



Journal Club: The HEARTS EU Project and Its Initial Results on Fragmented High-Energy Heavy-Ion Single-Event Effects Testing

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The HEARTS EU Project and Its Initial Results on Fragmented High-Energy Heavy-Ion Single-Event Effects Testing

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Abstract— We perform single-event effect (SEE) tests with well-characterized fully fragmented (i.e., beyond Bragg peak) high-energy heavy-ion beams and compare the results with those expected from conventional, mono-linear energy transfer (mono-LET) measurements, showing a satisfactory level of agreement between the two. This compliance paves the way for the exploitation of simulation tools for accurately quantifying the ion fragmentation impact on SEE rates for both ground-level testing conditions and space galactic cosmic-ray (GCR) environments, with electronics operating behind significant thicknesses of

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shielding. The satisfactory agreement level is also encouraging in view of the possible usage of fragmented heavy-ion beams for ground-level SEE testing of electronics.

Index Terms— CERN, electronics testing, high-energy heavy ions, Monte Carlo simulations, nuclear reactions, single-event effect (SEE), single-event upset (SEU).

I. INTRODUCTION

THE European Union (EU)-funded “High-Energy Accelerators for Radiation Testing and Shielding” (HEARTS) project [1] is aimed at enhancing Europe’s capacity of replicating galactic cosmic-ray (GCR) conditions and effects at ground level for shielding, radiobiology, and microelectronics testing applications. The four-year project, which was kicked off in January 2023, incorporates CERN and GSI as accelerator infrastructures (along with their radiation effects

Article Information

REFERENCES

- [1] *HEARTS EU-Project Website*. Accessed: Jan. 30, 2004. [Online]. Available: <https://hearts-project.eu/>
- [2] 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. Nucl. Sci.*, vol. 58, no. 6, pp. 2976–2982, Dec. 2011.
- [3] C. La Tessa, M. Sivertz, I.-H. Chiang, D. Lowenstein, and A. Rusek, "Overview of the NASA space radiation laboratory," *Life Sci. Space Res.*, vol. 11, pp. 18–23, Nov. 2016.
- [4] M. A. Fraser et al., "Feasibility of slow-extracted high-energy ions from the CERN proton synchrotron for CHARM," presented at the IPAC, Bangkok, Thailand, Jun. 2022.
- [5] E. Johnson et al., "Beam delivery of high-energy ion beams for irradiation experiments at the CERN proton synchrotron," in *Proc. 14th Int. Part. Accel. Conf.*, May 2023, pp. 297–300.
- [6] E. Johnson, A. Bilko, M. Delrieux, L. Esposito, N. Emriskova, and M. Fraser, "Beam optics modelling of slow-extracted very high-energy heavy ions from the CERN proton synchrotron for radiation effects testing," in *Proc. IPAC*, Nashville, TN, USA, 2024, pp. 3554–3557.
- [7] K. Bilko et al., "CHARM high-energy ions for microelectronics reliability assurance (CHIMERA)," *IEEE Trans. Nucl. Sci.*, vol. 71, no. 8, pp. 1549–1556, Aug. 2024.
- [8] P. Fernández-Martínez et al., "SEE tests with ultra energetic Xe ion beam in the CHARM facility at CERN," *IEEE Trans. Nucl. Sci.*, vol. 66, no. 7, pp. 1523–1531, Jul. 2019.
- [9] R. G. Alía et al., "Ultraenergetic heavy-ion beams in the CERN accelerator complex for radiation effects testing," *IEEE Trans. Nucl. Sci.*, vol. 66, no. 1, pp. 458–465, Jan. 2019.
- [10] N. Emriskova, A. Waets, O. D. L. R. Du, K. Klimek, and R. G. Alía, "Characterisation of degraded very-high-energy heavy ion beams using the HEARTS LET booster," *IEEE Trans. Nucl. Sci.*, early access, Jan. 1, 2025, doi: [10.1109/TNS.2024.3521185](https://doi.org/10.1109/TNS.2024.3521185).
- [11] A. Waets et al., "Microdosimetry of very-high-energy heavy ion beams for electronics testing using silicon-on-insulator detectors," *IEEE Trans. Nucl. Sci.*
- [12] A. Pflaum et al., "Characterisation of a ^{208}Pb heavy ion beam at CHARM," *IEEE Trans. Nucl. Sci.*
- [13] A. Coronetti et al., "SRAM-based heavy ion beam flux and LET dosimetry," *IEEE Trans. Nucl. Sci.*, early access, Oct. 29, 2024, doi: [10.1109/TNS.2024.3487647](https://doi.org/10.1109/TNS.2024.3487647).
- [14] A. Coronetti et al., "Results of single event effect testing at the new HEARTS@CERN high-energy heavy ion facility at CERN," in *Proc. IEEE Radiat. Effects Data Workshop (REDW) (Conjunct With NSREC)*, Jul. 2024, pp. 1–9.
- [15] J. R. Schwank, M. R. Shaneyfelt, and P. E. Dodd, "Radiation hardness assurance testing of microelectronic devices and integrated circuits: Test guideline for proton and heavy ion single-event effects," *IEEE Trans. Nucl. Sci.*, vol. 60, no. 3, pp. 2101–2118, Jun. 2013.

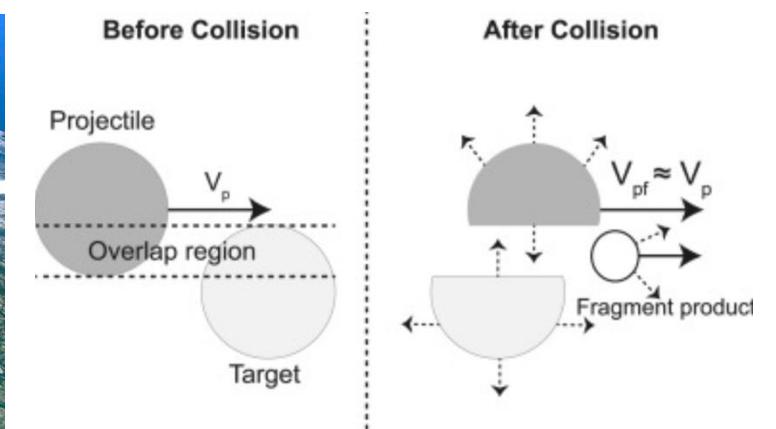
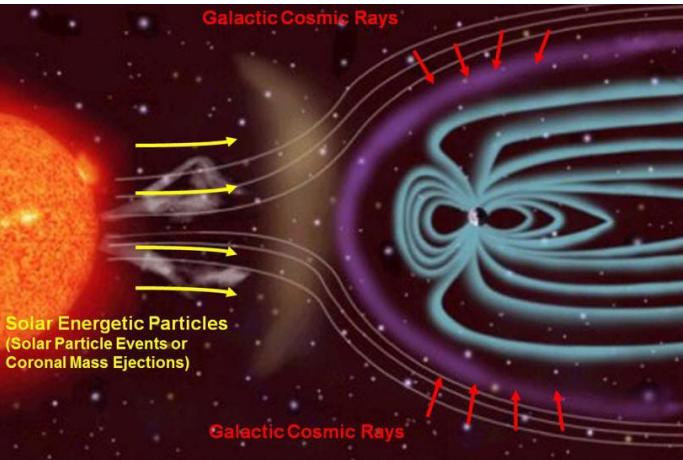
Article Information

- [22] V. Ferlet-Cavrois et al., "Influence of beam conditions and energy for SEE testing," *IEEE Trans. Nucl. Sci.*, vol. 59, no. 4, pp. 1149–1160, Aug. 2012.
- [23] R. G. Alía et al., "Sub-LET threshold SEE cross section dependency with ion energy," *IEEE Trans. Nucl. Sci.*, vol. 62, no. 6, pp. 2797–2806, Dec. 2015.
- [24] R. G. Alía et al., "Proton dominance of sub-LET threshold GCR SEE rate," *IEEE Trans. Nucl. Sci.*, vol. 64, no. 1, pp. 388–397, Jan. 2017.
- [25] M. Kastriotou et al., "Single event effect testing with ultrahigh energy heavy ion beams," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 1, pp. 63–70, Jan. 2020.
- [26] M. S. Barbero et al., "Characterization of fragmented ultrahigh-energy heavy ion beam and its effects on electronics single-event effect testing," *IEEE Trans. Nucl. Sci.*, vol. 71, no. 8, pp. 1557–1564, Aug. 2024.
- [27] V. Wyrwoll et al., "Longitudinal direct ionization impact of heavy ions on see testing for ultrahigh energies," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 7, pp. 1530–1539, Jul. 2020.
- [28] V. Wyrwoll, "On-line beam monitoring and dose profile measurements of a ^{208}Pb beam of 150 GeV/n with a liquid-filled ionization chamber array," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 987, Jan. 2021, Art. no. 164831.
- [29] A. de Bibikoff and P. Lamberbourg, "Method for system-level testing of COTS electronic board under high-energy heavy ions," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 10, pp. 2179–2187, Oct. 2020.
- [30] J. F. Ziegler, M. Ziegler, and J. Biersack, "SRIM—The stopping and range of ions in matter (2010)," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 268, no. 11, pp. 1818–1823, Jun. 2010.
- [31] C. C. Foster et al., "Certification of parts for space with the variable depth Bragg peak method," *IEEE Trans. Nucl. Sci.*, vol. 59, no. 6, pp. 2909–2913, Dec. 2012.
- [32] N. J-H. Roche et al., "Validation of the variable depth Bragg peak method for single-event latchup testing using ion beam characterization," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 6, pp. 3061–3067, Dec. 2014.
- [33] R. G. Alía et al., "Heavy ion energy deposition and SEE intercomparison within the RADNEXT irradiation facility network," *IEEE Trans. Nucl. Sci.*, vol. 70, no. 8, pp. 1596–1605, Aug. 2023.
- [34] C. Ahdida et al., "New capabilities of the FLUKA multi-purpose code," *Frontiers Phys.*, vol. 9, Jan. 2022, Art. no. 788253.
- [35] H. Sorge, H. Stöcker, and W. Greiner, "Poincaré invariant Hamiltonian dynamics: Modelling multi-hadronic interactions in a phase space approach," *Ann. Phys.*, vol. 192, no. 2, pp. 266–306, Jun. 1989.
- [36] V. Andersen et al., "The Fluka code for space applications: Recent developments," *Adv. Space Res.*, vol. 34, no. 6, pp. 1302–1310, Jan. 2004.
- [37] H. Aiginger et al., "The FLUKA code: New developments and application to 1 GeV/n iron beams," *Adv. Space Res.*, vol. 35, no. 2, pp. 214–222, Jan. 2005.
- [38] A. Waets et al., "Heavy ion beam characterization for radiation effects testing at CERN using Monte Carlo simulations and experimental benchmarking," in *Proc. 14th Int. Part. Accel. Conf.*, May 2023, pp. 5165–5168.
- [39] A. Waets et al., "Characterization of fully fragmented high-energy heavy ion beams for SEE testing through measurements and simulations," *IEEE Trans. Nucl. Sci.*, early access, Nov. 15, 2024, doi: [10.1109/TNS.2024.3492039](https://doi.org/10.1109/TNS.2024.3492039).
- [40] S. Uznanski et al., "The effect of proton energy on SEU cross section of a 16 Mbit TFT PMOS SRAM with DRAM capacitors," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 6, pp. 3074–3079, Dec. 2014.

Overview

- **Goals:**
 - Evaluate whether **high-energy, fully fragmented heavy-ion beams** can be used reliably for **SEE testing**
 - **Measure SEE rates** using fully fragmented Pb beams
 - **Compare experimental SEE rates with Monte Carlo simulations**
 - Characterize **beam-fragmentation methods** for **GCR-representative testing**
- **Context:**
 - **Galactic Cosmic Rays (GCRs)** at Earth: energies in the **GeV/n range**
 - When **heavy ions** pass through material, they undergo **fragmentation**, producing:
 - **Secondary particles** with a **broad LET spectrum**
 - Variability due to **shielding, packaging, and degraders**
 - **Standard heavy-ion tests** use **mono-LET beams**, which **do not capture the true GCR environment**

Context



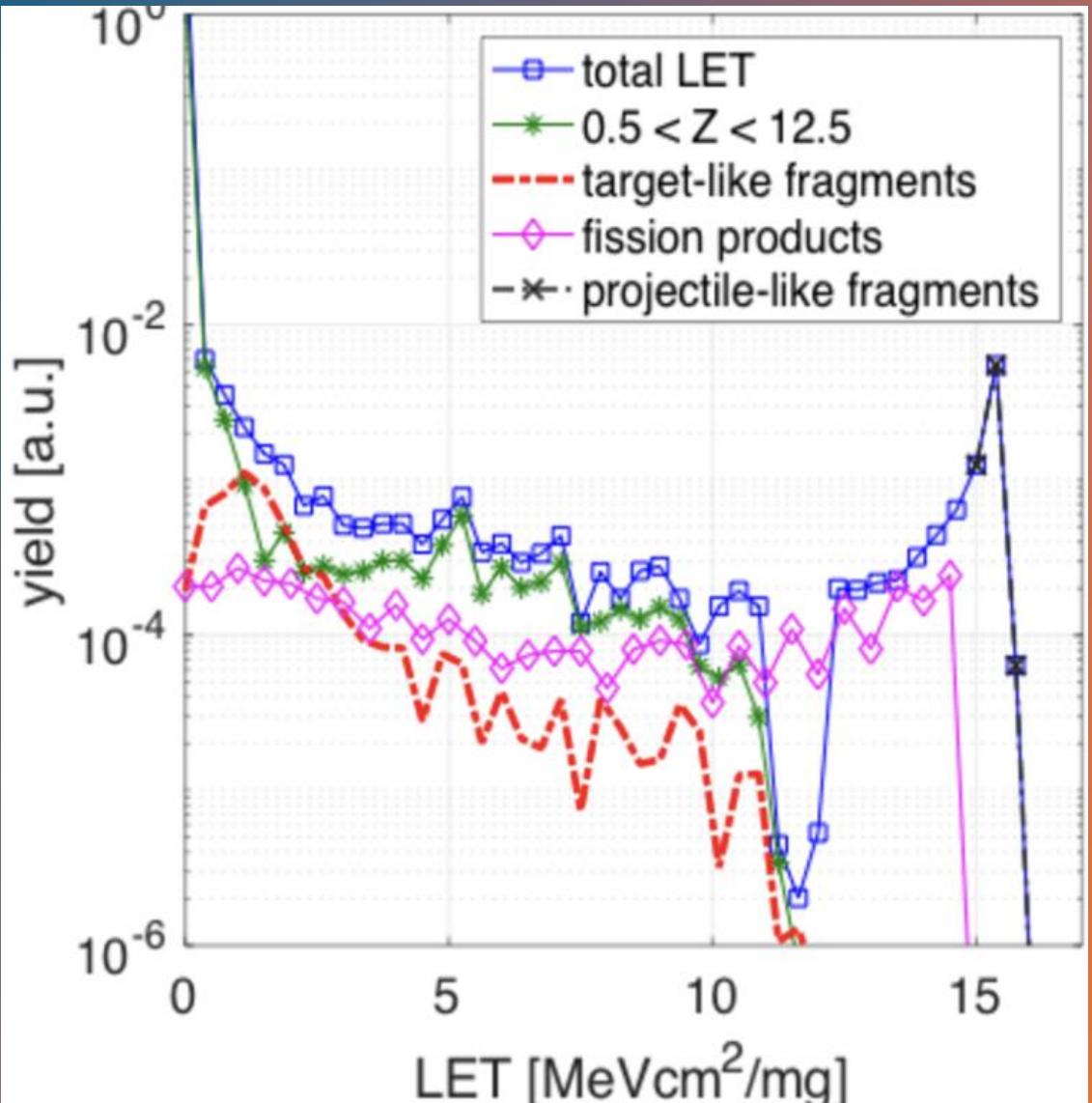
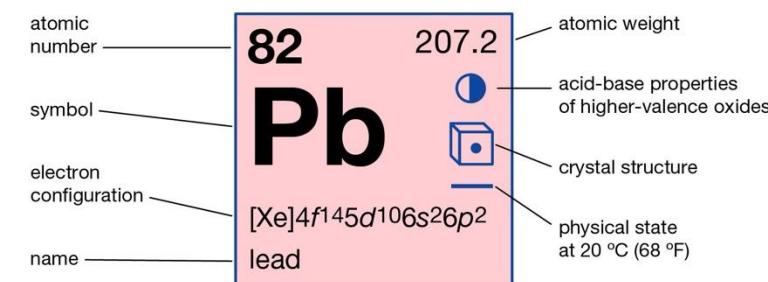


Fig. 1. Full Z distribution of standard energy heavy ion (20 Ne and 40 Ar) fragmentation in comparison to high energy protons on a 140 μm silicon target, as obtained from FLUKA MC simulations.

Challenges

- **Heavy-Ion Fragmentation:**
 - Primary ions break into **secondary high-energy fragments** when passing through materials, packages, or degraders
 - These fragments create a **broad LET spectrum**, not a single clean LET value
 - Secondary fragments can cause SEEs in both the **device under test (DUT)** and nearby components
- **LET Accuracy vs. Depth:**
 - Mono-LET beams maintain LET within $\pm 10\%$ for only $\sim 230 \mu\text{m}$ at 60 $\text{MeV}\cdot\text{cm}^2/\text{mg}$ -> very limited for testing

Lead



| | | | |
|--|--------------------|--|-------------------------|
| | Other metals | | Solid |
| | Face-centred cubic | | Equal relative strength |



Fig. 2. PMMA degrader and the copper mask system, followed by a parallel-plate ionization chamber, placed roughly 1-m upstream of the DUT location, which is to the right of the plot.

Methods

- Monte Carlo simulations (FLUKA) to model the fragmentation process
- SRIM to study LET vs depth behavior
- 1 GeV/n and 750 MeV/n Pb-208 beams at **PMMA fragmenter** of various thicknesses (46–78 mm)
- After the PMMA, the primaries stop → only **fragments reach the device**
- Irradiated **3 commercial SRAMs**:
 - 2 low LET threshold SRAMs
 - 1 hardened, high LET threshold SRAM

Mono-LET Heavy-Ion Beam

- Shows how a **mono-LET heavy-ion beam** only maintains its target LET value over a **very small depth range** in material
- Demonstrates the **limitation of conventional mono-LET beams** for SEE testing:
 - They cannot provide **high-LET exposure** through thick materials
 - LET drops sharply as ions slow down and approach the Bragg peak

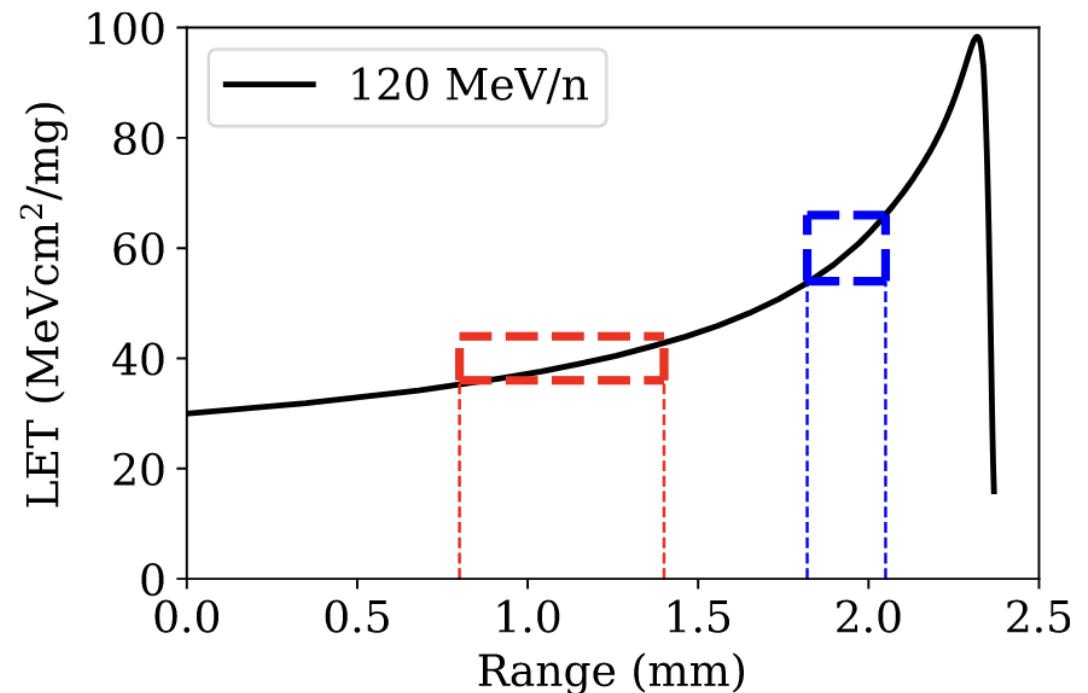


Fig. 1. LET versus range for lead in silicon, with an initial energy of 120 MeV/n, and as retrieved from SRIM [30]. The boxes show a ±10% tolerance around the 40- and 60-MeVcm²/mg LET values and include the respective range limits, which become smaller as the LET increases and the ions get closer to the Bragg peak.

Results

- Fragmentation does **not** produce a single LET value -> **full LET spectrum**
- Simulation and Experiment matched within a factor of 1.5
- Fragment fields **behave similarly to GCR portions**
- SEU cross section rate attenuated, decreases after end range (45mm)
- Ground level GCR is possible
- We need more validation, quantitate testing/qualification

Integral Flux vs. LET

- Shows **reverse-integral LET spectra** at the DUT for 660 MeV/n Pb beams fragmented by **47 mm** and **50 mm** PMMA
- Increasing fragmenter thickness -> **lower fluence** and **shift to lower LET values**
- Includes **GCR LET spectrum** to show how fragmented beams resemble the **high-LET portion of the space environment**
- LET distribution is later combined with device SEU curves to **predict SEE rates**

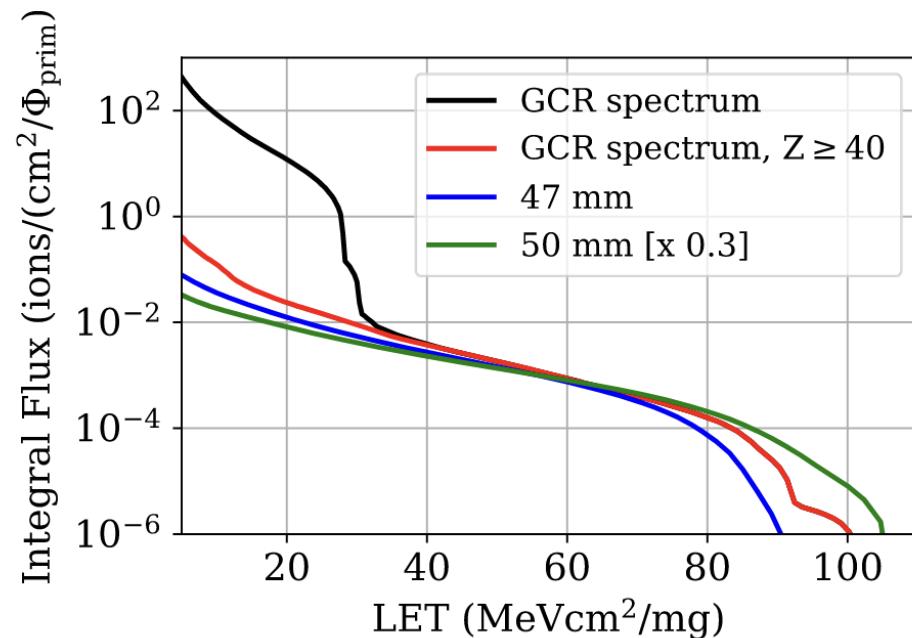


Fig. 3. Reverse integral of the simulated LET spectrum at the DUT location for a 660-MeV/n lead beam on the PMMA fragmenters with thicknesses of 47 and 50 mm. The fragmented spectra are normalized per unit primary fluence (Φ_{prim}), with a factor of 0.3 applied to the thinner fragmenter to compensate for the larger secondary ion fluence. The GCR LET spectrum (both full and limited to ions with Z equal to or larger than 40) is also included for reference, normalized arbitrarily to match the absolute value of the spectrum used in this work.

SEU Cross Section vs. LET

- Shows **SEU cross section vs. LET** for all three SRAM memories
- The Cypress and ISSI memories have **low LET thresholds** ($< 1 \text{ MeV}\cdot\text{cm}^2/\text{mg}$)
- The Renesas memory shows **critical-charge hardening** -> **much higher LET threshold** ($\sim 13 \text{ MeV}\cdot\text{cm}^2/\text{mg}$)
- Weibull curves are plotted and later used to **predict SEU rates** in the fragmented beam environment

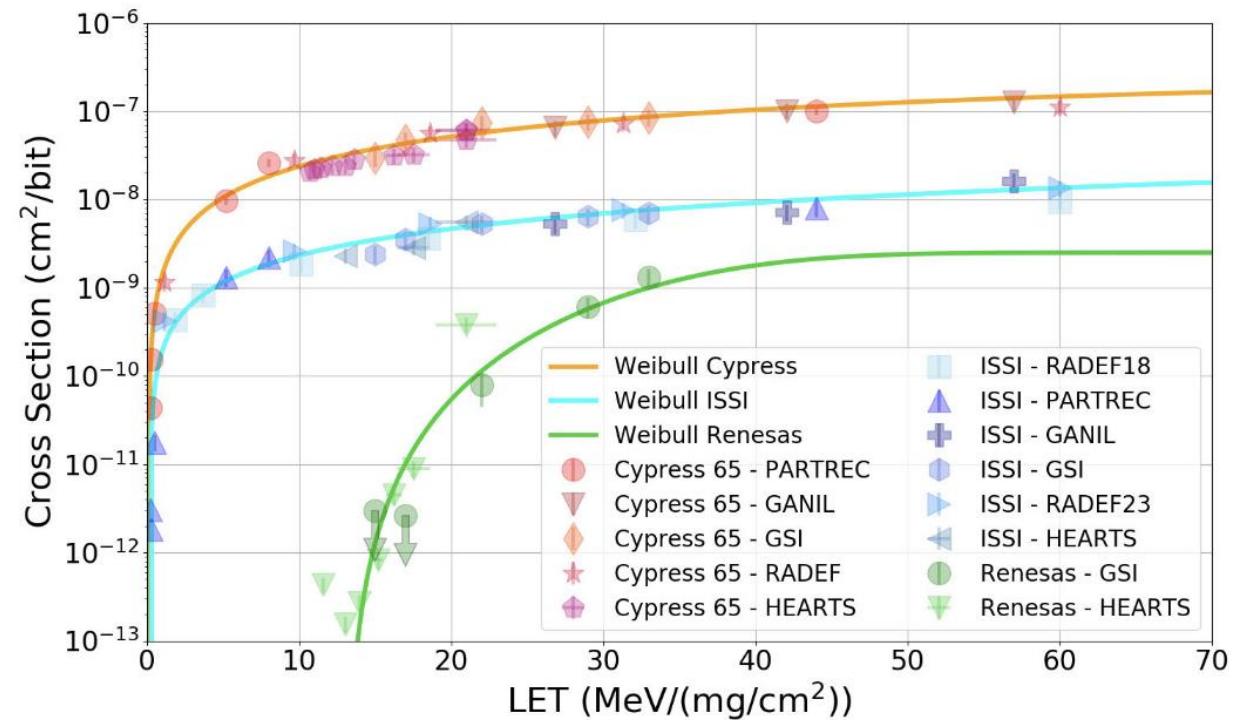


Fig. 4. SEU cross sections as a function of LET for the three memories considered in this work, as collected in multiple heavy-ion facilities.

SEU Cross Sections vs. PMMA Thickness

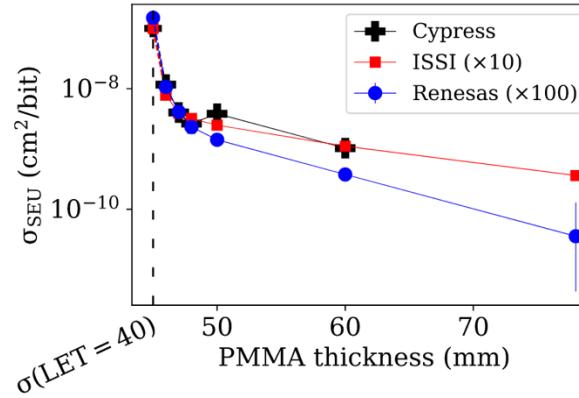


Fig. 6. 660-MeV/n lead beam experimental fragmented SEU cross sections as defined in (1) on different PMMA thicknesses, including the mono-LET value at 40 MeV·cm²/mg for comparison purposes.

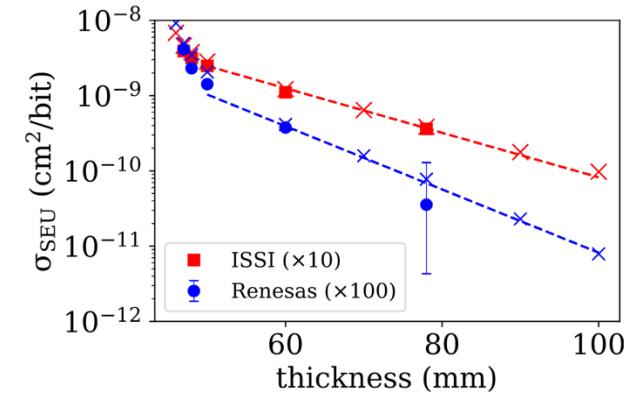


Fig. 7. Same experimental data as included in Fig. 6, incorporating also the simulated fragmented SEE cross sections (see Table II) as “X” markers. The dashed lines correspond to the exponential fit to the simulated data as per (2), with the parameters reported in Table III.

- **Figure 6:**
 - Plots **experimental fragmented-beam SEU cross sections** vs. PMMA thickness (46–78 mm)
 - Includes **mono-LET SEU point at 40 MeV·cm²/mg** for comparison
 - Demonstrates that fragmented beams still produce **significant SEU rates**, even beyond the primary ion range
- **Figure 7:**
 - Compares **experimental** fragmented-beam SEU cross sections with **simulated** values (shown as “X” markers)
 - Adds **exponential attenuation fits** for each memory type, highlighting how SEU rate decreases with depth

SEU Fragmented Beam

- Calculates SEU cross section using a **LET spectrum** instead of a single LET
- Integrates **device response** ($\sigma(\text{LET})$) over **fragmented LET distribution**
- Accounts for **all secondary fragments** hitting the DUT

$$\sigma_{\text{frag}} = \frac{N_{\text{SEE}}}{\Phi_{\text{prim}}} = \frac{\int \frac{d\Phi(\text{LET})}{d(\text{LET})} \cdot \sigma(\text{LET}) \cdot d(\text{LET})}{\Phi_{\text{prim}}}. \quad (1)$$

Conclusions

- **Strong agreement** between **experimental** and **simulated** SEU results
- **Shielding** is largely **ineffective** against high-energy ions
- **Two-phase attenuation behavior:**
 - **Fast attenuation:** $\sim 10\times$ SEU reduction in the **first 5 mm** past the ion range
 - **Slow attenuation:** Exponential decay beyond 5 mm
 - To achieve another $10\times$ reduction:
 - **34 mm** for **low-LET threshold memories**
 - **24 mm** for **high-LET threshold memory**

Activity

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Draw & Annotate the High-Energy Heavy-Ion Beamline

[Accelerator] -> [Beamline] -> [PMMA Degrader] -> [DUT]

Particles: ^{208}Pb , $\sim 660 \text{ MeV/n}$, LET: $\sim 13 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ (mono-LET)

1. Annotate each region with:

- What particles are present (primaries? fragments?)
- Approx. LET behavior (mono-LET? broad spectrum?)
- Energy changes

2. Sketch the LET distribution:

- Before degrader
- Inside degrader
- After degrader (at DUT)

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Activity

- What happens to **primary ions** as PMMA thickness increases?
- How does the **LET spectrum** change?
- Why does the **SEU rate** drop?
- Why is the fragmented spectrum useful for **GCR-like testing**?

Future Research Directions

- **Simulation tools** can model how **fragmentation influences SEE rates**
- **High-energy heavy-ion beams** show strong potential for **ground-based GCR testing**
- **Fragmented beams** offer **deep penetration and high-LET spectra**, closer to the real space environment
- Need reliable methods to **translate ground-level fragmented SEE rates into accurate in-orbit prediction**
- **Broader Characterization of Fragmentation:**
 - Wider range of **ion species**
 - **Higher and lower beam energies**
 - Various **fragmenting materials and thicknesses**
 - Additional **device types and SEE mechanisms**

Discussion Questions

- Why do engineers care about LET instead of just the ion's energy?
- If fragmentation creates many secondary ions with various LETs, what challenges might that cause for interpreting SEE results?
- How do PMMA fragmenter thickness and beam energy influence the LET spectrum reaching the device under test (DUT)?
- If packaging barely influences high-energy fragmented beams, should we stop de-lidding devices for these tests?
- In multi-chip or full-board assemblies, what challenges arise in achieving a target LET at all sensitive depths?
- How do SEU cross sections vary between low-LET threshold memories (ISSI, Cypress) and high-LET threshold memories (Renesas), and what does this imply for radiation-hardening strategies?



Discussion Questions

- Do you think that enough justification for this study was presented? Do you think the findings contribute in a meaningful/novel way to the scientific community?
- What were some (technical) aspects of the paper they did well?
- What were some (technical) aspects of the paper they could have done better?
- Did they communicate their method and findings well?
- Would you trash or stash this article?

Works Cited:

- R. García Alía et al., "The HEARTS EU Project and Its Initial Results on Fragmented High-Energy Heavy-Ion Single-Event Effects Testing," in IEEE Transactions on Nuclear Science, vol. 72, no. 4, pp. 1040-1049, April 2025, doi: 10.1109/TNS.2025.3530502.
- V. Wyrwoll et al., "Heavy Ion Nuclear Reaction Impact on SEE Testing: From Standard to Ultra-high Energies," in IEEE Transactions on Nuclear Science, vol. 67, no. 7, pp. 1590-1598, July 2020, doi: 10.1109/TNS.2020.2973591.