Variable-Depth Bragg Peak Method for High-Energy Single-Event Effects Testing

C. Foster (FCS) and <u>S. Buchner (NRL)</u>

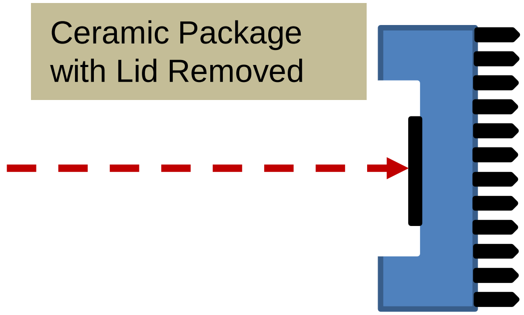
Outline

1. Motivation for using the VDBP method
2. Description of the VDBP method
3. Implementation
4. Examples
5. Conclusion

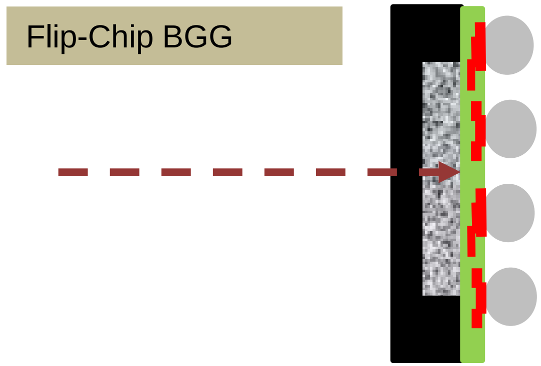
1. Motivation for Using VDBP Method

SEE Testing with Low-Energy Ions

- SEE testing with **low-energy ions** requires exposing the IC by removing part of the package.
  - Ceramic packages – remove the metal lid
  - Plastic packages – etch away the plastic with acid



- Flip-chip and ball-grid arrays require irradiation from the back side. Material removed by:
  - Mechanical polishing for bulk devices
  - Etching with XeF_2 for SOI devices

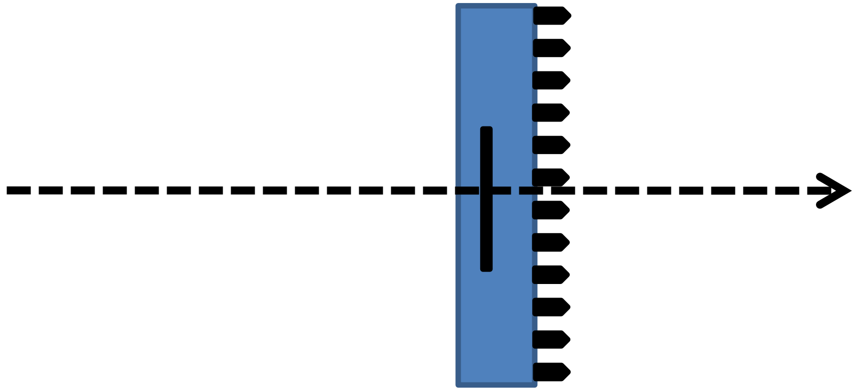


SEE Testing with High-Energy Ions

- Alternate approach is to use high-energy ions.
  - No need to open package.
  - Assume that the LET does not change between surface and sensitive volume.

- Depending on accelerator, might only get one ion species at a single energy.

- LET can be varied by:
  - ➢ Changing angle of incidence
  - ➢ Inserting degraders to lower energy of incident ions
  - ➢ Changing ion species



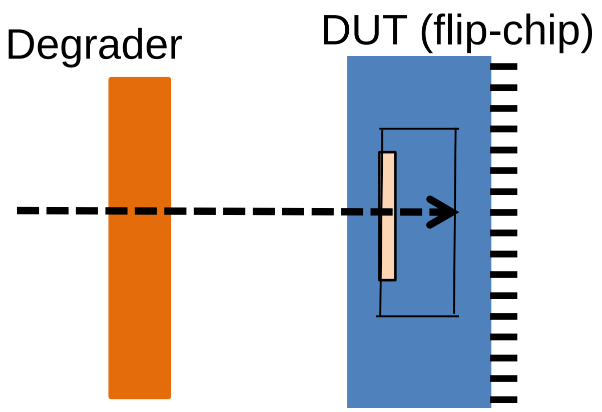
Using Degraders to Adjust Ion LET

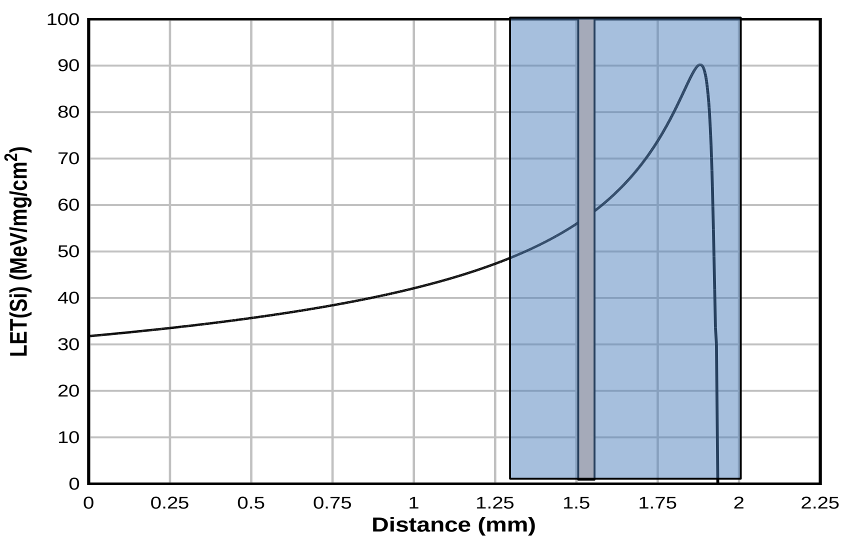
- Criswell et al. (1987) did SEE testing at the BEVELAC at LBL. They used a column of water as a degrader to reduce the ion energy and increase the *incident* LET.
- Degraders are routinely used to increase *incident* LET or position Bragg Peak at sensitive region when doing SEE testing.
- Adjusting the location of the Bragg peak by inserting degraders into the beam is routinely done to deposit radiation dose in a localized area when treating cancers.

2. Description of the VDBP method

VDBP Method

- **V**ariable **D**epth **B**ragg **P**eak is a variation of this approach. It uses calibrated degraders to sweep the Bragg Peak through the sensitive volume and **TRIM** to calculate the LET at the sensitive volume of the DUT.
- *The depth of the sensitive volume need <u>not</u> be known.*





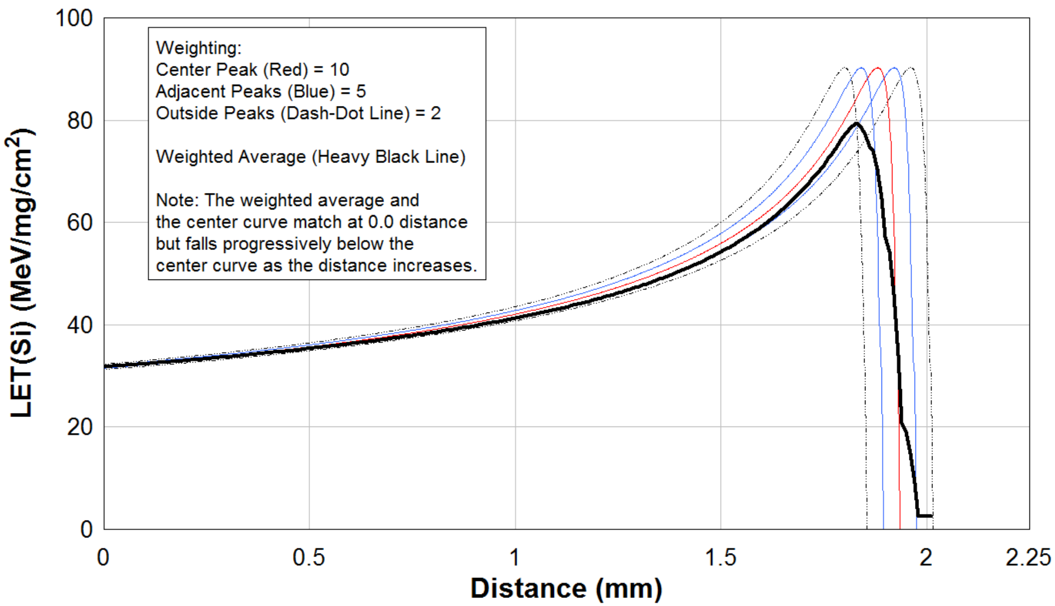
Concept 1

- Bethe Bloch equation assumes <u>continuous energy loss</u>

$$\frac{dE}{dx} = -\frac{4\pi N z^2 e^4}{m_0 v^2} B$$

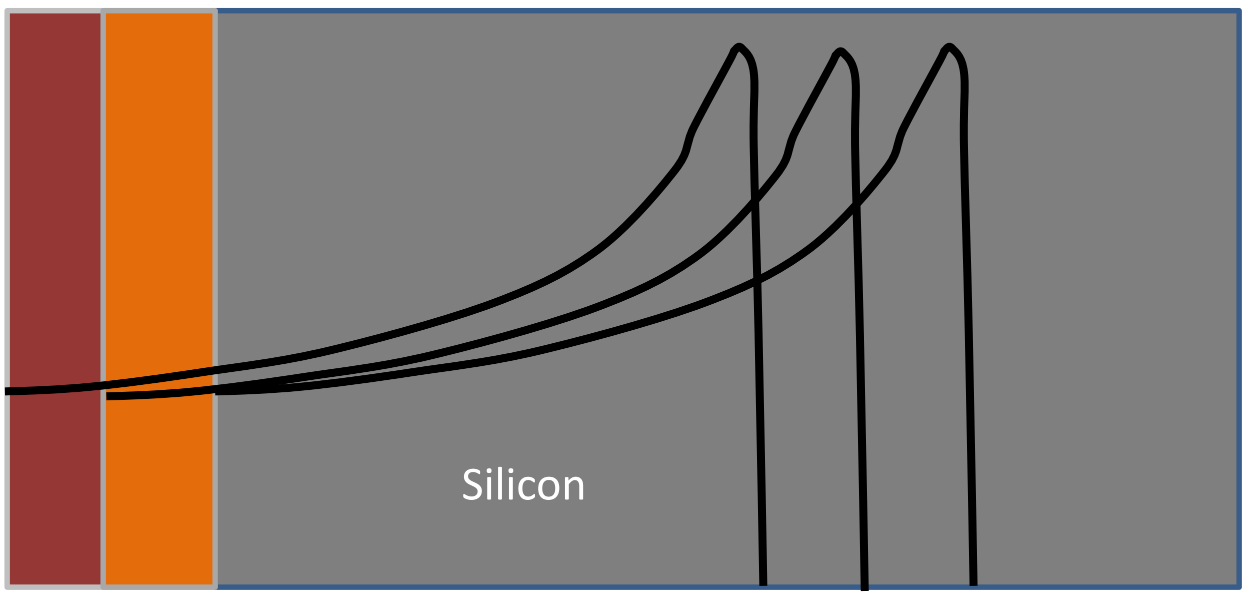
$$B = Z\left[ln\frac{2m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

- But, energy loss is a **stochastic** (random) process. A Monte Carlo calculation, **TRIM**, gives a more accurate representation by calculating **average energy loss** with distance.
- Calculation should include <u>energy spread and beam angle spread</u>



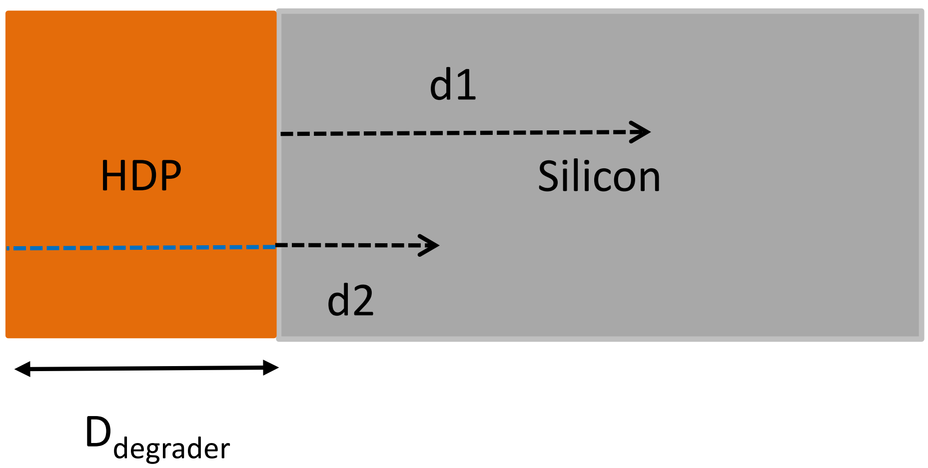
Concept 2

- Shape of Bragg peak for an ion with a fixed incident energy **in silicon does not depend** on degrader material or thickness.
- Calculate LET vs distance in silicon for a particular ion energy.



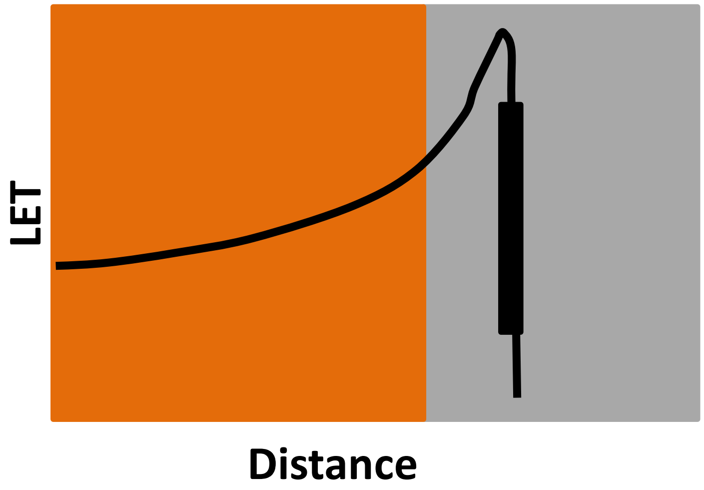
Concept 3

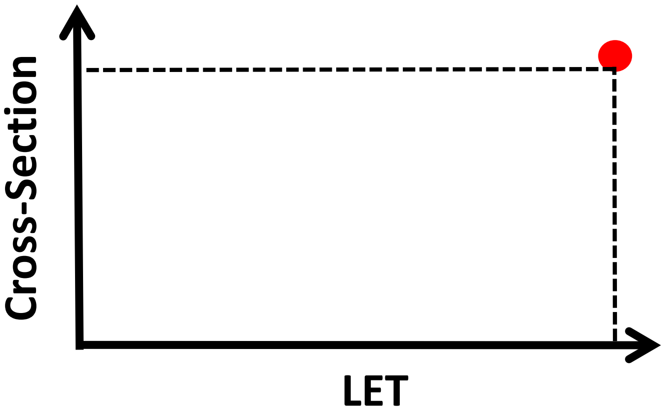
- **Calculate:** Shift of Bragg peak when degrader added.
  - Using actual energy of beam, calculate the range (d1) of the ions in silicon.
  - Add a known thickness ($D_{degrader}$) of degrader material in front of the silicon and calculate the range (d2) in silicon.
- **Result:** $D_{degrader}$ is equivalent to (d1-d2) in silicon.



Concept 4

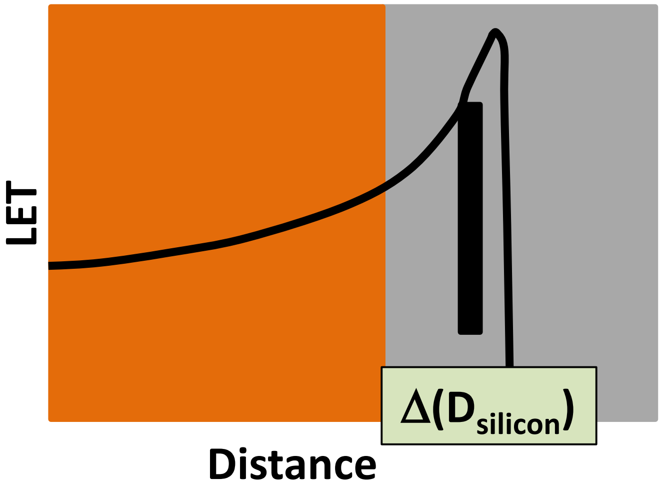
- Establish a fiduciary point - the Bragg peak is located in the sensitive volume where the **LET** and the **cross-section** are **maxima** by adjusting degrader thickness.
- **LET** at Bragg peak is **calculated** with TRIM taking into account energy spread and angle spread.
- **Cross-section** is **measured** experimentally.

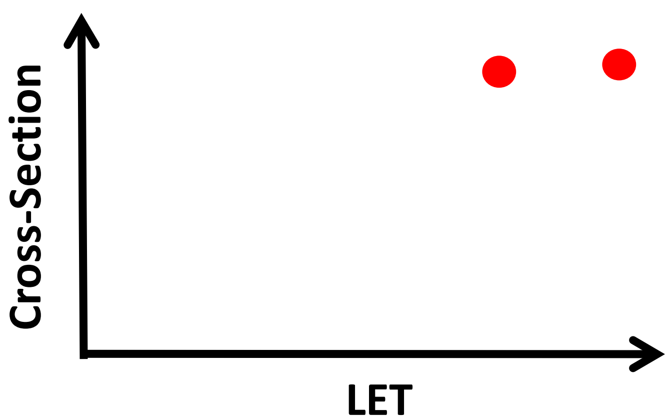




Concept 4

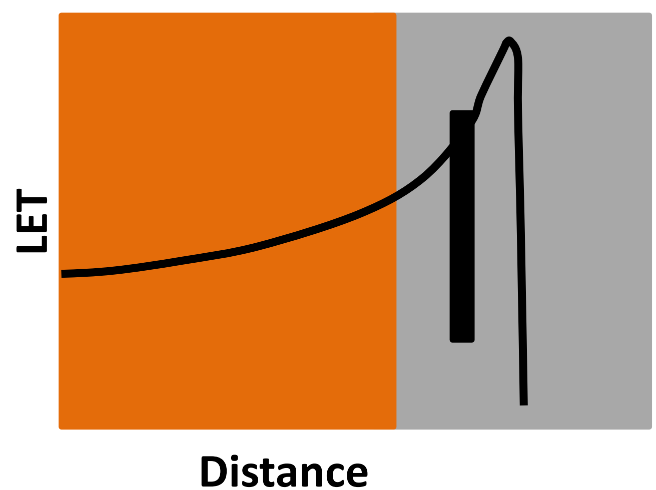
- Remove some degrader material to move the Bragg peak beyond the sensitive volume.
- Convert $\Delta(D_{degrader})$ to $\Delta(D_{silicon})$
- Calculate the new LET
- Measure the new cross-section.

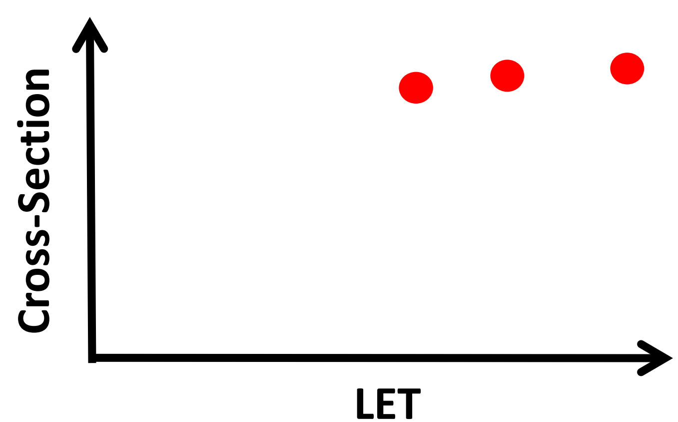




Concept 4

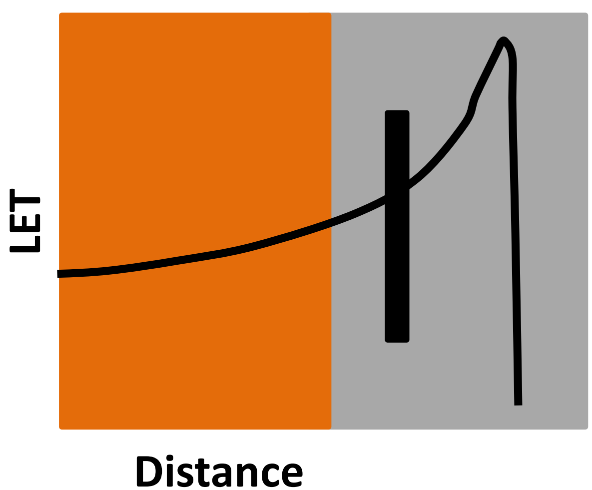
- Repeat the procedure.

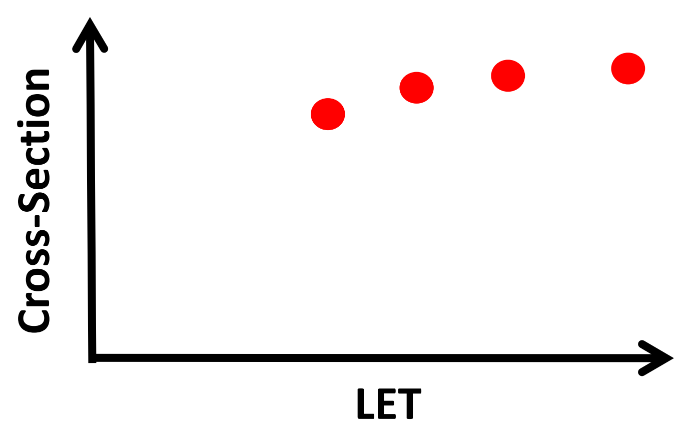




Concept 4

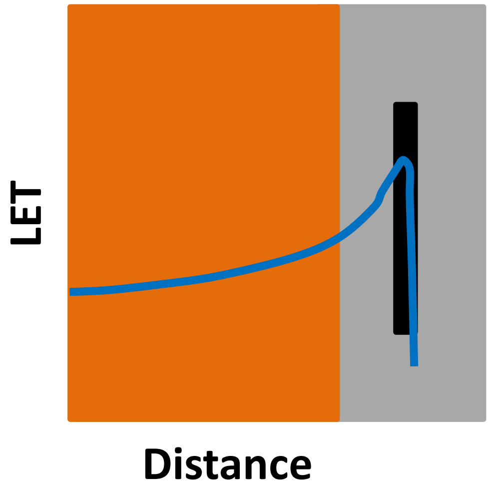
- Repeat the procedure.

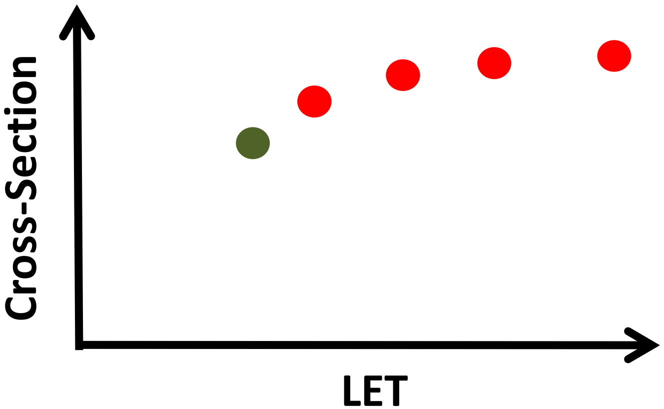




Concept 5

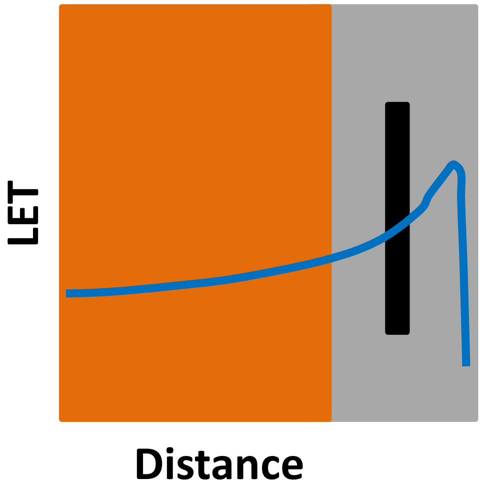
- Select a new ion to cover the remaining LET range.
  - Measure its energy
  - Calculate LET vs depth in silicon
  - Position Bragg peak at sensitive volume and measure cross-section

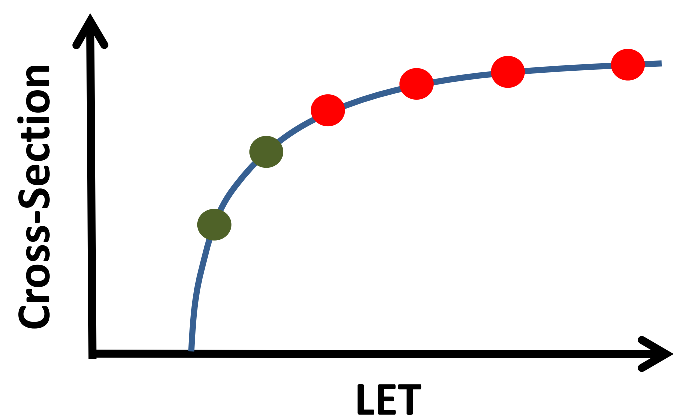




Concept 5

- Remove some degrader material to move Bragg peak beyond sensitive volume.
- Determine equivalent silicon thickness for thickness of degrader removed.
- Calculate new LET and measure cross-section.





3. Implementation

Original Degrader System at NSRL

Degrader System designed by C. Foster – two wheels each with 9 different degraders to give 81 different thicknesses in steps of 0.1 mm.

New Degrader System at NSRL

It is a small version of NSRL's large "binary filter", and provides polyethylene degrader in steps of 0.1 mm (just like the wheel) up to a max of 51.1 mm.

Degrader Thicknesses

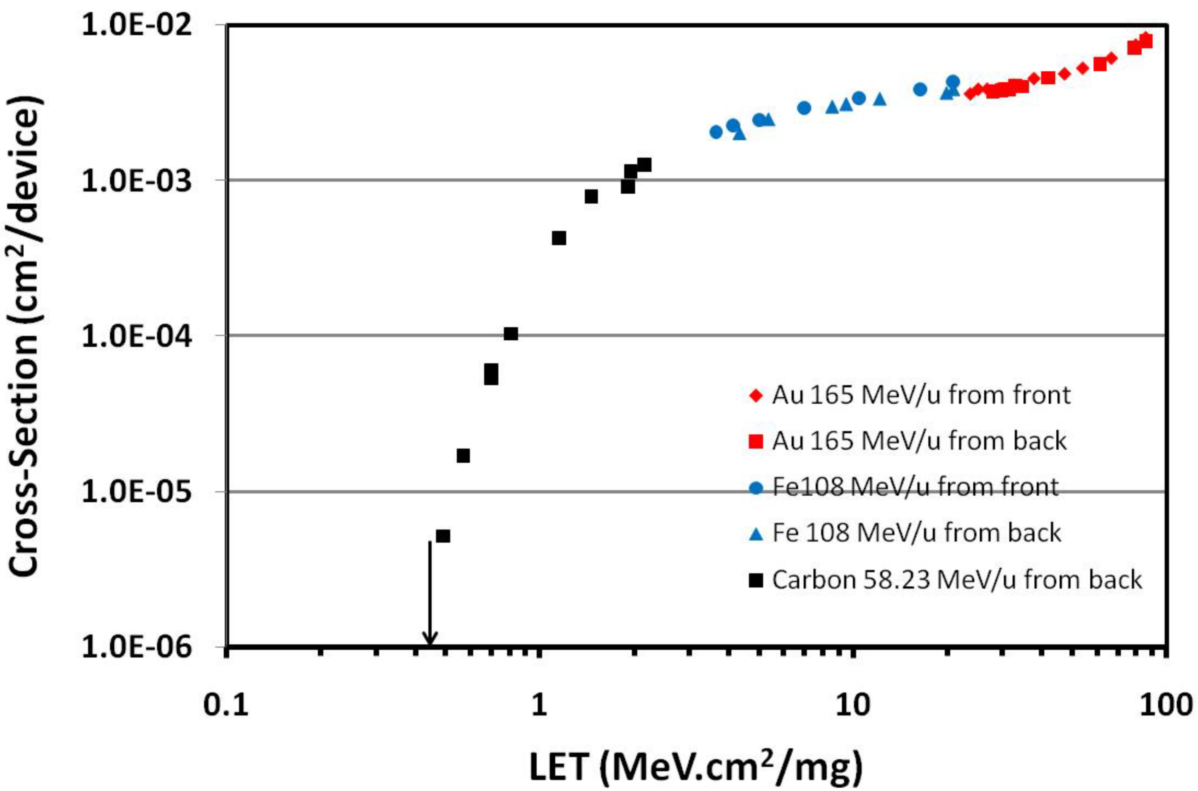
0.1 mm
0.2 mm
0.4 mm
0.8 mm
1.6 mm
3.2 mm
6.4 mm
12.7 mm
12.8 mm
25.6 mm
51.1 mm

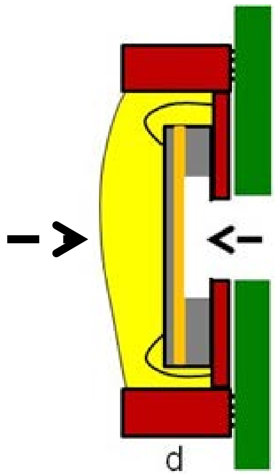
Refinements to TRIM Calculation

- **TRIM assumes** a mono-energetic pencil beam with no spatial or angular spread
- **Actual beam** has:
  - Gaussian spread in energy
  - Spatial spread
  - Angular spread
- **Refinements:**
  - SRIM Supporting Software Module
    - Input beam parameters such as angular spread and energy spread to produce an output file suitable for TRIM
    - Perform the TRIM calculation on a laptop computer

4. Examples

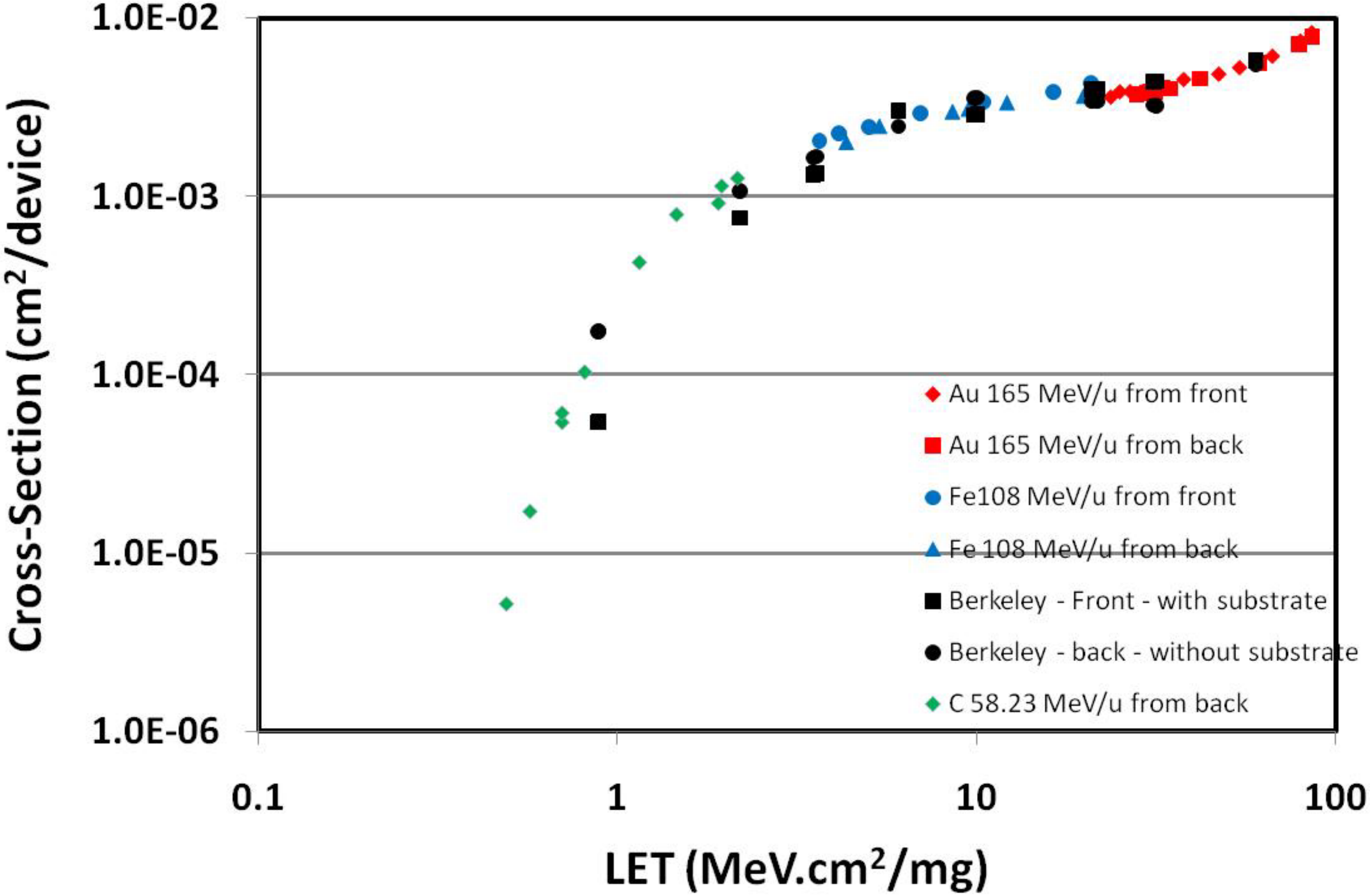
4 Mbit SOI/CMOS SRAM





$0.44\ \mathrm{MeV \cdot cm^2/mg} < LET_{th} < 0.48\ \mathrm{MeV \cdot cm^2/mg}$

4 Mbit SOI/CMOS SRAM



Certification Test

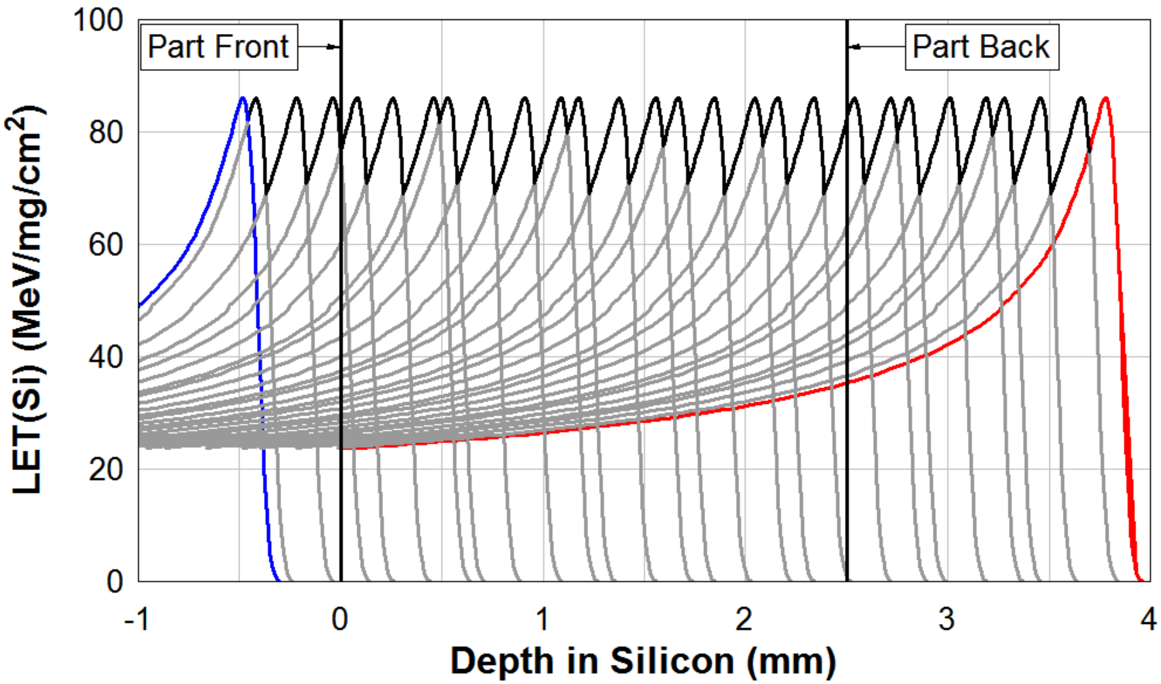
- Expose every depth in a COTS part to LET(Si) > 60 MeV/mg/cm^2 with 1E6 ions/cm^2.
- Poly degrader thickness is changed in small (~0.3 mm) steps after each exposure to the specified fluence so that Bragg peak positions in the part are close together.
- If part does not fail, it is “certified.”

Exposure sequence:

❖ *1st exposure - no degrader, red curve, all depths at minimum LET.*

❖ *2nd exposure – sufficient degrader to stop beam before part, blue curve.*

❖ *Then remove degrader material in steps of 0.3 mm.*



5. Summary & Conclusions

Summary and Conclusions

1. SEE testing can be done without opening packages using the **V**ariable **D**epth **B**ragg **P**eak method.
2. The method requires that a **fiduciary point** be established using degraders to place the Bragg peak in the sensitive volume and **calculating the equivalent LET using TRIM**.
3. **Equivalence** between degrader material and silicon must be calculated.
4. Degrader thickness **varied** to change LET at sensitive volume.
5. The method has been shown to provide **excellent agreement** with data obtained from low-energy beams.
6. The VDBP can also be used to certify a part as not failing destructively below a certain LET.

References

- S. Buchner, N. Kanyogoro, D. McMorrow, C. C. Foster, P. M. O'Neill and K. V. Nguyen, "Variable Depth Bragg Peak Method for Single Event Effects Testing," *IEEE Trans. on Nucl. Sci. Vol. 58, No. 6, pp. 2976 – 2982, Dec.2011.*

- C. C. Foster P. M. O'Neill, B. D. Reddell, K. V. Nguyen, B. H. Jones, N. J.-M. Roche, J. Warner, S. Buchner, "Certification of Parts for Space with the Variable Depth Bragg Peak Method," *IEEE Trans. on Nucl. Sci. Vol 59, No. 6, pp. 2009-2013, Dec. 2012.*

- N. J-H. Roche, S. P. Buchner, C. C. Foster, M. P. King, N. A. Dodds, J. H. Warner, D. McMorrow, T. Decker, P. M. O'Neill, B. D. Reddell, K. V. Nguyen, I. K. Samsel, N. C. Hooten, W. G. Bennett, and R. A. Reed, "Validation of the Variable Depth Bragg Peak Method for Single-Event Latchup Testing Using Ion Beam Characterization," *IEEE Trans. on Nucl. Sci. Vol 61, No. 6, pp. 3061-3067, Dec. 2014.*

- T. L. Criswell, P. R. Measel, and K. L. Wahlin, "Single event testing with relativistic heavy ions," *IEEE Trans. Nucl. Sci., vol. 31, no. 6, pp. 1559–1561, Dec. 1984.*