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2025 Seville, Spain
25 - 27 March

SESSION:
COTS RADIATION
TEST DATA

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Member of CERN's Radiation
to Electronics (R2E) team

Talk:

Heavy ion testing of COTS components at CERN: recent results and facility development

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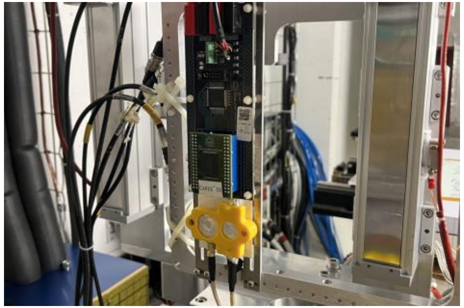
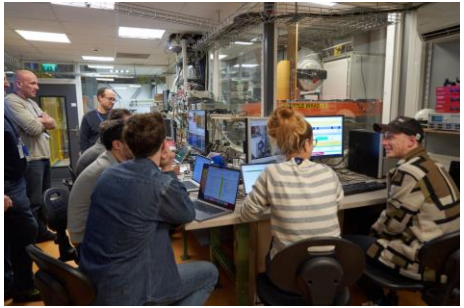
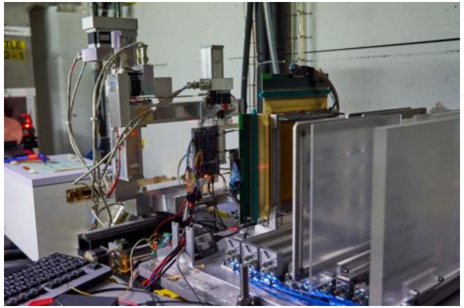
COTS Heavy Ion Testing at CERN: recent results and facility development

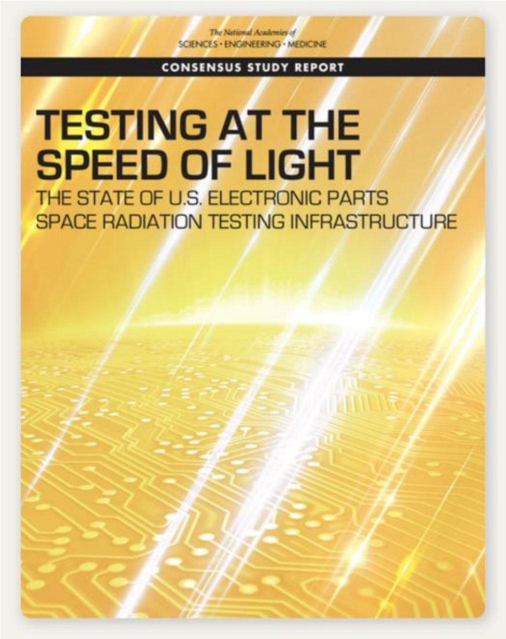






Andreas Waets, Rubén García Alía, Natalia Emriskova,
Daniel Söderström, Daniel Prelipcean, Mario Sacristan Barbero, Matteo Ceccheto, Ivan Slipukhin,
Federico Ravotti, Kacper Bilko on behalf of the **HEARTS@CERN team** and supporting groups

“Demand”: Very-High-Energy (VHE), heavy ions for space electronics qualification



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.

Finding: The complicated packaging and high level of integration of many COTS (commercial-off-the-shelf) parts has made them increasingly difficult to test at conventional heavy-ion accelerators. In many cases, the only options for testing such parts are the following:

1. Costly and risky modification and/or repackaging of the part to ensure ion beams can reach sensitive volumes in the device.
2. Testing at an expensive and difficult-to-access ultra-high-energy ion accelerator to ensure that ions have the range to reach device sensitive volumes.
3. Testing with protons only and accepting the residual risk of heavy-ion-induced destructive SEE or other hidden SEE modes not revealed by such a test.

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.

“Supply”: worldwide status of Very-High-Energy, heavy ion electronics testing

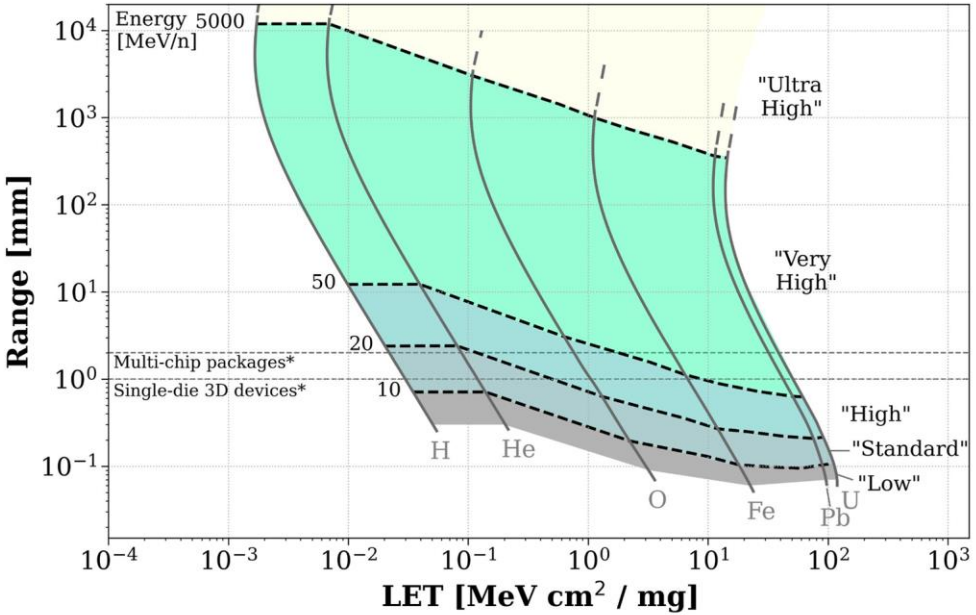
- Current heavy ion (all energies) beam time worldwide: **10Kh**, Europe: 4Kh

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

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

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

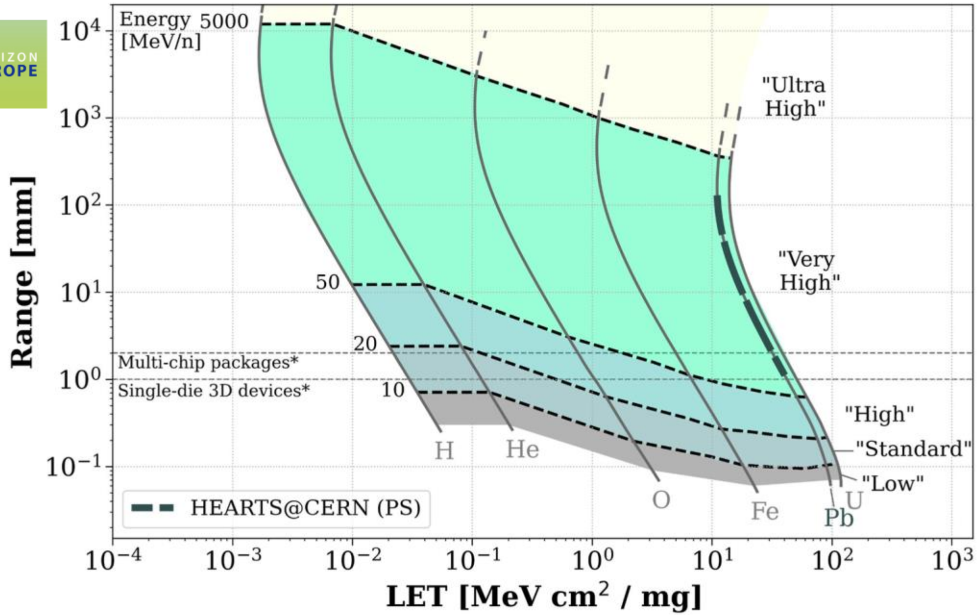
- Supply gap of **another 10Kh** in the coming decade.



Bridging the gap: The HEARTS EU project

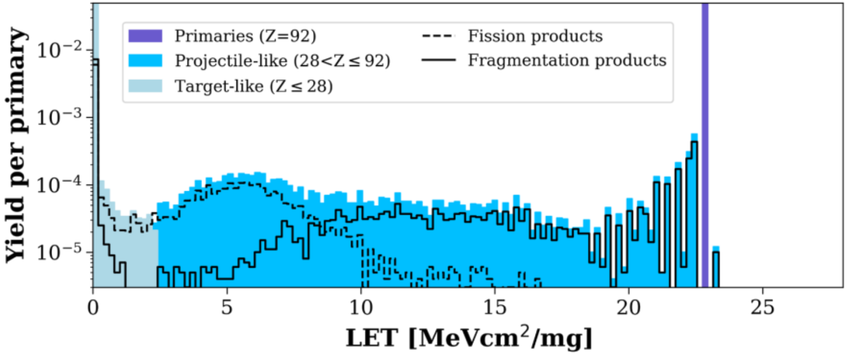
- **Predecessor:** ESA-sponsored CHIMERA activity.
- EC Space activity responding to the EU Space R&I Programme part of Horizon Europe, topic: **“Space critical technologies for European non-dependence”.**
- Expanding Europe’s accessibility to VHE, heavy ion beams for space radiation effects testing.

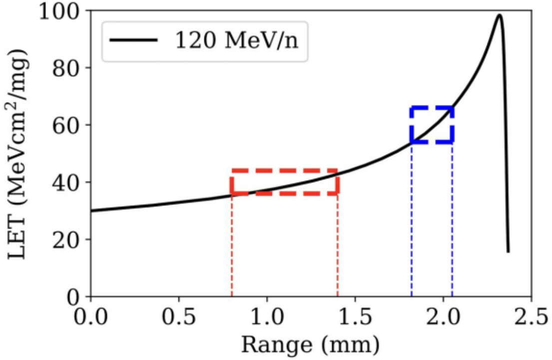
- **HEARTS@CERN**: leveraging CERN’s infrastructure, scientific programme (Pb ions) and expertise to provide commercial beam time and access for external users.



Website: https://hearts-project.eu/, EC project description DOI: 10.3030/101082402
K. Bilko et al., "CHARM High-Energy Ions for Microelectronics Reliability Assurance (CHIMERA)," in IEEE Transactions on Nuclear Science, vol. 71, no. 8, pp. 1549-1556, Aug. 2024, DOI: 10.1109/TNS.2024.3358376
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.

Using VHE, heavy ion beams for electronics testing





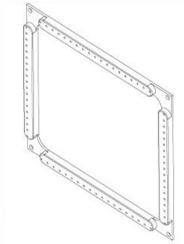
		VHE, heavy ion beams	Modern microelectronics		
SEE σ	LET	Beam **fragmentation** through inelastic interactions (spallation, fission)	(Unknown) material budget inside device-under-test (DUT), **uncertainty on LET** close to the Bragg peak	**Energy deposition (LET) distribution**	SEE σ
	Fluence	**Flux 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**	

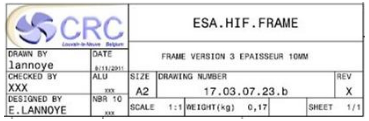
A. Waets et al., "Very-High-Energy Heavy Ion Beam Dosimetry Using Solid State Detectors for Electronics Testing," in IEEE Transactions on Nuclear Science, vol. 71, no. 8, pp. 1837-1845, Aug. 2024, DOI: 10.1109/TNS.2024.3350667
R. G. Alía et al., "The HEARTS EU Project and its Initial Results on Fragmented High-Energy Heavy Ion Single Event Effects Testing," in IEEE Transactions on Nuclear Science, DOI: 10.1109/TNS.2025.3530502.

HEARTS beam requirements

- TRL 6-7 for HEARTS electronics testing facilities by 2026.
- **Compliance with ESCC No. 25100** “Single Event Effects Test Method And Guidelines”.
- **LET** requirements:
  - Provide 3 to 5 steps within **0.1 to 60 MeVcm²/mg** range,
  - +/- 10% LET spread (FWHM).
- **Flux/Fluence** requirements:
  - Provide tunable flux between **10^2 - 10^5 ions/cm²/s**, max. instantaneous flux of 10^6, reaching 10^7 as fast as possible,
  - +/-10% on irradiation area (4 to 400cm²), dosimetry and reached fluence.
- **User support**:
  - Provide a user-friendly tool to help users determine range and LET at SV depth,
  - Provide calibration data on user request,
  - User interface/display of test beam parameters, temporal information (spill timing + structure), “instant” beam stop,
  - Provide quick irradiation room access and setup space.

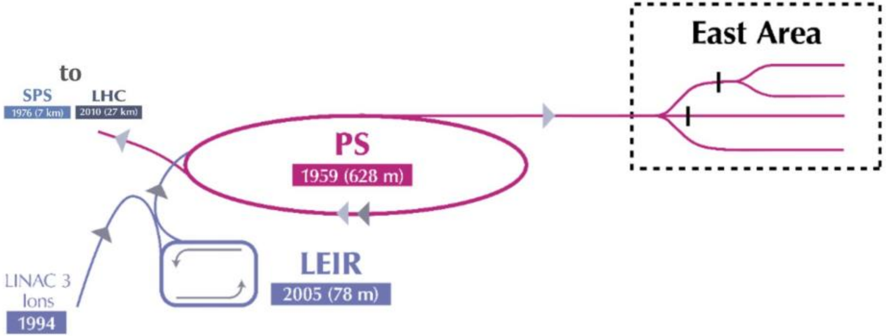
	Eq. range in Si
Wire-bonded chip with plastic package	> 0.5 mm
Flip-chip device without lid, glue removed	> 0.8 mm
Single-die 3D devices	> 1 mm
Chip with ceramic package lid	> 1 mm
Flip-chip device with plastic package	> 2 mm
Multi-chip package	> 2 mm
Chip with heat spreader	> 3 mm





Single Event Effects Test Method and Guidelines, Doc. 25100, ESCC Basic Specification, European Space Agency, 2014, no. 2.

The HEARTS@CERN facility (1)



Pb oven ion source + LINAC3

Low Energy Ion Ring (LEIR)

Proton Synchrotron (PS)

T8 beam line to PS East Area hall

✷ Pb oven ion **source**

⇨ **LINAC3**: long 4.2 MeV/n pulses

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

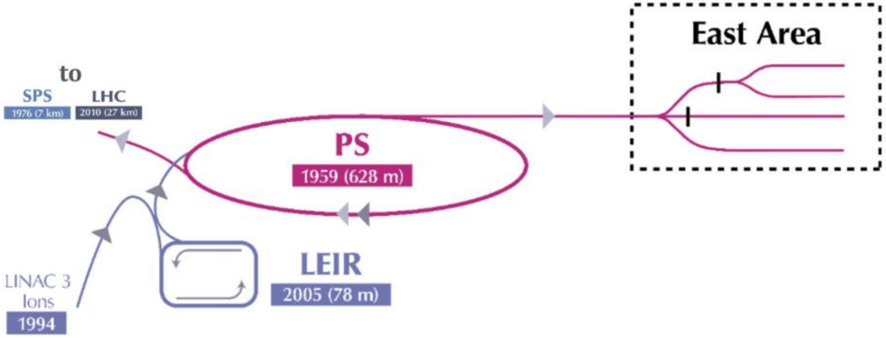
⇨ **PS**: acceleration up to 2 GeV/n

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

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

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

The HEARTS@CERN facility (1)




Pb oven ion source + LINAC3


Low Energy Ion Ring (LEIR)

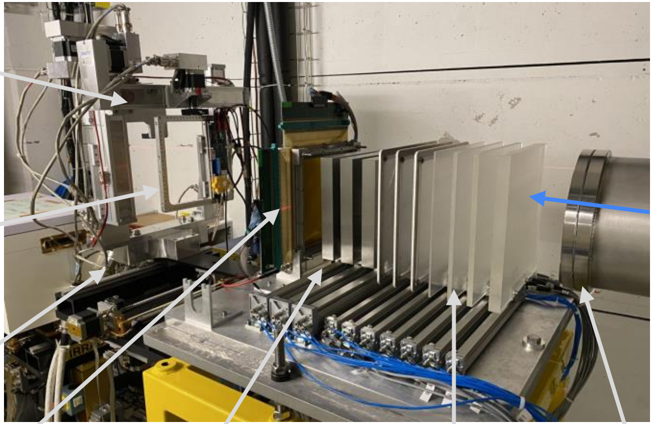

Proton Synchrotron (PS)


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.
- **Duty cycle: 1 spill every ~10 seconds** (subject to supercycle programming), a fluence of 10^7 ions/cm^2 can be reached in minutes - 10s of minutes.

The HEARTS@CERN facility (2)

IRRAD HEARTS@CERN test station



Movable XYR stage*
+
Laser alignment

ESA DUT support **frame** (24x24cm^2)

Patch panel to control room

Multi-Wire Proportional Chamber (MWPC, **profile monitor**)

W beam masks* (25x25, 50x50, 75x75 mm^2 apertures cutting off Gaussian beam tails)

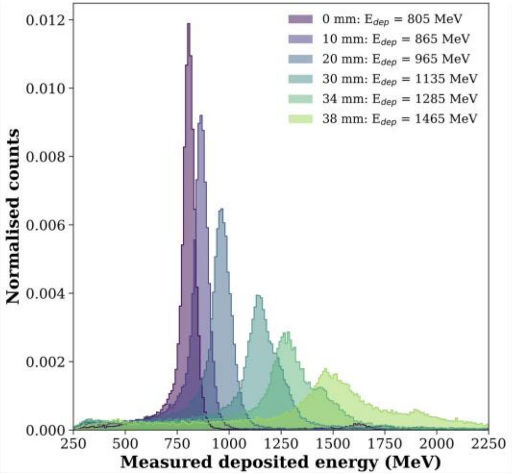
LET booster*: PMMA energy degraders (cfr. binary filter)

Vacuum window

** Remotely controlled*

The HEARTS@CERN facility (2)

Beam calibration

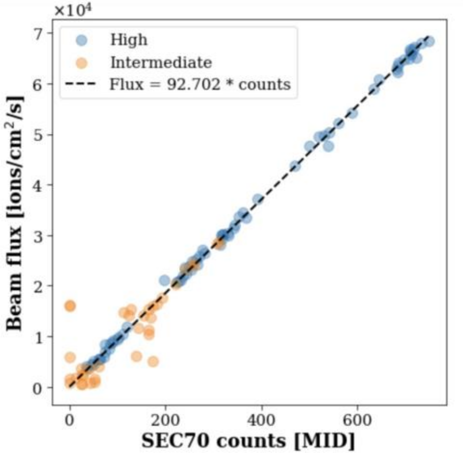


LET

- Experimental determination of DUT radiation field using Si diode.
- Verification of LET boosting: **10 - 40 MeVcm²/mg** (Si, surface) in combination with FLUKA MC simulations.

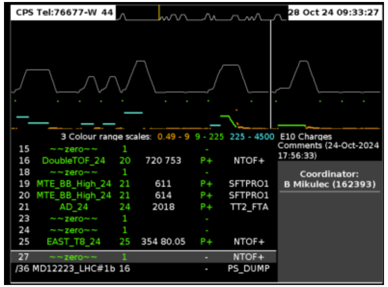
Flux/fluence

- Calibration of upstream beam intensity monitors (secondary emission and ionization chambers) using diode at DUT location.
- **Flux range: 10 - 10^6 ions/cm²/s** with RFKO.

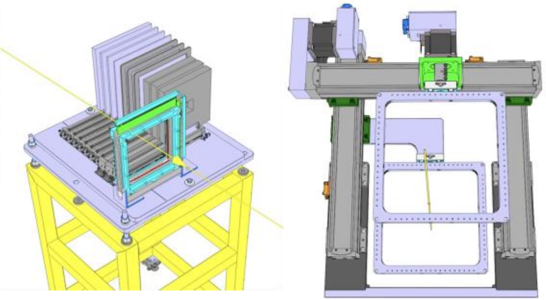


The HEARTS@CERN facility (3)

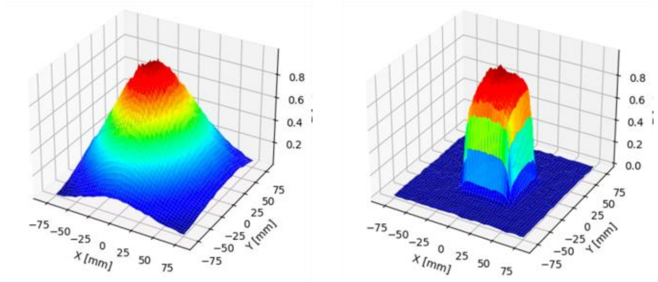
- During testing, beam configurations (energy, degraders, flux, spill profile …), and instrumentation values providing calibrated dosimetry are **logged** and continuously **visible for users and operators** through dedicated user interfaces.
- The **user has control** (via the operator) **over the beam energy, flux (on/off), the target fluence, beam size** (through setting of the W masks) and which target DUT on the **movable XYR stage** to be irradiated.



PS Vistar showing spill timing.

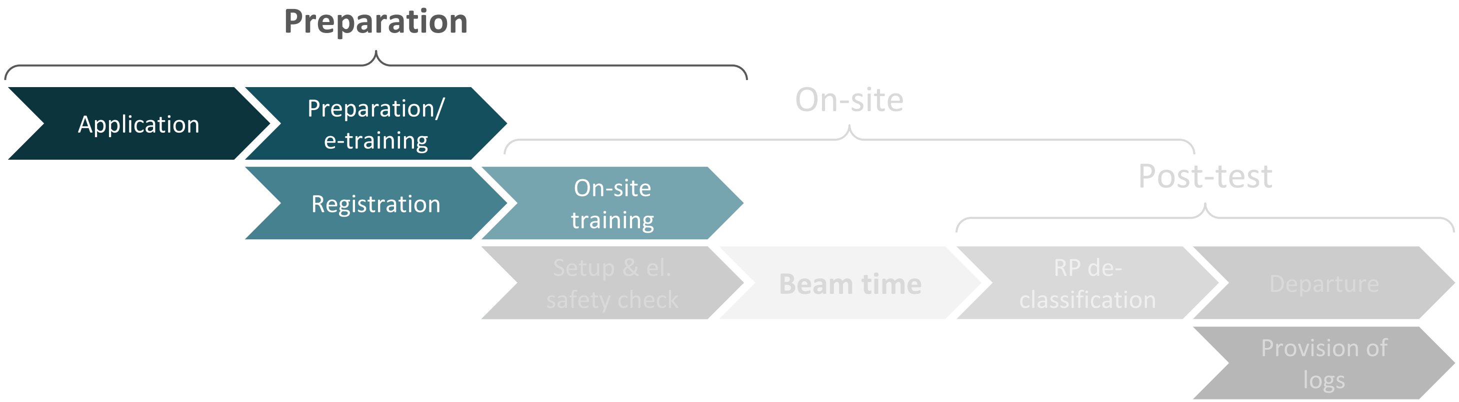


Remote control GUI for movable stage and LET booster.



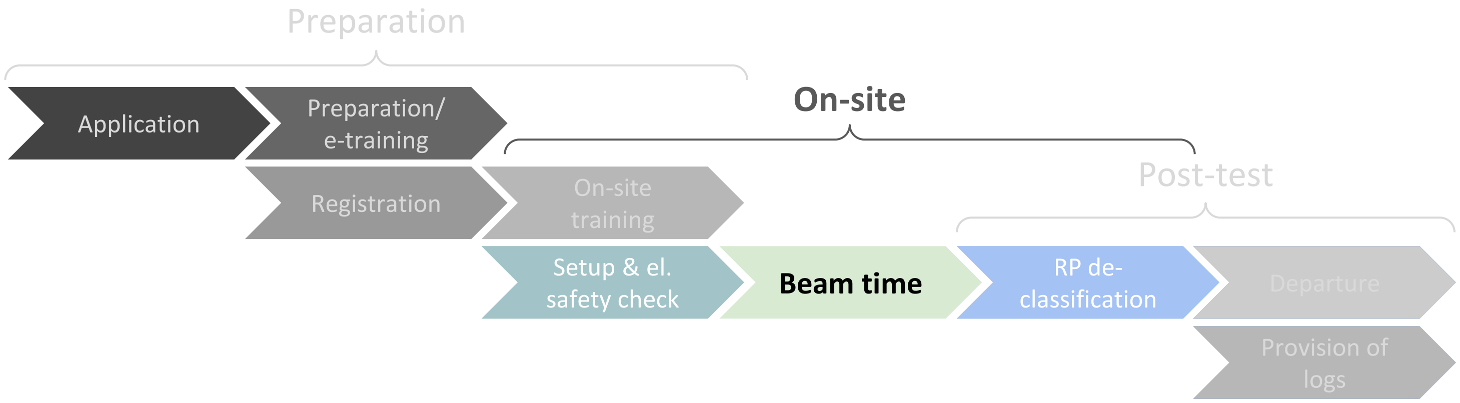
Beam profile on Octavius array (M. Lapp, PTW).

Testing at HEARTS@CERN: user lifecycle and support



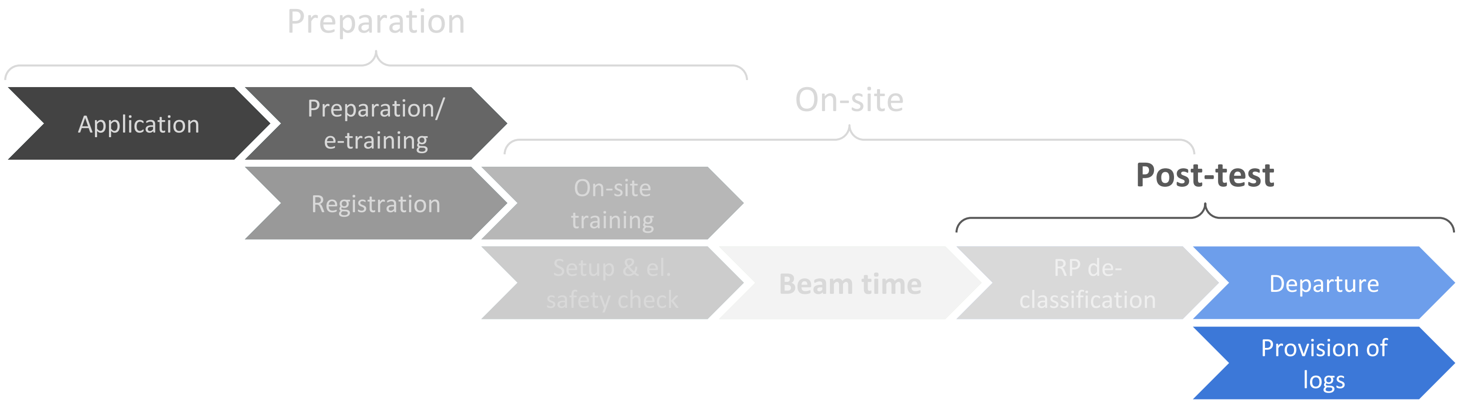
- Initial communication through **application/preparation form**,
- Follow-up communication: newsletter, **user guide**, technical meeting,
- Online training, **registration** and preparation of transport/shipment.

Testing at HEARTS@CERN: user lifecycle and support



- Collection and registration of equipment through shipment service,
- Setup in preparation space and electrical safety check,
- Irradiation facility access for beam time
- Cool-down of activated equipment and RP declassification.

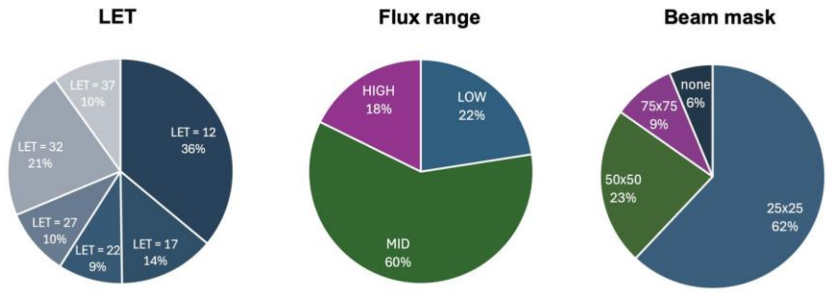
Testing at HEARTS@CERN: user lifecycle and support



- Organization of **transport/shipment return**,
- Provision of **dosimetry logs** for test analysis.

Testing at HEARTS@CERN: a view on the 2024 pilot test campaign with external users

$^{208}_{82}\mathrm{Pb}^{82+}$			FLUKA		SRIM
PS extraction energy [MeV/n]		**Degrader set** [mm]	**Energy** (FWHM spread) [MeV/n]	**LET in Si** (FWHM spread) [MeVcm^2/mg]	**Range in Si** [mm]
1000			908 (10)	12.3 (0.1)	50.0
500			387 (10)	16.5 (0.1)	14.5
	13.0	(10 + 2 + 1)	210 (12)	22.2 (0.5)	6.0
	16.5	(10 + 4 + 2 + 0.5)	153 (14)	26.6 (1.1)	3.5
	18.5	(10 + 8 + 0.5)	113 (14)	31.7 (2.2)	2.3
	19.5	(10 + 8 + 1 + 0.5)	88 (16)	36.3 (3.3)	1.5
	20.0	(20)	77 (17)	40.1 (5.4)	1.2



- CERN welcomed **10 user groups**:
  - 7 industrial, commercial access test teams
  - 3 HEARTS (CERN-external) partners
- 33 users on-site from 7 countries
- **168h of delivered beam time**
- Remainder of beam time used as buffer and R2E scientific purposes.
- ~ 1 facility access per hour

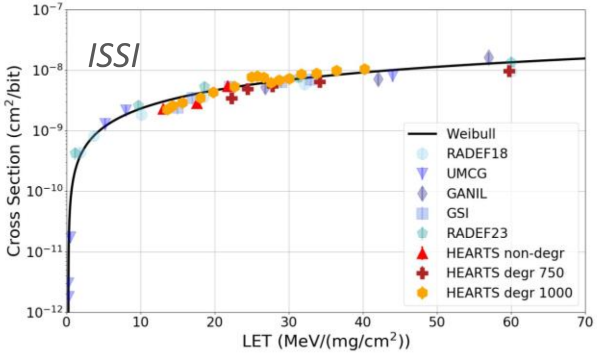
- **User feedback**:
  - "**Professional service of high-energy, heavy ion beam time**, very useful for components that are difficult to test/not possible at "conventional" heavy ion facilities.
  - Collected **suggestions** on each aspect, e.g. increase availability, improve spill pattern, LET points, laser alignment, access modalities, …

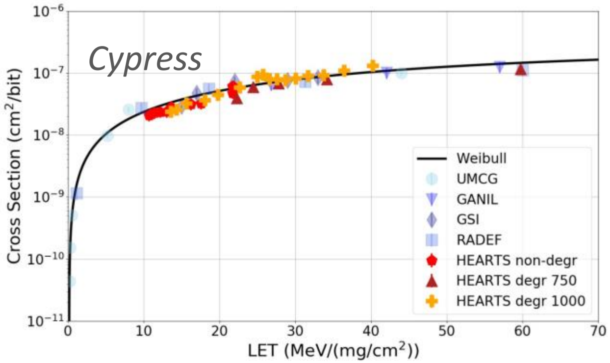
Test results: SEU (HEARTS 2023)

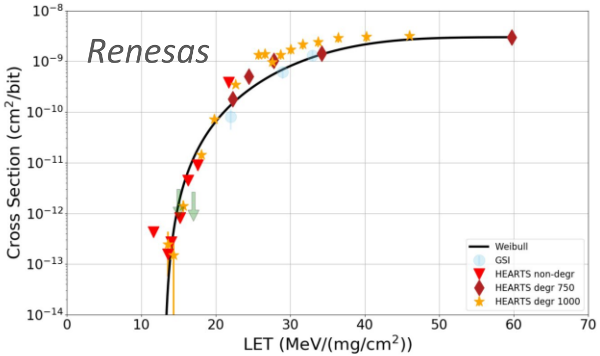
DEVICES UNDER TEST FOR SEU MEASUREMENTS.

Manufacturer	Reference	Date code	Size	Technology
ISSI	IS61WV204816BLL-10TLI	1650	32 Mbits	40 nm
Cypress	CY62167GE30-45ZXI	1731	16 Mbits	65 nm
Renesas	RMLV0816BGSA-4S2	9062	8 Mbits	110 nm

- **SRAM SEU cross sections** as a function of, **collected in multiple heavy-ion facilities** (cross sections error bars: 95% confidence level taking into account 10% fluence uncertainty),
- **Agreement** obtained for ISSI and Cypress (de-lidded, threshold below 1 MeVcm^2/mg), i**s excellent for HEARTS@CERN primary energies, degraded energies and data from lower energy facilities**.
- Renesas (critical charge hardening: 13 MeV/cm^2/mg threshold) Weibull fit obtained by fitting GSI and HEARTS@CERN data shows higher spread. Data should be shifted to higher LETs since it was tested with package with unknown thickness.





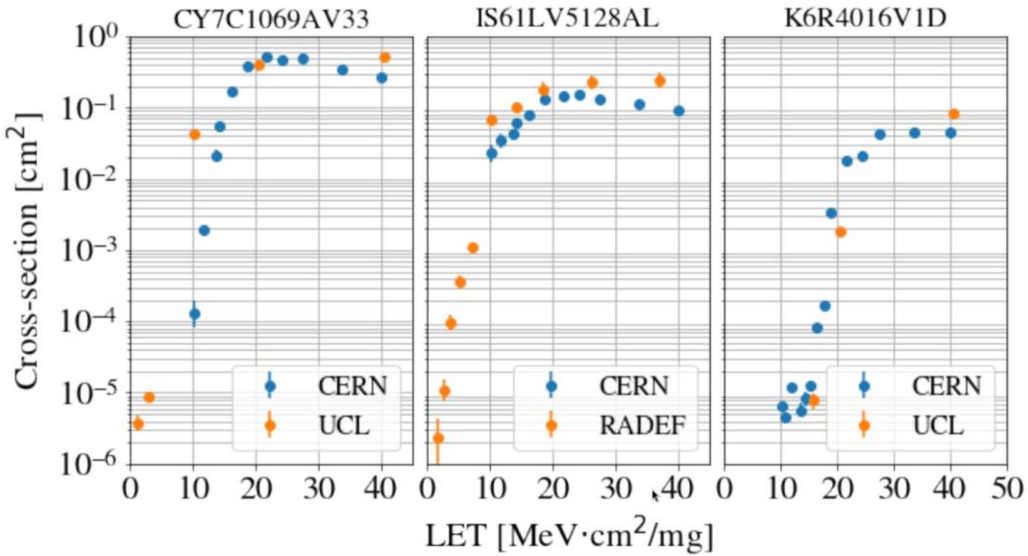


A. Coronetti et al., "Results of Single Event Effect Testing at the New HEARTS@CERN High-Energy Heavy Ion Facility at CERN," 2024 IEEE Radiation Effects Data Workshop (REDW) (in conjunction with 2024 NSREC), Ottawa, ON, Canada, 2024, pp. 1-9, DOI: 10.1109/REDW61286.2024.10759246.

Test results: SEL (HEARTS 2023)

DEVICES UNDER TEST FOR SEL MEASUREMENTS.

Manufacturer	Reference	Date code	Size [Mbit]	Technology [nm]
ISSI	IS61LV5128AL	1416	16	180
Cypress	CY7C1069AV33	1237	4	180
Samsung	K6R4016V1D	922	4	180

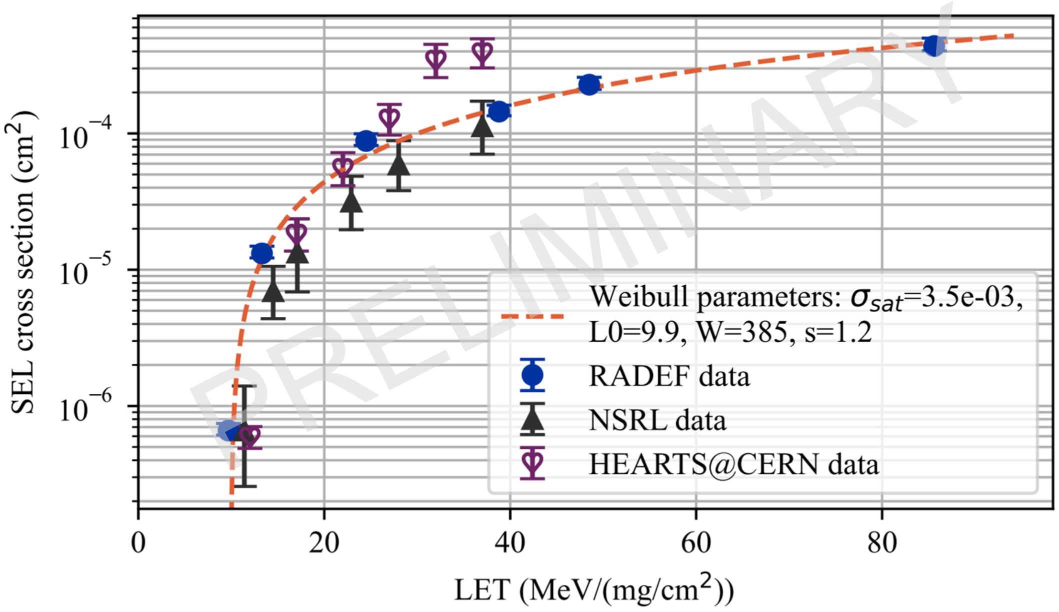


- **SEL cross-sections** as function of LETs resulting from a combination of primary beam energies and degraded beam energies.
- Tested at room temperature, under normal irradiation and 3.3 V bias, original packaging.
- ISSI cross-section is almost saturated for every LET value given its low threshold.
- Samsung threshold is approximately 12 MeVcm^2/mg, being the cross-section likely dominated by ion nuclear events for lower LETs.
- **Very good level of agreement with lower energy heavy ion facilities** (UCL and RADEF).

A. Coronetti et al., "Results of Single Event Effect Testing at the New HEARTS@CERN High-Energy Heavy Ion Facility at CERN," 2024 IEEE Radiation Effects Data Workshop (REDW) (in conjunction with 2024 NSREC), Ottawa, ON, Canada, 2024, pp. 1-9, DOI: 10.1109/REDW61286.2024.10759246.

Test results: SEL (HEARTS 2024)

- **AD7801 DAC (5V VCC) was tested for SELs** at HEARTS@CERN, NSRL and RADEF, the cross section results are the combined results of eight tested DUTs.
- Devices tested (8) produced by the manufacturers with the same date code, and thus likely originating from the same production lot.
- Analysis is still ongoing for the data sets of HEARTS@CERN and NSRL: the two high-LET data points of the HEARTS@CERN data set are significantly above the RADEF and NSRL data sets, which require further analysis.

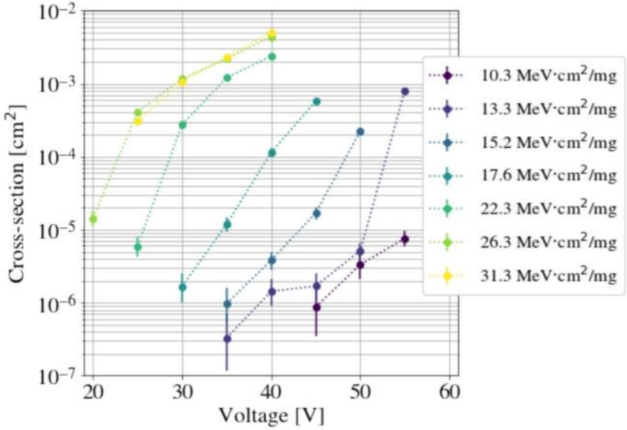


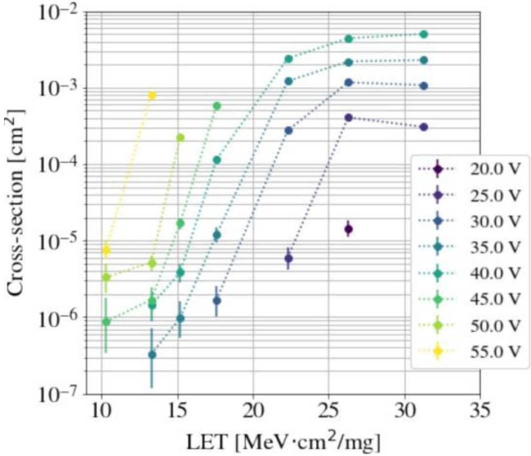
Test results: SEB (HEARTS 2023)

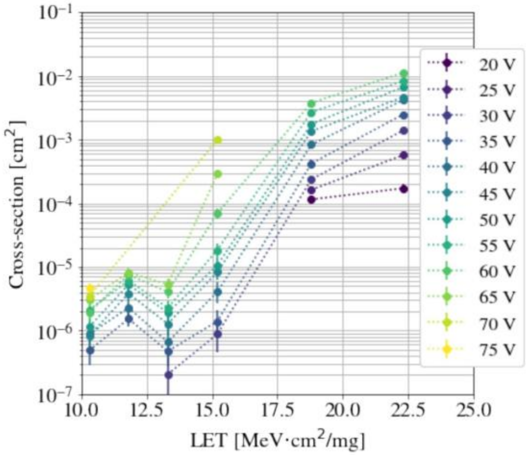
- **All devices were tested for SEBs with original packaging** at room temperature, normal incidence, biased in off-mode with the gate grounded while the drain voltage was kept constant; 1 MΩ shunt resistor and 100 pF decoupling capacitors in series with a 1 kΩ series resistor.
- As the beam LET increases, the threshold voltage to induce SEBs decreases, while the cross-section slope increases, reaching quickly saturation values.
- For higher voltages, the cross-section saturation value increases, while the LET threshold becomes smaller.

DEVICES UNDER TEST FOR SEB MEASUREMENTS.

Manufacturer	Reference	Date code	Vmax [V]	Imax [A]
Infineon	IRFR4105ZPbF	P548G-1N-UC	55	30
STMicroelectronics	STD10NF10T4	GF105629	100	13

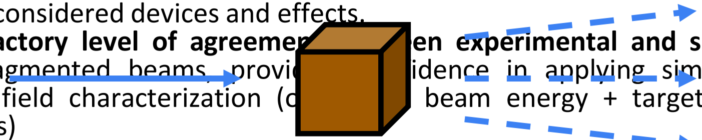


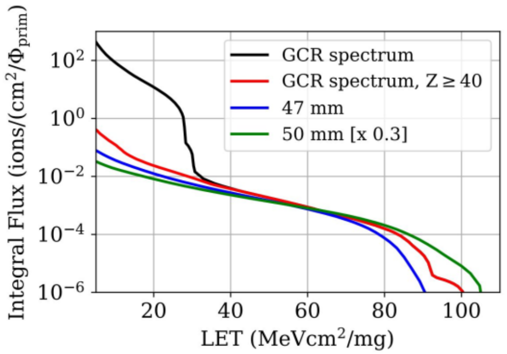


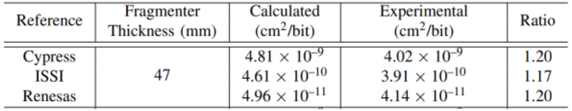


R&D: fully fragmented testing

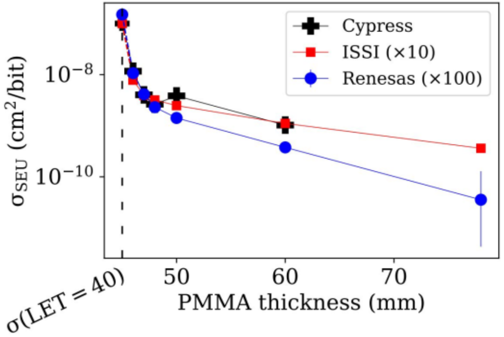
- Novel approach that simultaneously ensures a high LET as well as high penetration with a continuous LET profile as opposed to single LET testing → **highly advantageous for complex components for which large uncertainties on the LET value at the sensitive location exist**.
- Utilizing the resemblance of the spectrum produced by a Pb beam + target to the GCR spectrum.
- Comparing:
  - Experimentally obtained SEE rates.
  - MC simulated fragmented fields and known LET response of the considered devices and effects.
- A **satisfactory level of agreement between experimental and simulated SEEs** from fragmented beams, provide confidence in applying simulations more broadly field characterization (concerning beam energy + target material and thickness)
- The SEE rate attenuation is relatively small in matter for a fragmented high-energy, ion beam, which could open the door to **ground level testing with fragmented beams**, with very similar LET spectra to those in space, and **high penetration capacity, i.e. small changes in LET spectrum and SEE rate in the mm range**.
- R&D activities are ongoing, further development and validation efforts needed before quantitative SEE testing can be carried out.





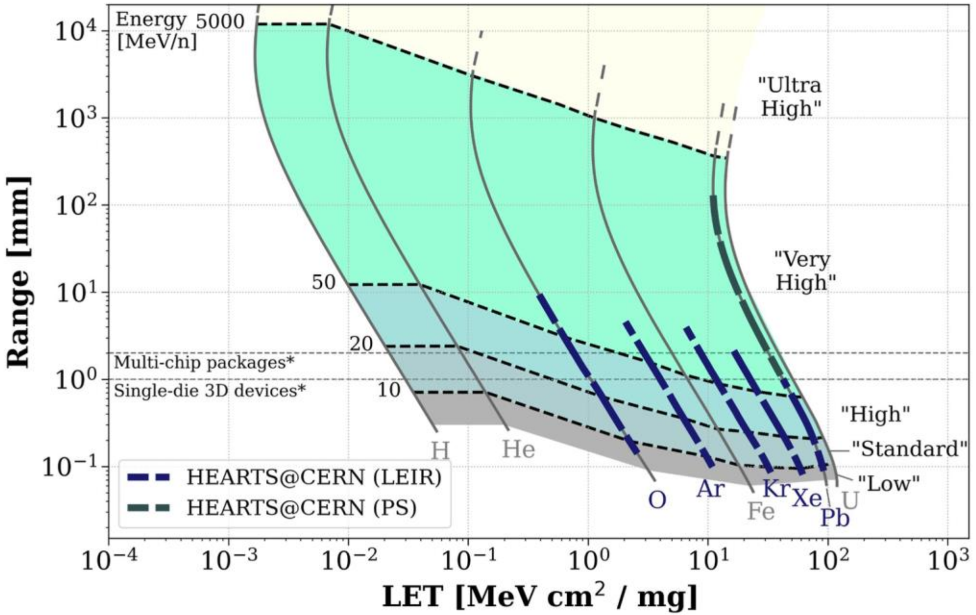


Reference	Fragmenter Thickness (mm)	Calculated (cm^2/bit)	Experimental (cm^2/bit)	Ratio
Cypress	47	4.81×10^{-9}	4.02×10^{-9}	1.20
ISSI		4.61×10^{-10}	3.91×10^{-10}	1.17
Renesas		4.96×10^{-11}	4.14×10^{-11}	1.20



HEARTS@CERN: (near) future prospects

- Study kicked off to estimate the **feasibility of constructing a dedicated high-energy, heavy ion testing facility at CERN**, with beams extracted from the **LEIR** (in addition to existing PS-derived facility).
- Requirements:
  - More versatile ion source,
  - HW upgrades in LEIR,
  - Dedicated beam line and experimental area.
- Benefits:
  - Much higher accelerator/facility availability (up to **2000 h/y**).
  - Extended LET range offered (down to 0.1 MeVcm²/mg level)
- **Space sector partners, expertise and external funding needed.**



How to apply for HEARTS@CERN beam time?

Contact the facility coordinators:
natalia.emriskova@cern.ch and
andreas.waets@cern.ch

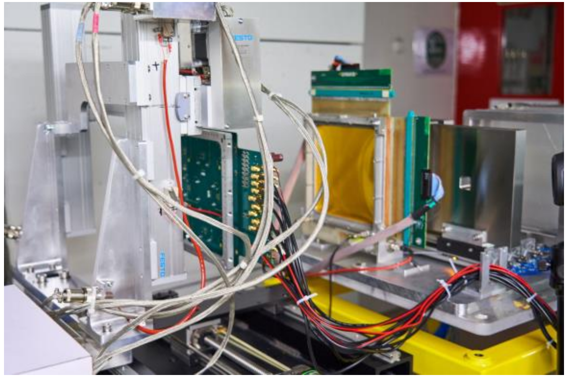
Or

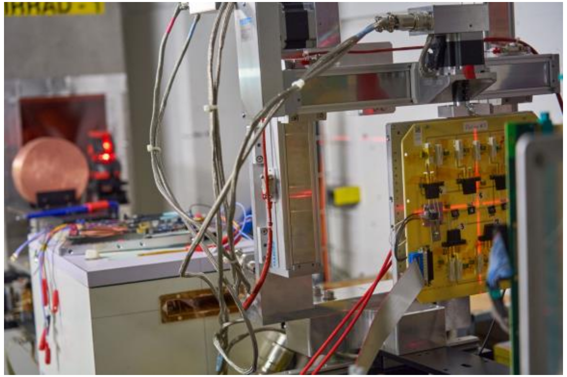
Keep an eye on the next RADNEXT call in may: **radnext.web.cern.ch**

RAD NEXT

Next availability

November 2025





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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