vacuum chamber



Benitez, 2017

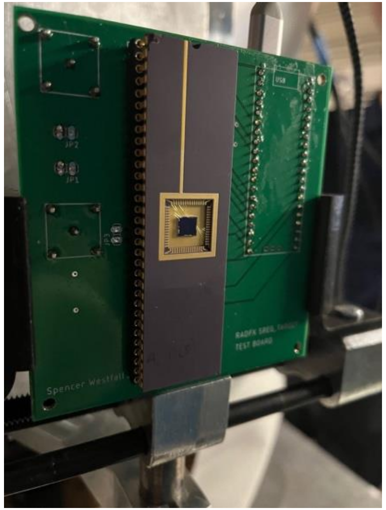


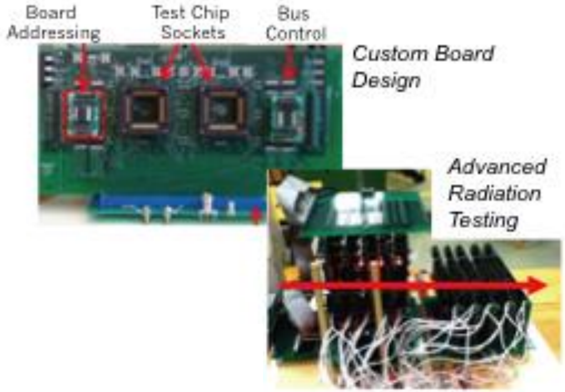
Setting up your system

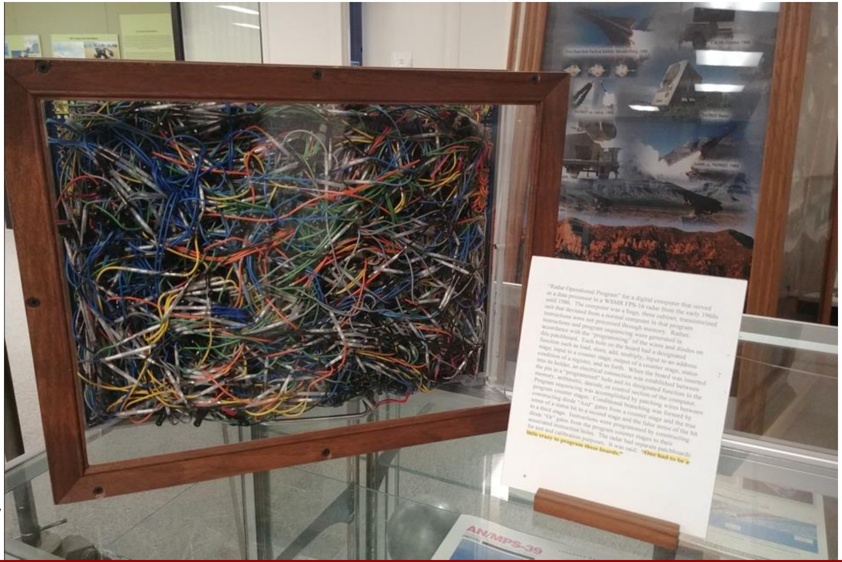
Pro tip: They will have plenty of clamps and mounts there. You should worry more about cabling

Cabling

Pro tip: Bring extra cables (of every type), connectors. Use the cables you have tested with and verified



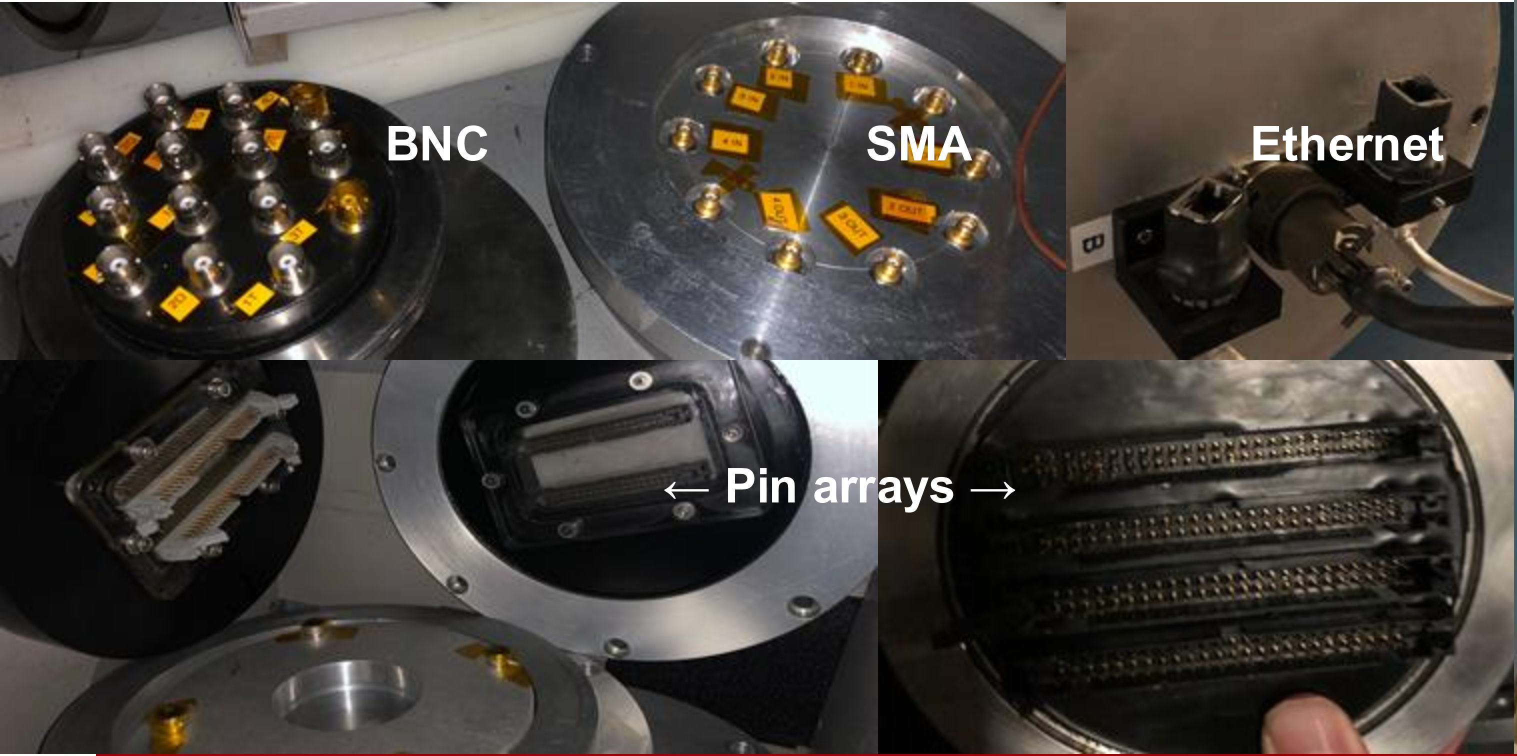


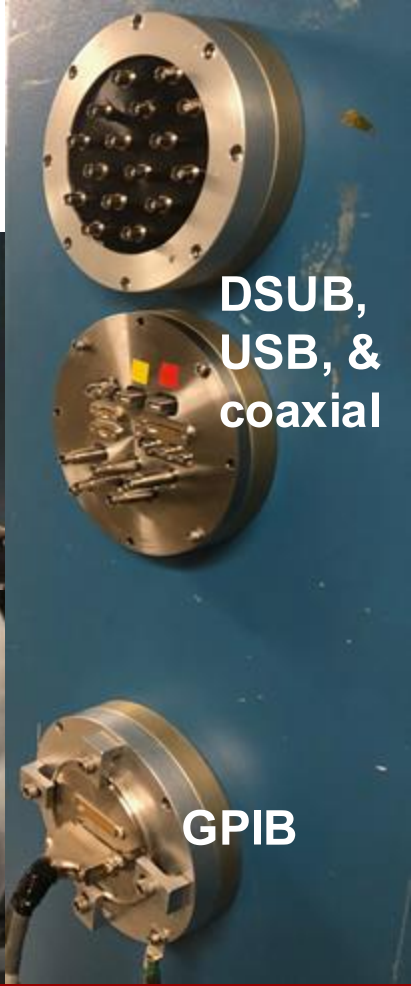


Courtesy NASA GSFC

Vacuum chamber bulkhead connections

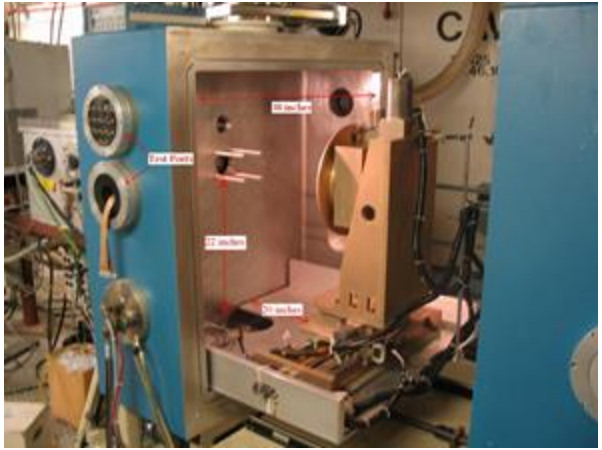
More info:
[88-Inch Cyclotron - Heavy Ions (lbl.gov)]



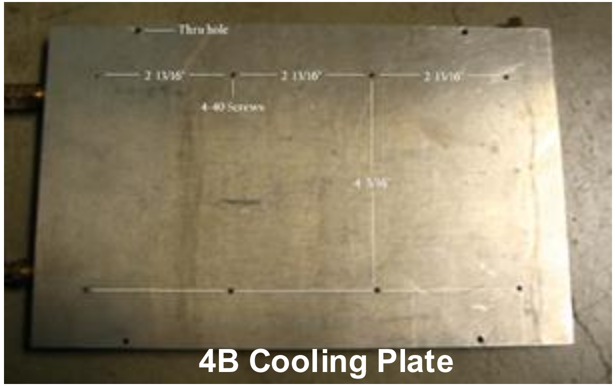


Vacuum chamber

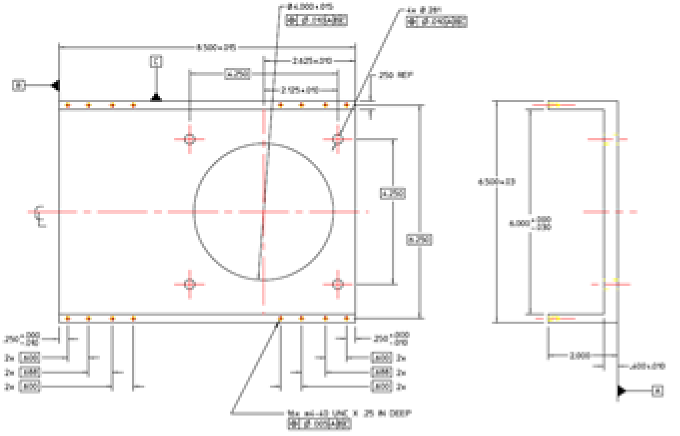
- Tests can be performed in **air** for the 16, 20, and 30 MeV Cocktails
- All cocktails can be performed under vacuum
- While in vacuum the angel can be changed from the control room
- More info: [88-Inch Cyclotron - 4B Drawings (lbl.gov)]



4B Mounting Bracket

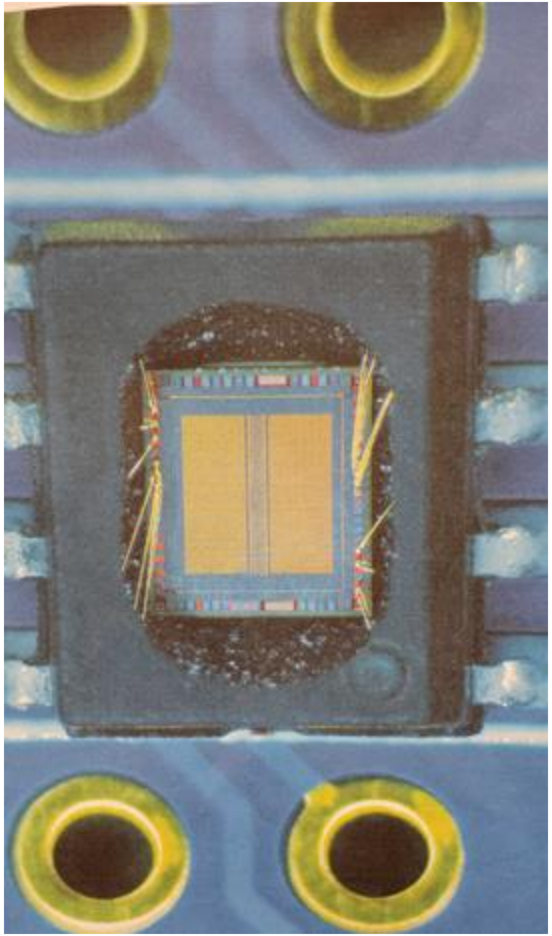


4B Cooling Plate



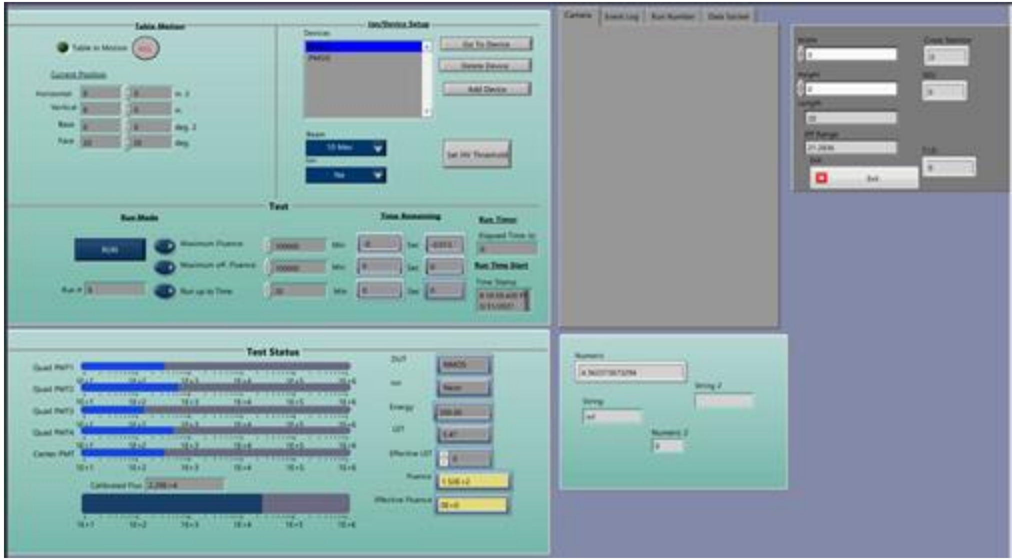
Before heading to California...

- Decapsulate your parts as soon as possible
- Ship your gear early
- Checked baggage has to be ≤ 99lb
- Request specific ions if necessary

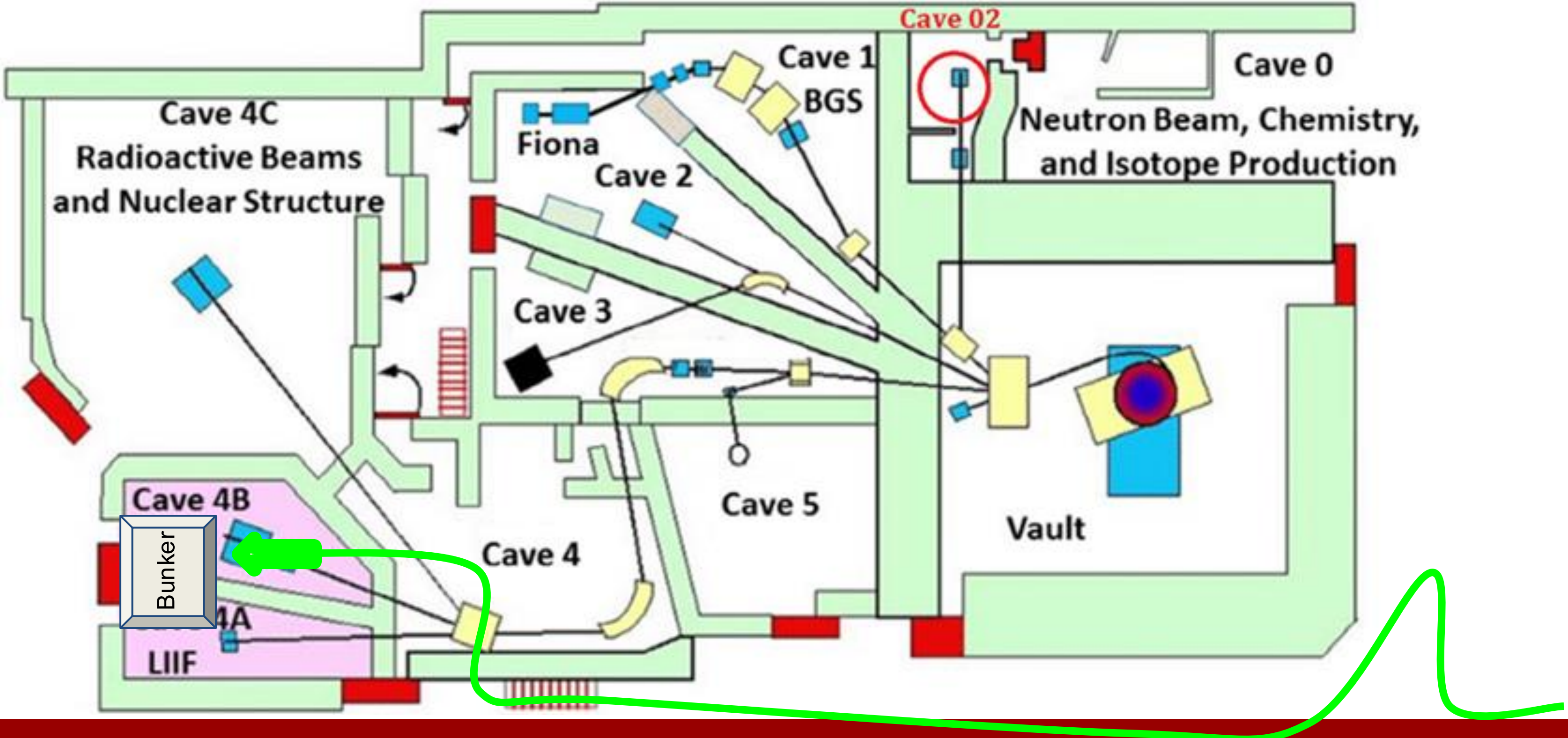


Tips on being prepared

- Familiarize yourself with the software
- Bring snacks and something to kill time
- Rest as much as possible beforehand



Walking to the Bunker



Walking to the Bunker

Cave 4B

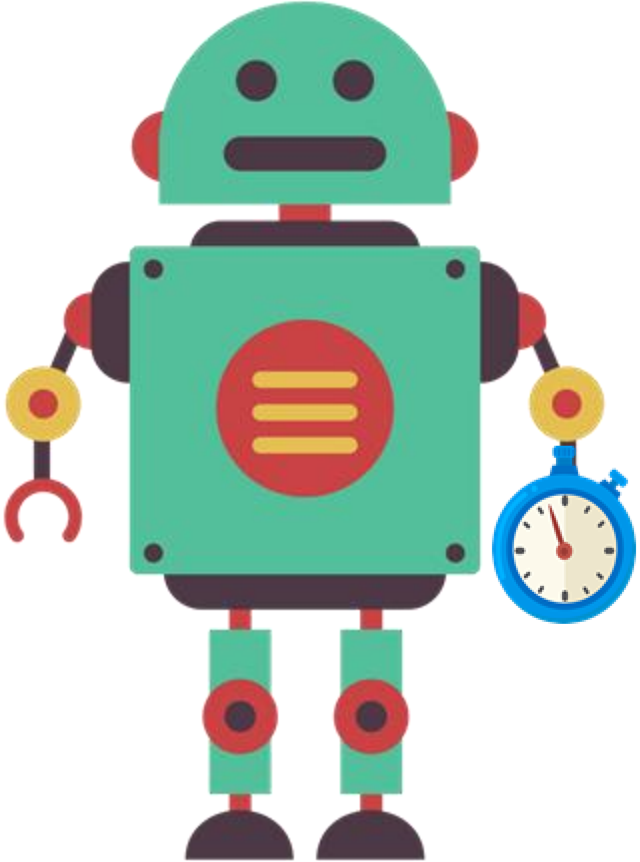
Getting data

- Usually tests are broken up into short runs 1 to 5 minutes long
- You can do longer runs, you just need to plan accordingly
- Make sure that all data logs have the same run numbers
- Periodically check that the run numbers are in sync
- Spreadsheets are great!
- You can also generate them automatically with scripts

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	#	Ion	LET (er	DUTs	File	Dista	Time	VDD (V)	Fluence (cm	Avg I	Peak	A1 SEUs	A2 SEUs	A3 SEUs			C1 SEUs	C2 SEUs	C3 SEUs	Dose (rac	TID (krac	SEU XS (1)	SEU XS (2)
2	0	N	1.16	H01, H02, H0	data/sram/seu/H_check.csv	1	60	0.7	4.20E+06			0*								78.05	0.08	#DIV/0!	
3	1	N	1.16	H01, H02, H0	data/sram/seu/H_check.csv	1	60	0.7	5.32E+06			0*								98.86	0.18	#DIV/0!	
4	2	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar.csv	1	60	0.7	5.22E+06			144384	129024	137216			11264			607.95	0.78	2.62E-02	
5	3	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar.csv	1	60	0.7	5.46E+06			8192	7168	14336			142336			635.90	1.42	1.81E-03	
6	4	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar.csv	1	60	1	5.19E+06			6144	4096	3072			8192			604.46	2.03	8.55E-04	
7	5	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar.csv	1	60	1.3	5.34E+06			6144	2048	2048			4096			621.93	2.65	6.39E-04	
8	6	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar.csv	1	60	3.3	5.30E+06			3072	4096	3072			1024			617.27	3.26	6.44E-04	
9	7	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar_new.csv	1	60	0.7	5.70E+06											663.85	3.93	#DIV/0!	
10	8	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar_new.csv	1	60	1	5.71E+06			131072*	6755	131072*			12541			665.02	4.59	1.18E-03	
11	9	Ar	7.27	H01, H02, H0	data/sram/seu/H_Ar_new.csv	1	60	1.3	5.48E+06											638.23	5.23	#DIV/0!	
12	10	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	60	0.7	5.23E+06			24816	24745	23564						609.11	0.61	4.66E-03	
13	11	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	60	0.7	5.11E+06			24476	23879	22624						595.14	1.20	4.63E-03	
14	12	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	60	0.6	5.18E+06			21601	21923	20889						603.29	1.81	4.14E-03	
15	13	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	60	1.5	6.36E+06			20691	18395	16824						740.72	2.55	2.93E-03	
16	14	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	60	2.4	1.33E+05											15.49	2.56	#DIV/0!	
17	15	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	11	2.4	4.52E+05			????								52.64	2.62	#DIV/0!	
18	16	Ar	7.27	I01, I02, I03	data/sram/seu/I_Ar.csv	1	10	2.4	4.36E+05			Suspected latchup								50.78	2.67	#DIV/0!	

Getting data

- Automate, automate, automate!
- This will save a lot of time and headache
- Use Python, MATLAB, VBA, or whatever tools are available
- Minimize user interactions
- Move quickly - time is a commodity
- Prioritize the most relevant data and optimize the run order
- Consider testing multiple parts or conditions simultaneously



Acronyms

- B: Magnetic Field
- BNL: Brookhaven National Laboratory
- δ: Density
- FRIB: Facility for Rare Isotopes Beam
- IU: Indiana University
- LBNL: Lawrence Berkeley National Laboratory
- LET: Linear Energy Transfer
- LET_{TH}: Threshold LET
- LINAC: Linear accelerator
- MSU: Michigan State University
- N: Number of Events or Particles
- NSRL: NASA Space Radiation Laboratory
- Q_{CRIT}: Critical Charge
- RF: Radio Frequency
- RPP: Rectangular Parallel Piped
- s: Path Length (& sometimes range)
- σ: Cross section
- σ_{SAT}: Saturated σ
- S: Shape Parameter in Weibull Distribution
- SEE: Single Event Effects
- SRIM: Stopping Range of Ions in Matter
- SUESS: TAMU's Cyclotron Institute Radiation Effects Facility Control Software
- SV: Sensitive Volume
- t: Thickness
- θ : Incident Angle
- TAMU: Texas A&M University
- TID: Total Ionizing Dose
- TRIUMF: Tri-University Meson Facility
- TvdG: Tandem Van der Graff
- W: Width Parameter in Weibull Distribution
- x: Length of SV
- y: Width of SV
- z: Depth of SV
- Z: Atomic Number