HEARTS and HEARTS++, the present and future of radiation effects testing with very-high-energy, heavy ion beams in Europe.

Andreas Waets
on behalf of the HEARTS and HEARTS++ project teams

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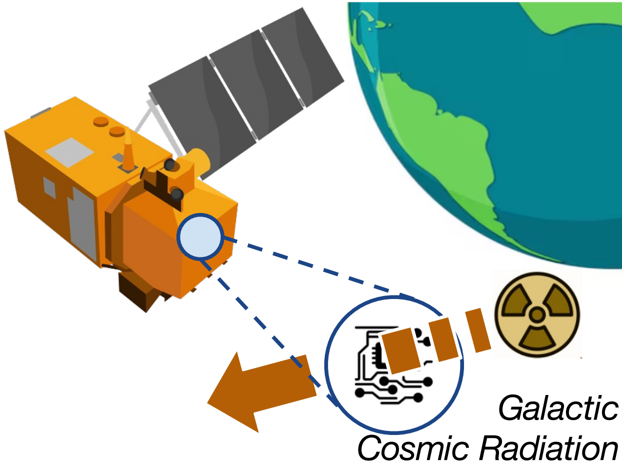
RHIC/AGS AUM

Outline

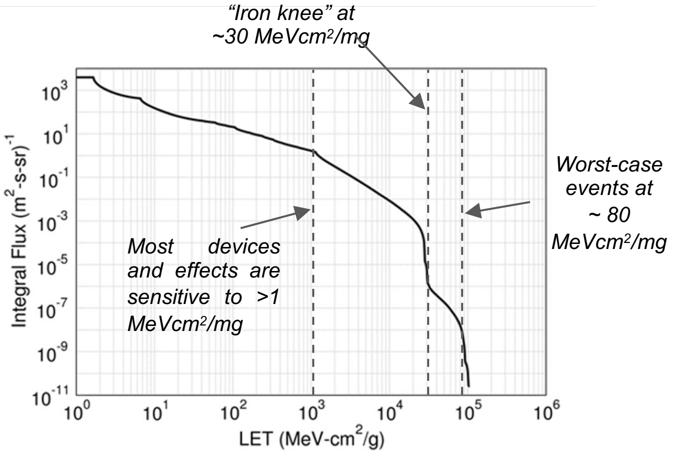
- The challenge: electronics and space radiation
- Radiation testing with high-energy, heavy ion beams
- The HEARTS project
- The HEARTS@CERN facility
- Radiation effects on electronics research (focus on results obtained at NSRL)
- The future: HEARTS++

Electronics and space radiation



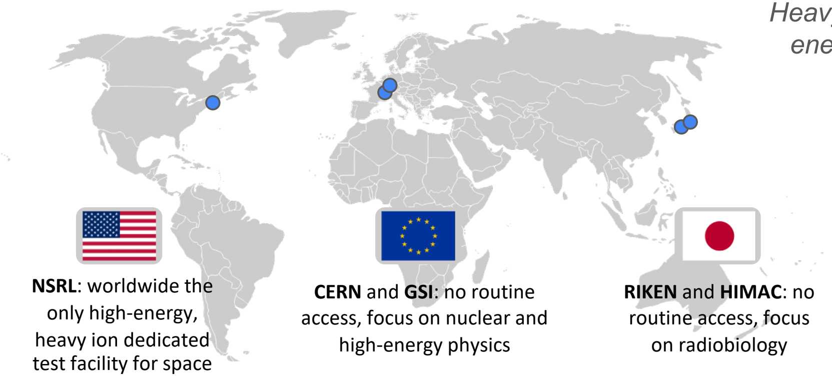
- **Electronics are essential in any space mission**
  - Platform: Power distribution, thermal control, avionics, telecommunication
  - Payload: atomic clocks, antennas, cameras for astronomical observations, sounding instruments for weather forecasting
- Space sector increases the use of state-of-the-art **commercial off-the-shelf components (COTS)** for cost, performance (e.g. GPUs) and availability.
- **Primary concern**: exposure to highly energetic (100s of MeV/n), highly penetrating **ionizing radiation** in the form of Galactic Cosmic Radiation.

Modern electronics *(radiation tolerant, not radiation hard) can be very* ***susceptible to radiation induced errors (Single Event Effects)*** *in the* ***space*** *or* ***accelerator radiation environment***



The challenge

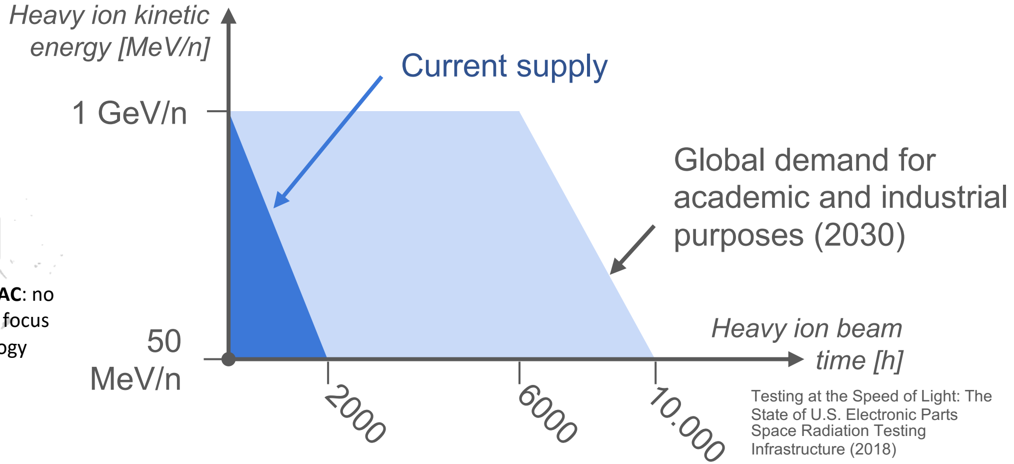
- **Understanding** a modern electronic component's **reliability** during a space mission **requires testing** in an Earth-based laboratory.
  - Heavy ions at > 50 MeV/n, up to GeV/n kinetic energy are needed to mimic effects induced by GCRs.
  - ➡️ Only available in **synchrotron** facilities (5): availability for testing is scarce worldwide



NSRL: worldwide the only high-energy, heavy ion dedicated test facility for space users (2000 h/y)

CERN and **GSI**: no routine access, focus on nuclear and high-energy physics

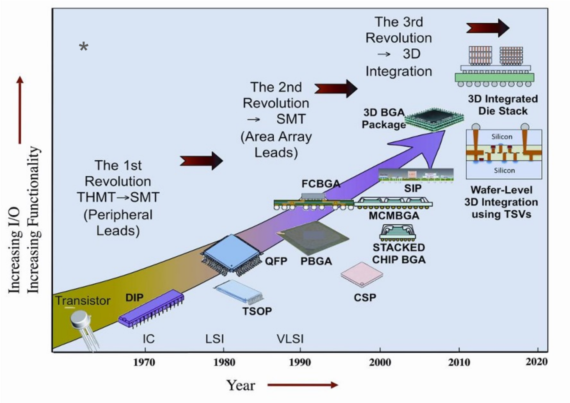
RIKEN and **HIMAC**: no routine access, focus on radiobiology

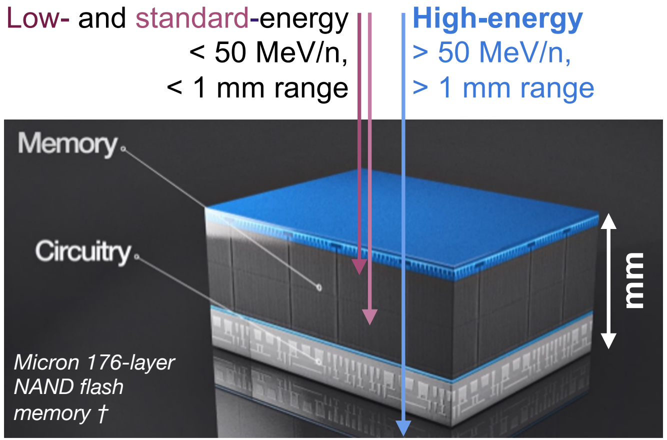


Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure (2018)

Testing increasingly complex COTS

‡ seeable future. Although simulation and modeling is valuable for understanding the radiation risk to microelectronics, there is no substitute for testing, and an increased use of commercial-off-the-shelf (COTS) parts in spacecraft may actually increase requirements for testing, as opposed to simulation and modeling.





- Testing with **higher energy** (>50 MeV/n) ion beams becomes the **only solution to evaluate state-of-the-art components** (non-planar, complex topologies, heat sinks, …) or assess board-level response to the **space or accelerator** radiation **environment** by **combining high linear energy transfer (LET) with high penetration range**.

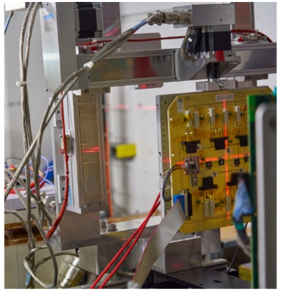
* https://polymerinnovationblog.com/polymers-electronic-packaging-introduction-flip-chip-packaging/
† As published on: https://www.eetimes.com/micron-leapfrogs-to-176-layer-3d-nand-flash-memory/. Image courtesy of Micron Technologies, Inc.
‡ National Academies of Sciences, Engineering, and Medicine. 2018. *Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24993.

CERN’s expertise and role in space

- CERN is a **well-established partner in space exploration**, fostering partnerships with with various agencies (ESA, NASA, CNES)
- CERN’s role can be strengthened by exploiting the unique combination of
  - Expertise of radiation effects on electronics (including accelerator applications)
  - Rare provision of high-energy, heavy ion beams to be a key enabler of space sector R&D

CELESTA cubesat: in-orbit radiation monitoring demonstration

ESA-CERN collaboration: testing of emerging technologies



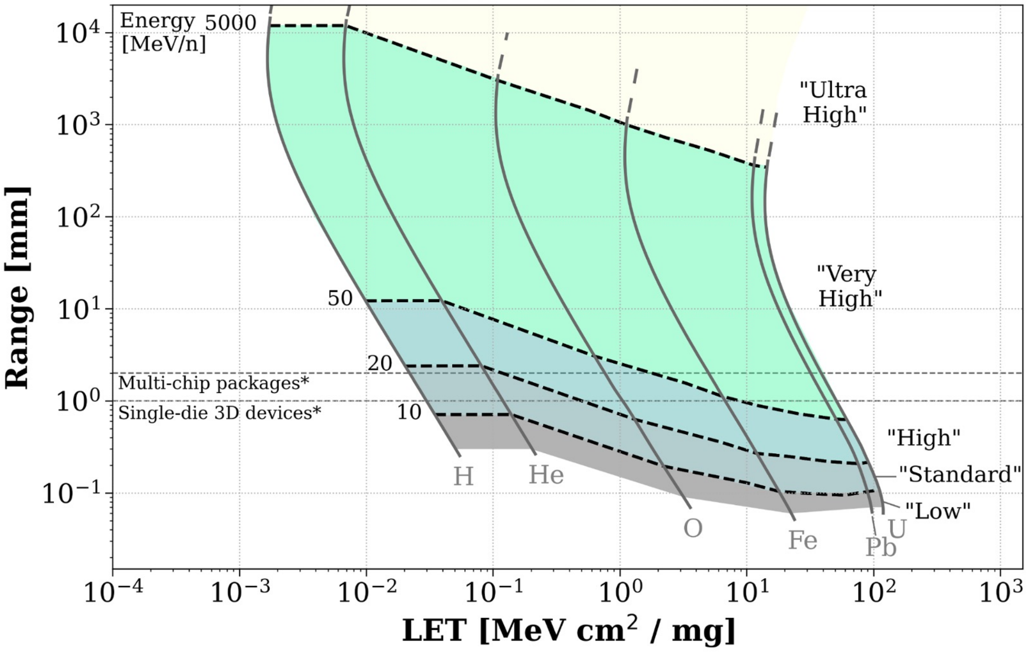
HEARTS@CERN: heavy ion testing of space applications

HEARTS: High Energy Accelerators for Radiation Testing and Shielding

- European Commission Space activity responding to the EU Space R&I Programme part of Horizon Europe, topic: **“Space critical technologies for European non-dependence”.**
- 2023 - 2026. Main goal: expanding Europe’s accessibility to VHE, heavy ion beams for space radiation effects testing.
- Two heavy ion facilities in Europe + space industry and academia partners

- **HEARTS@CERN**: leveraging CERN’s infrastructure, scientific programme (Pb ions) and expertise to provide scientific and commercial beam time by allowing access for external users.

VHE heavy ion beams: advantages



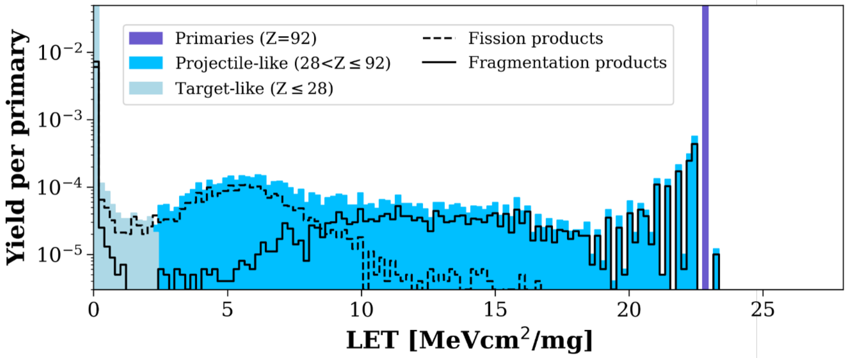
Standard energy:
< 50 MeV/n & < 1mm range

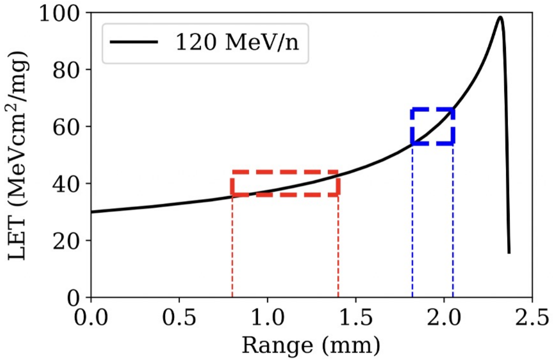
Very high energy:
50 - 5000 MeV/n & > 1mm range

Particularly **interesting for SEE testing** due to their **combination of high LET and high penetration range**

- avoid testing in vacuum and delidding of parts,
- reach all sub-layers of a device under test (state-of-the-art microelectronics with complex / 3D architectures),
- ensure the LET can be as constant as possible across the device.

Using VHE, heavy ion beams for electronics testing



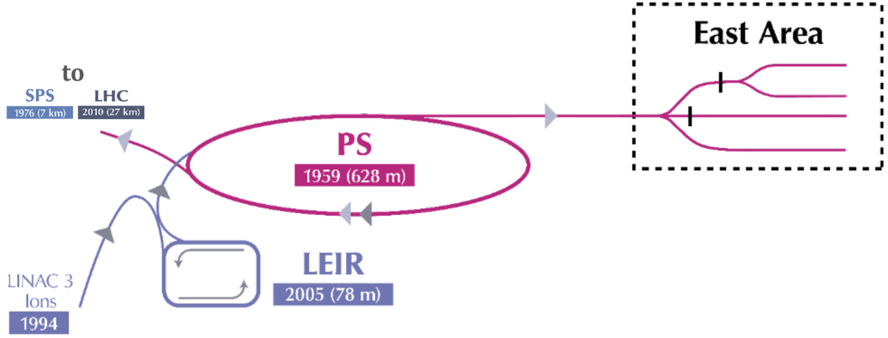


	VHE, heavy ion beams	Modern microelectronics	
LET	Beam **fragmentation** through inelastic interactions (spallation, fission)	(Unknown) material budget inside device-under-test (DUT), **uncertainty on LET** close to the Bragg peak	**Energy deposition (LET) distribution**
Fluence	**Flux attenuation of** primary particles (secondary particle population due to fragmentation)	**Range distribution** due to straggling, uncertainty on particle range and if SV inside DUT can be reached)	Range distribution**, primary fluence attenuation**

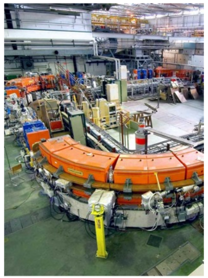
SEE σ → LET / Fluence → SEE σ

A. Waets et al., "Very-High-Energy Heavy Ion Beam Dosimetry Using Solid State Detectors for Electronics Testing," in IEEE Transactions on Nuclear Science, vol. 71, no. 8, pp. 1837-1845, Aug. 2024, DOI: 10.1109/TNS.2024.3350667
R. G. 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, DOI: 10.1109/TNS.2025.3530502.

HEARTS@CERN




Pb oven ion source + LINAC3


Low Energy Ion Ring (LEIR)


Proton Synchrotron (PS)


T8 beam line to PS East Area hall

- **Availability of Pb ions for radiation effects testing is thanks to CERN's scientific programme**
- Dedicated ion physics in SPS and LHC during < 2 months of the year, **2-3 weeks for HEARTS**
- Required VHE energies can only be obtained through the PS, CERN workhorse serving many users in the complex.

✷ Pb oven ion **source**

⇨ **LINAC3**: long 4.2 MeV/n pulses

⇨ **LEIR**: short and dense 70 MeV/n ion bunches

⇨ **PS**: acceleration up to 2 GeV/n

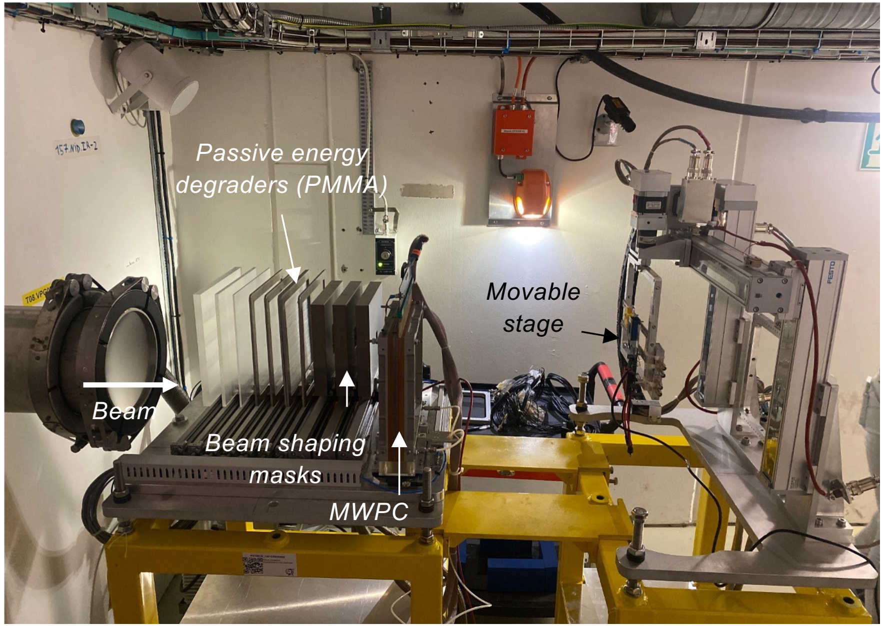
⇨ (RFKO) **slow extraction** of (up to) 1s spills, energy between 500 and 1000 MeV/n (2024), up to 4 spills per supercycle

⇨ transport through **T8** line to PS East Area hall

⇨ Delivery to **IRRAD** facility and **test station**.

HEARTS@CERN: facility

	Typical value	Extra information
Ion species	^{208}Pb	
Beam flux	$10^2 - 10^5$ ions/cm^2/spill	
Spill timing	1s length and repeating every ~10s	
Beam delivery	Static beam position	
Beam size	Square beam with side 25, 50 or 75mm	The beam is re-sized with collimators.
Uniformity	10 – 20%	Depends on the collimator choice.
LET range	12.3 – 36.3 MeV·cm^2/mg	
Degraders	PMMA	Density: 1.19 g/cm^3



- The HEARTS facility is **optimized** such that the **maximum level of autonomy and flexibility** can be achieved, exploiting the beam time as much as possible.
  - Fully remote operation of the test station inside the irradiation cave (LET, flux tuning) from the IRRAD control room
  - High-level beam settings done through communication with PS operators in main CERN CC
  - Dedicated RP support for irradiation cave access

HEARTS@CERN: facility

- HEARTS@CERN facility web page details the **up-to-date configurations and associated beam offer**.
- Beam LET and kinetic energy distributions extracted from FLUKA Monte Carlo simulations are available for download, along with a quantification of mean and spread for each configuration.
- Data can be used for users test preparation calculations, e.g. using the [NSRL stackup tool]!

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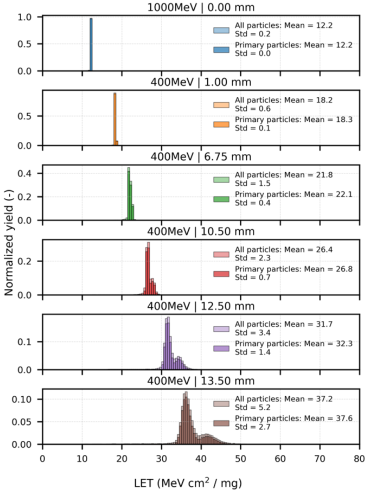
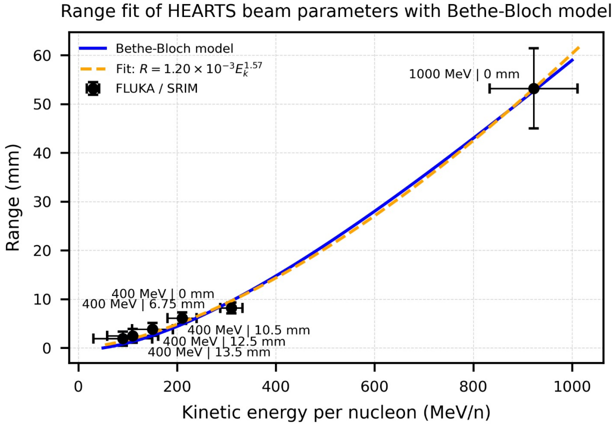
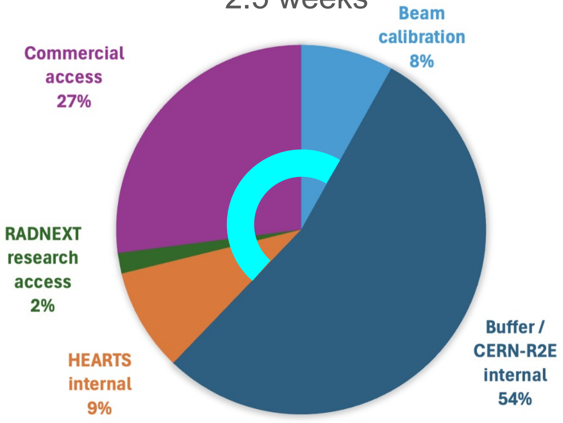




HEARTS@CERN: test campaigns

2024

2.5 weeks

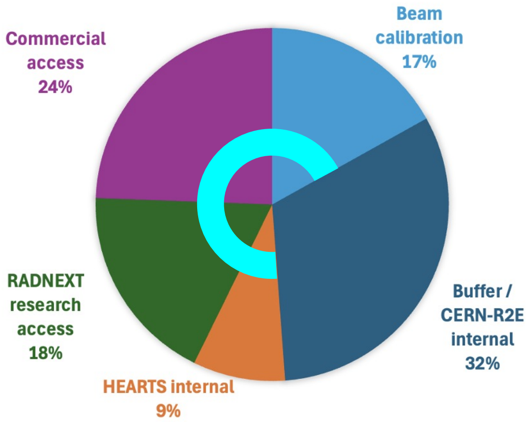


Focus on establishing **technological readiness** in terms of **compliance with radiation effects testing standards** using heavy ion beams.

- External access: 168 h
- 10 user teams, 33 persons on-site

2025

2.5 weeks



Further technological optimization and **focus on access modalities** for **external users** (scientific through RADNEXT + commercial)

- External access: 204 h
- CERN internal use: 24h (non-R2E)
- 17 user teams, 50 persons on-site

2026

Last campaign before LS3. Commercial + scientific access, finalization of HEARTS deliverables.

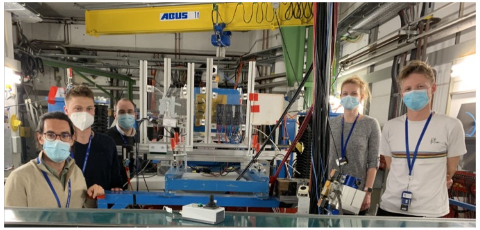
Diversity adds complexity in supporting process. We welcomed

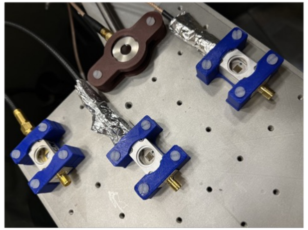
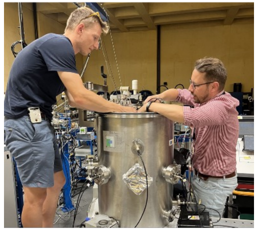
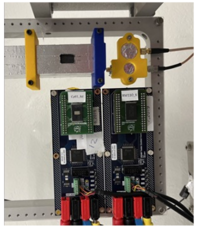
- Space primes
- New space
- Intermediaries
- Academia

which each have different needs, originating from 11 countries.

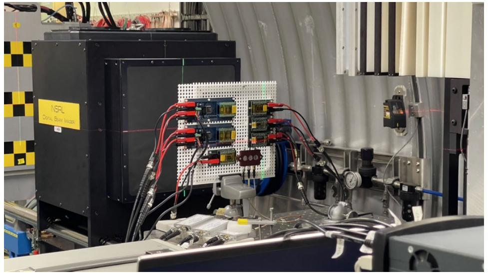
Ongoing research through HEARTS

- Testing with high-energy, heavy ion beams is relatively **new** when compared to standard energy testing at cyclotron facilities.
- This requires **essential research activities** carried out within the Radiation-to-Electronics (R2E) activity at CERN in the scope of HEARTS, **also carried out at other facilities** like e.g., NSRL and GSI.
- Current topics:
  - Very-high-energy, heavy ion beam dosimetry
  - Development, benchmarking and use of simulation tools (FLUKA.CERN, G4SEE) for radiation matter-interactions and beam line development
  - Deepen understanding of radiation-matter interactions on nm-µm level.
  - Electronic device susceptibility and response when exposed to GCR-like beams.
  - Reconciliation with standard-energy radiation effects testing.

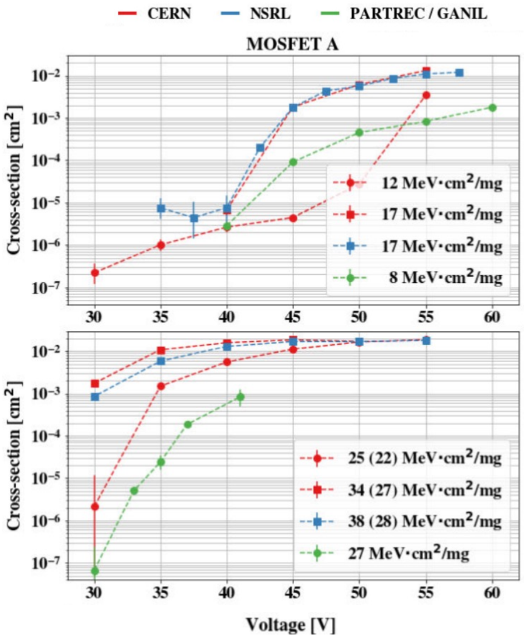





Focus on results obtained at NSRL



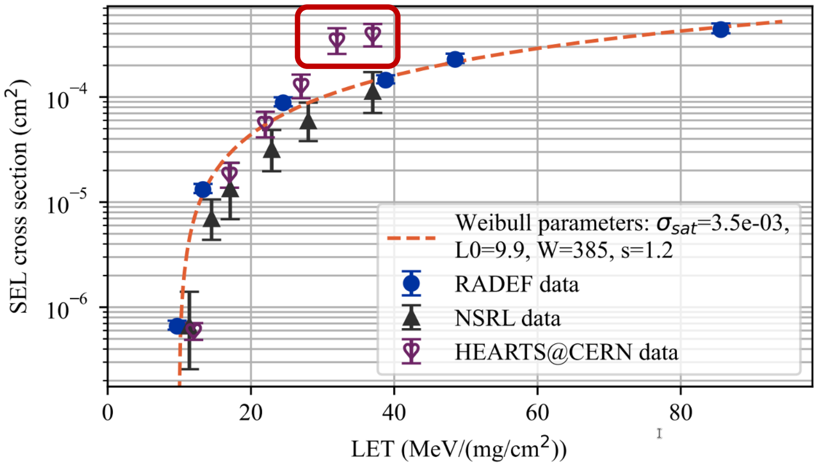
- Research on representative devices (SRAM, power MOSFETs) for several single event effect types: single-event-upsets (SEU), single-event-latchups (SEL), single-event-burnouts (SEB) at different-energy facilities (standard-energy: PARTREC, GANIL, high-energy: CERN, **NSRL**) allow a deeper understand heavy ion test results.

	Observed effect in very-high-energy vs. standard-energy ion beams	Explanation
SEU	Higher cross section in SRAMS for highly degraded beams	Confirmation of the role of the beam fragments, particularly when large cumulative beam degrader thicknesses are used.
SEL	Higher cross section in sub-threshold region for SRAMS	Cannot be justified by fragments but potentially by inelastic collisions with W atoms present in some SRAMs.
SEB	Different SEB cross section for one MOSFET device	Decapsulation, lower on-resistance, further research needed.



Focus on results obtained at NSRL

- An Analog Devices digital-to-analog converter **AD7801 DAC** (5V VCC) was tested at HEARTS@CERN, **NSRL** and RADEF
- The **SEL cross section** results are the combined results of eight tested DUTs (same date code).
- **Significant discrepancies** are found for the two highest LET points: 32 and 37 $MeVcm^2/mg$, measured at HEARTS@CERN with respect to RADEF and NSRL data.
- Extensive analysis of **silicon solid state detector data** of energy deposition allowed to **reconstruct an LET spectrum** for each of the HEARTS@CERN configurations. If these LET spectra are folded with the RADEF Weibull cross section, the **agreement** between HEARTS@CERN and NSRL **improves** to within a factor 2.
- The main **origin** for the discrepancies can be attributed to the **spread** in energy and LET of the main primary beam peak, as well as the **generation of secondary particles** of other ion species, resulting in a different response of the DUT compared to a fully monoenergetic beam.
- In addition particles of high LET can be stopped in the thick **package** of the device, not reaching the sensitive regions.



D. Söderström et al., "Single-Event Latch-up Data from Heavy-Ion Irradiation of COTS Components with Inter-Lot Variability Study, accepted to NSREC 2025 Radiation Effects Data Workshop Proceedings.

Focus on results obtained at NSRL

- **Benchmarked very-high-energy, heavy ion (VHEHI) dosimetry method** used in HEARTS@CERN relies on the combination of silicon solid state detector (diode) measurements with FLUKA Monte Carlo simulations.
- This method was applied to CERN, GSI, HIMAC and **NSRL**, **performing consistently** across all four facilities.
- MC simulations were carried out thanks to “first step” calculation results provided by NSRL team.
- In all cases, **heavier primary ions consistently out- perform highly degraded lighter ions** by providing higher achievable LET values with reduced spectral dispersion and larger penetration ranges, simplifying dosimetry and improving the reliability of SEE interpretation.
- Detector pulse-shape analysis allowed to disentangle detector-related artifacts and allowed filtering of the measured energy deposition spectra, leading to refined results in close agreement with simulation results.

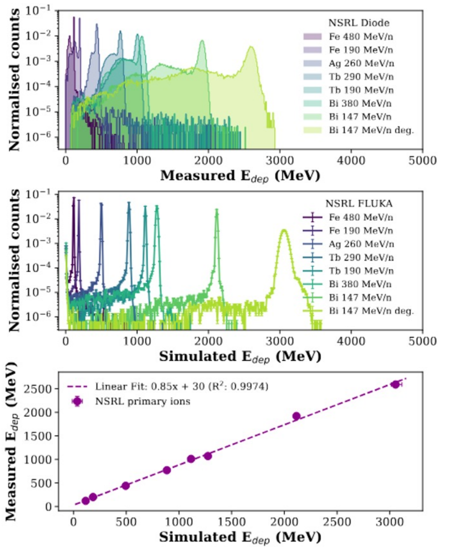


Fig. 3. Energy deposition spectra measured with the silicon diode at NSRL with various primary ions (top), the associated FLUKA simulation (middle) and the correlation between the two (bottom).

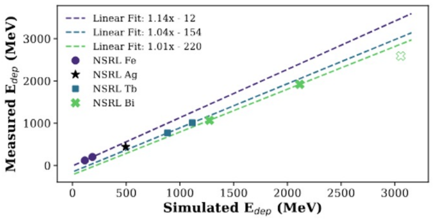


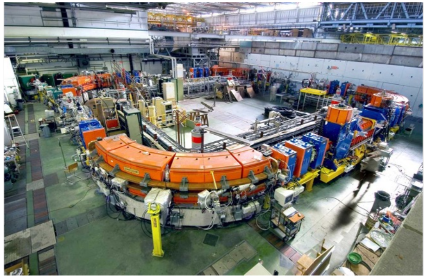
Fig. 4. Correlation between diode measurements and FLUKA simulations done separately for each NSRL ion species.

Future developments at CERN: HEARTS++

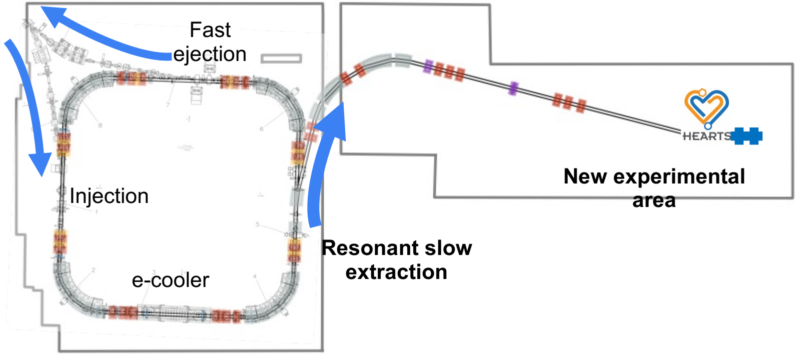
- Current offer within HEARTS is limited in terms of LET range and beam time available.
- What's next after the conclusion of the HEARTS project (max. August 2027) and CERN's Long Shutdown 3?

  → Consolidation of current HEARTS operation, extracting beams from Proton Synchrotron

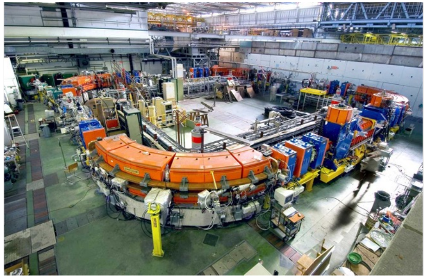
  → **HEARTS++**
- **Main idea:** make better use of the LEIR machine (idle during proton operation)
- Implementing slow-extraction from LEIR and coupling to a second, dedicated source would allow to use O, Ar, Kr, Xe beams in addition to Pb (fast switching)
- Construction of a dedicated experimental area, tailored for radiation effects testing.



Low Energy Ion Ring



Future developments at CERN: HEARTS++

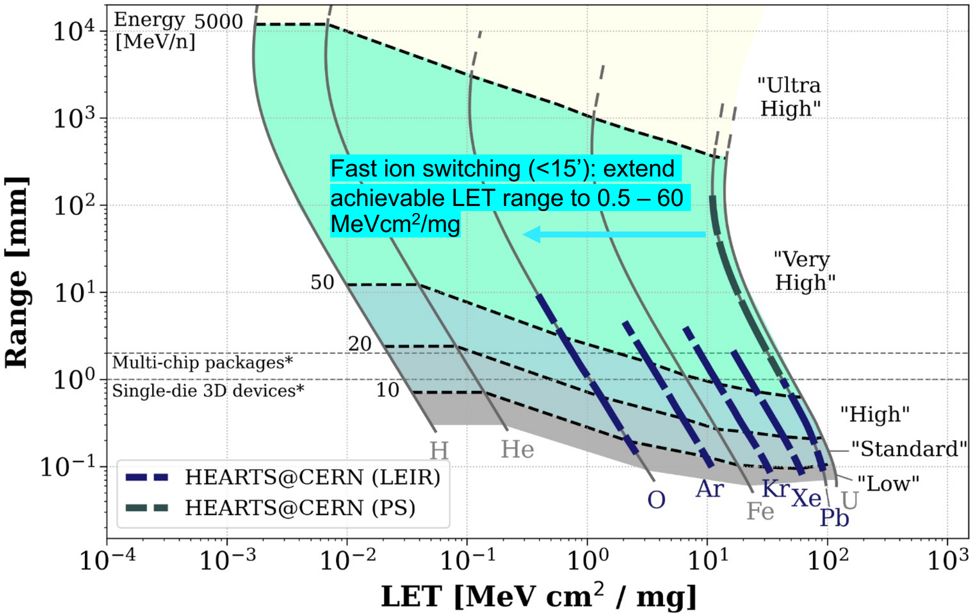


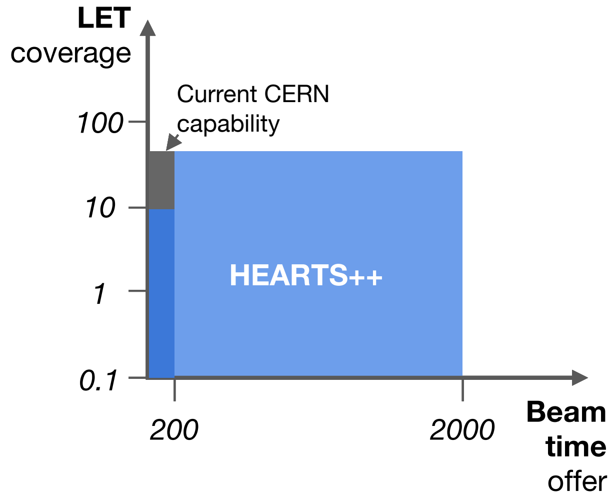
- HEARTS++ facility could run fully in parallel to proton physics at CERN (PS, SPS, LHC)
- 24/7 facility operation yields **2000+ hours per year** for radiation effects testing by scientific and commercial users, in addition to CERN-internal needs.

Annual accelerator schedule:

LEIR/PS/SPS/ LHC	Commissioning (10w)	Proton physics (21w)	Ion physics (7w)
HEARTS++	Parasitic (up to 5w)	Dedicated (up to 11w)	✗

Future developments at CERN: HEARTS++





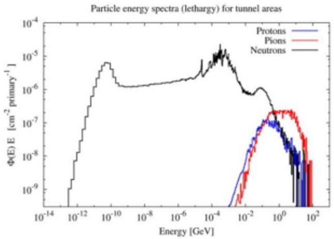
Future developments at CERN: HEARTS++

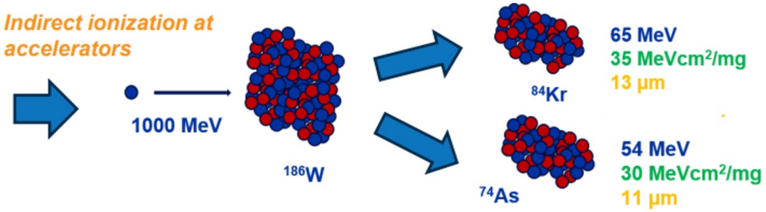
- **A heavy ion irradiation facility for space electronics and an in-house capability for CERN** (detectors + accelerators).
  - Accelerators: Ions can reveal device latch-up sensitivity or help identify other unpredicted failure modes (!)
  - Detectors: SEE qualification using heavy ions of ASICs used in Experimental Physics detector electronics or beam instrumentation.
- Now: build a clear picture for CERN management to decide, mapping resources, ensuring compatibility with accelerator and maintenance operation and development of “business model”.
- Approval opens the way for EU proposal submission with deadline on Sept. 2026, answering to “Space Critical Technologies for EU Non-Dependence” call.

European Commission

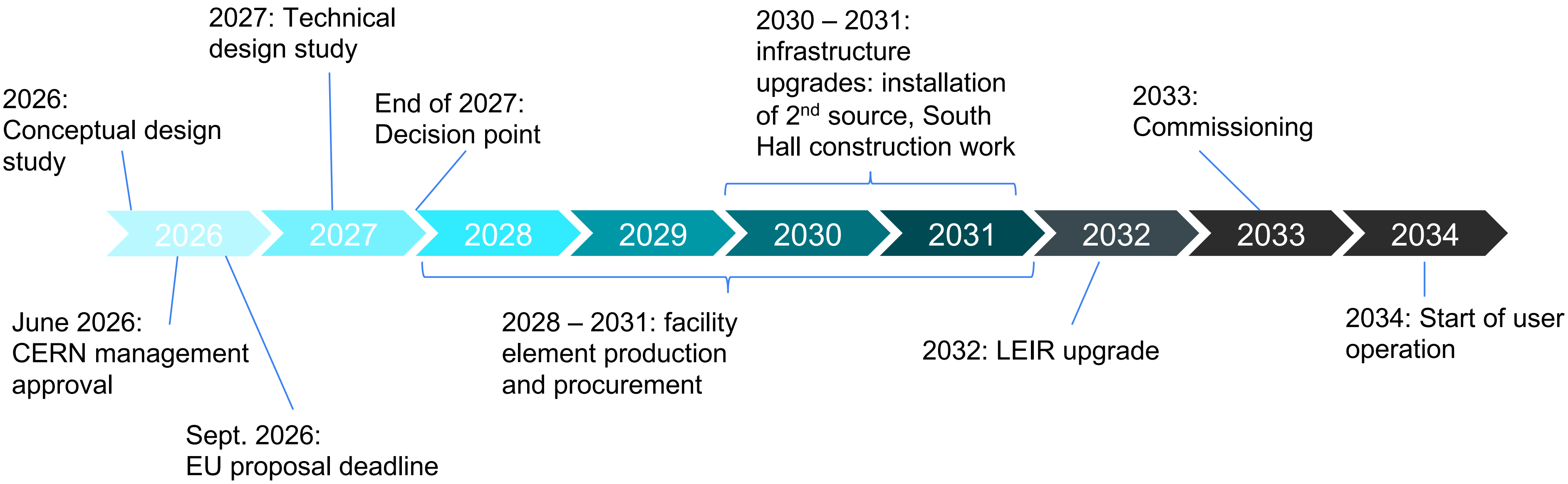
Space Critical Technologies for EU Non-Dependence

Technical Guidance Document of Horizon Europe Space Work Programme 2026



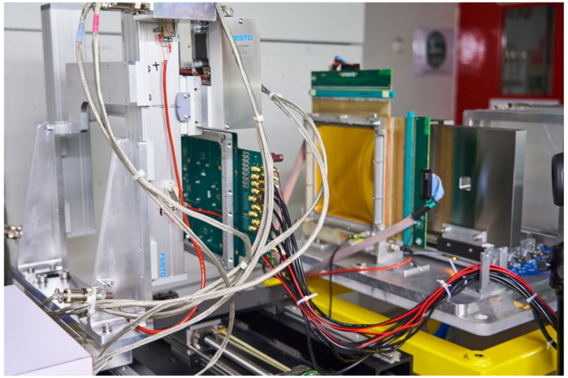


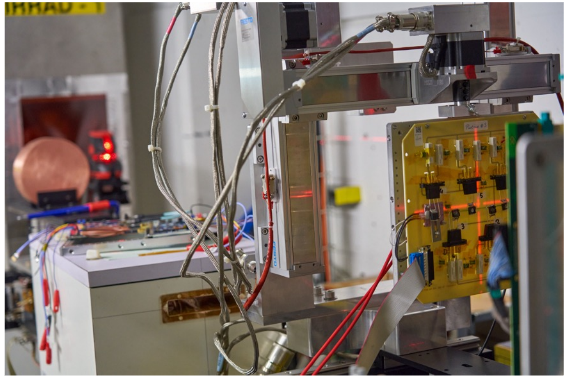
Future developments at CERN: HEARTS++



Conclusions

- Within the HEARTS project, the CERN heavy ion testing facility grew from an experimental test platform to a **well-established name within the radiation effects community**.
- In addition, the facility also demonstrated to be
    - a platform for scientific research in radiation effects on electronics, benchmarking of beam-matter interaction models and codes, …,
    - **a CERN in-house platform for qualification** of critical accelerator/detector applications.
- **NSRL has been a stepping stone for CERN R2E and the HEARTS project:**
    - Continued inspiration as the reference space radiation effects facility
    - **Highly valued active cooperation on radiation effects research, beam line dosimetry, simulations, …**
- Despite an **excellent level of cooperation** across CERN within this activity, in its current configuration, the HEARTS@CERN facility
    - hits a ceiling in terms of achievable LET range, beam size, …,
    - has a limited in offered beam time,
    - has no dedicated user facility.
- **Service quality could be fundamentally improved with a dedicated beam line and experimental facility, operating multiple ion species: HEARTS++.**





Thank you for your attention!

https://hearts-project.eu/

https://www.linkedin.com/company/hearts-eu/

HEARTS@CERN 2024 campaign
photos taken by G. Datzmann.

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