Single-Event Effects

Part 3 – Measuring SEE

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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.

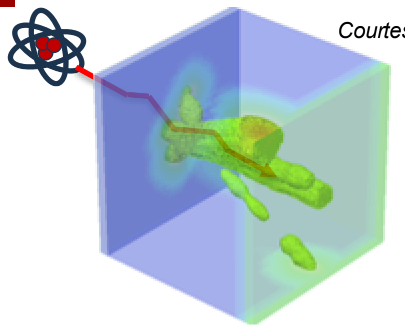
Outline

- Measuring SEE
  - SEE Cross Section and LET Threshold
  - Modeling SEE Cross Section
  - Sensitive Volume
  - From Experiment to On-orbit Rate Estimate
- Practical Considerations

05

MEASURING SEE

Single-Event Effects In Microelectronics



Courtesy Vanderbilt

Single-Event Effects (SEE):

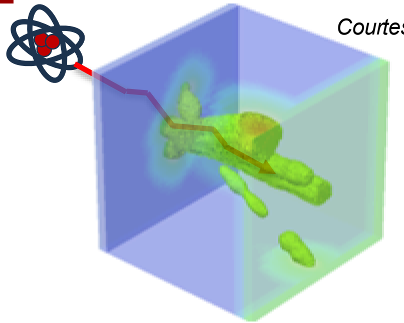
- **Caused by the interaction of a single energetic particle**
- **SEE are determined by:**
  - Charge generation
  - Charge collection
  - Circuit response

- **Types:**

Non-destructive:
- Single-event transients
- Single-event upsets (soft errors)
- Single-event functional interrupt
- Multiple-bit upsets

Destructive:
- Single-event latchup
- Single-event burnout
- Single-event gate rupture
- Single-event snap-back

Single-Event Effects In Microelectronics



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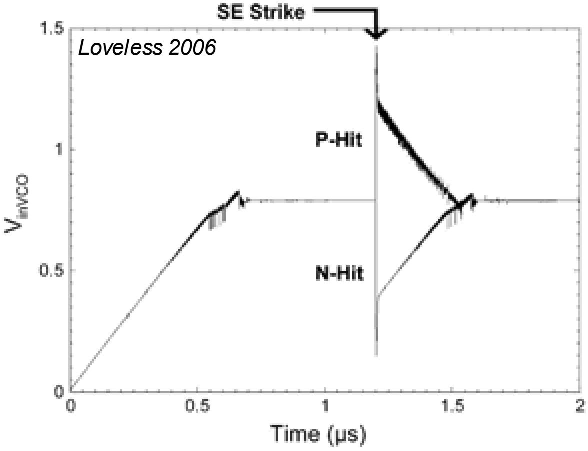

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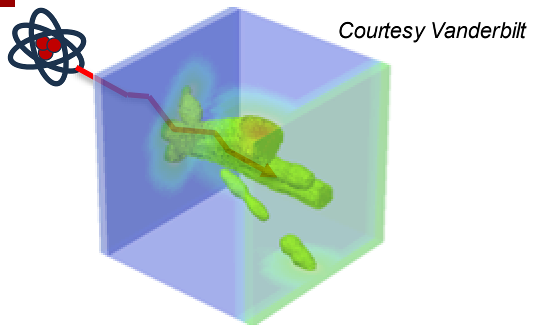

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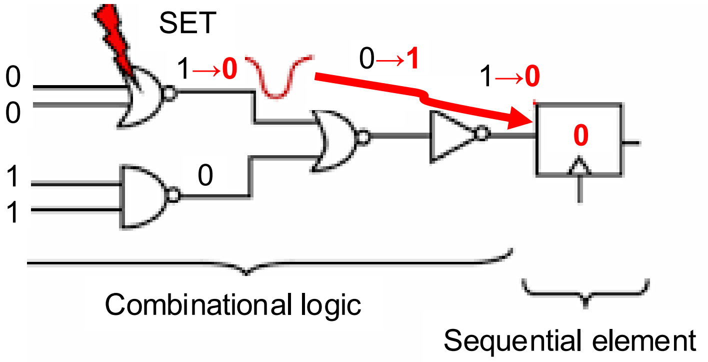

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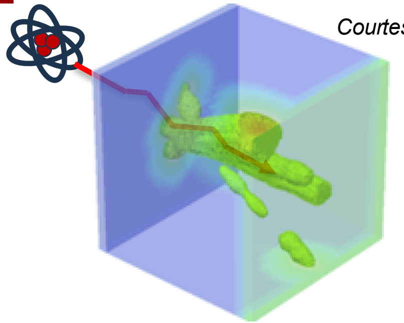

Courtesy Vanderbilt

Control Registers/Logic

0
1
0
0

0	1	1	0	1	0
1	0	0	0	0	1
0	0	1	1	0	1
0	1	1	1	1	1

Conceptual Memory

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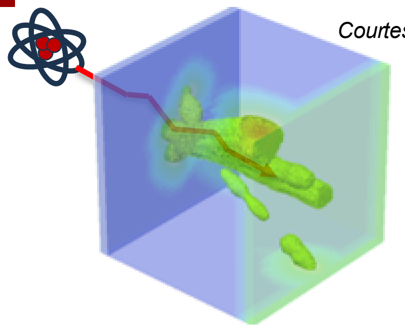

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Example of an SEU causing a bit flip in a conceptual memory

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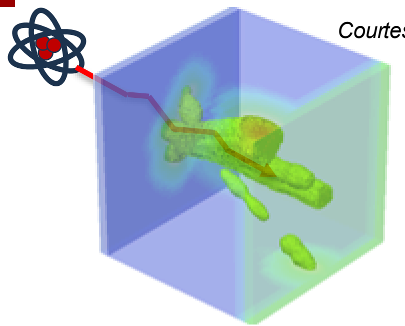

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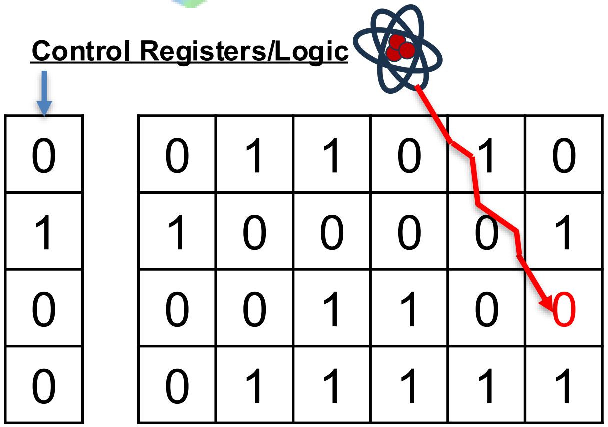

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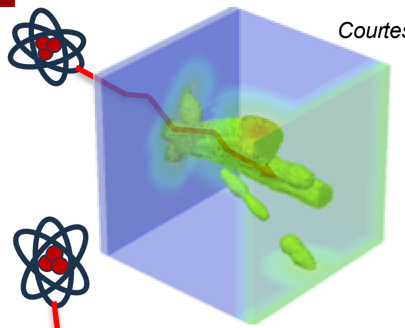

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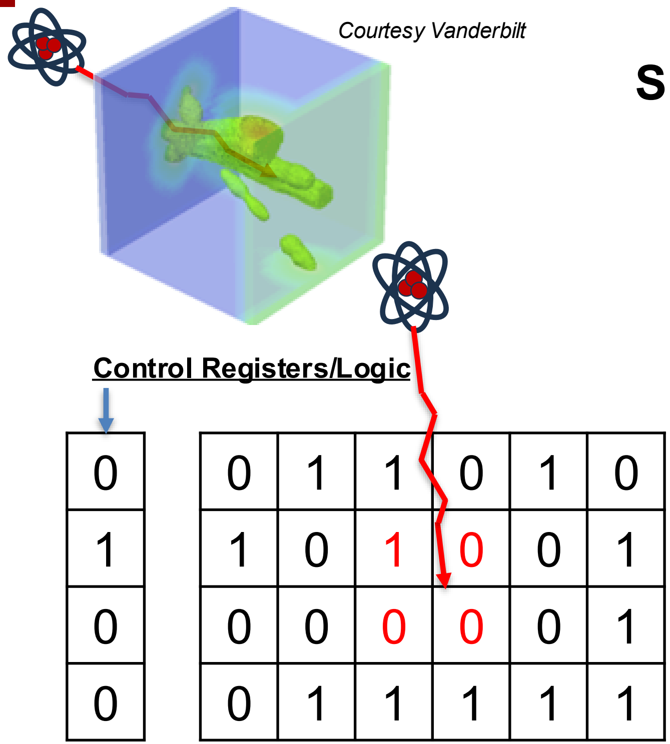

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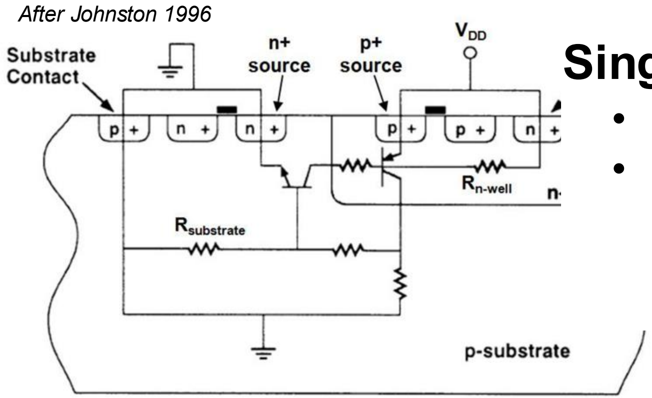
Single-Event Effects In Microelectronics

After Johnston 1996



Cross-section of typical CMOS technology showing **parasitic thyristor** that can be triggered into low impedance state

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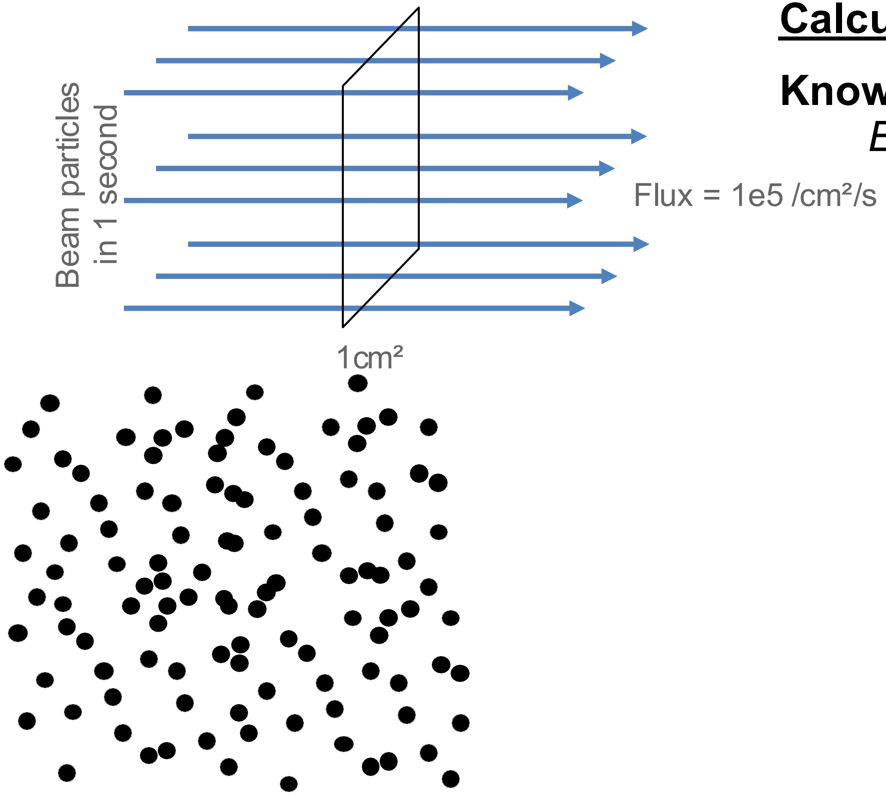
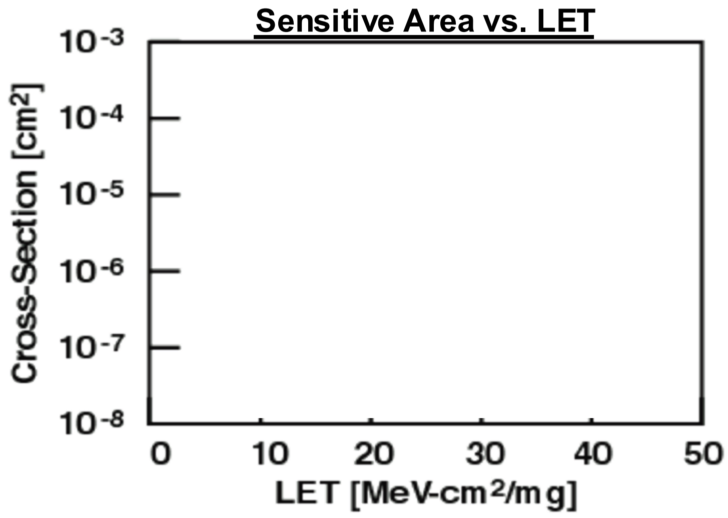
SEE Cross-Section



Calculation of SEE Cross-Section

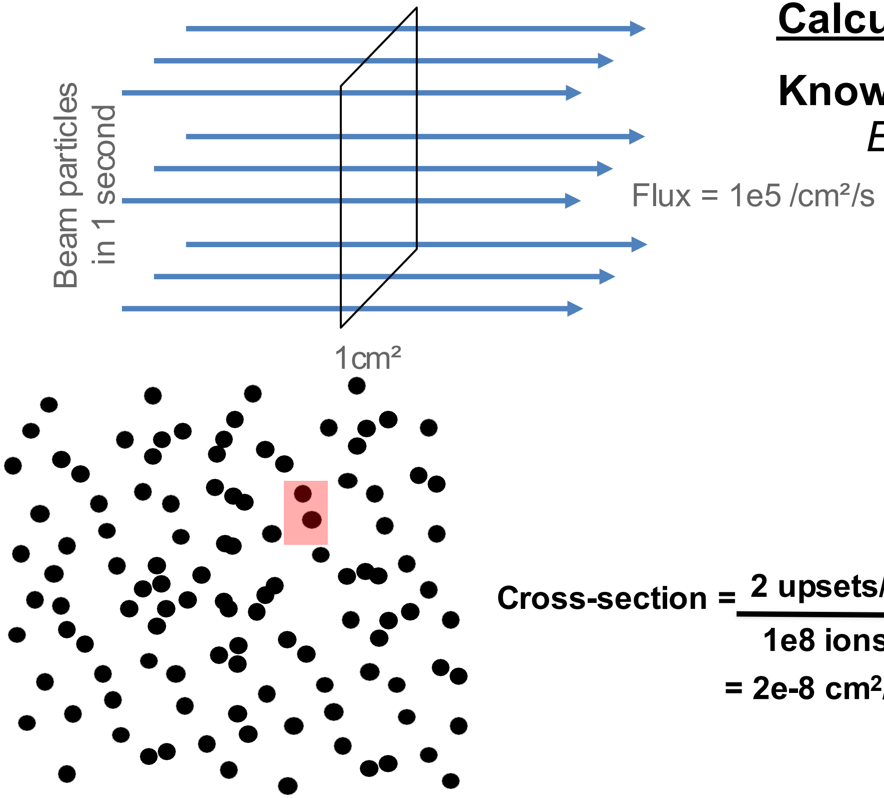
Known Fluence (Ions)

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



LET = Linear Energy Transfer

SEE Cross-Section



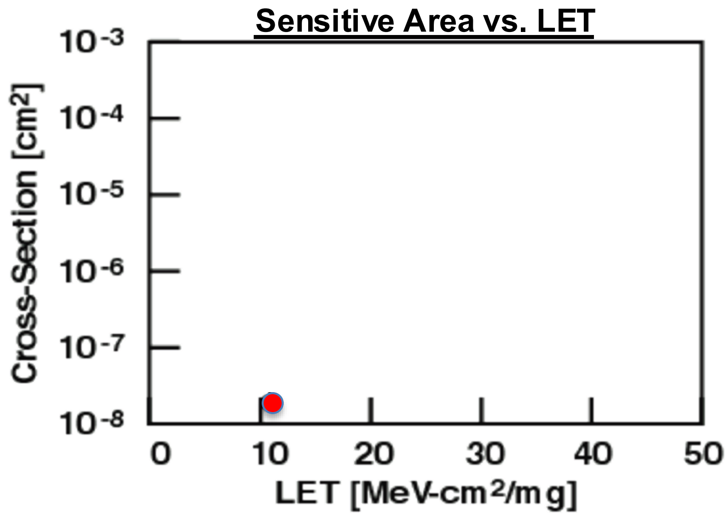
Calculation of SEE Cross-Section

Known Fluence (Ions)

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

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

= 2e-8 cm²/device



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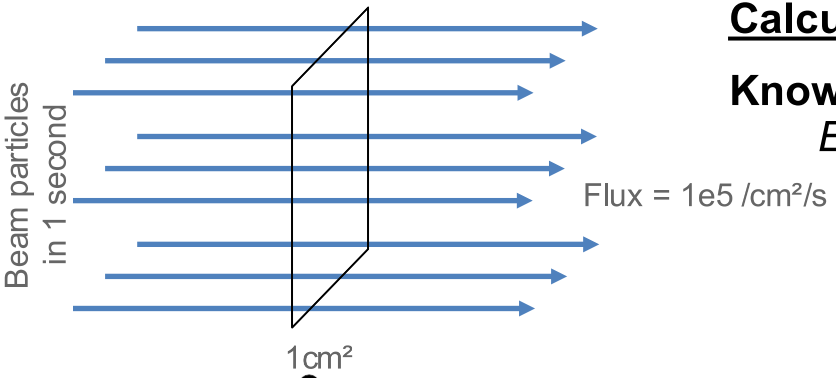
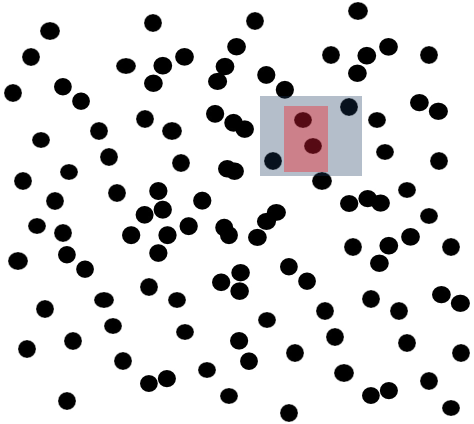
SEE Cross-Section





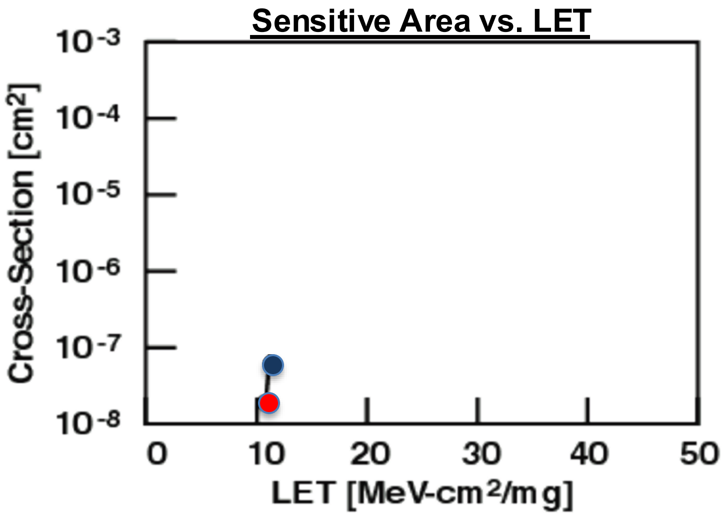
Calculation of SEE Cross-Section

Known Fluence (Ions)

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

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

$= \text{4e-8 cm}^2\text{/device}$



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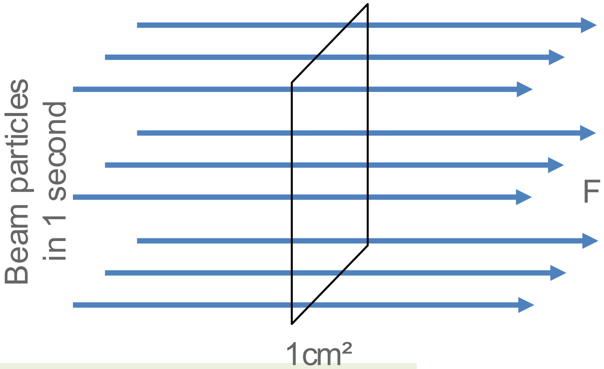
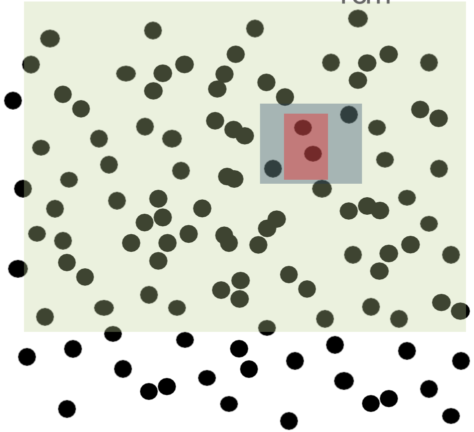
SEE Cross-Section



Flux = 1e5 /cm²/s



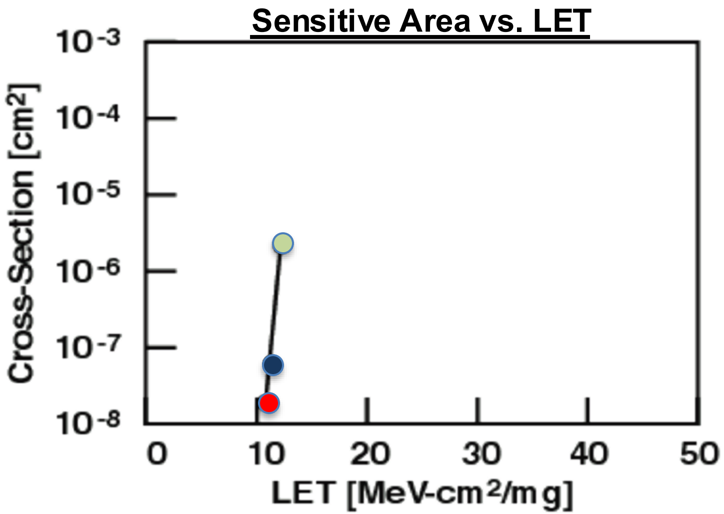
Calculation of SEE Cross-Section

Known Fluence (Ions)

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

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

$$= \text{1.2e-6 cm}^2\text{/device}$$



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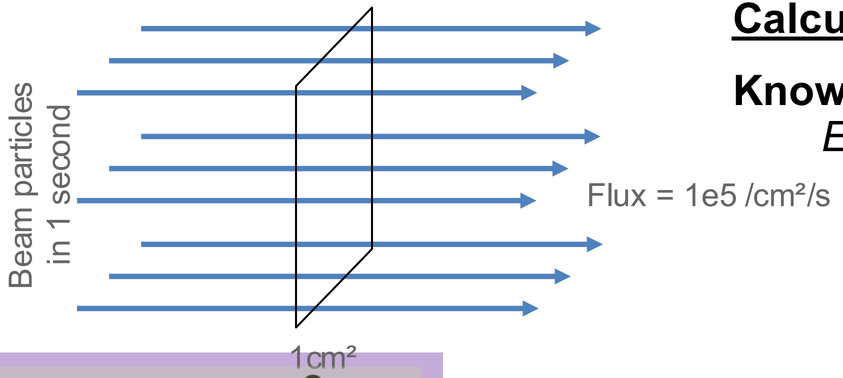

Calculation of SEE Cross-Section

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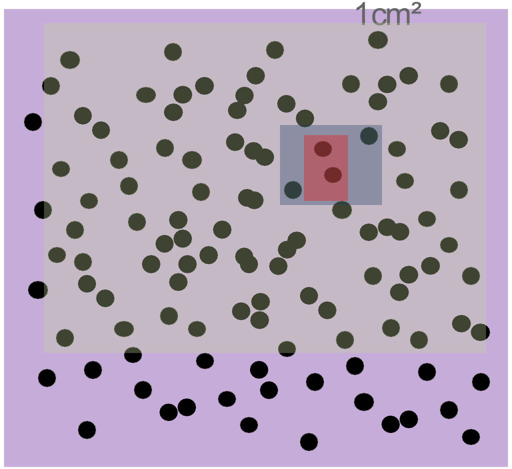
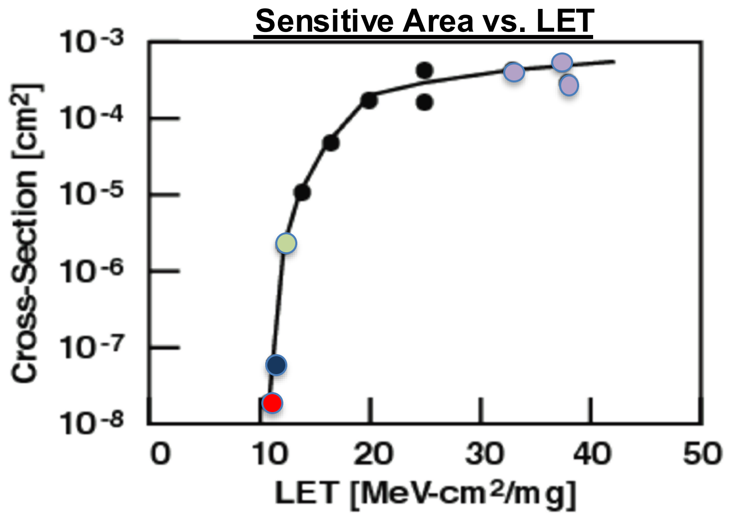


Cross-sections are measured vs. LET until the LET threshold (onset LET) and saturated (or limiting) cross-section can be determined

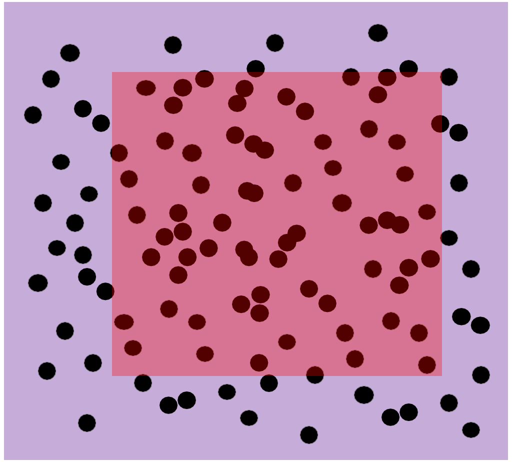


LET = Linear Energy Transfer

SEE Cross-Section

Radiation hardening aims to increase the LET threshold and decrease the saturation cross-section

Rad-Hard Parts may have very few events and require long exposures – this can be particularly challenging in complex parts



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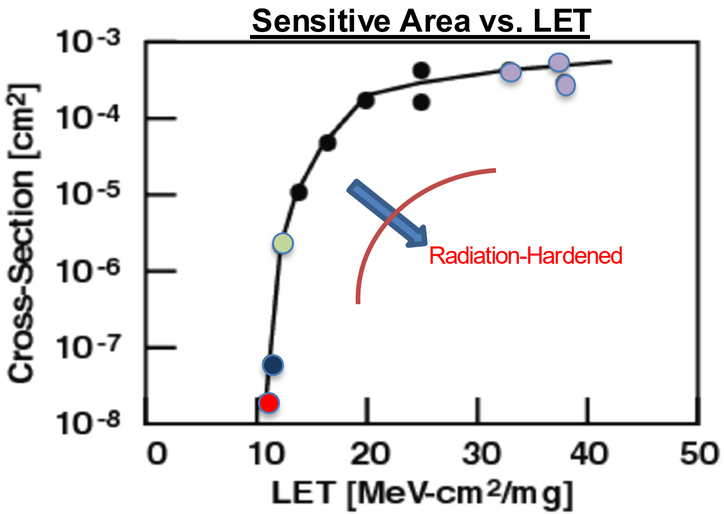

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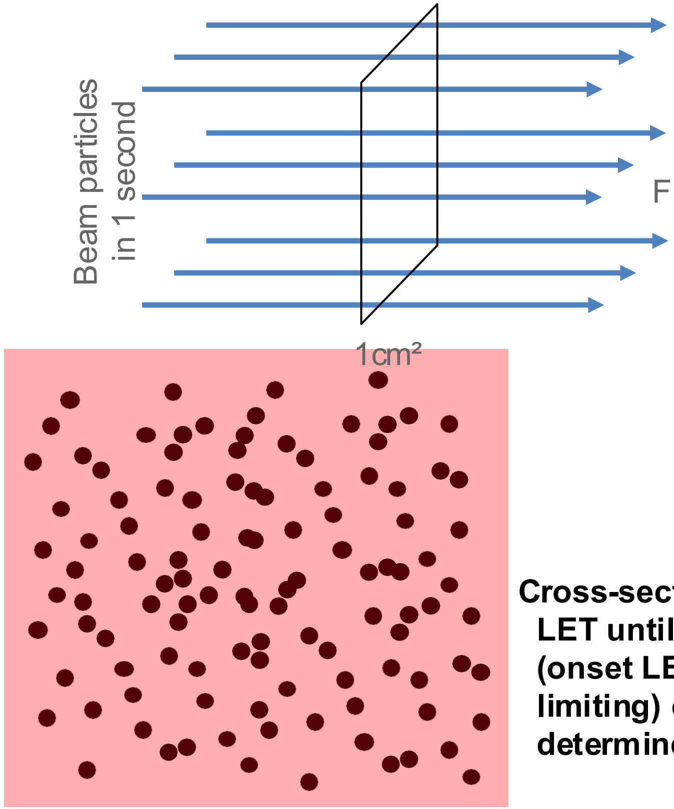

Calculation of Cross-Section

Known Fluence (Ions), LET

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

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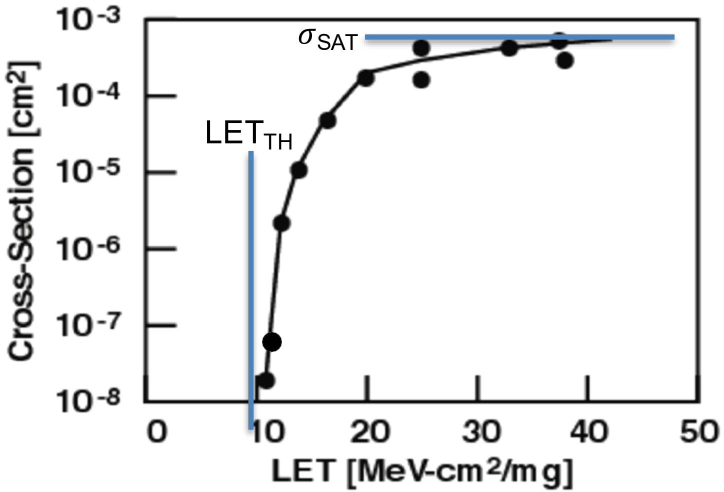
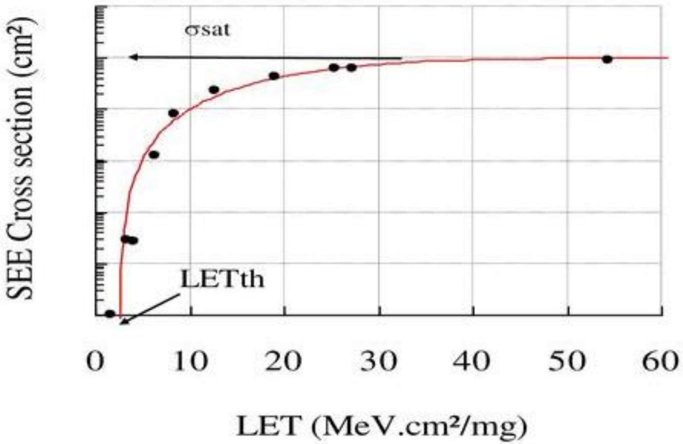
Sensitive Area vs. LET



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]

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

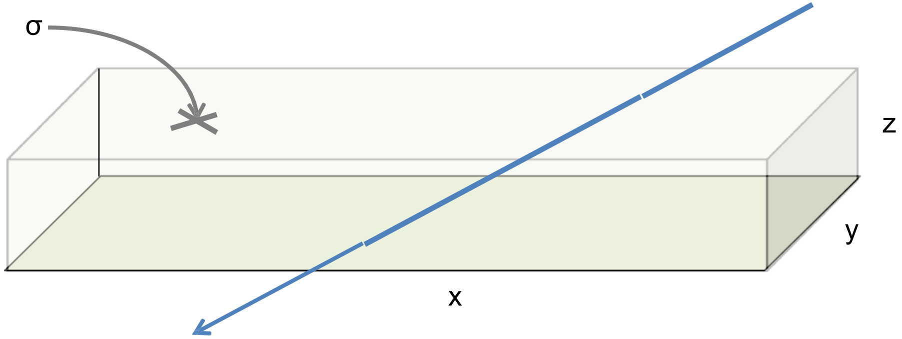
Fit with Weibull (integral form)

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

W and S are fitting parameters

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

Rectangular Parallel Piped (RPP) Model



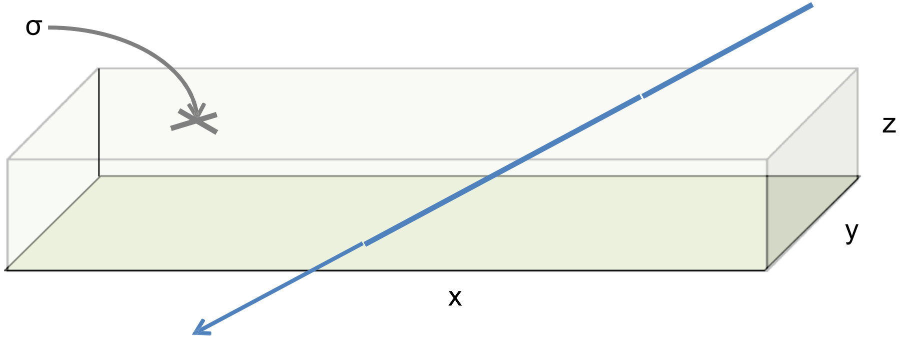
- Cross-Section:
  - $\sigma = x * y$
  - The top-down area of the SV (or sensitive area)

- Depth of sensitive volume, z

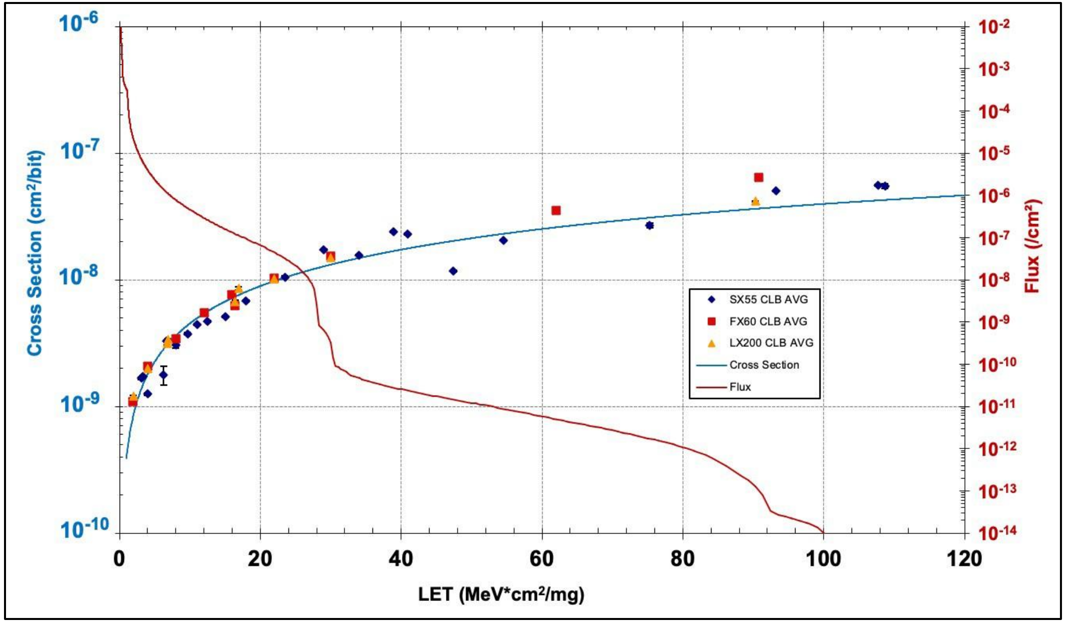
- Path Length, distance traveled by ion through the SV (———)

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 later



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

06

PRACTICAL CONSIDERATIONS

Example: LBNL 88” Cyclotron BASE Facility

About the facility

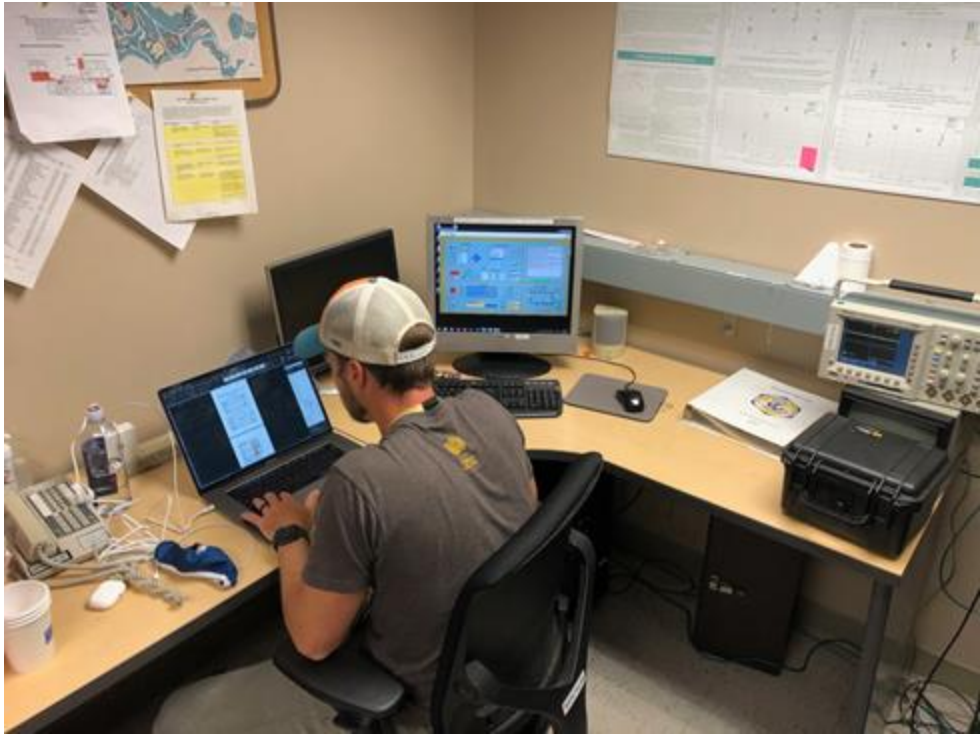
- 88” Cyclotron built in the 60s
- Heavy ions available in “cocktails”
- Example 16 MeV/amu cocktail below – don’t rely on quoted LET values!

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

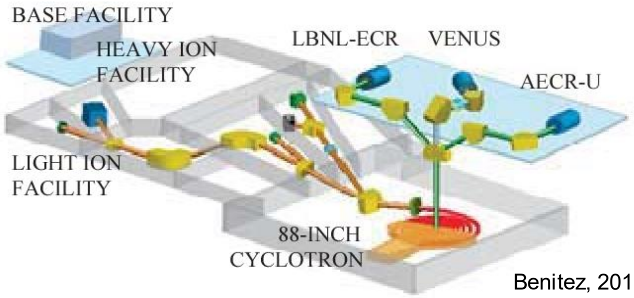
- Advantages
  - Changing ions (LET) is fast and easy
    - Usually just a few minutes
    - Not the case at other facilities!
  - Flux can be tuned with attenuators
  - They have a sparkling water machine



About the facility

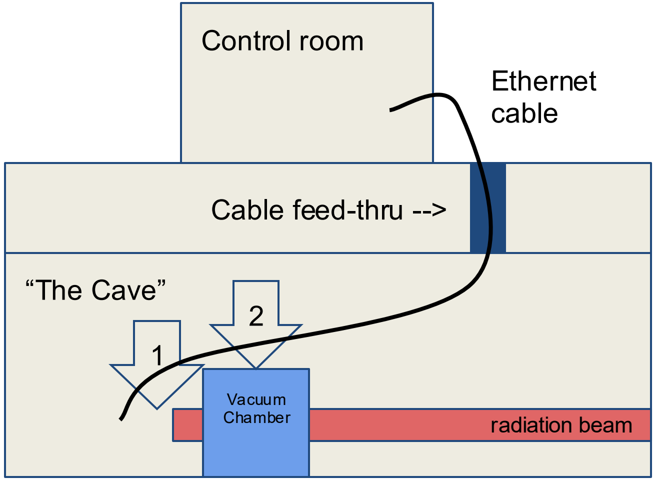
- Disadvantages
  - The beam goes down often for hours at a time
  - The beam runs 24 hours/day so you lose a lot of sleep

Setting up your system



Benitez, 2017

- 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

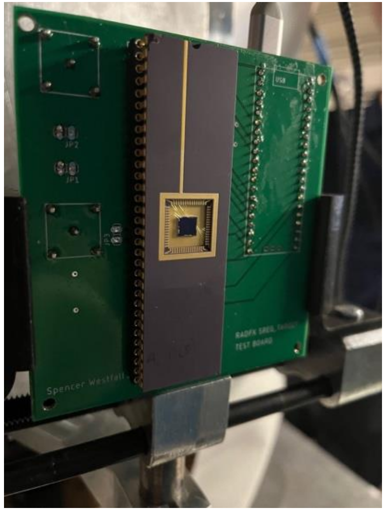


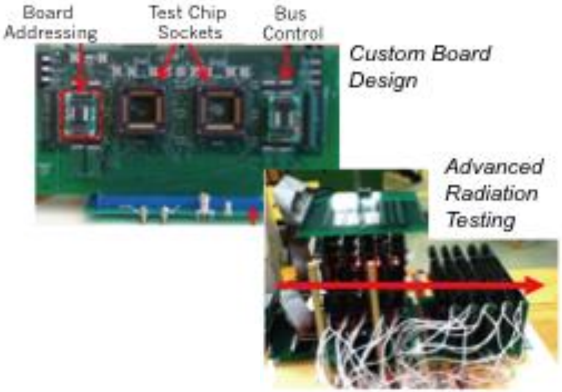
Setting up your system

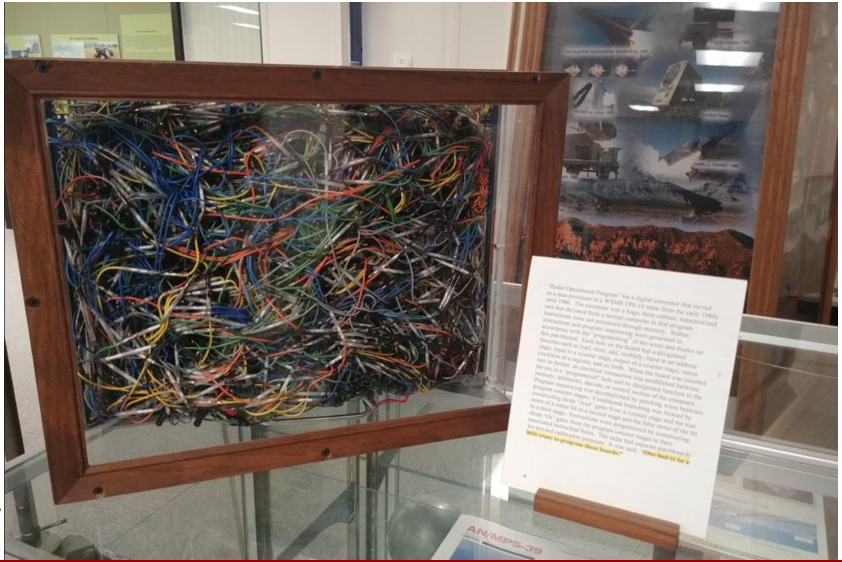
Pro tip: They will have plenty of clamps and mounts there. You should worry more about cabling

Cabling

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



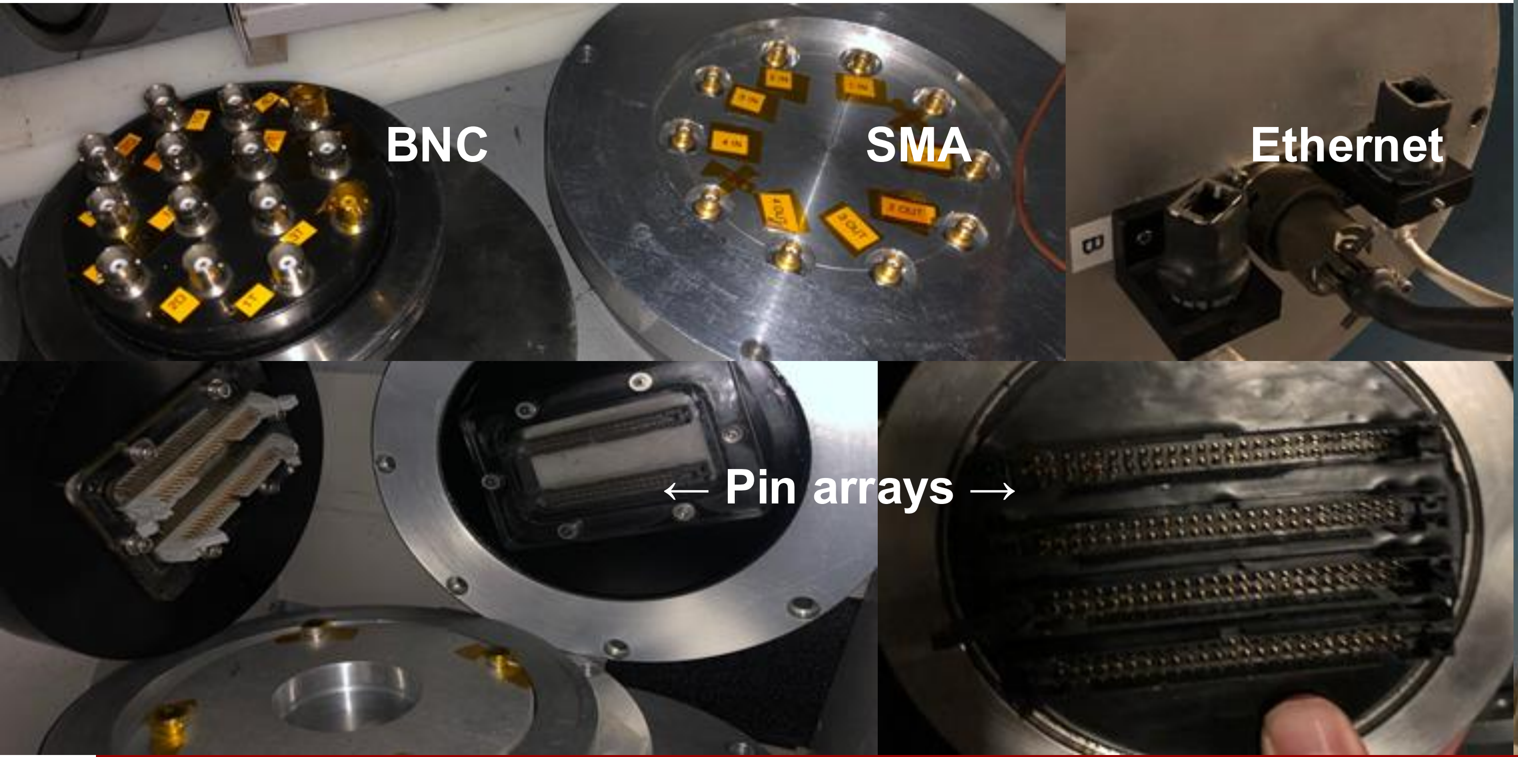


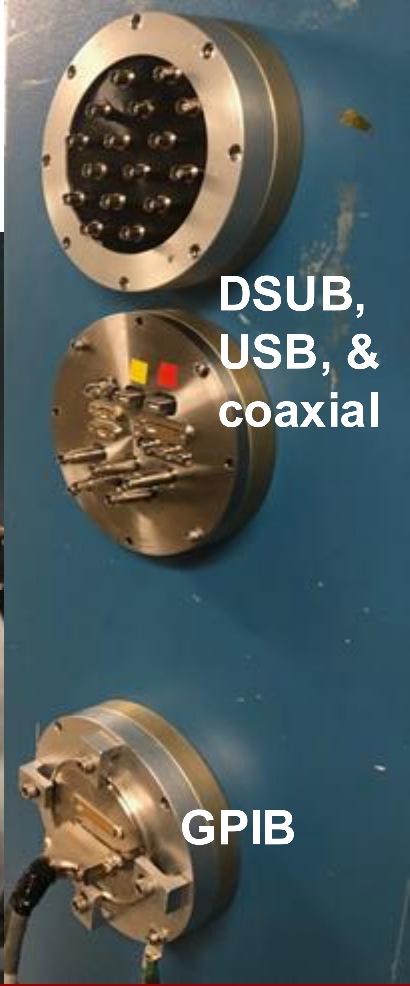


Courtesy NASA GSFC

Vacuum chamber bulkhead connections

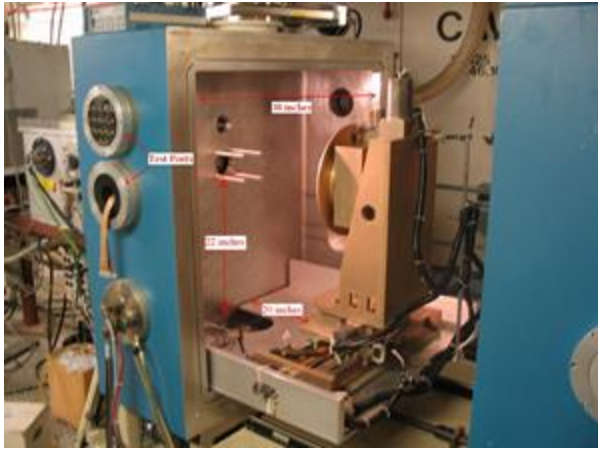
More info:
[88-Inch Cyclotron - Heavy Ions (lbl.gov)]



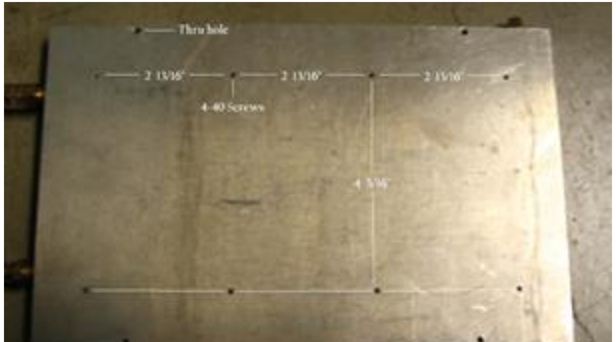


Vacuum chamber

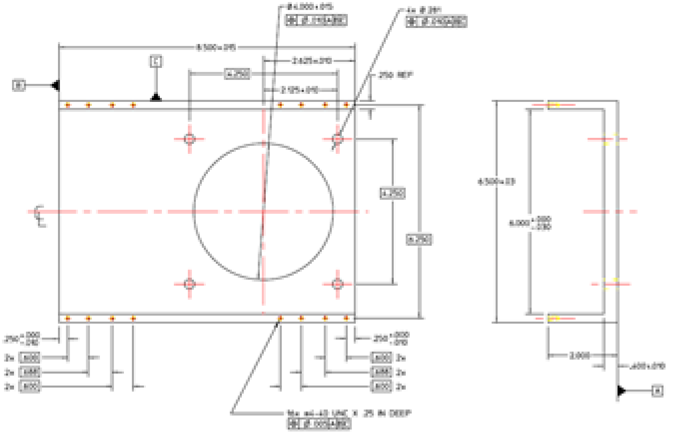
- Tests can be performed in **air** for the 16, 20, and 30 MeV Cocktails
- All cocktails can be performed under vacuum
- While in vacuum the angel can be changed from the control room
- More info: [88-Inch Cyclotron - 4B Drawings (lbl.gov)]



4B Mounting Bracket

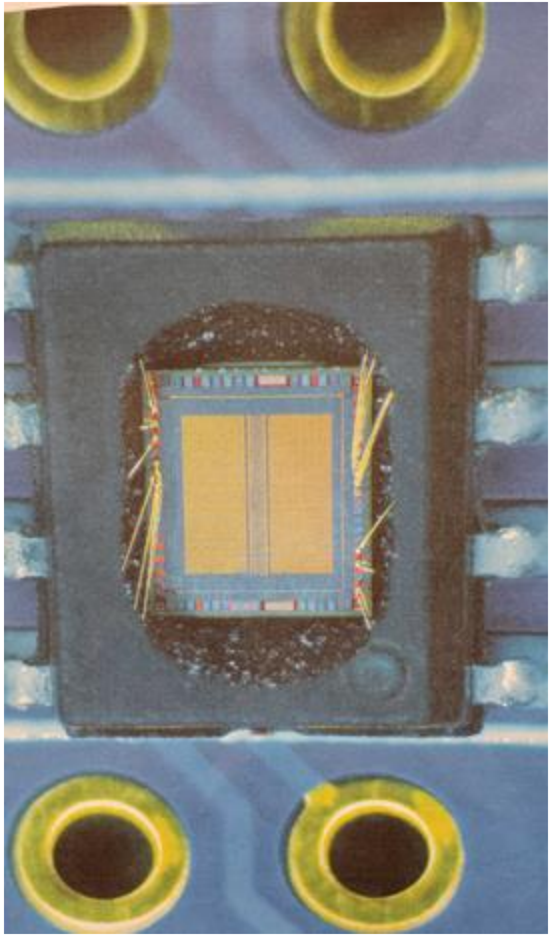


4B Cooling Plate



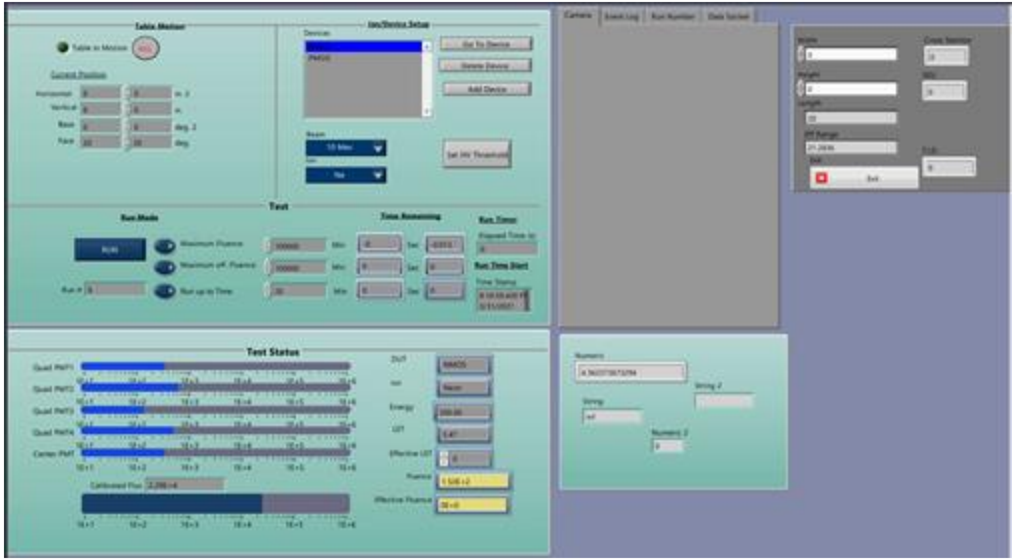
Before heading to California...

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

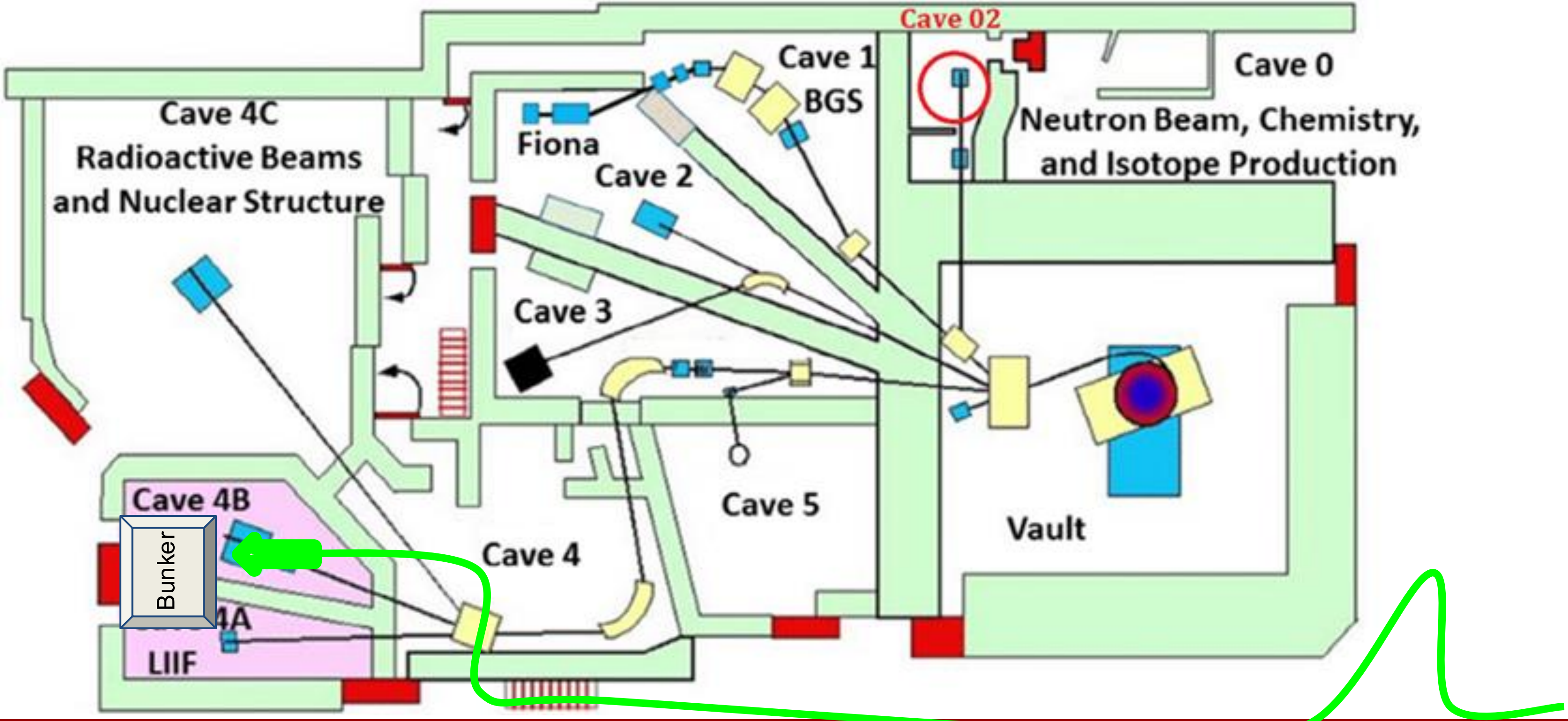


Tips on being prepared

- 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

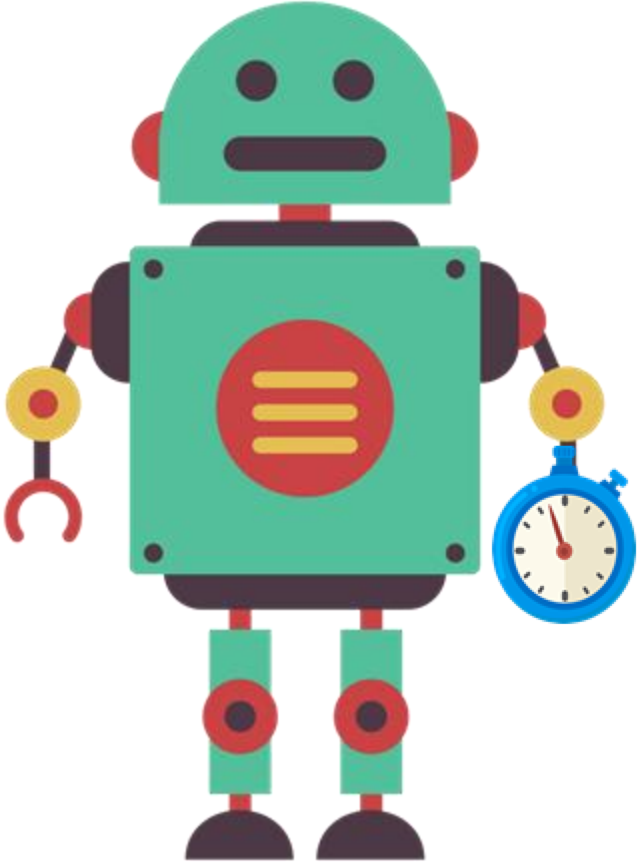
Getting data

- 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	Dist	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