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U.S. DEPARTMENT OF ENERGY

Electronics Testing with High Energy Heavy Ions at the NASA Space Radiation Laboratory

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15 February 2024

Overview

A) Short meandering talk about cosmic rays

B) Physics considerations in electronic parts testing

C) Logistical considerations in electronic parts testing

D) Future directions at BNL

Galactic Cosmic Ray Composition

Hydrogen	~90%
Helium	~9%
Carbon – Iron	~1%
Heavier than Fe	~0.1%

Flux ratio

$\phi(Si)/\phi(H) = 10^{-3}$

$\phi(Bi)/\phi(H) = 10^{-9}$

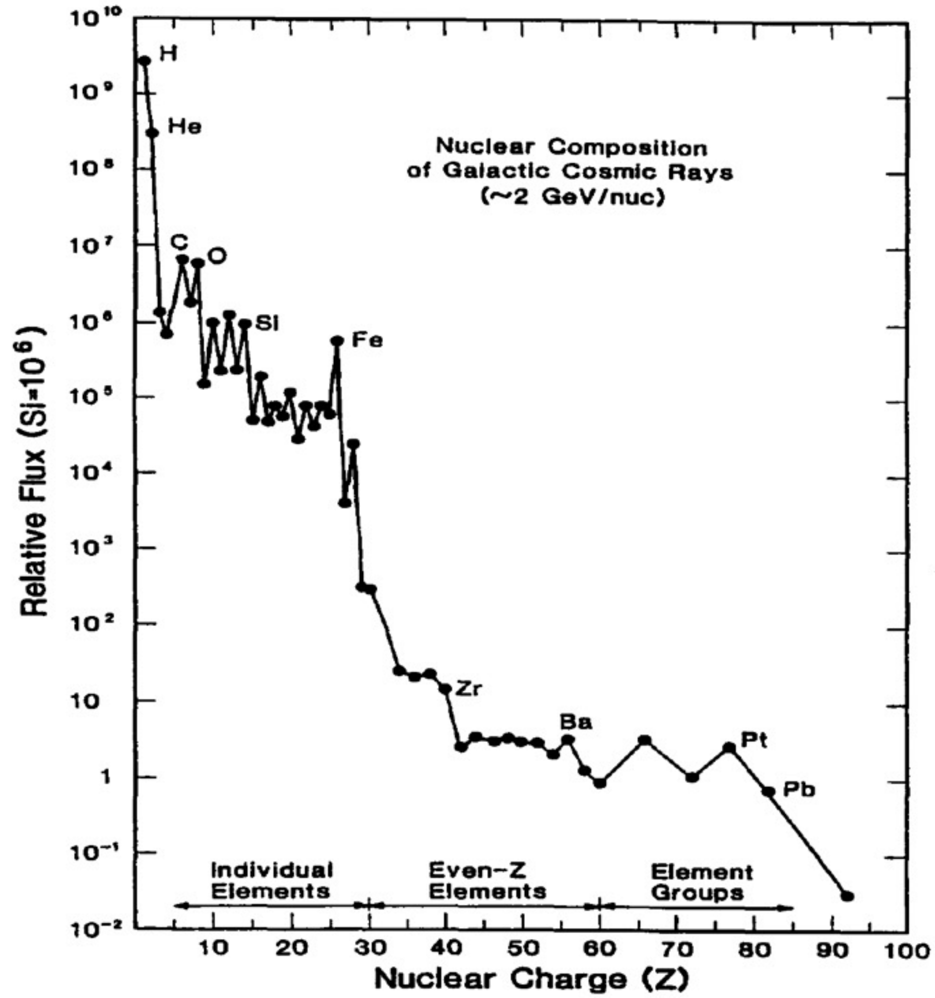

Fig. 1. Relative flux of cosmic ray nuclei as a function of nuclear charge, *Z*, at a typical energy of ~2 GeV/nuc (from /6/).

R. A. Mewaldt, Galactic Cosmic Ray Composition and Energy Spectra, *Adv. Space Res.* Vol. 14, No. 10. pp 737-747, (1994).

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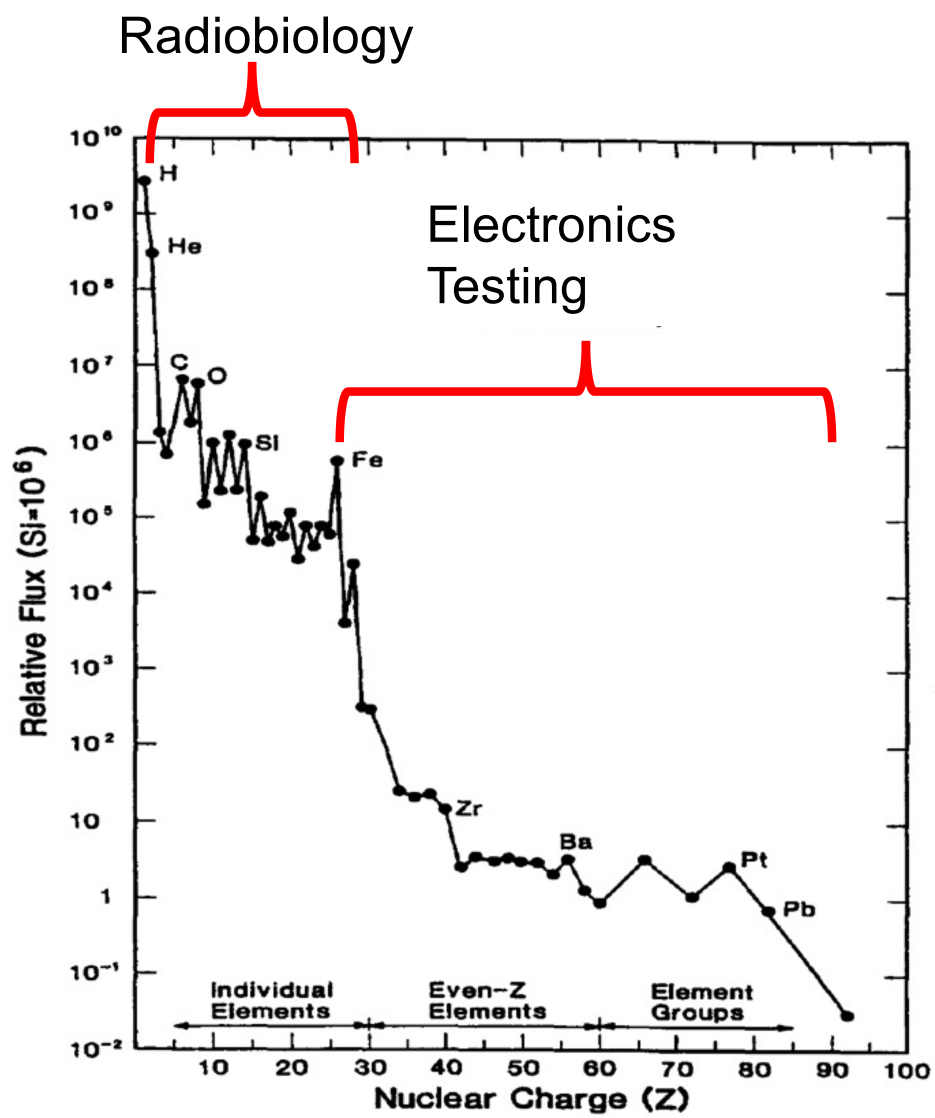

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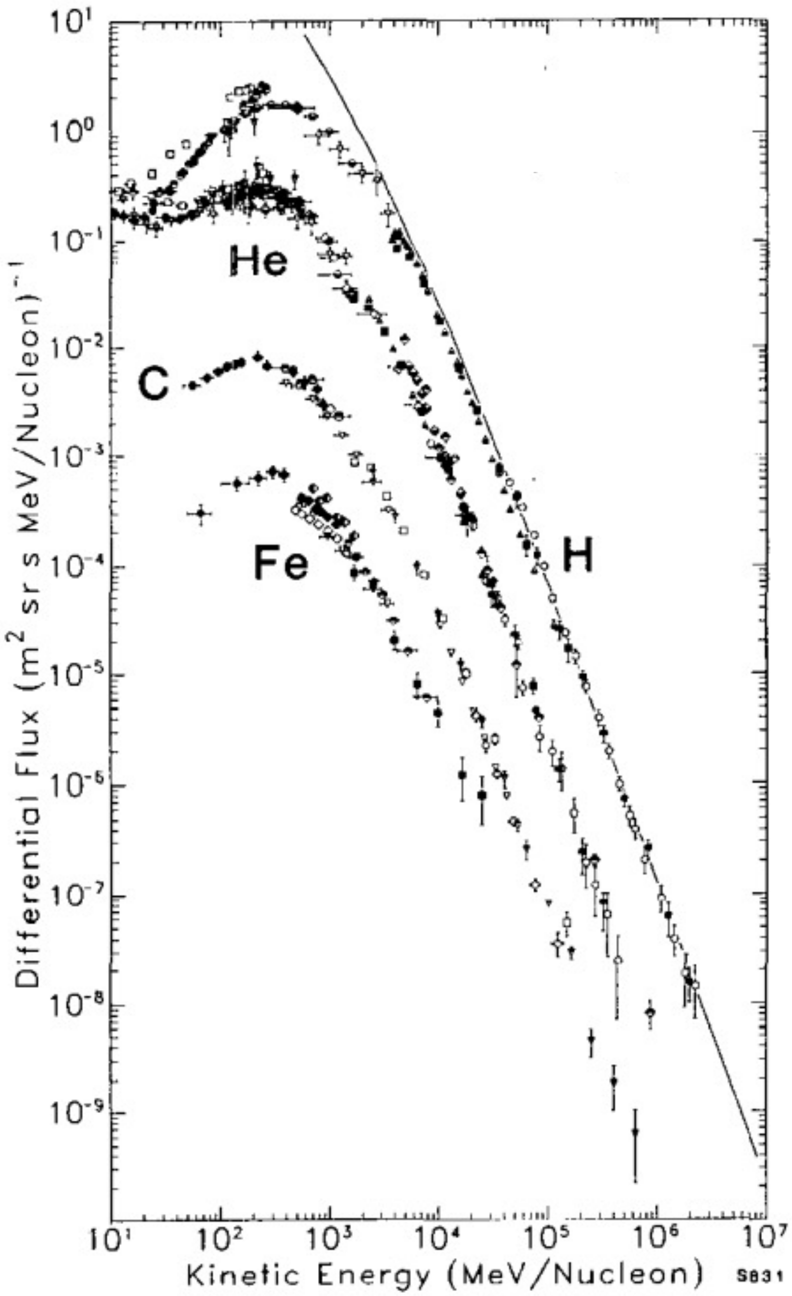
Galactic Cosmic Ray Energy Spectrum

The cosmic ray kinetic energy spectrum has a broad peak that is nearly independent of ion species, from H to U.

The peak extends from ~300 to 1000 MeV/n.



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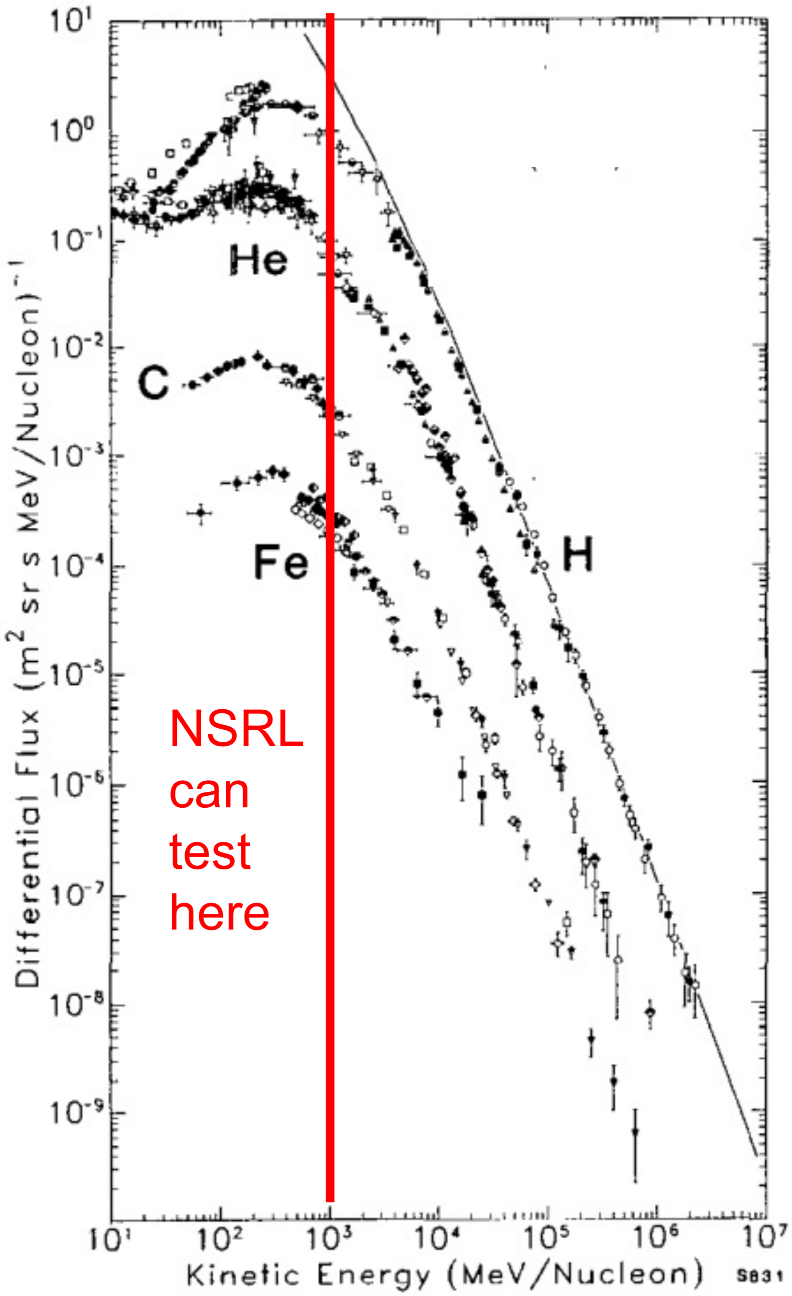

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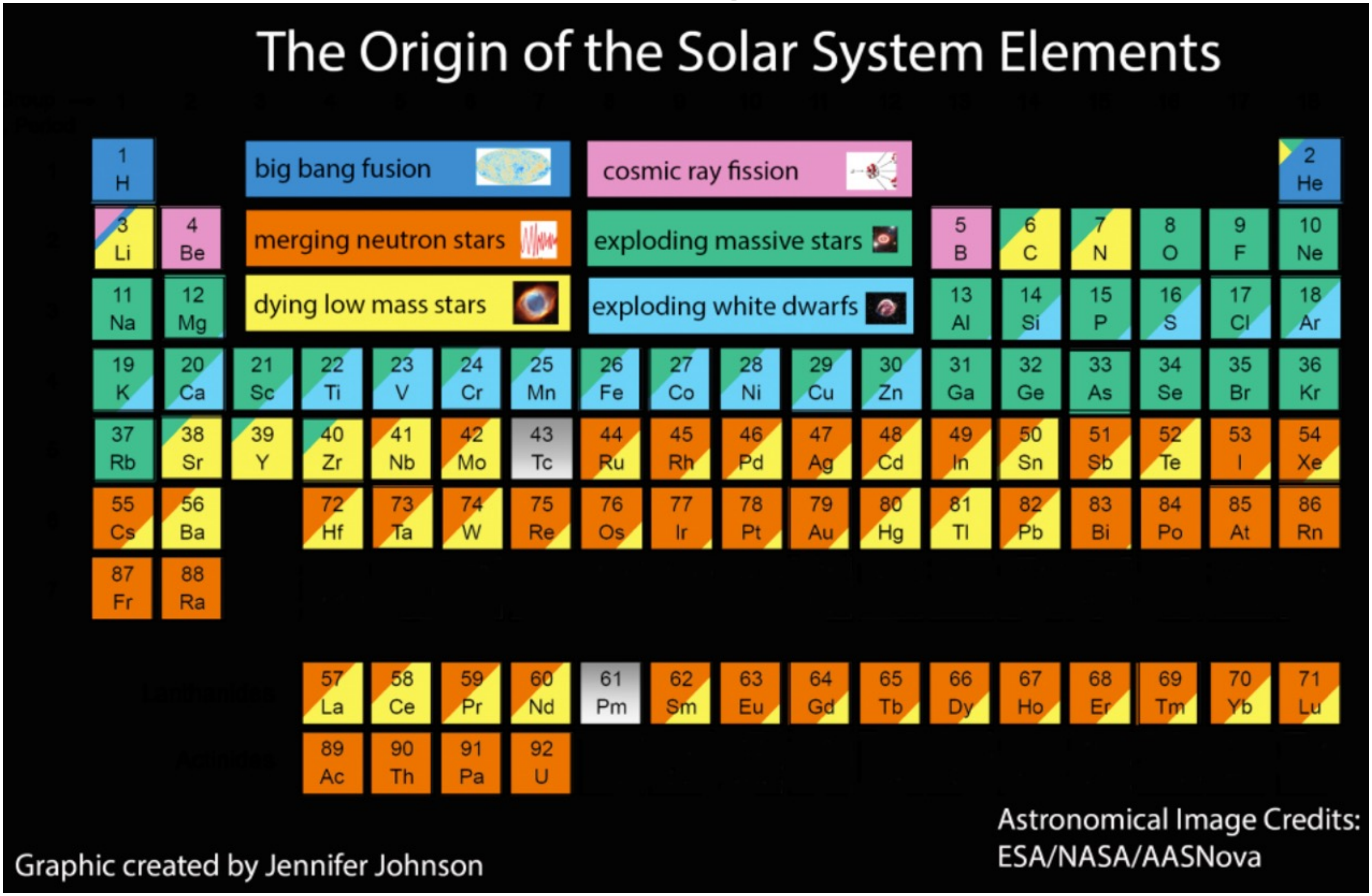
Galactic Cosmic Ray Sources



https://blog.sdss.org/2017/01/09/origin-of-the-elements-in-the-solar-system/

What are the important physics issues for electronics testing with high energy heavy ions?

- What are the relevant interactions?
  - Ionization (i.e. electron scattering) ?
  - Displacement damage (i.e. nuclear scattering) ?
- Bragg Curves
  - Protons – no fragmentation or tails
  - Carbon – tails
  - Iron – fragmentation and tails
  - Xenon
  - Variable Depth Bragg Peak method
  - Spread Out Bragg Peak work
- Is LET the (only, most) relevant parameter?
  - What about different ions/energies with same LET?
- How is the energy deposited in the sample?
  - Electron density in the ionization cloud
- “Effective” LET?
  - Working at angles

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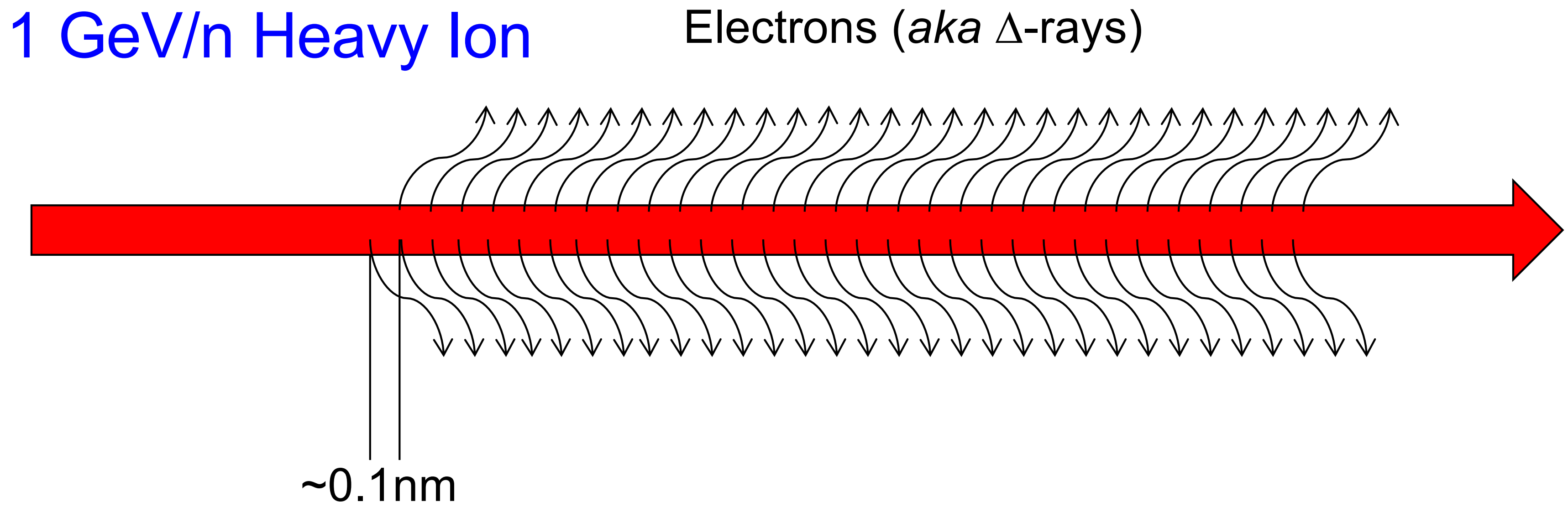
Interactions: Ionization

Most energy loss by charged particles traveling through material is by Ionization. For most ions at most energies, ionization represents 99.9% of all energy loss.

Many small scattering processes produce electrons with a characteristic energy of ~few eV, producing "delta-rays"



LET: Energy Loss per unit length or dE/dx

Typically in units of MeV-cm^2/mg

Interactions: Nuclear Scattering

NIEL (Non Ionizing Energy Loss)

Displacement damage (i.e. nuclear scattering) represents only a small fraction (~0.1%) of the total energy lost by a charged particle during the passage through material.

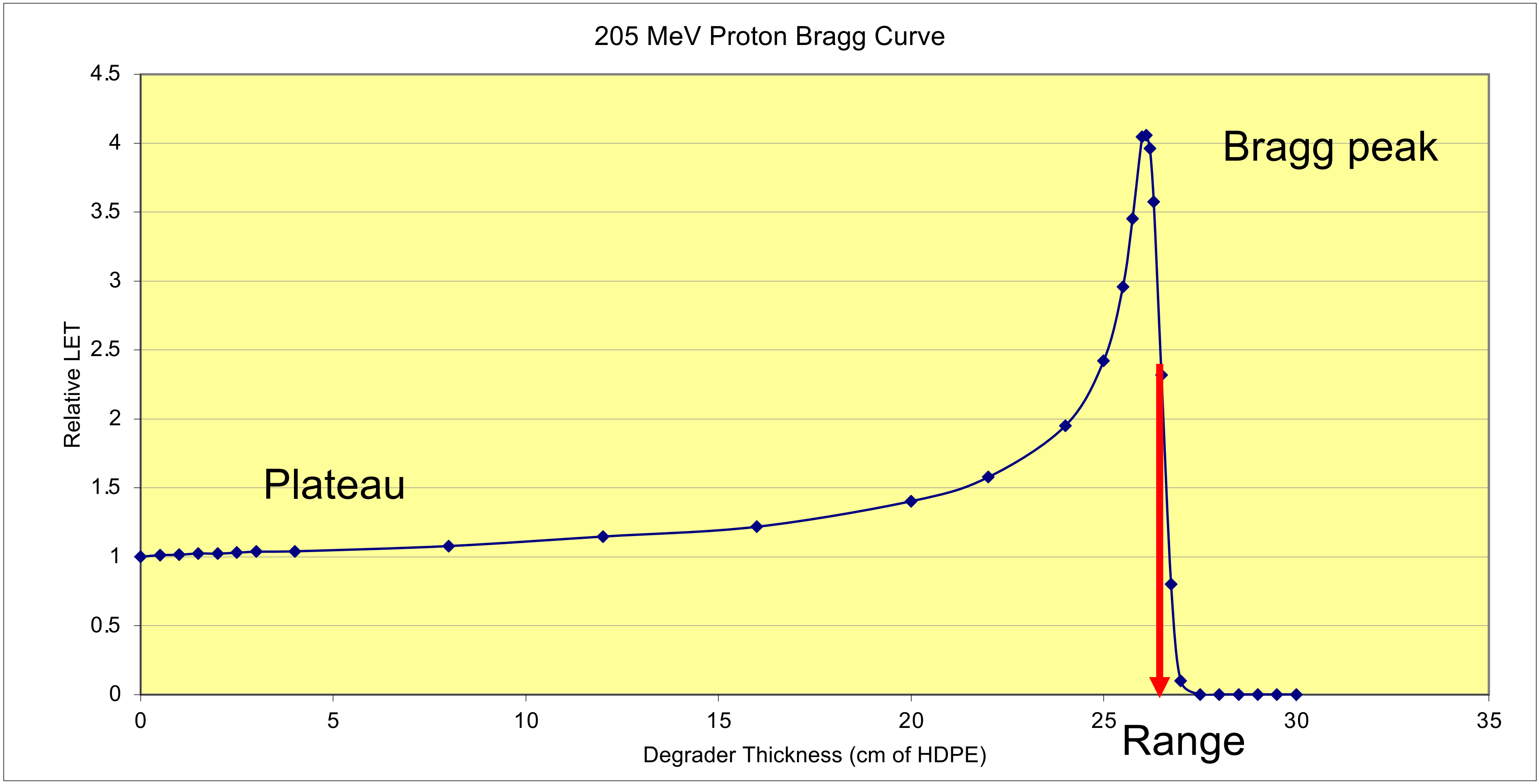
- Can change the trajectory of the incoming projectile.
- Can result in a large energy loss.
- Can produce heavily ionizing secondary particles with long residual range.

The only method for neutron energy loss.

Some displacement damage can recover through annealing (heating) or even self-annealing.

See for example Elizabeth Auden's lecture at the 2019 LANL Summer School:
https://uspas.fnal.gov/materials/19NewMexico/Radiation/lecture_4.pdf

LET: Bragg Curves - Protons



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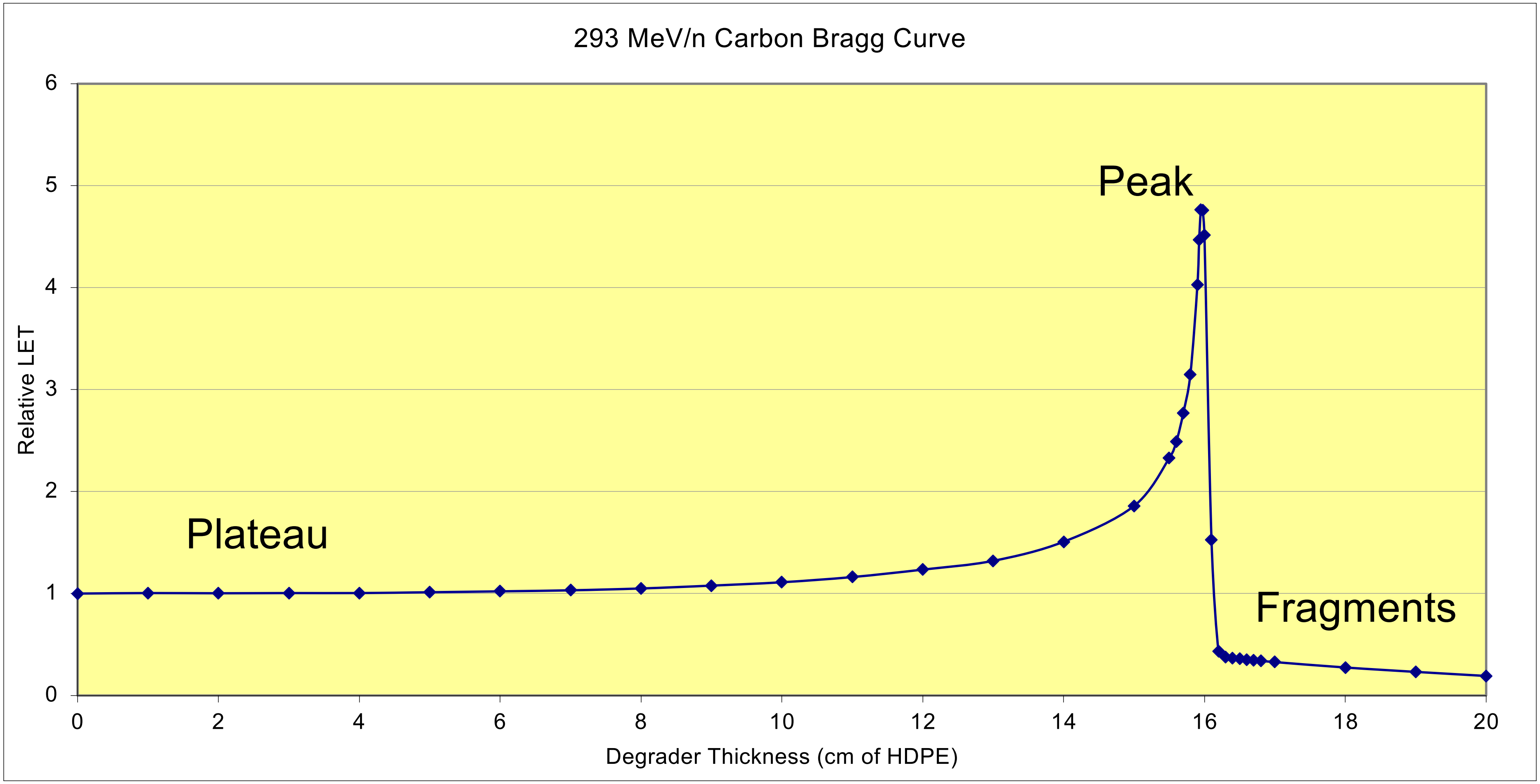
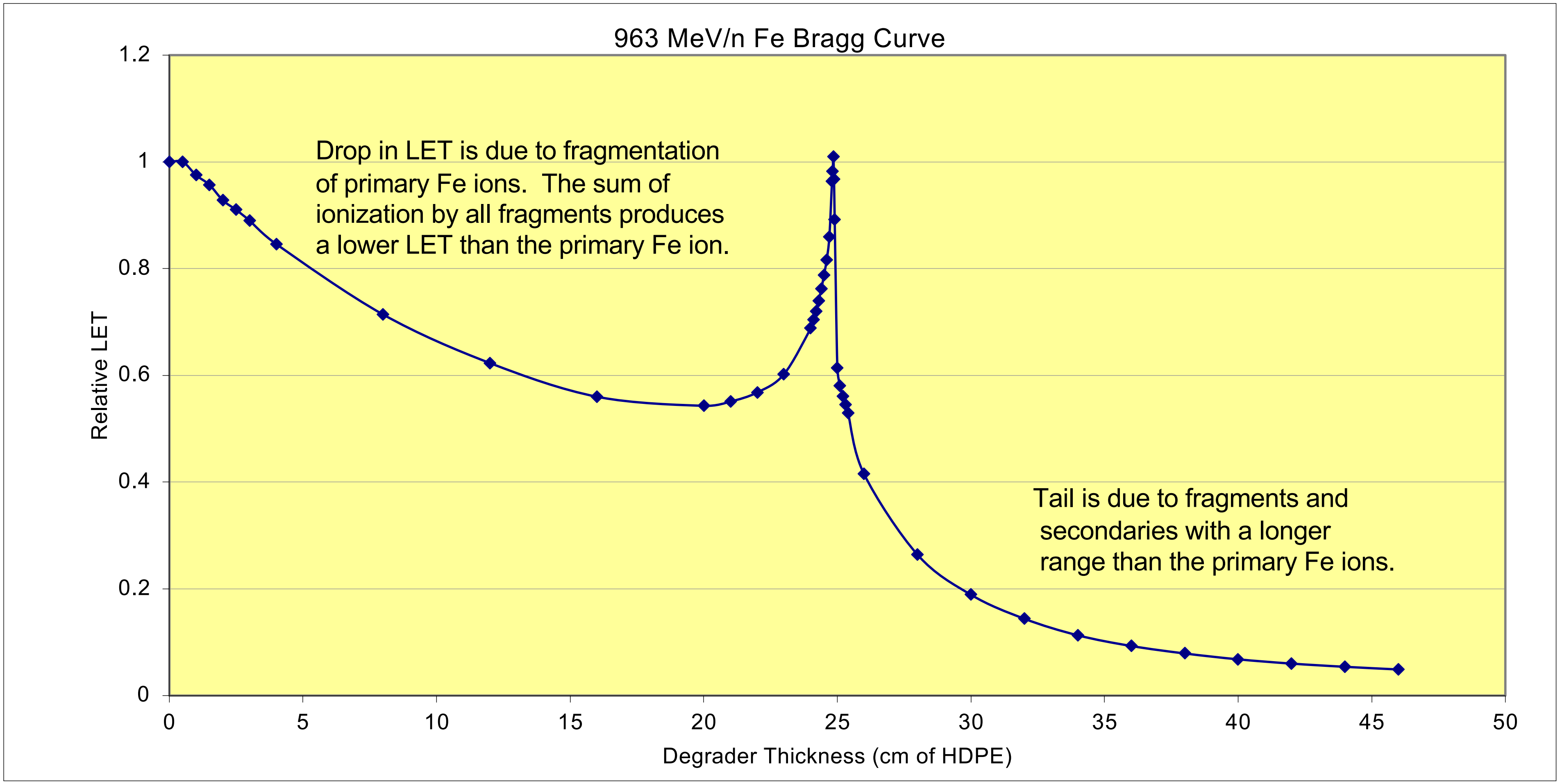
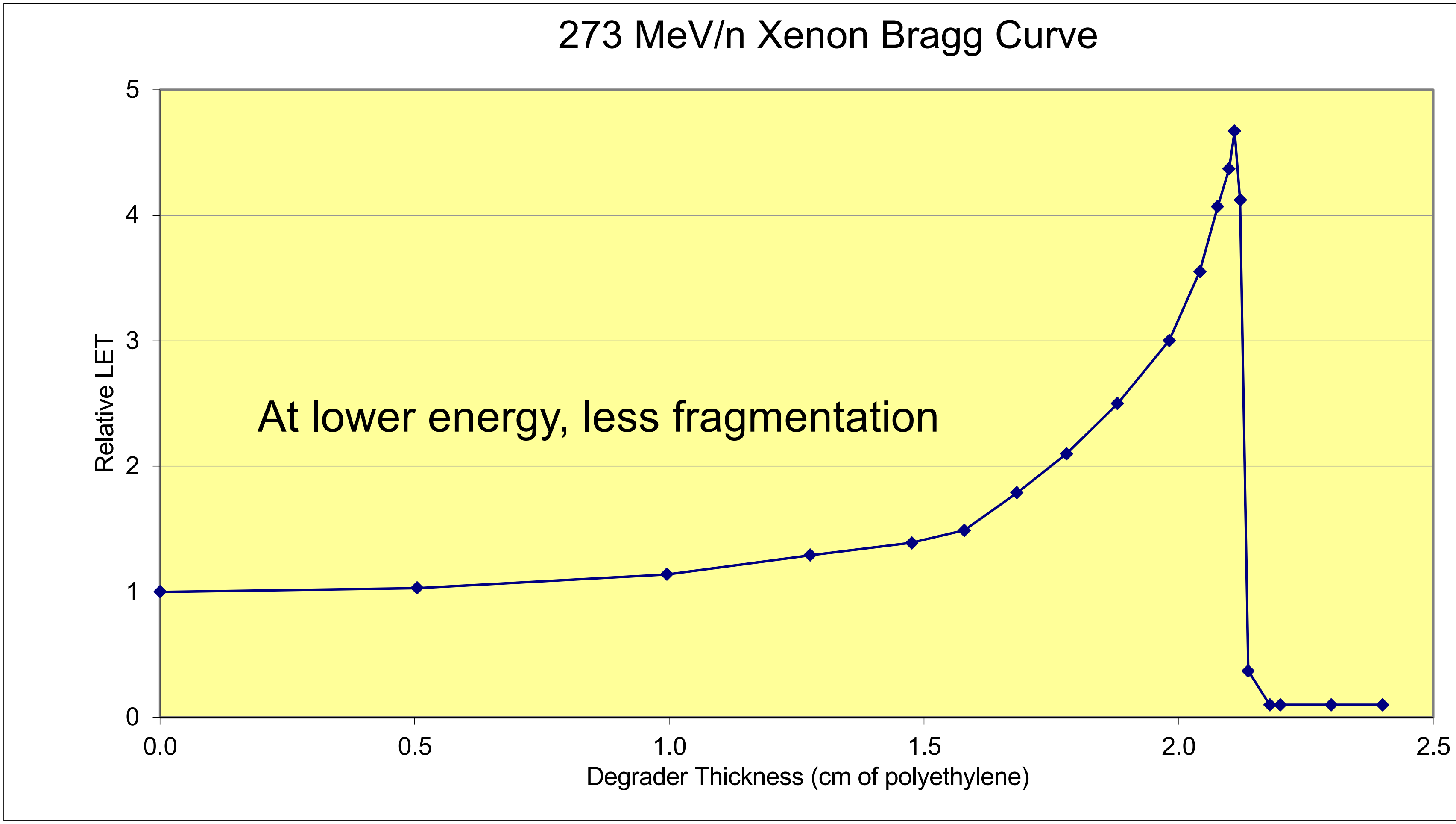
LET: Bragg Curves - Carbon



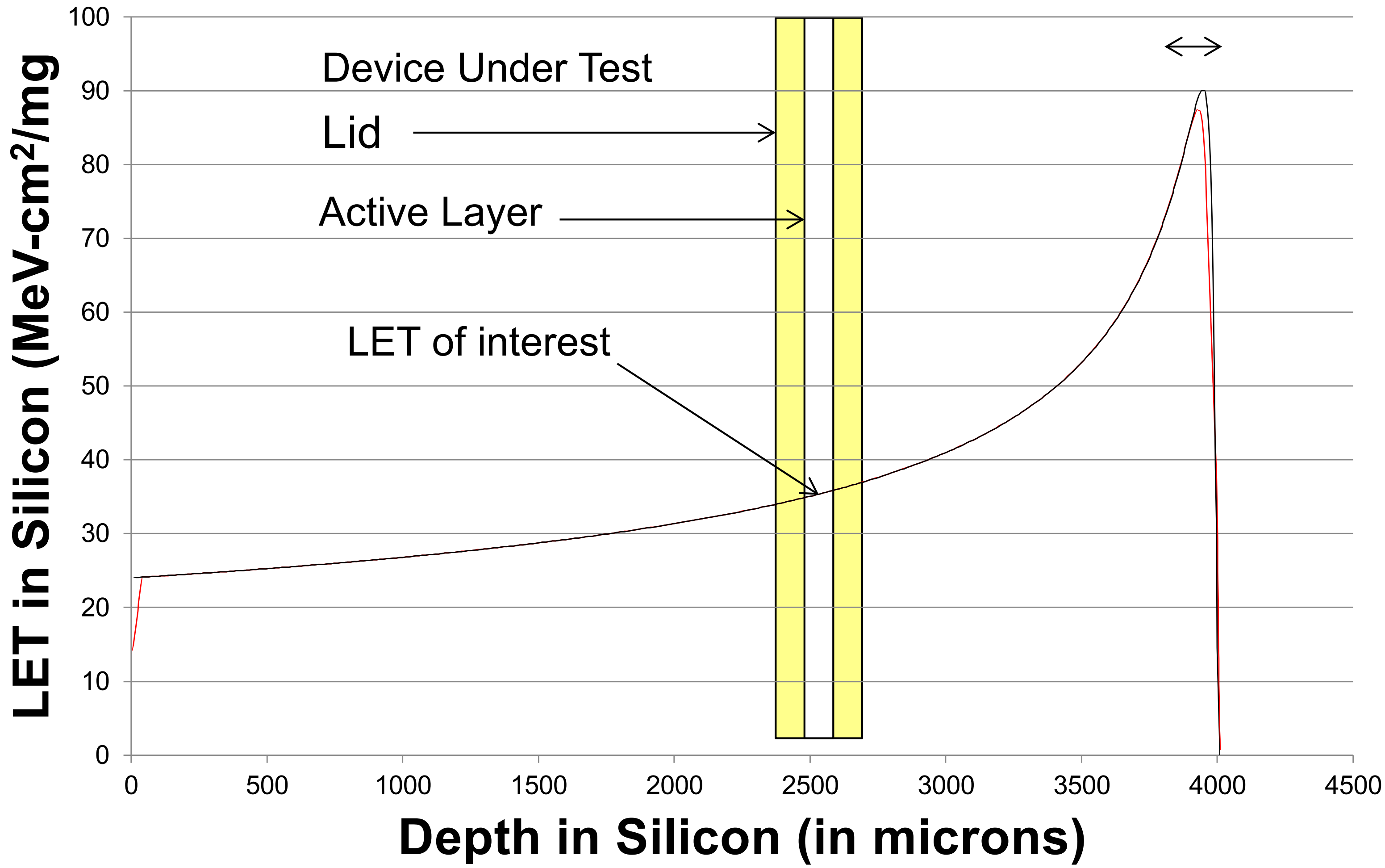
LET: Bragg Curves - Iron



LET: Bragg Curves - Xenon

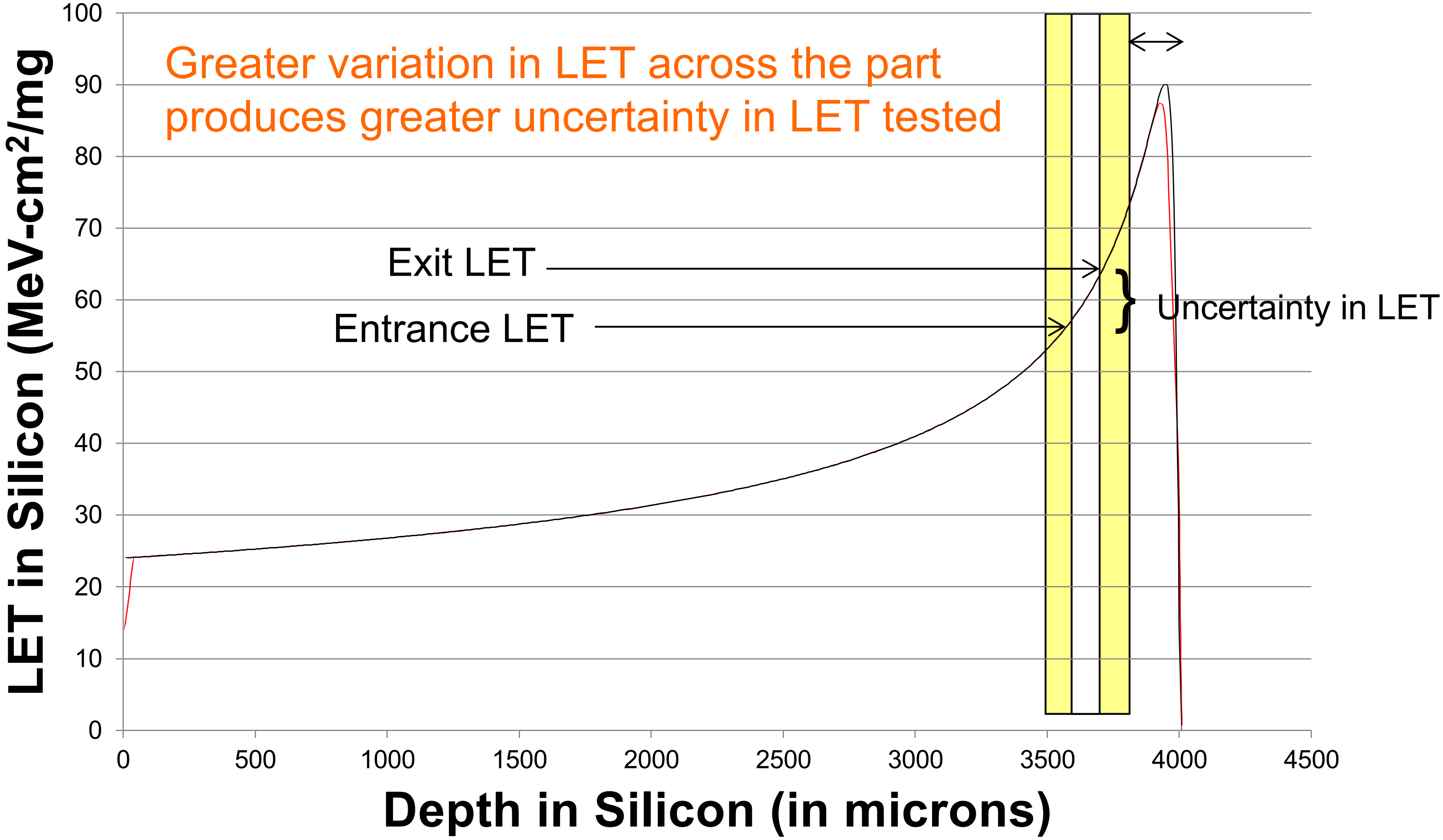


Bragg Peak vs Entrance LET



Example of 170 MeV/n Gold ions in Silicon

Bragg Peak vs Entrance LET



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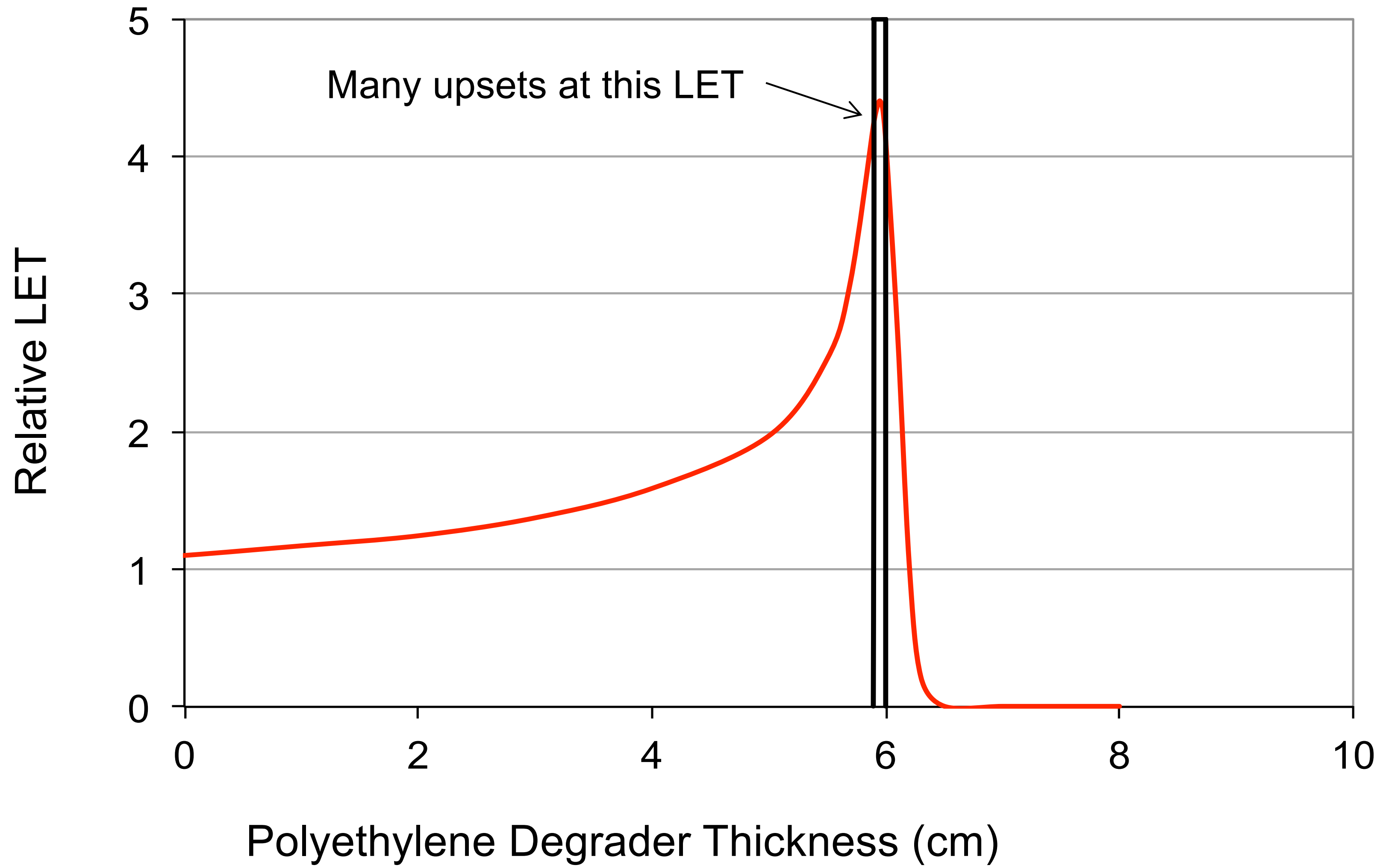
Variable Depth Bragg Peak

What if you don't know the material in your DUT?
Or you don't know the thicknesses of each of the layers in the part?

Start your test with enough degrader to completely stop the beam, removing it a little at a time until you start to see upsets. This indicates that the Bragg peak is located in the active layer. Continuing to remove degrader puts lower and lower LET ions into the active layer.

Variable Depth Bragg Peak



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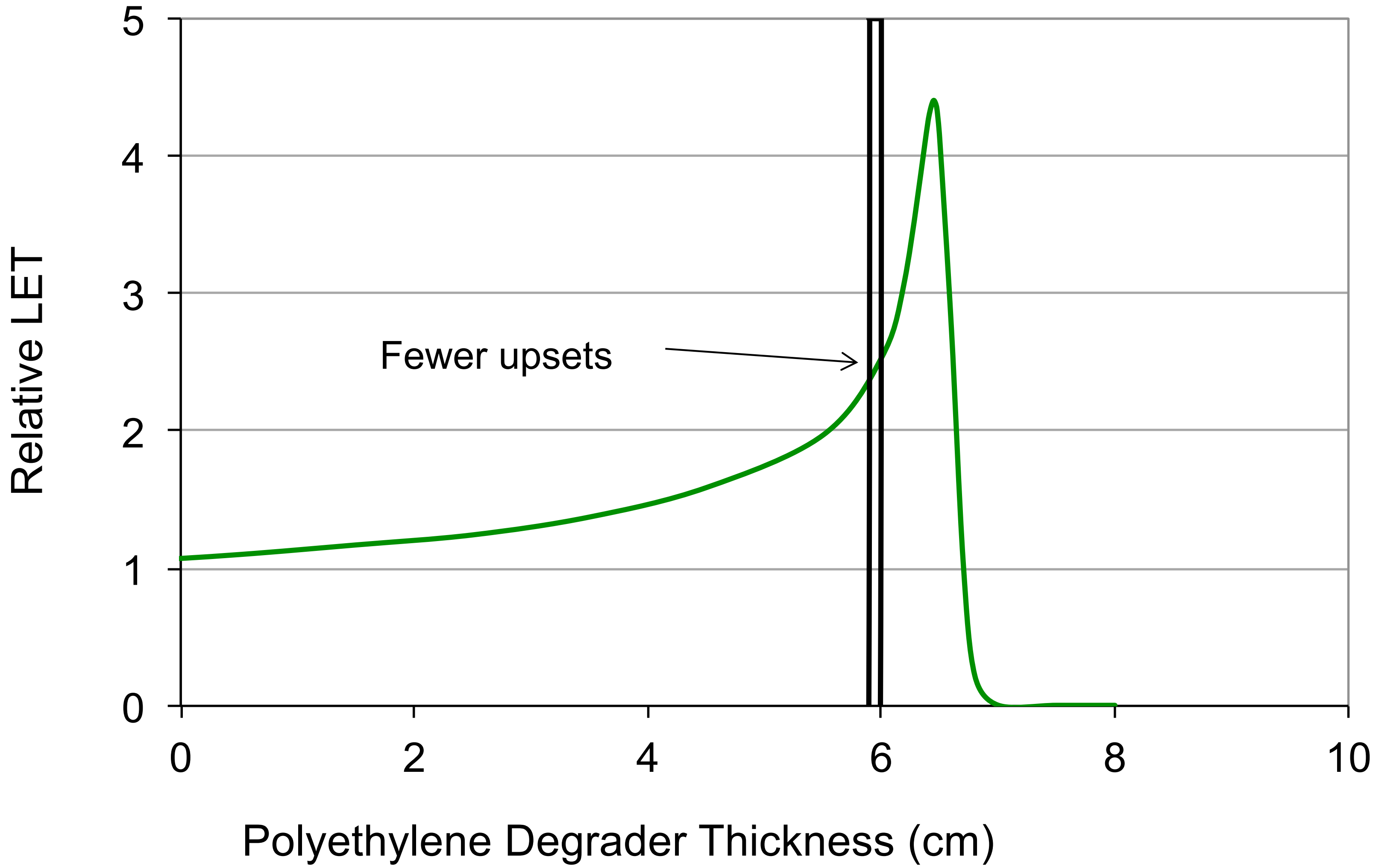

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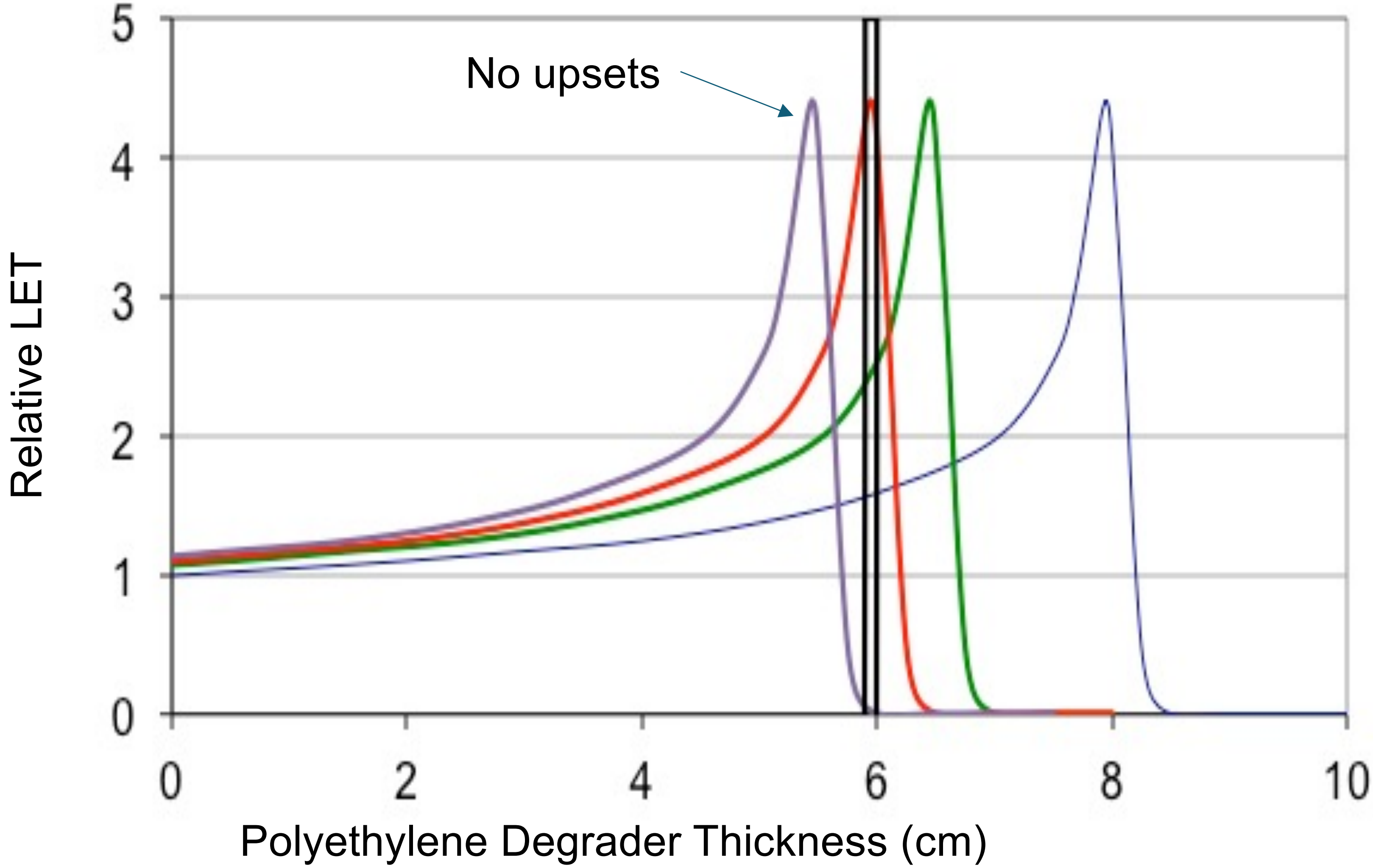
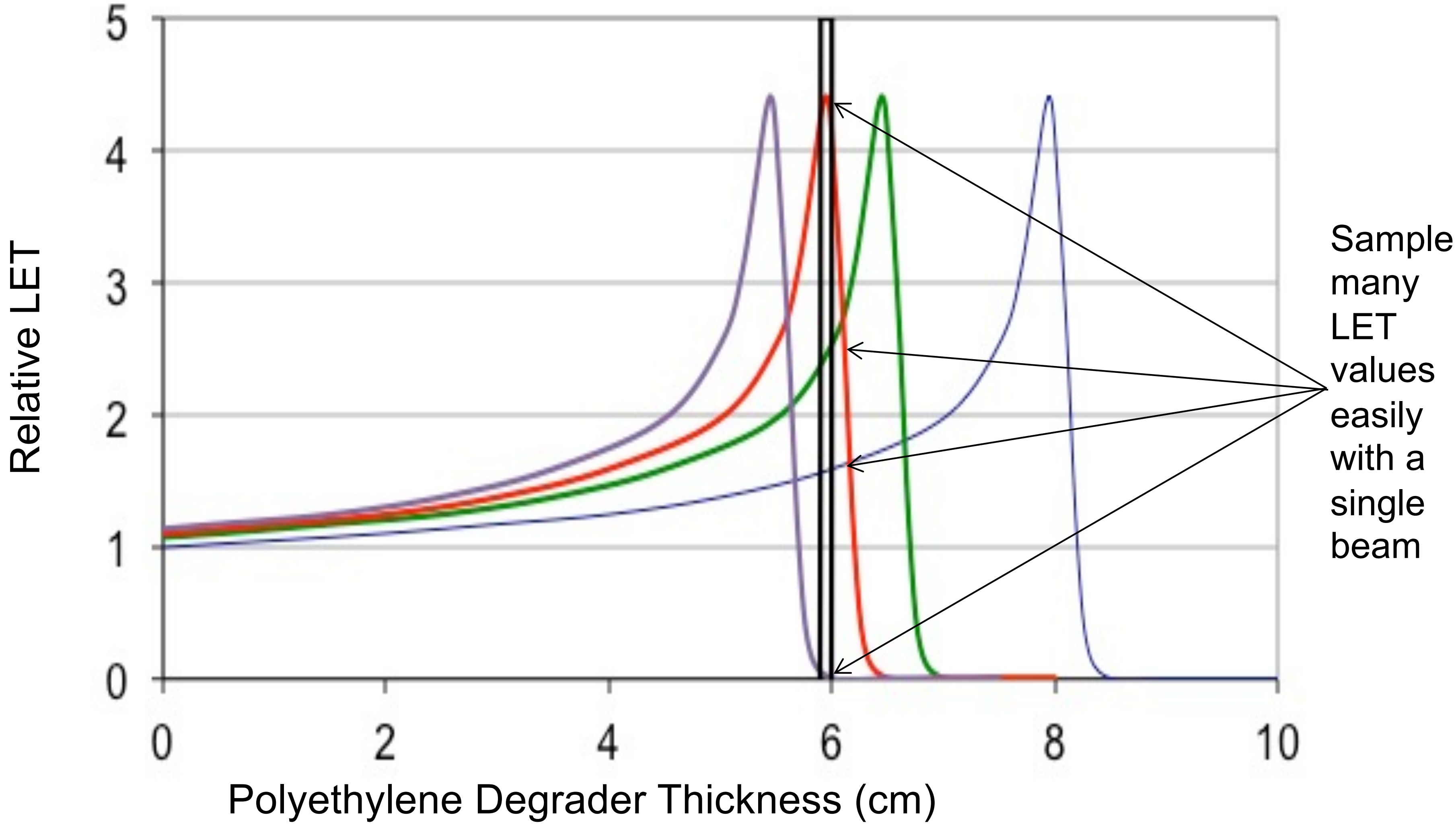


Variable Depth Bragg Peak



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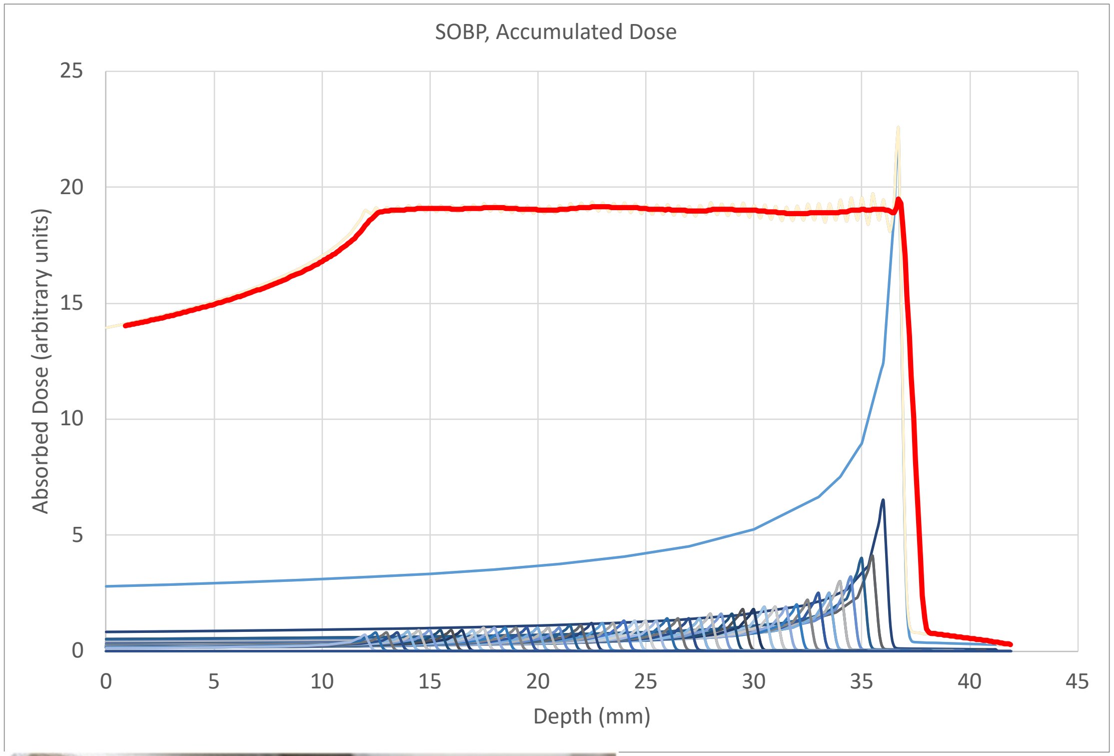
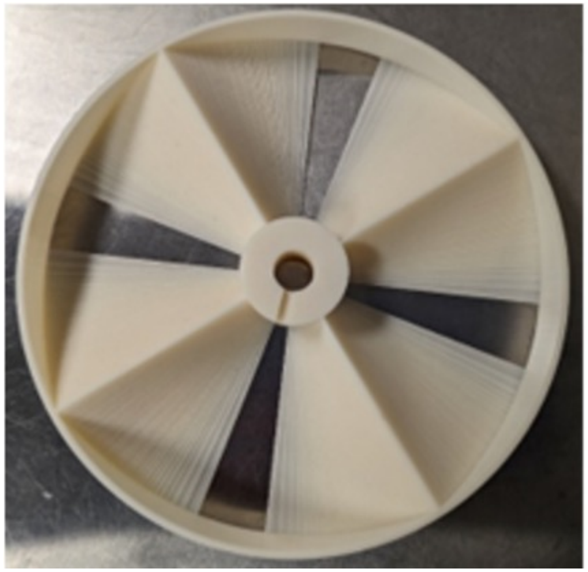
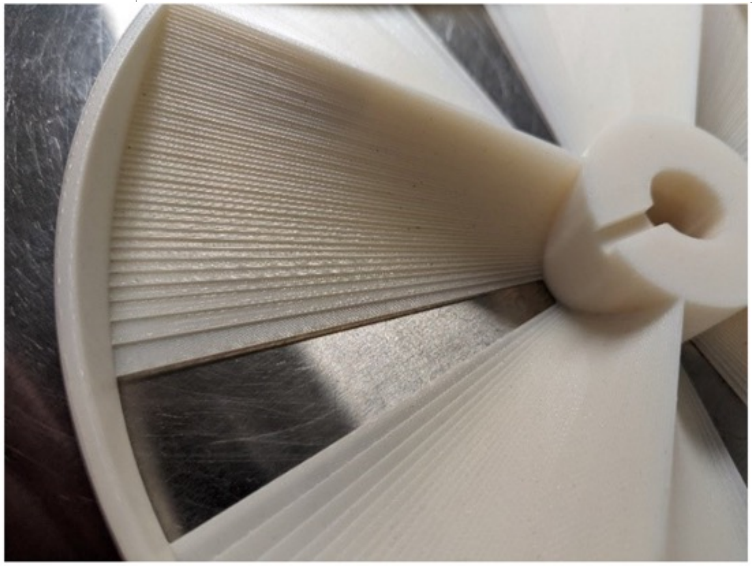
Spread Out Bragg Peak: (SOBP)

Take a set of pristine Bragg peaks and add them together, weighted in such a way that they produce a single uniform dose throughout the sample (tumor). The SOBP below was made with a 108 MeV/n Carbon beam, and a degrader wheel with 50 steps of thickness 0.5mm spinning at 200 RPM. It is used regularly to irradiate tumors in biological samples.







LET: Is that all that matters?

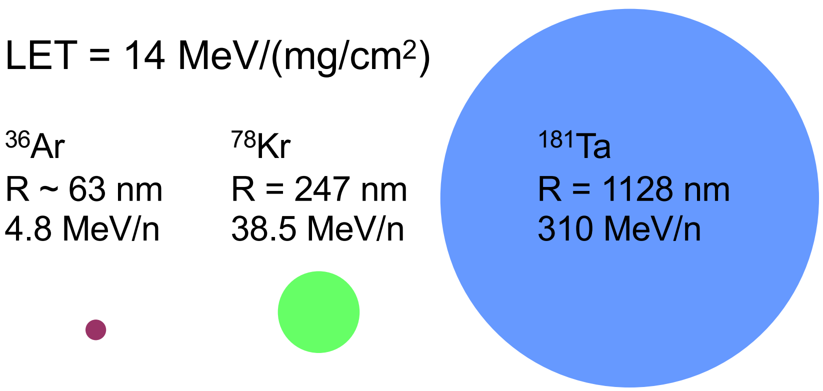
Not all energy depositions (LET) are equal.

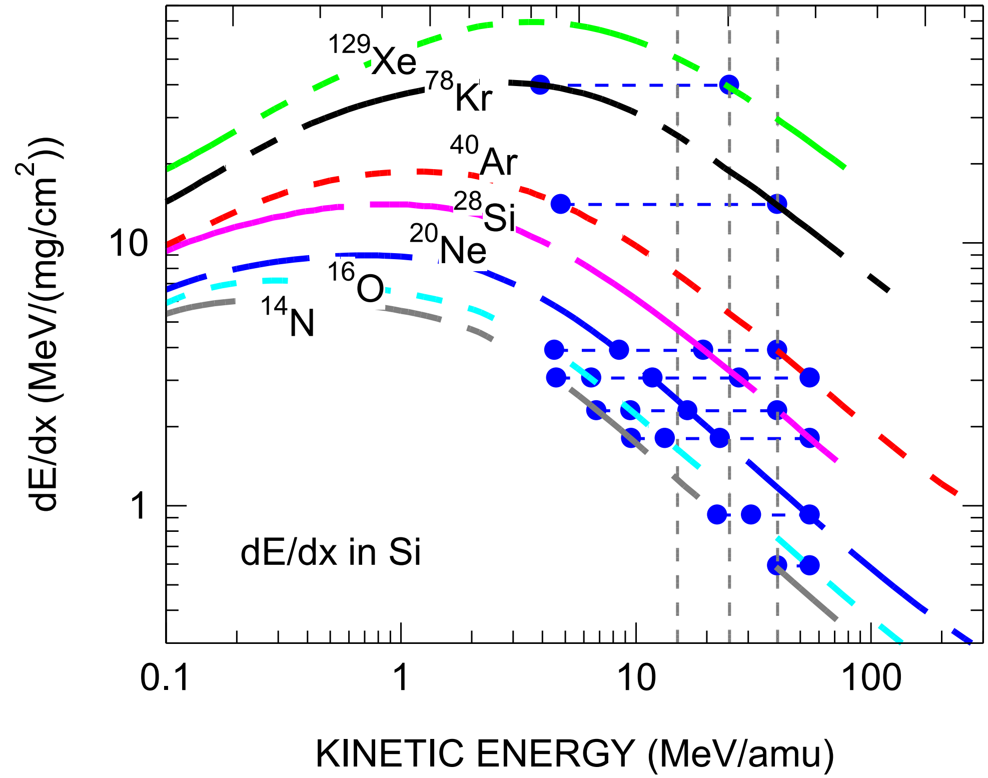
There are many ways you can achieve the same LET value.

Different heavy ions can have the same LET = 14 MeV/(mg/cm^2), they will not have the same upset effectiveness.

Consider the charge cloud radius, i.e. the radius containing 50% of the total ionization.

LET = 14 MeV/(mg/cm^2)





Different kinetic energies have different charge densities.

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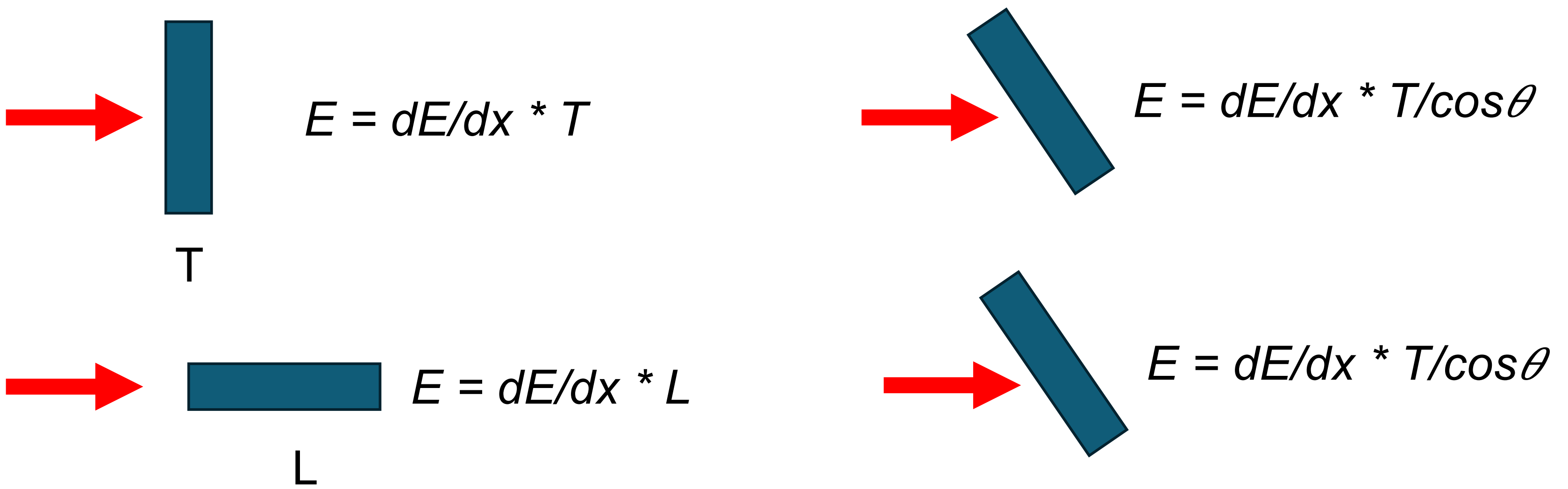
“Effective” LET

LET is “energy deposit per unit length”.

LET does not change with incident angle.

Deposited energy can change with angle, sometimes increasing, sometimes decreasing.



Logistics

- Access to the Target Room
  - Labyrinth vs Plug Door
- Beam monitoring
  - Beam camera
  - Segmented Wire Ion Chamber
  - Beam Edge Scintillator Counters
- What sample holders are available?
  - Vises, Clamps, Window frame holder
  - Mounting plate with optical bench treaded holes
- What alignment tools do you have?
  - Laser cross hairs
  - Collimator laser
  - Modular beamline component on rails
- Data acquisition systems
  - VME-based flexible ADC/QDC/TDC/WFD/Scalers
  - CAEN DT5725 8-channel digitiser
- Patch panels
  - HV
  - Signal
  - Ethernet
  - Fibre Optic (not yet)
- Activated material storage
- SRIM StackUp Tool
- User Experience at NSRL
  - What is a typical run like?

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Target Room Access: Labyrinth

People are identified with an iris scan that checks their training and unlocks a key with an RFID tag.

Infrared curtain counts people.
RFID counter counts keys.
Beam enabled when all keys are returned.
Interlocks broken if attempted entry without a key.

Typical access times between Beam_Off and Beam_On are 3 to 5 minutes + (work time) depending on inclusive or exclusive access controls.

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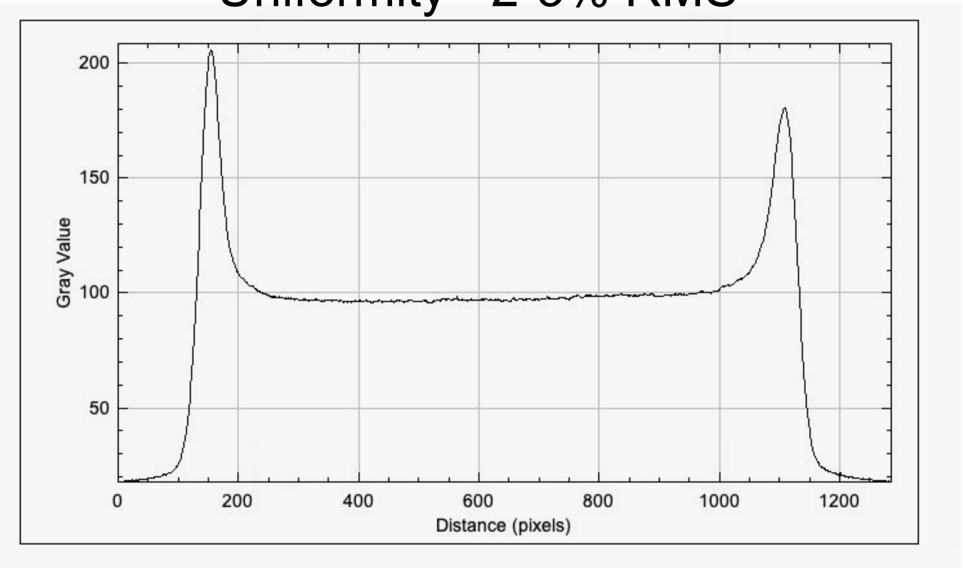
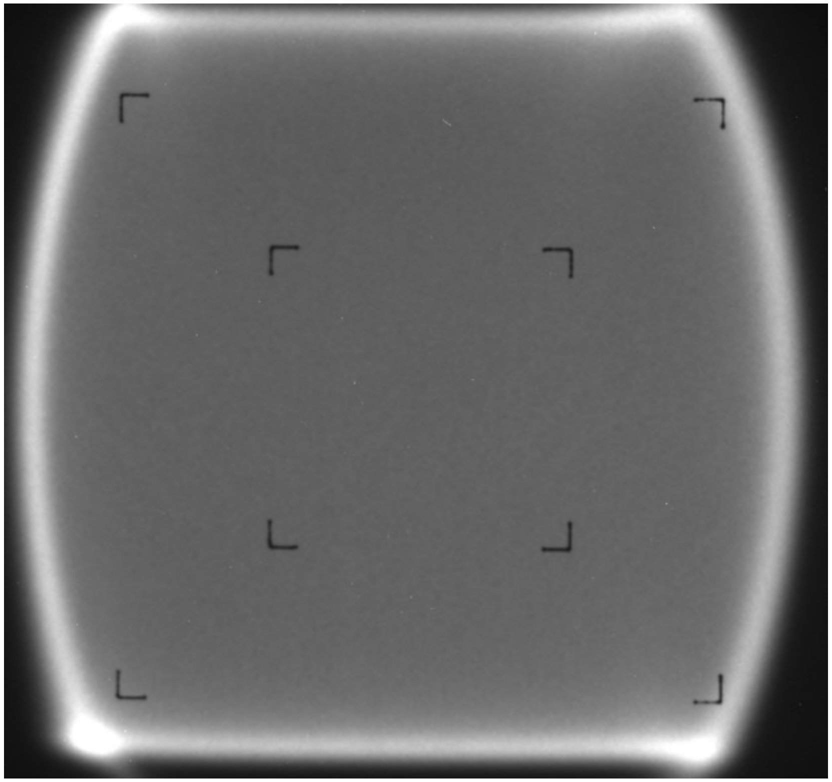
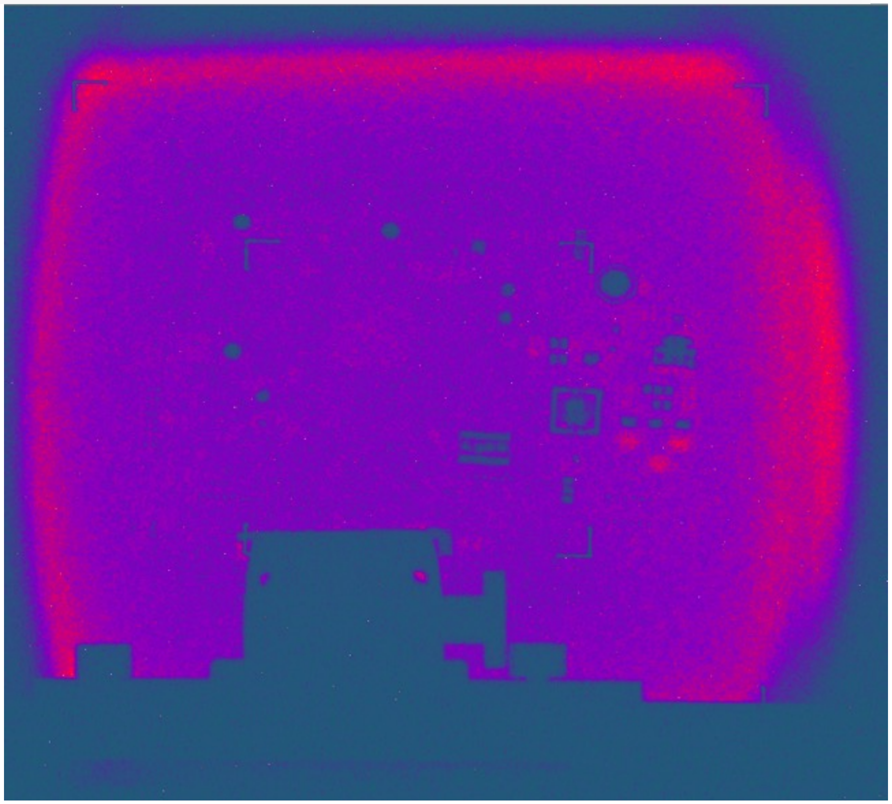
NSRL Tools: Beam Camera

Digital Beam Imager uses a fluorescent film (ZnCdS:Ag) over beam area, double mirrors to periscope light into Hamamatsu CCD camera. Software reads in data and integrates image of full spill duration. Can observe beam size and DUT position readily.

Uniformity ~2-3% RMS

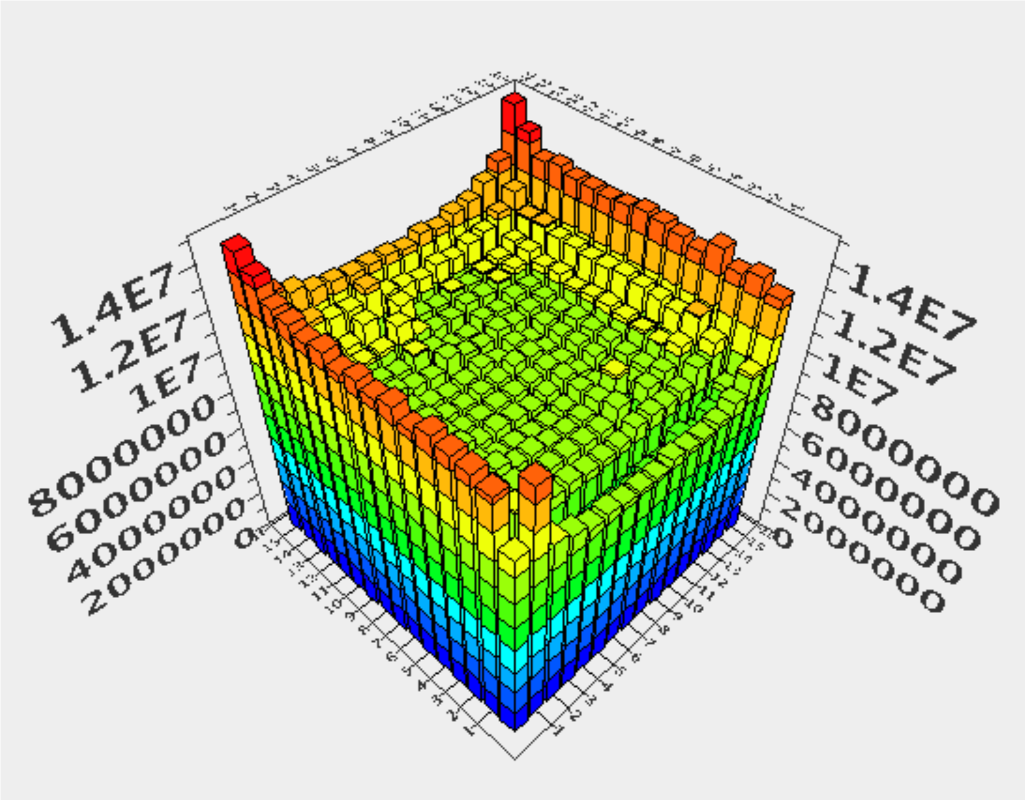




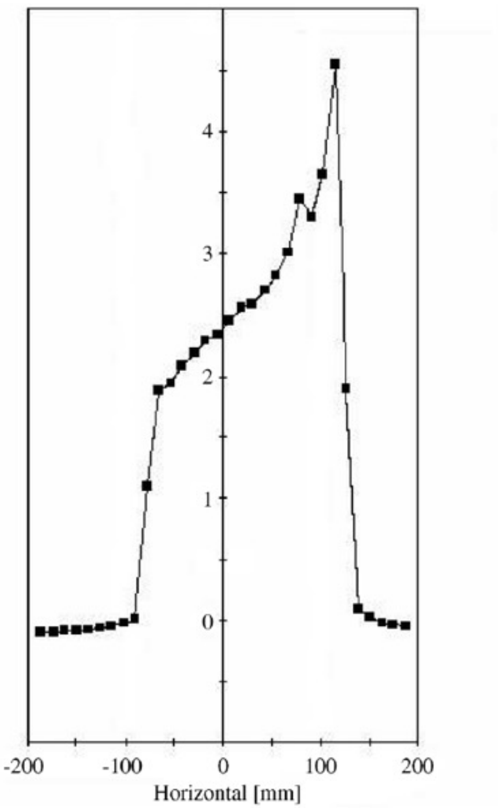


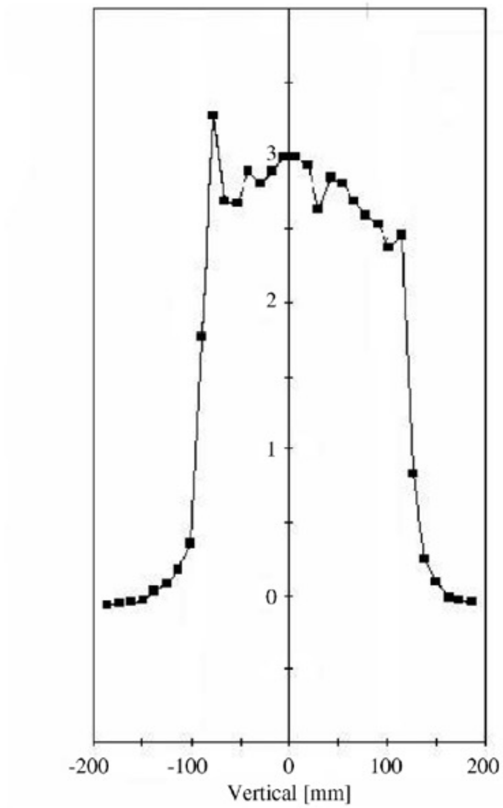
NSRL Tools: 80 x 80 cm^2 1024 Pixel Ion Chamber

When running in large beam spot format (60 x 60 cm^2) the beam shape is monitored using a large pixelated ion chamber with 1024 pixels, each 2.54 x 2.54 cm^2. The "wings" of the beam can be clearly seen, with a central region of good uniformity. It is helpful to keep the wings in view so that the beam is not being lost on the upstream beampipe.



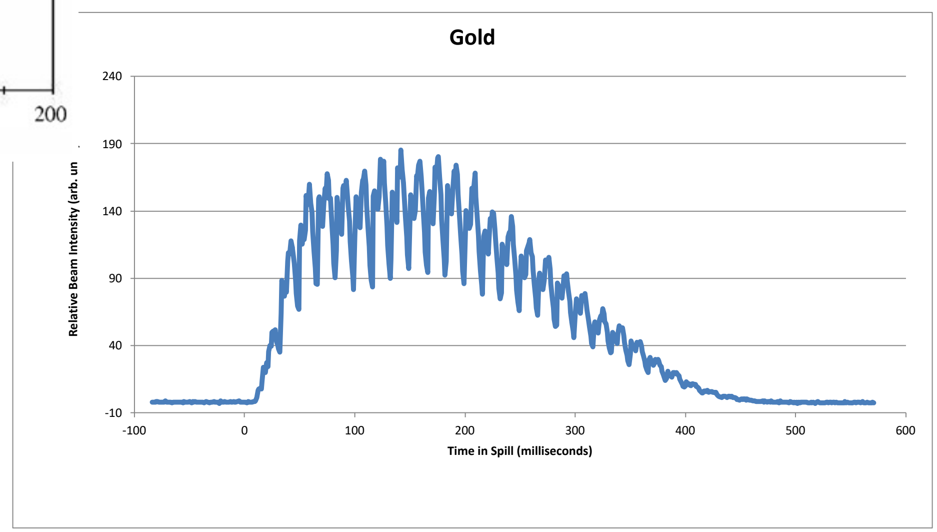
NSRL Tools: Segmented Wire Ion Chamber





32 wires in both the horizontal and vertical plane, giving a beam profile in both dimensions.

Fast Readout gives the temporal profile of the beam in 1 millisecond steps.



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NSRL Tools: Edge Counters

Four 1 cm^3 scintillators inserted into the halo of the beam.

Used to measure beam uniformity when operating at low flux or when other instruments see too little signal to operate.

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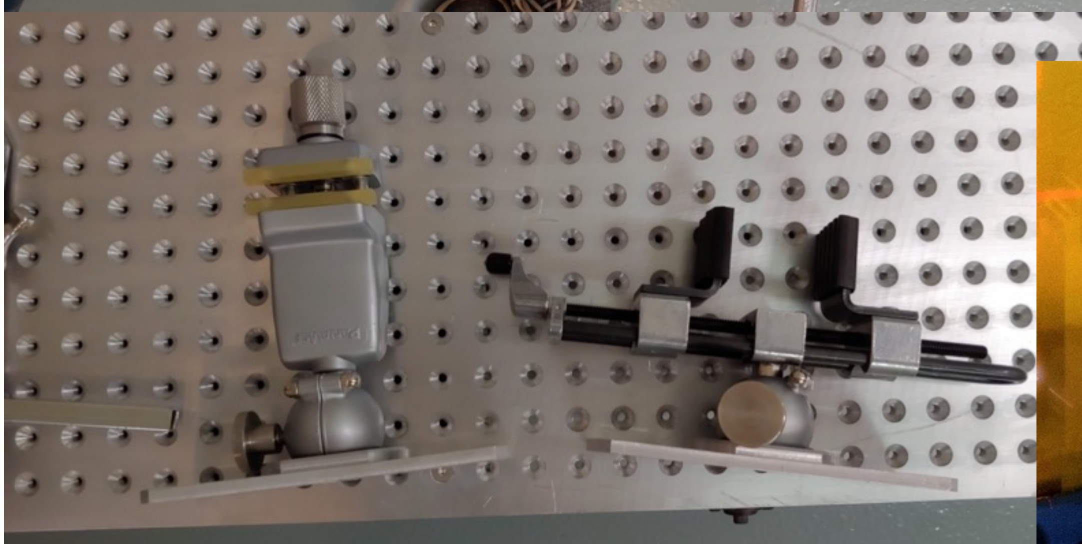
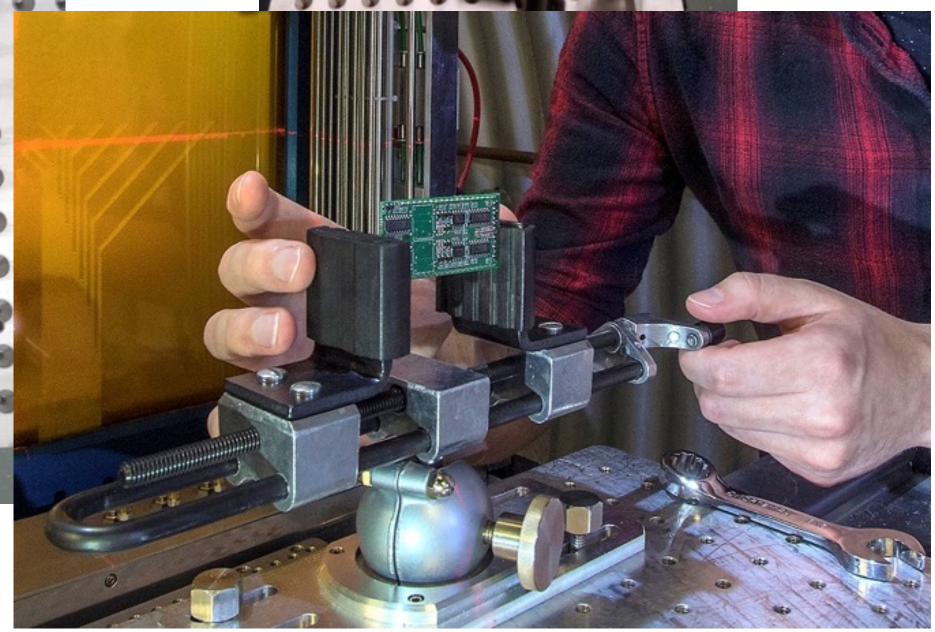
Sample Holders & Breadboards





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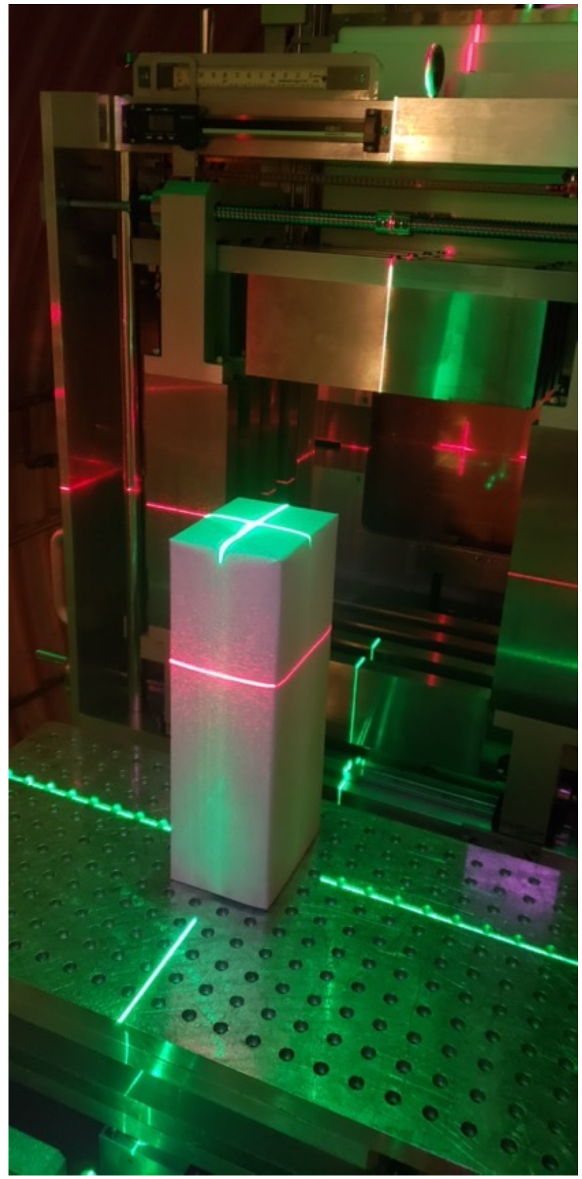
Alignment Tools: Laser Crosshairs and Collimator

Laser alignment system:

Aligning test equipment with beam centre.

Collimator alignment tool shows the shadow of all four edges of the collimator on the circuit board or DUT.



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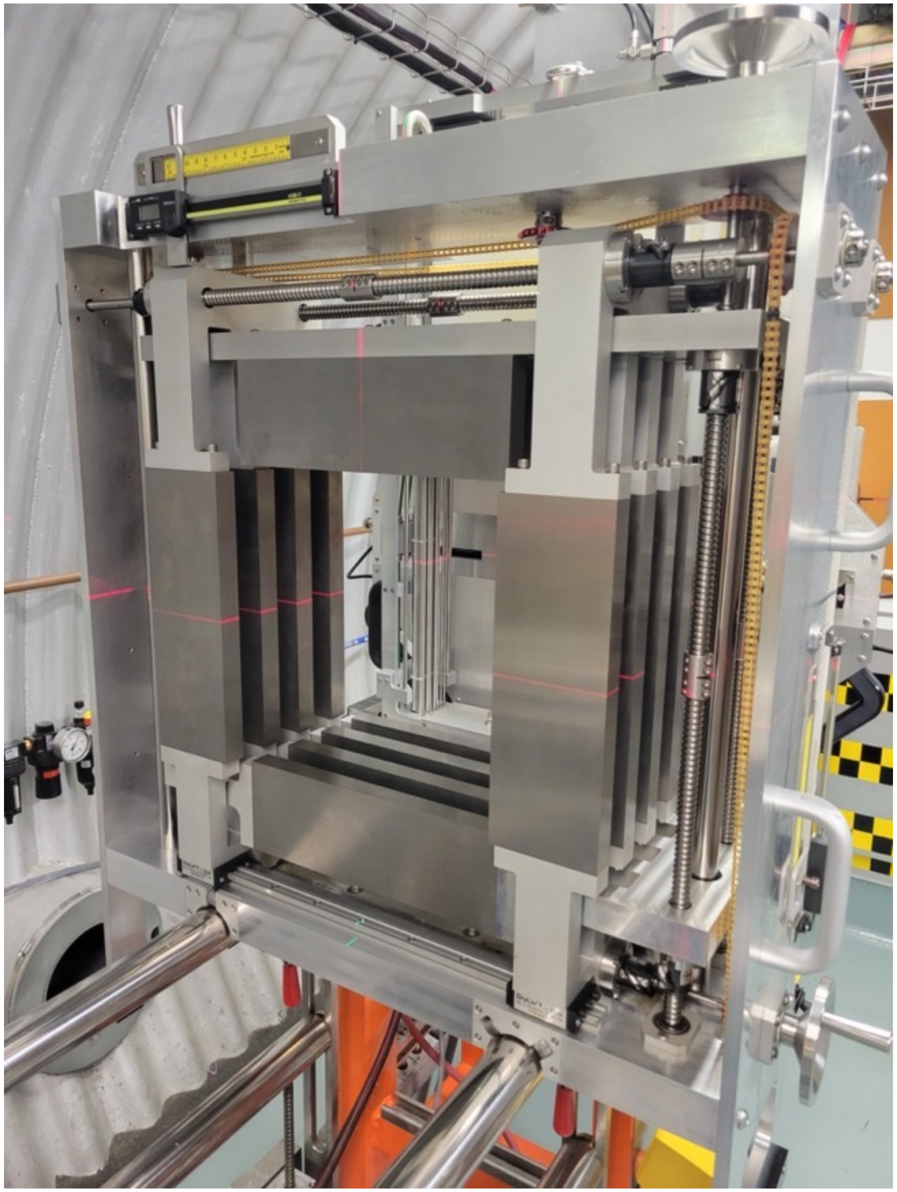
Adjustable Tungsten Collimators

Manually adjustable from 30 cm to 0 cm.

Minimum thickness is 10 cm.
Chosen to range out 450 MeV protons and all other fragmentation products.

Operated as close to DUT as possible to minimize scattered secondary particles.



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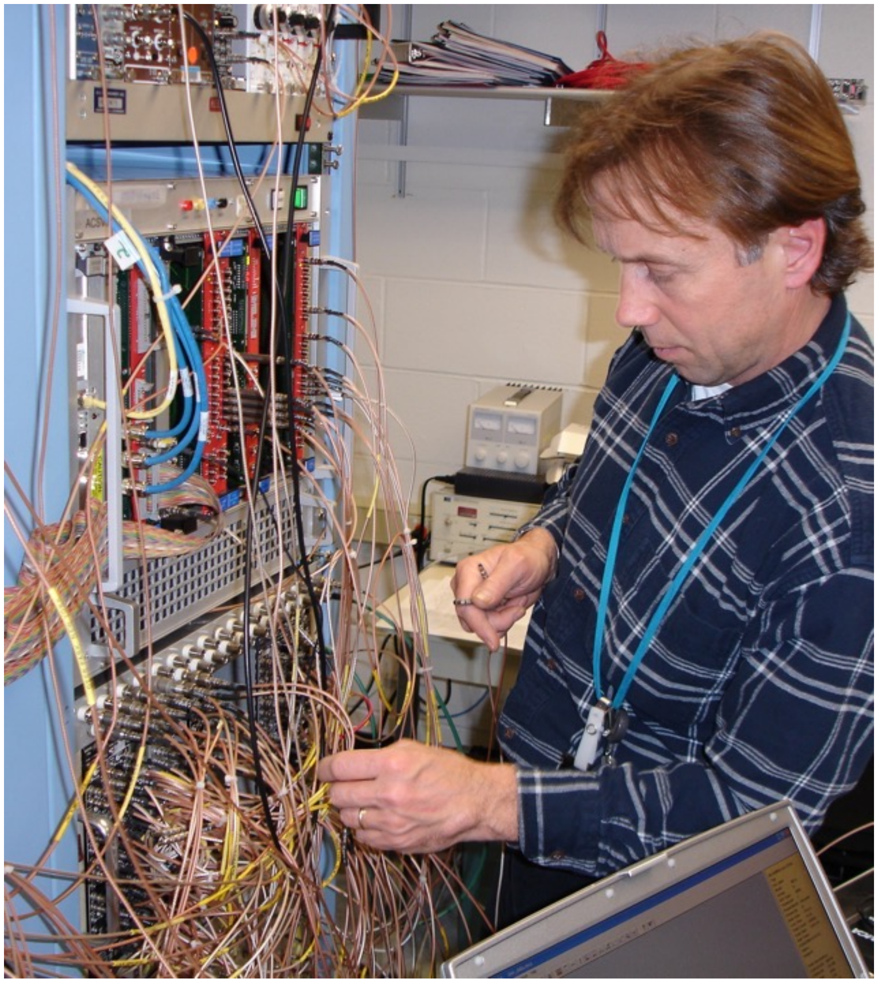
Data Acquisition

DT5725
+
DPP-PHA



VME-based data acquisition system

- Flexible, user configurable
- ~2 kHz event rate
- 12 and 16-bit ADC and QDC
- 35-ps TDC
- 300 MHz scalers
- Optical Bridge

CAEN DT5725 8-channel digitiser

32-channel +/- HV and LV PS

96 RG-58 50Ω signal cable patch panel with BNC termination

64 RG-59 75Ω HV cable patch panel with SHV termination

3 Tri-Ax high-speed low-loss cables

18 CAT5e Ethernet cables

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NSRL Tools: Beam Control

Beam present signal:

A scintillator near the beam (but out of uniform area to not be destructive to beam quality) produces signal and this is processed into a TTL high signal that is sent to users either in the target room or at the user area

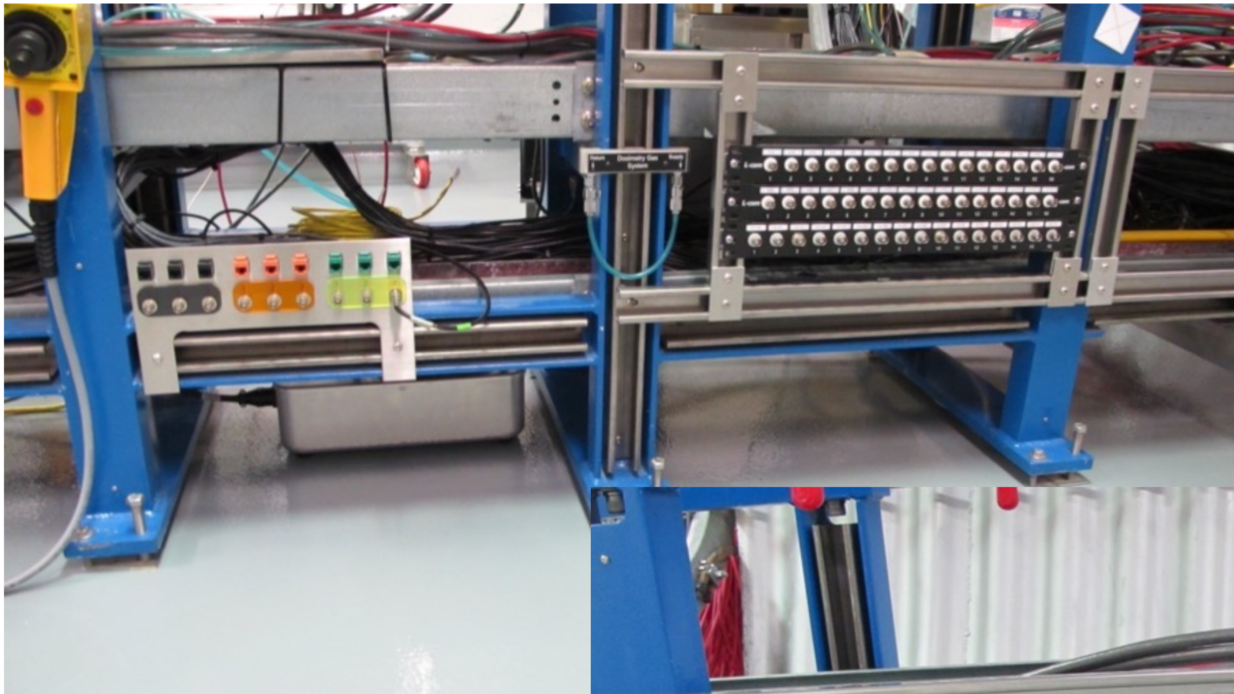
Beam off switch:

Our dosimetry control unit has set of cutoff or "clamp" inputs which check for 50Ω impedance or open circuit. This has a very fast cutoff response, but even without, users can use this switch to stop beam during hardware errors.

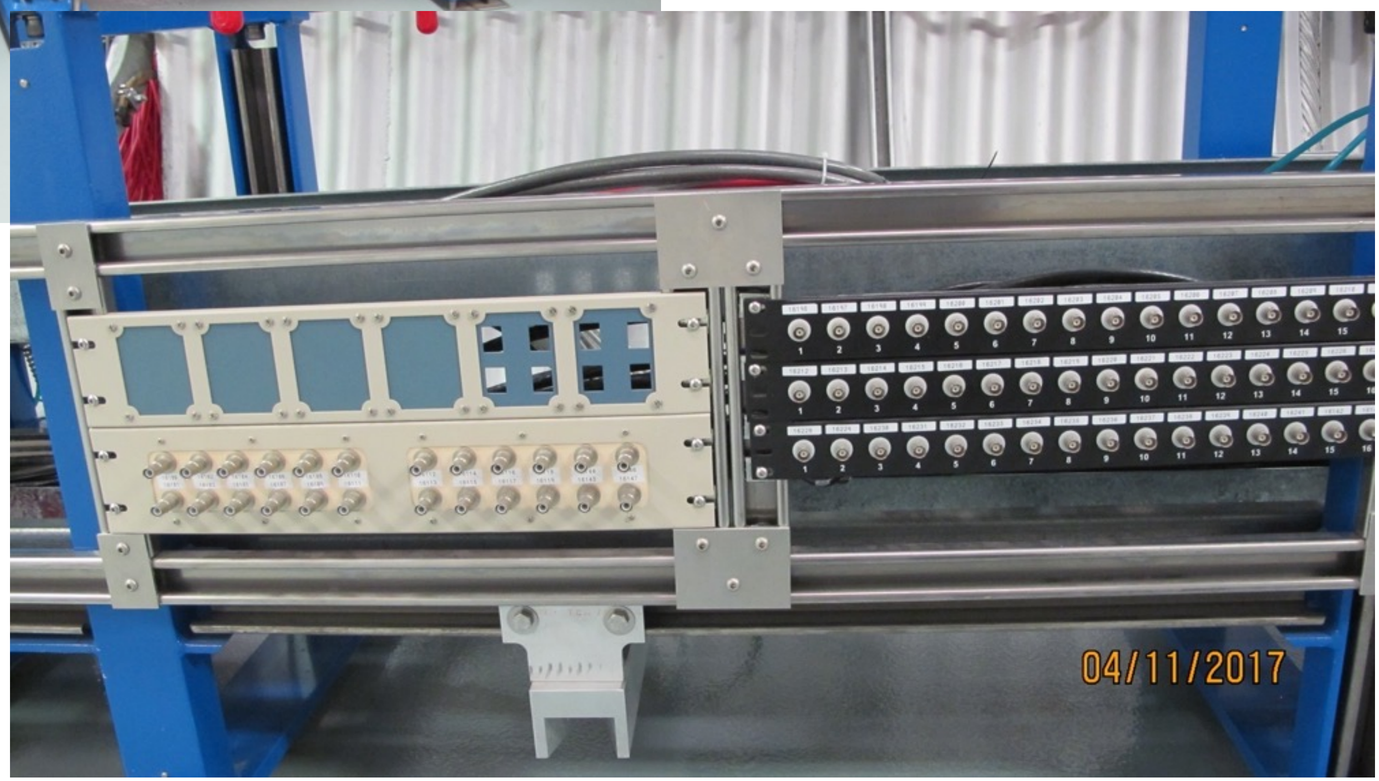
Control Room to Target Room Patch Panel
Ethernet and RG-58 signal cables: ~150 feet

Patch Panels

Downstream Patch Panel



Upstream Patch Panel



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SRIM StackUp Tool

Target:	Silicon
Ion:	Au

E/ΔE/Δx Calculator

Energy [MeV/u]	dE/dx [MeV/(mg/cm²)]	Range [mm]	Z Straggling [mm]	XY Straggling [mm]		
400	15.0350	14.9340	0.5866	0.0352	4.15E+03	ions/cm²/rad

Range [mm]	Energy [MeV/u]	dE/dx [MeV/(mg/cm²)]	Z Straggling [mm]	XY Straggling [mm]		
1.3	80.3723	36.3012	0.0439	0.0045	1.72E+03	ions/cm²/rad

dE/dx [MeV/(mg/cm²)]	Range [mm]	Energy [MeV/u]	Z Straggling [mm]	XY Straggling [mm]		
70	0.2299	21.1877	0.0068	0.0016	8.92E+02	ions/cm²/rad
	0.0212	0.9805	0.0007	0.0009	94.3661	10.491
					max dE/dx	min dE/dx

Multiple Layers Calculator

Beam Energy [MeV/u]: 400

	Material	Thickness [mm]	Exit Energy [MeV/u]	Residual Range [mm]	Entrance LET	Exit LET
Layer 1:	Copper	1.5	308.92	3.15	12.62	14.20
Layer 2:	Epoxy	1.5	279.64	8.97	20.24	21.30
Layer 3:	Aluminum	0.5	267.46	7.12	17.30	17.72
Layer 4:	Kovar	0.1	260.60	2.50	15.84	16.06
Layer 5:	Silicon	0.1	258.45	7.65	18.49	18.57
Layer 6:	Silicon	7	48.81	0.65	18.57	47.83

Typical run

- Experimenters often run around 12-16 hours per day due to high demand and low availability. Asking for 1 day to 1 week at a time.
- Typically ask for 4-5 different ions, spanning large dE/dx or focus on specifically 1 ion and spend the entire time on that.
- Users often request 1E6 to 1E7 ions/cm^2 total fluence per part.
- Intensity changes may be frequent until finding tolerance point e.g. starting low, 1e2 to 1e3 (ions/cm^2)/spill, and increase to max intensity by asking for 2x, 5x or 10x steps.
- Access to Target Room may be after every 1e7 run or may comprise many runs. Since beam changes are quick (2-3 minutes) it is most efficient to change beams rather than change DUTs.

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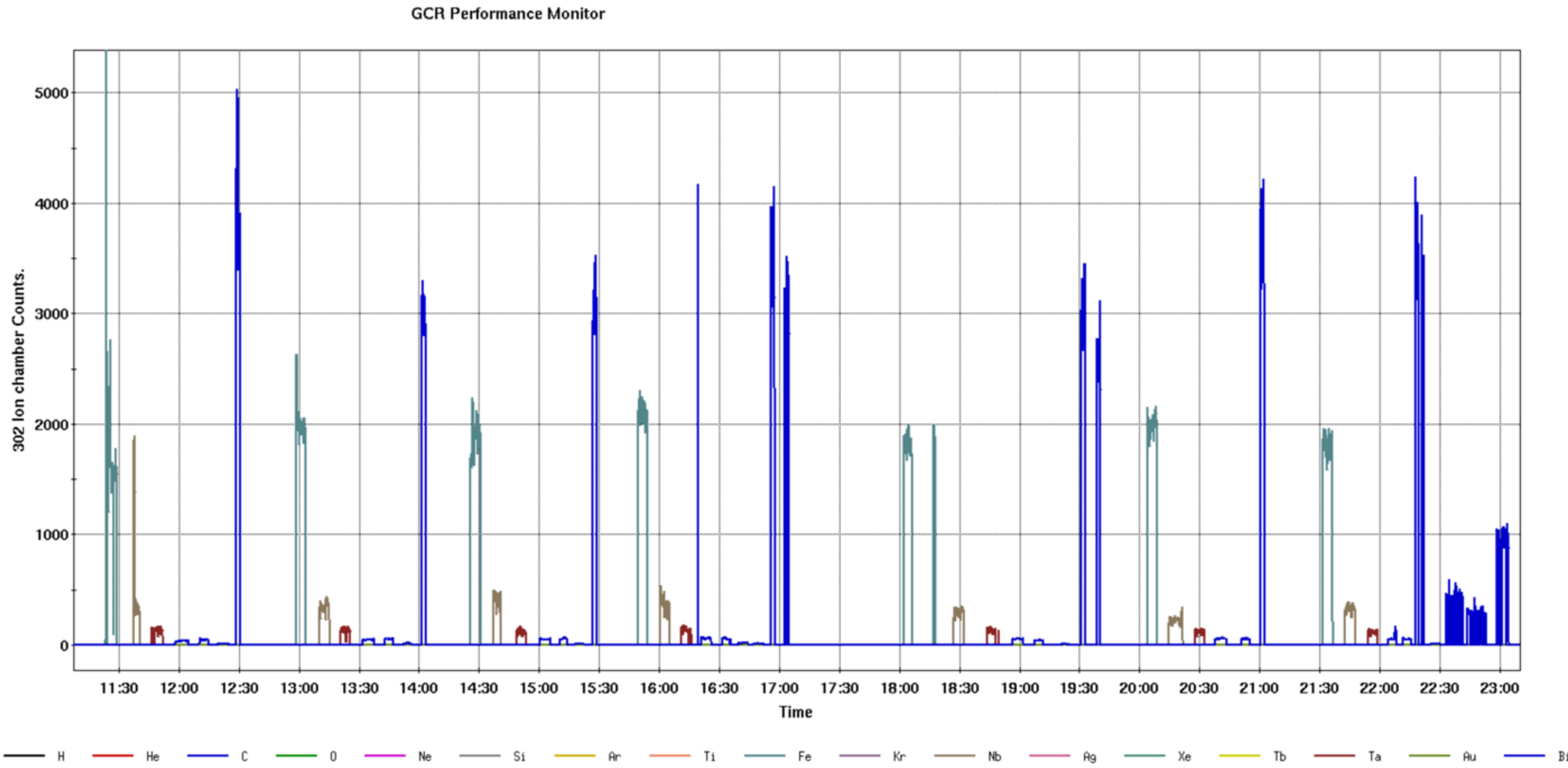
Ion Species/Energy Changing



User cycling through Fe, Nb, Ta, Bi to hit LETs of 2 to 30+ MeV/(mg/cm^2)

Communication

Users set up their test monitoring areas just across the room from our beam line controls area. This allows for easy communication when there are requests for intensity, energy, or ion species changes.

There is a single point of contact! Less confusion.

The dosimetry control program lets users enable beam to reach total fluence, add comments, run numbers. Hardware switches let them “pause/play” or “end run”

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Recommendations

- Electronics responds to deposited energy, not to LET. Working at angles changes the deposited energy, not the LET.
- Whenever possible, work on the plateau. LET is not changing rapidly with depth.
- Use the highest-Z ion at the highest energy possible to give you the desired LET and longest range.
- Combine tests of single parts with system tests.
- Do not de-lid your parts. It is costly, dangerous, and produces erroneous results.
- If you do not have an accurate profile of your part, you may benefit from a variable-depth-Bragg-peak study.

Complaints

Higher beam intensity

- We often have low beam intensity from the ion source. Running to 1e7 ions/cm^2 can take a long time (and therefore cost)

Continuous beam (longer spills)

- The Booster Synchrotron has ~10% duty factor compared to ~100% for Cyclotrons

More beam time and faster scheduling turn-around

- Since we schedule around NASA work, it's hard to get beamtime