DEPARTMENT OF INFORMATION ENGINEERING
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Present and Future Perspectives for High-Energy Ion Testing

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RREACT

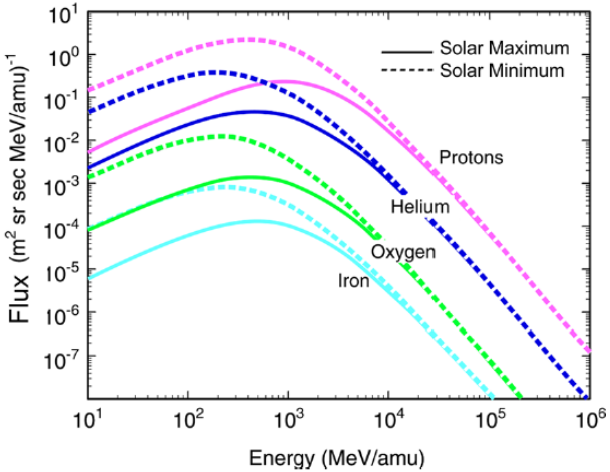
- Introduction
- Motivations for high-energy ion testing
- Case study: PIN diode
- State-of-the-art and perspectives for high-energy ion facilities
  - HEARTS EU project

Funded by the European Union

- The interest in using **high-energy ion beams** for accelerated Single Event Effect (SEE) testing of electronics has been increasing over the last years
  - **More representative** of galactic cosmic rays
  - **Necessary** for the test of state-of-the-art devices
- However, the interactions with high-energy beams may differ from what has been traditionally observed with low- and medium-energy beams, leading to unexpected results
- Increasing efforts in the community towards better understanding of the mechanisms, exploitation of existing high-energy beams, inter-comparison between data at different energies, and development of new facilities

Galactic Cosmic Rays

- Galactic cosmic rays originating from outside our solar system are mostly made of protons, but they include all elements. The energy of GCRs can reach **10^{11} GeV** and the **maximum flux is around 1 GeV/n**
  - These particles are very penetrating and impossible to shield with reasonable amount of material: calculations for ^{56}Fe show that inside a spacecraft ~50% of the flux has energy above 1 GeV/n, regardless of shielding(*)
  - The interaction of a single ionizing particle with sensitive regions of electronic chips (**Single Event Effect**) is critical for space components: the stochastic nature of SEE can compromise the mission success already at an early stage



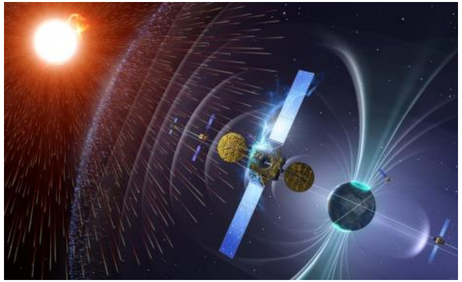
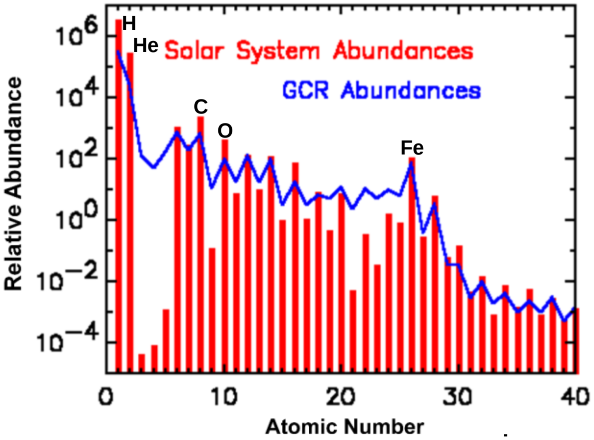


Image: ESA

Hadron Composition	Energies	Flux
90% protons 9% alphas 1% heavier ions	Up to ~10^{20} eV	1 to 10 $cm^{-2}s^{-1}$

(*) J.A. Pellish et al, "Heavy Ion Test With Iron at 1 GeV/amu", TNS 2010

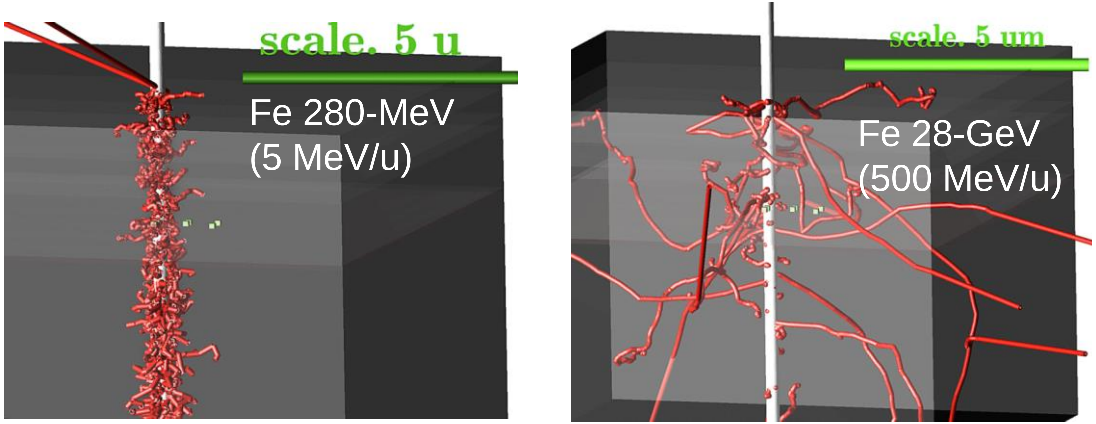
Figures: M. Xapsos, 2018 NSREC Short Course



Track Structure

- Appreciable differences can be observed in the **structure of ionization tracks** and energy deposition for low- and high-energy ions
  - Energetic (~10 keV) secondary electrons (δ-rays) are generated with high-energy ions, with a larger range than the secondaries from lower energy ions: δ-rays can travel away from the primary path, impacting on several cells at the same time
- SEE tests in **high-energy facilities** might lead to **different patterns of energy deposition**, which may represent a worst-case condition compared to lower energy facilities

Monte Carlo simulation of Fe ions at different energies interacting with an SRAM cell array (22-nm technology)

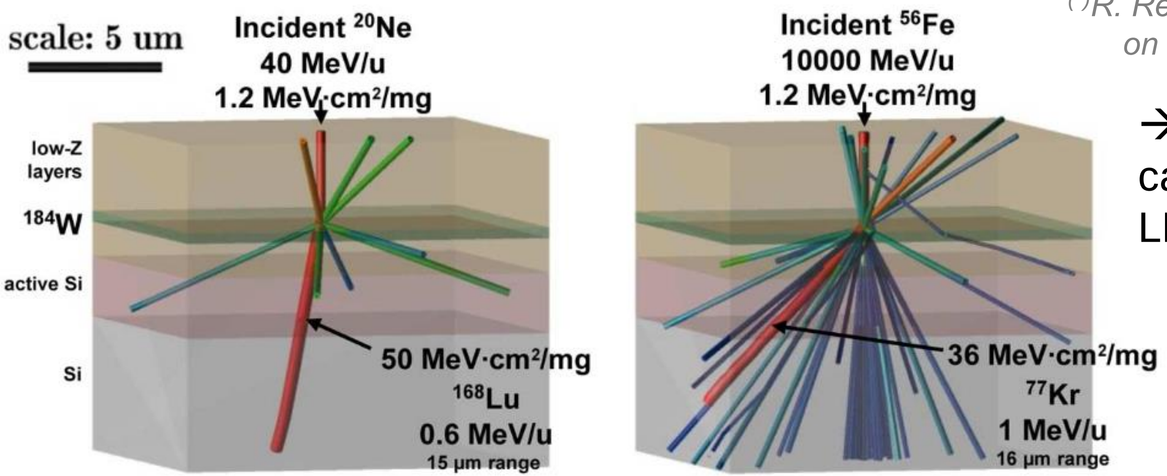


M.P. King, et al., "The impact of delta-rays on single-event upsets in highly scaled SOI SRAMs," IEEE TNS, 2010

Solid white track = incident ion track
Red tracks = generated delta-electrons along the ion track
Green structures = sensitive volumes of neighboring devices

- **Nuclear reactions** between heavy ions and IC materials are also a critical aspect: SEUs due to nuclear interactions in space have been shown to increase the error rate by up to 3 orders of magnitude compared to the predicted rate based on ground measurements(*)
- The **secondary by-products** induced by nuclear reactions (number of secondaries, energy, LET, range) **induced by ions at higher energies can be significantly different** compared to those induced by lower energies ions

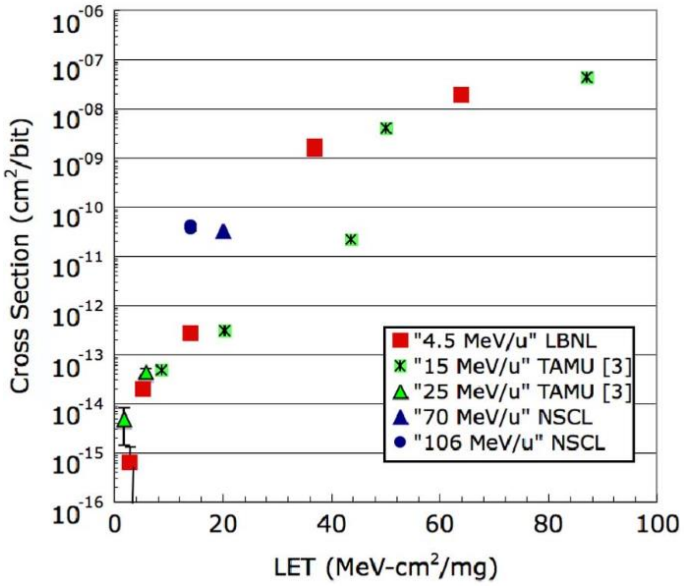
(*)R. Reed, et al., "Impact of ion energy and species on single event effects analysis," TNS 2007



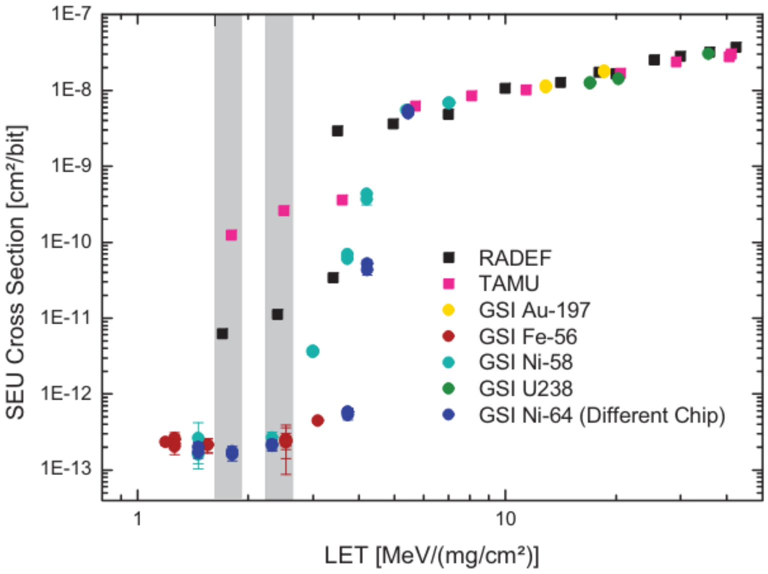
→ Simulated nuclear reactions caused by ions with the same LET and different energy

N. A. Dodds, et al., "Charge Generation by Secondary Particles From Nuclear Reactions in BEOL Materials," TNS 2009

- As a result, experimental data may show **multiple values for the SEU σ** when irradiated with ions with the **same LET but different energy** (and mass)
  - Dependence on DUT sensitivity, threshold LET, materials (e.g. presence of high-Z), etc.

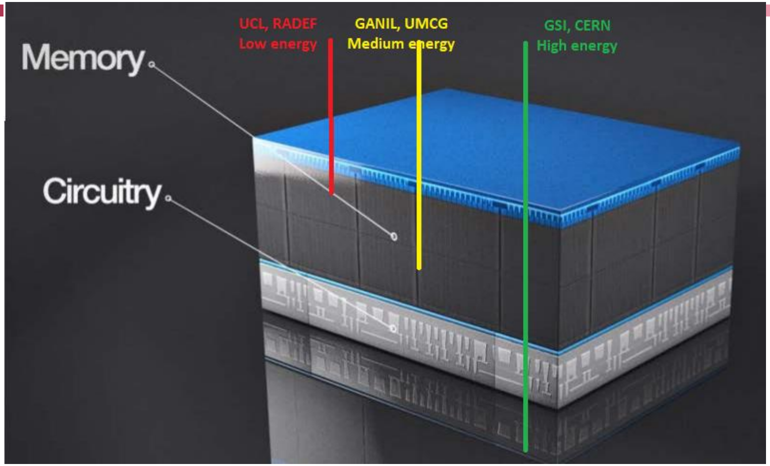


R. Reed, et al., "Impact of ion energy and species on single event effects analysis," TNS 2007



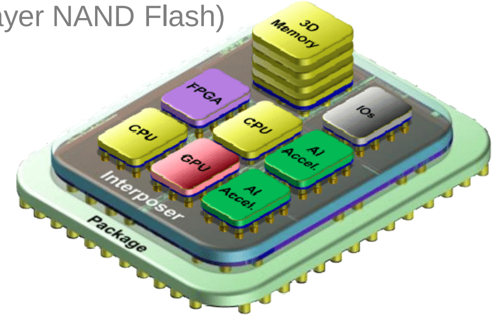
S. Hoeffgen, et al., "Investigations of Single Event Effects with Heavy Ions of Energies up to 1.5 GeV/n," TNS 2012

- Evolution of technology is leading to devices with **3D structures**, increasing **complexity**, larger **power** density, including a variety of **materials**. All of these are attractive for "**New Space**" applications
  - SoC, GPU, …
- There are practical advantages in using high-energy ions, mostly related to the feature of modern devices
  - Ability to penetrate 3D and multi-layer devices
  - No need for testing in vacuum (power dissipation issues)
  - Possibility of testing complex devices without removing the package/heatsink
  - Possibility of performing board-level testing
  - The beam can be tilted at large angles (90°)
- Ions with E > 100 MeV/n can cover most of the LET range of standard-energy ions, while reaching penetration depths in the order of 1 mm - 1 cm with the LET remaining constant over this entire range



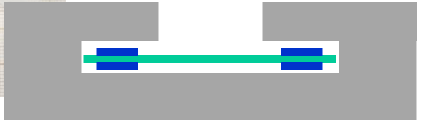
Courtesy of Micron (176-layer NAND Flash)

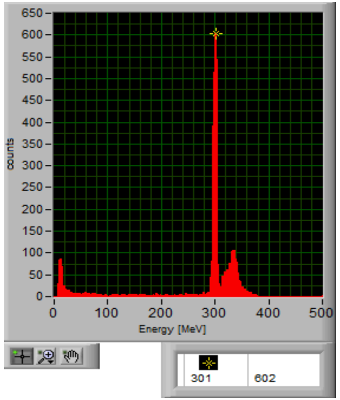
https://wccftech.com/

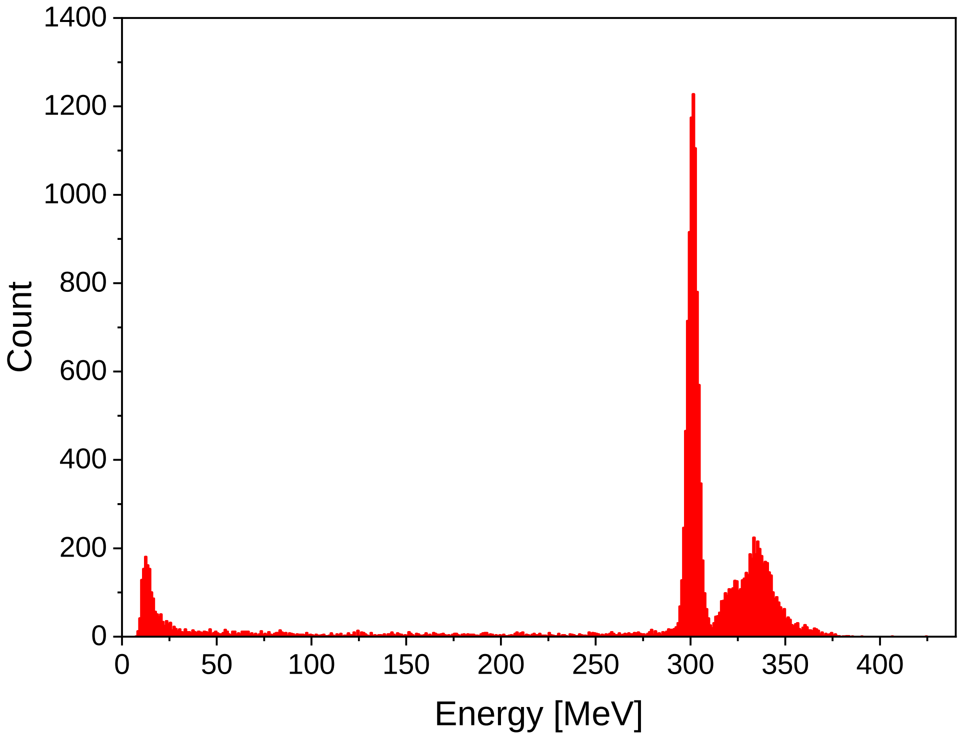


IntAct: A 96-Core Processor With Six Chiplets 3D-Stacked on an Active Interposer With Distributed Interconnects and Integrated Power Management

- Passivated Implanted Planar Silicon (PIPS) diodes, routinely used by ESA to characterize the energy of heavy-ion beams
  - The top part of the package is a ring and it is 0.5-mm thick. ~ 60% of the diode active area is covered by the package
  - The Si chip is held by two elastomer rings at the edge of the 0.5-mm thick stainless-steel package
- **Irradiated with ultra-high energy ions at CERN, SPS line H8, NA** (40 GeV/n Xe, 150 GeV/n Pb)
  - Biased at nominal voltage during irradiation, connected to a charge sensitive preamplifier. A high-bandwidth oscilloscope digitized the collected charge signal
  - Low ion flux (~ 10 ions/cm^2/s) to avoid multiple events



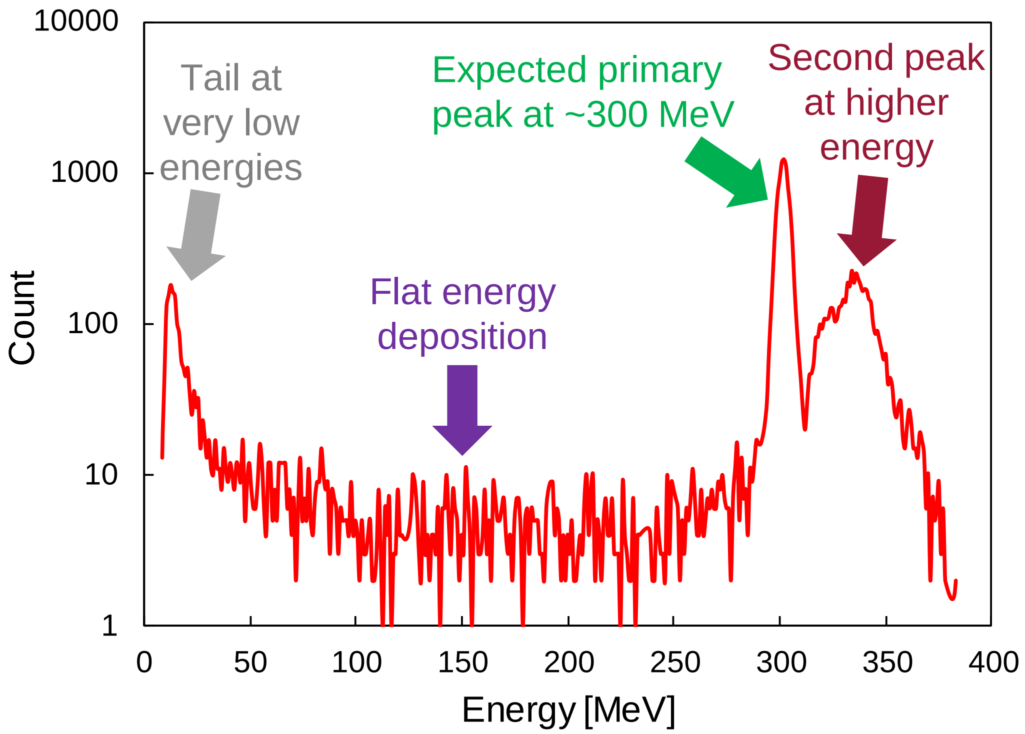




Experimental energy spectrum in a 300-μm PIPS diode, biased at +80 V, exposed to 40 GeV-n Xe at CERN

- The diode response is complex, with an unexpected peak at high energies that was never observed before
  - A peak at 300 MeV corresponding to the expected primary beam
  - A second peak at higher energy, broader and smaller
    - Contains about half of the events in the primary peak
- Flat deposition at intermediate energy values
- Tail at very low energies

M. Bagatin et al., "Characterizing High-Energy Ion Beams With PIPS Detectors," TNS 2020



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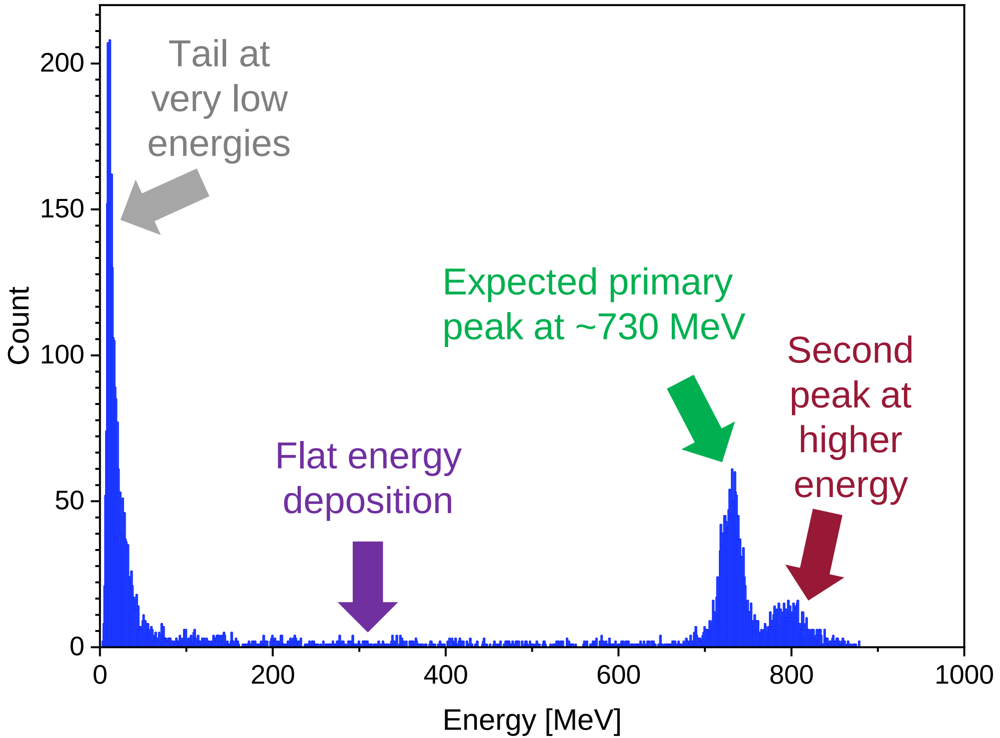
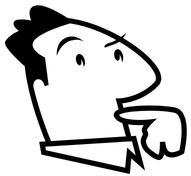
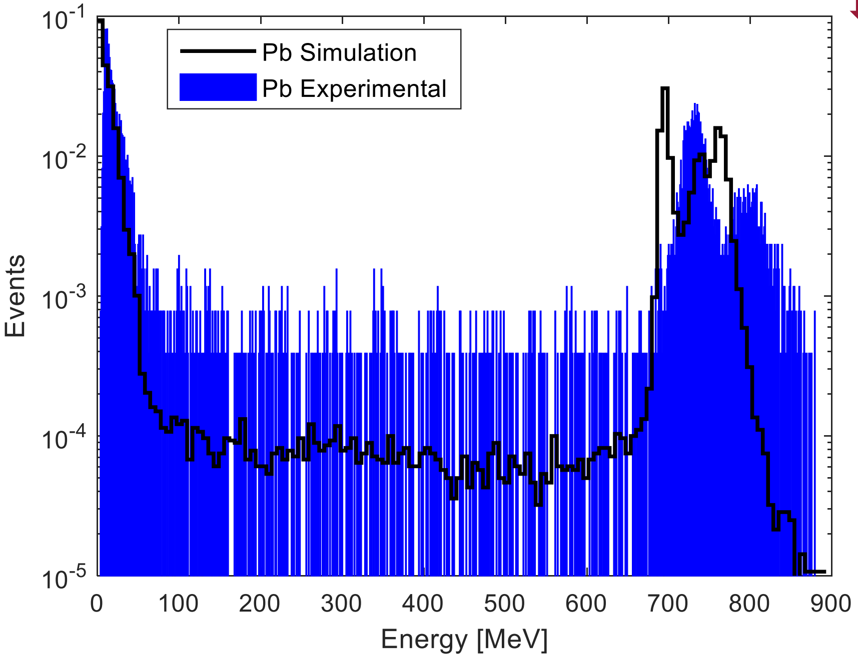


Experimental energy spectrum in a 300-μm PIPS diode, biased at +80 V, exposed to 150 GeV-n Pb at CERN

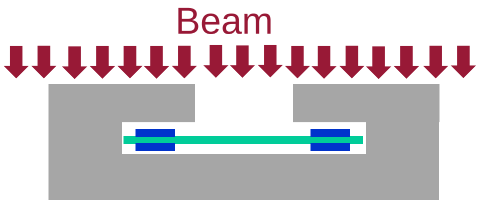
- Results are very similar to Xe
- **What is the origin of the second peak at high energy?**

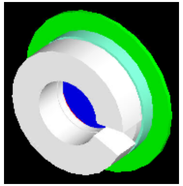


- LET of Xe and Pb is flat, or even slightly increasing in this energy range
  ⇒ energy loss in the primary beam before the active area cannot lead to an increase in the deposited energy

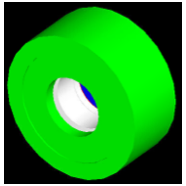


Simulated energy spectrum in a 300-μm PIPS diode, exposed to 150 GeV-n Pb



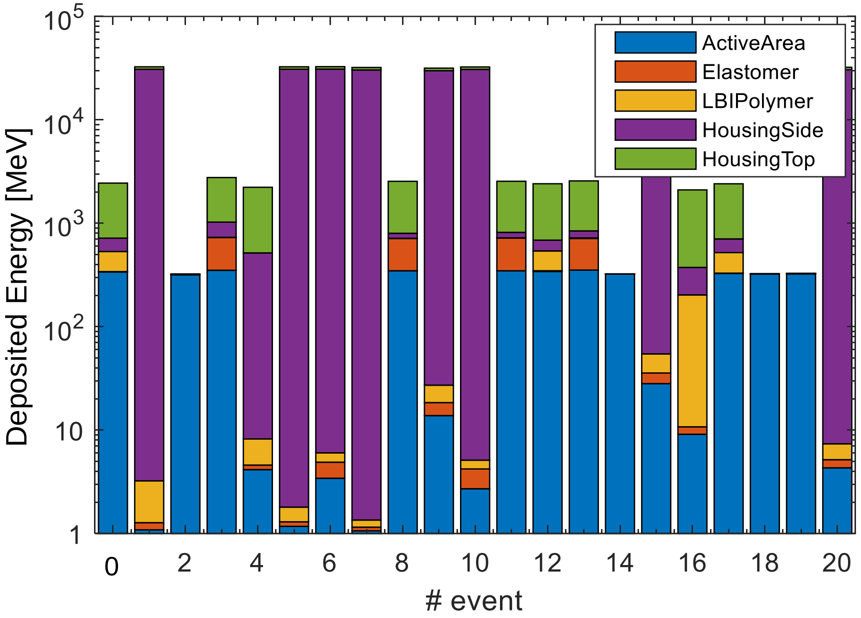


Lateral and top package not visible



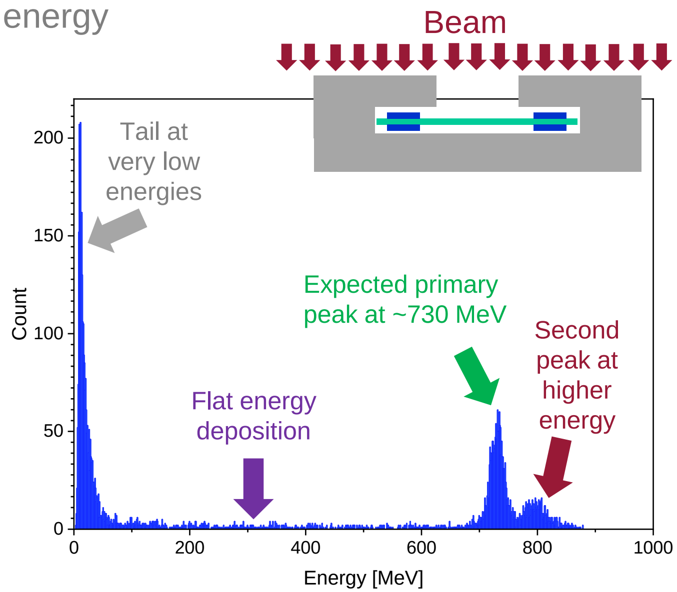
Lateral and top package visible

- Monte Carlo simulations (GRAS) were performed to study the secondaries originated in the different diode volumes and reaching the sensitive area
- The distance between simulated peaks matches the experimental one (despite the shift to lower energies compared to experiments)



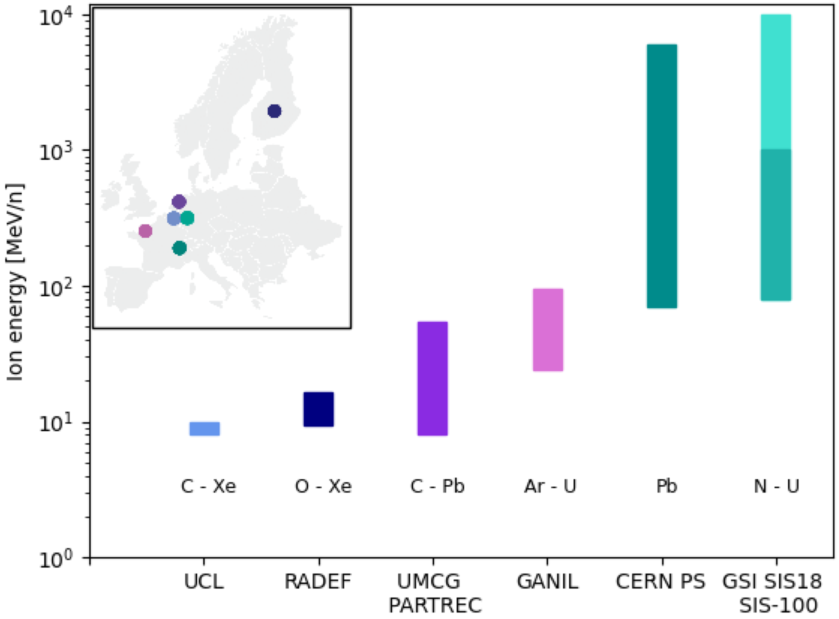
Energy deposited in the different physical volumes in a 300-μm PIPS diode, exposed to 40 GeV-n Xe

- Three types of strikes
  1) Strikes depositing energy only in the active area (#2) → primary peak (ions hitting the device at the center and only go through the active area)
  2) Strikes involving multiple volumes, depositing a smaller-than-average energy in the sensitive volume (#5) → tail at very low energy



3) Strikes involving multiple volumes, depositing a larger-than-average energy in the sensitive volume (#3) → second peak due to summation of energy deposited by the primary ions and the secondaries arising from interactions of the primary beam with the package materials

- **Qualifying** EEE devices in ground-based irradiation facilities is a key step to ensure their reliability in space
- The energies used for **ground accelerated heavy-ion testing are typically below 100 MeV/n**, much lower that those found in space
- **Very high-energy** (100 MeV/n - 5 GeV/n) and **ultra high-energy** (5 - 150 GeV/n) ion beams are more representative of the actual space environment
  - Two facilities in Europe with energy above 100 MeV/n: CERN PS, GSI SIS
- LET is the main metric, but in a variety of situations the observed phenomena may also exhibit a **dependence on the energy** (and species) of the particle



Heavy-ion facilities available in Europe. Credit: CERN

HEARTS Project

- **HEARTS (High Energy Accelerators for Radiation Testing and Shielding)** is an EU project (kicked-off Jan 2023, 4 years) combining the experience of the institutes operating heavy-ion accelerator facilities in Europe with academic and industry expertise
- The goal is to **enhance the availability, quality, and accessibility of very high-energy ion beams for space applications** (EEE component qualification, shielding and radiobiology effect studies) for both research and industry users
  - Simulation and testing approaches for beam characterization will be studied and developed
  - HEARTS project will be instrumental at reducing Europe’s dependence on critical infrastructures outside its borders
  - Strong link with RADNEXT (and previous RADSAGA)

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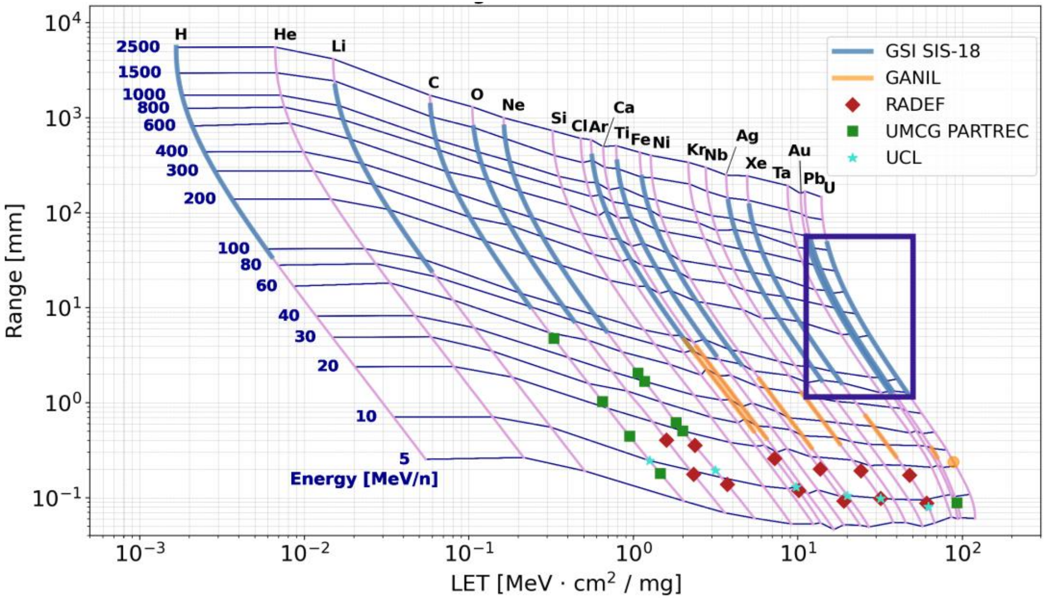
- By the end of the project, HEARTS will **provide two high-energy heavy ion beam facilities** (TRL 6-7) capable of meeting the domestic demand for electronics testing, shielding and radiobiology



- **CERN** (PS) → adaptation of **CHARM** beam line infrastructure to accommodate very high energy ion beams for radiation effects testing on electronics
- **GSI** (SIS18) → adaptation of **FAIR** facility to a GCR/SPE simulator: new SIS100 accelerator providing heavy-ion beams at energies up to 10 GeV/n

CERN Facility Upgrades

	Current situation	HEARTS upgrade
Ion Species	Lead	Lead
Beam Energy (MeV/n)	5000	70 - 8000
Beam LET ($MeVcm^2/mg$)	10	10 - 40
Beam average flux ($ions/cm^2/s$) (*)	$> 2 \times 10^6$	$10^2 - 10^5$
Beam shape and size	Gaussian, 10×10 cm^2	Rectangular, 20×20 cm^2
Beam homogeneity	trade-off between beam size and homogeneity	$\pm 10\%$
Beam instrumentation	Suited for high intensity proton beams	Tailored to ions in energy and intensity range above
Beam time structure	standard slow extraction spill structure	optimized for SEE testing
Benchmark against other facilities	Not yet completed	To be completed as part of HEARTS
Validation for industrial users	Not yet completed	To be completed as part of HEARTS
Access procedure for external users	Based on existing collaborations, and requiring case-by-case approach	Standardized approach enabling access through competitive scientific and industry proposals
Available beam time (per year)	5-15 x 8h shifts	40-60 x 8h shifts
TRL	**3**	**7**

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GSI Facility Upgrades

	Current situation	HEARTS upgrade
Ion Species	H to U	H to U
Beam Energy (MeV/n)	150 - 1000	150 - 10000
Beam LET ($MeVcm^2/mg$)	0.1 - 40	0.1 - 40
Beam average flux (ions/s)	$10^2 – 10^8$	$10^2 – 10^{10}$
Beam shape and size	Rectangular, 10×10 cm^2	Rectangular, 10×10 cm^2
Beam homogeneity	±5%	±5%
Beam instrumentation	Suited for cancer therapy experiments	Also suited for space radiation experiments
Beam time structure	Slow extraction 1 Hz	Slow extraction 3 Hz
Benchmark against other facilities	Not yet completed	To be completed as part of HEARTS
Validation for industrial users	Not yet completed	To be completed as part of HEARTS
Access procedure for external users	Based on existing collaborations, and requiring case-by-case approach	Standardized approach enabling access through competitive scientific and industry proposals
Available experimental caves	Cave A	Cave A and APPA cave
Available beam time (per year)	9 x 8h shifts	20 x 8h shifts
TRL	**3**	**6**

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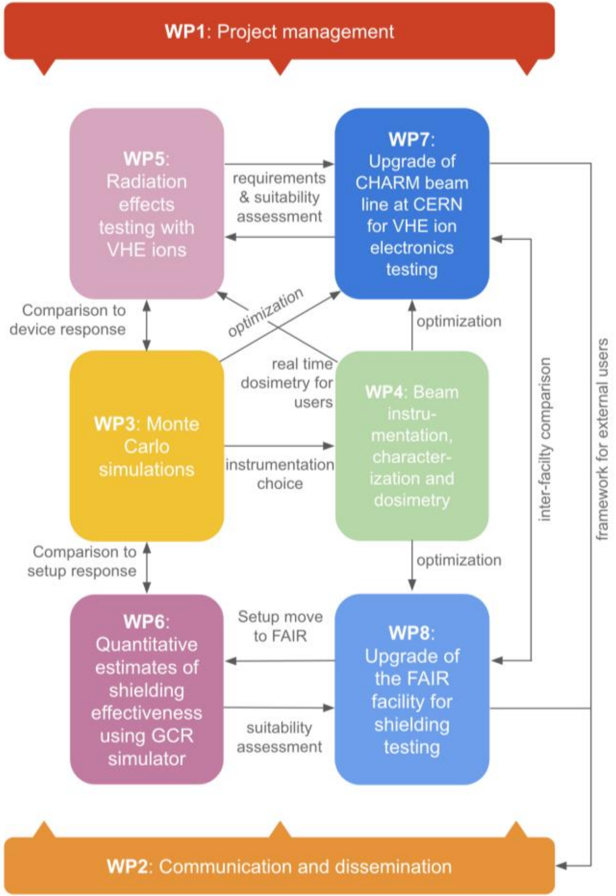


WP3: Monte Carlo **simulations**

- Simulation of beam properties and detectors
- Simulation of shielding materials and setup configurations
- Assessment of LET uncertainties in sensitive volumes
- Simulation of simple and medium-complexity electronic devices

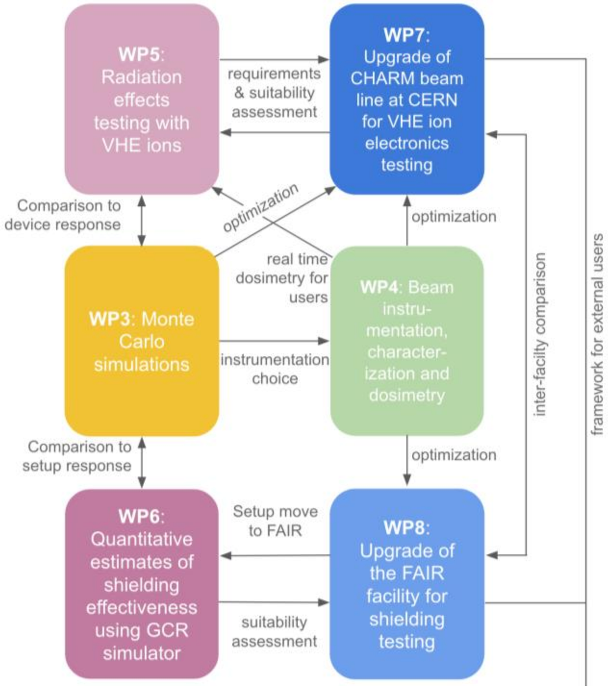
WP4: **Beam** instrumentation, characterization, dosimetry

- Calibration of VHE ion beam at CERN
- Beam delivery monitoring, target station, dosimetry at GSI
- Intercomparison between CERN and GSI beam lines

WP5: **Radiation effects testing** with VHE ions

- VHE ion beam requirements for SEE testing
- Analysis of a PIN diode for beam quality assessments
- Suitability of proposed VHE beams for 3D-integrated device structures
- Validation of the VHE beams for industrial use with TRL 6-7 achievement
- Qualification of high-complexity devices, board-level testing

HEARTS WPs



- WP6: Quantitative estimates of **shielding** effectiveness with GCR/SPE simulator
  - Standardized setup for the GCR/SPE simulation experiments
  - Quantitative measurement of shielding effectiveness
  - Radiobiological characterization
- WP7: Upgrade of **CHARM** beam line at CERN for VHE ion testing
  - Methodology for extracting variable energy ion beams to ensure parallel operation of the VHE ion facility
  - Achievement of the required beam parameters for microelectronics SEE testing
  - Framework for user access
- WP8: Upgrade of **FAIR** facility at GSI for shielding testing
  - GCR/SPE simulator installation in APPA cave or CBM vault
  - Test of the GCR/SPE simulator
  - Framework for user access

- The interest in **high-energy ion beams** has been increasing over the last years
  - More representative of the **actual space environment**
  - Necessary for **modern technologies** (AI, big-data processing, 3D chips, …)
  - **"New space" has new paradigms** for SEE testing
- **Case study**: PIN diode response to high-energy ions is complex, with an unexpected peak at high energies that was never observed before
  - Unexpected high-energy peak related to heavy-ion interactions with packaging materials, in particular to secondary electrons
- **HEARTS project** aims at enhancing the availability, quality, and accessibility of very high-energy ion beams for space applications for research and industry
  - Simulations, dosimetry, and tests with high-energy ions
  - Upgrade of CHARM facility (CERN) and FAIR facility (GSI) at energies up to 10 GeV/n