



# 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

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

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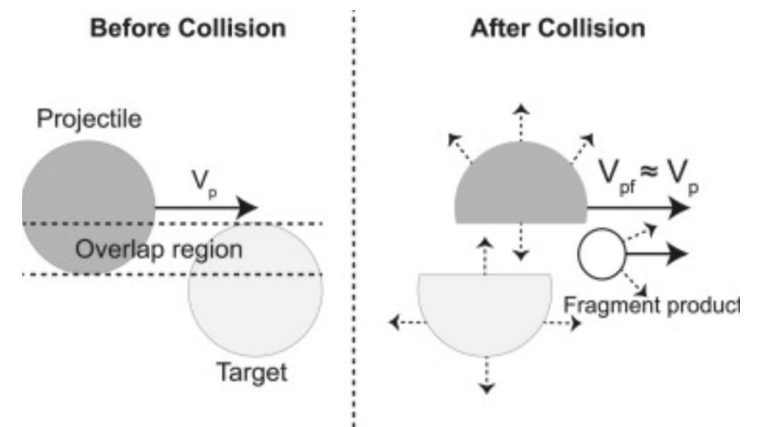
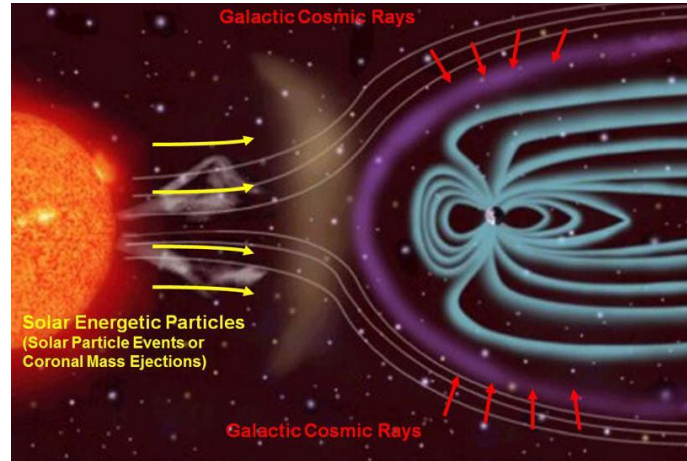


# Overview

- **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

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# 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  $60 \text{ MeV}\cdot\text{cm}^2/\text{mg}$   $\rightarrow$  very limited for testing

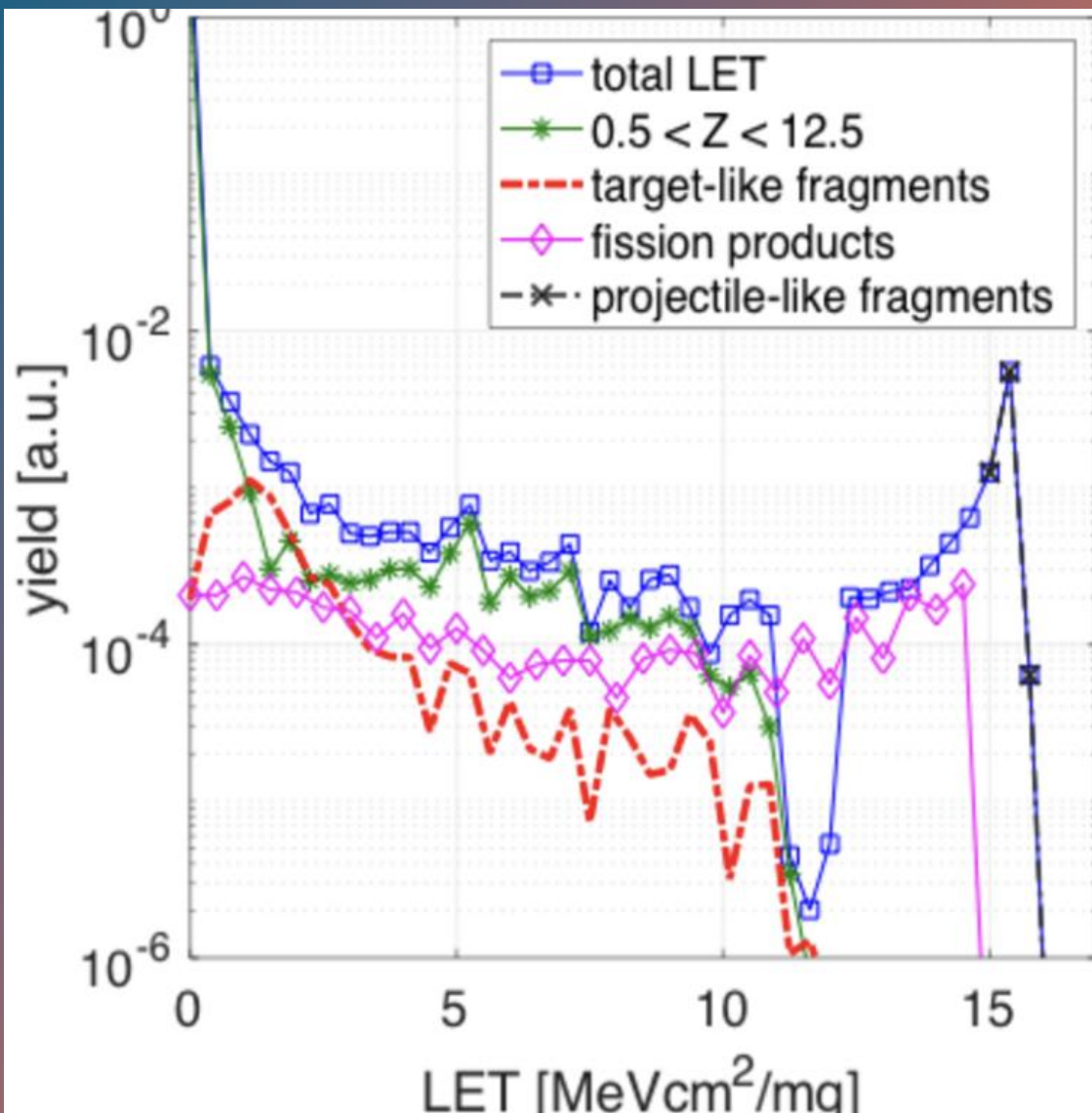





Fig. 1. Full Z distribution of standard energy heavy ion ( 20 Ne and 40 Ar) fragmentation in comparison to high energy protons on a 140  $\mu\text{m}$  silicon target, as obtained from FLUKA MC simulations.

## Lead

atomic number	82	207.2	atomic weight
symbol	Pb		acid-base properties of higher-valence oxides
electron configuration	[Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>2</sup>		crystal structure
name	lead		physical state at 20 °C (68 °F)

	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

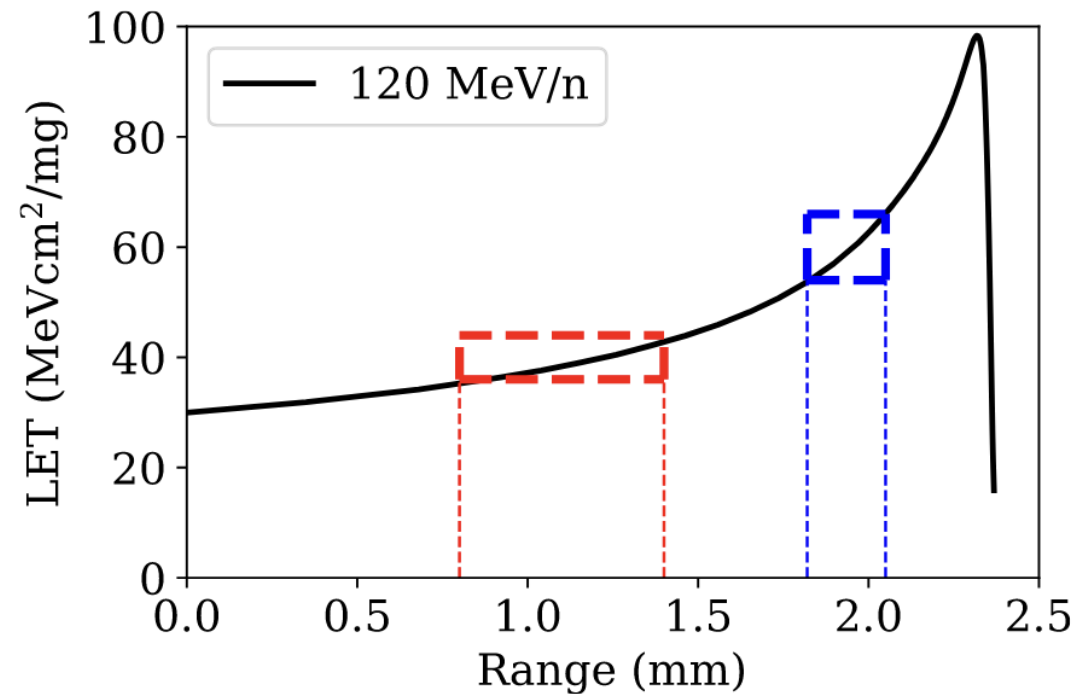



Fig. 1. LET versus range for lead in silicon, with an initial energy of 120 MeV/n, and as retrieved from SRIM [30]. The boxes show a  $\pm 10\%$  tolerance around the 40- and 60- $\text{MeVcm}^2/\text{mg}$  LET values and include the respective range limits, which become smaller as the LET increases 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**

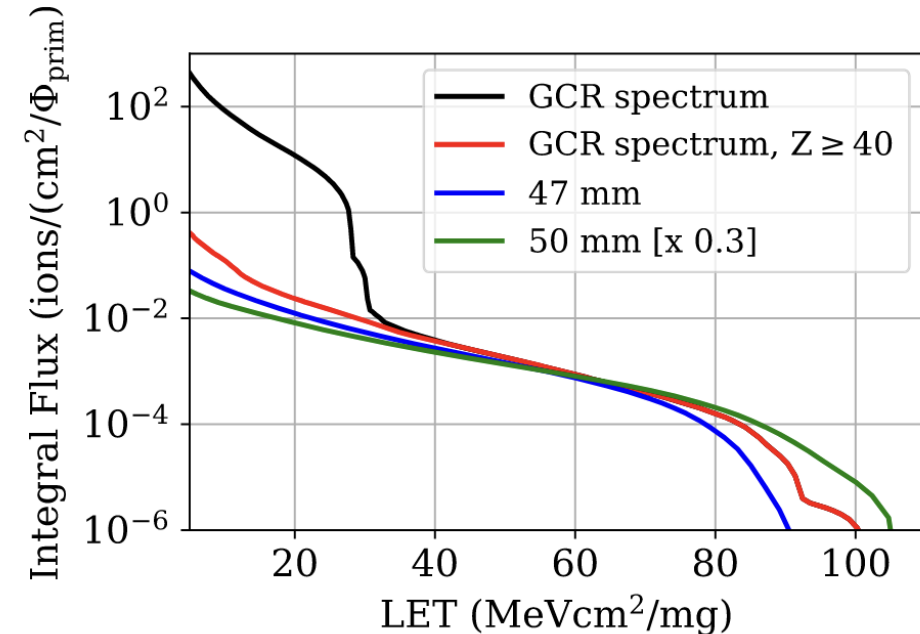


Fig. 3. Reverse integral of the simulated LET spectrum at the DUT location for a 660-MeV/n lead beam on the PMMA fragmenters with thicknesses of 47 and 50 mm. The fragmented spectra are normalized per unit primary fluence ( $\Phi_{\text{prim}}$ ), with a factor of 0.3 applied to the thinner fragmenter 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

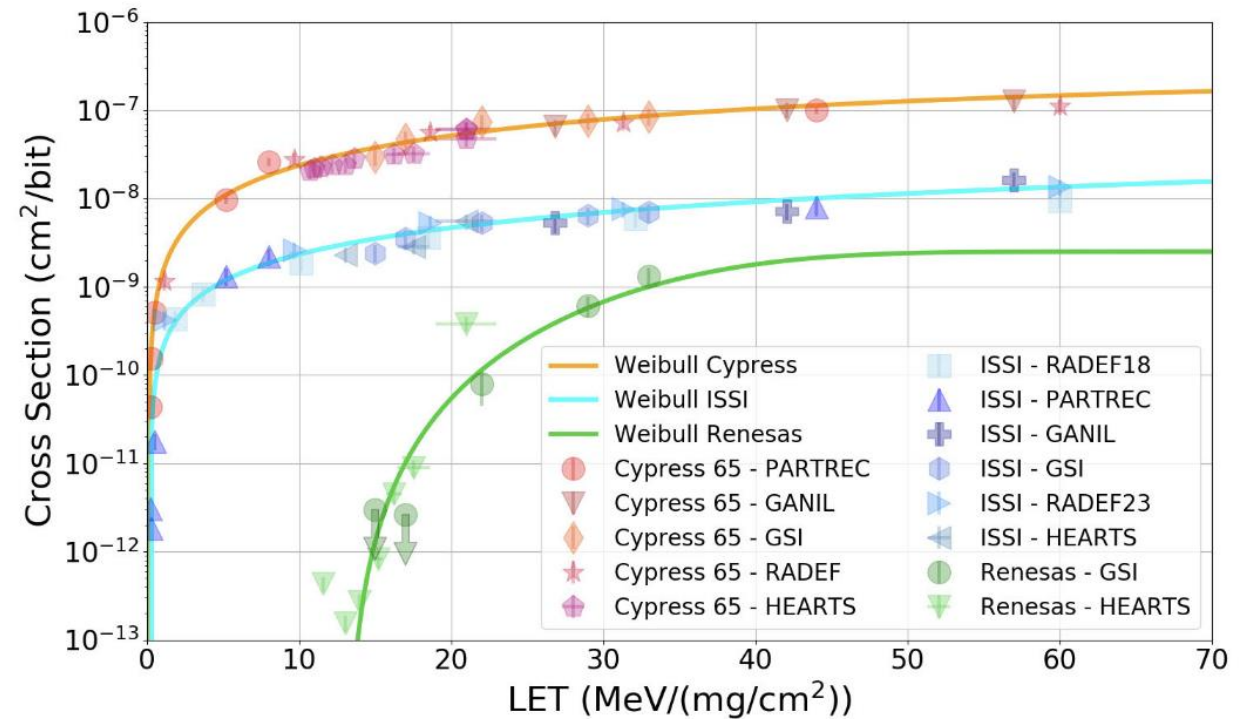


Fig. 4. SEU cross sections as a function of LET for the three memories considered in this work, as collected in multiple heavy-ion facilities.

# SEU Cross Sections vs. PMMA Thickness

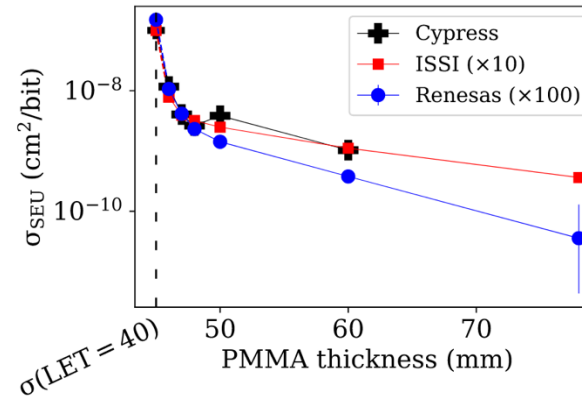


Fig. 6. 660-MeV/n lead beam experimental fragmented SEU cross sections as defined in (1) on different PMMA thicknesses, including the mono-LET value at 40 MeV·cm²/mg for comparison purposes.

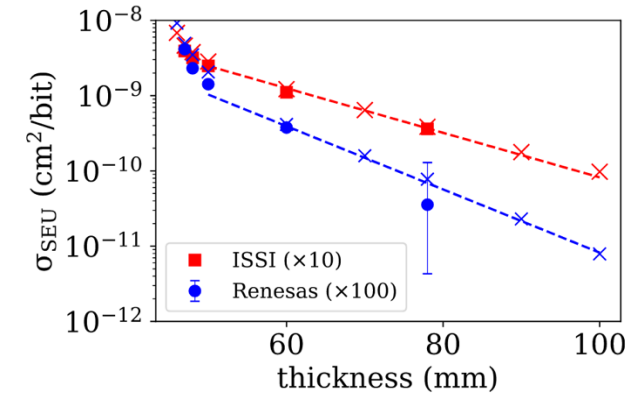


Fig. 7. Same experimental data as included in Fig. 6, incorporating also the simulated fragmented SEE cross sections (see Table II) as “X” markers. The dashed lines correspond to the exponential fit to the simulated data as per (2), with the parameters reported in Table III.

- **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



## Draw & Annotate the High-Energy Heavy-Ion Beamline

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

*Particles: 208Pb, ~660 MeV/n, LET: ~13 MeV·cm<sup>2</sup>/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)




# 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**
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# 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?

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# 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:

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- 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.
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