PS: Development and Characterization of HEARTS beams

4th February, 2025

MD Days

https://indico.cern.ch/event/1488714/

Marc Delrieux, Kacper Bilko, Pablo Arrutia, Andreas Waets, Natalia Emriskova, Rubén García Alía (on behalf of the HEARTS@CERN and PS OP teams)

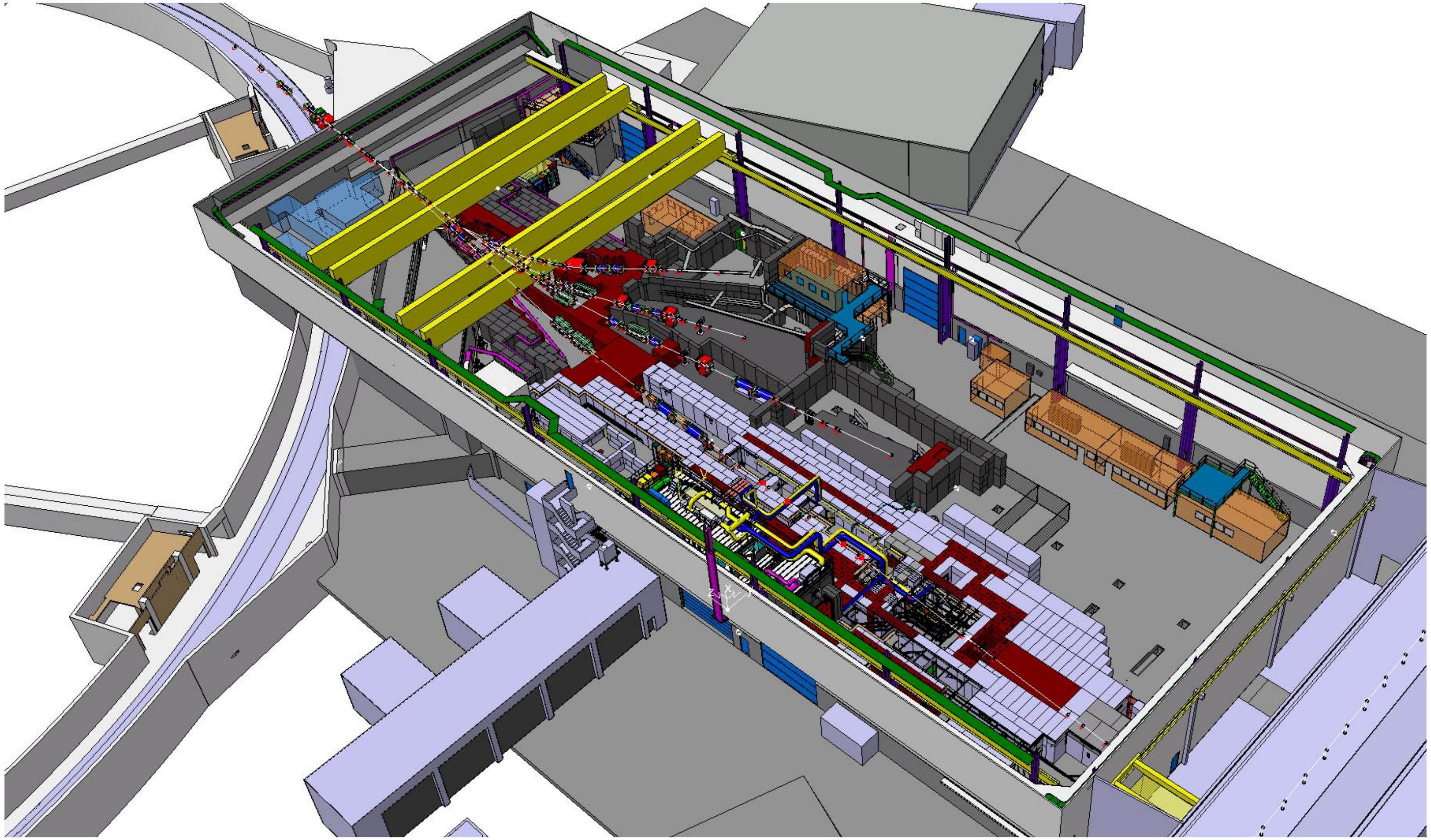
Funded by the European Union

HEARTS is a project funded by the European Union under GA No 101082402, through the Space Work Programme of the European Commission.

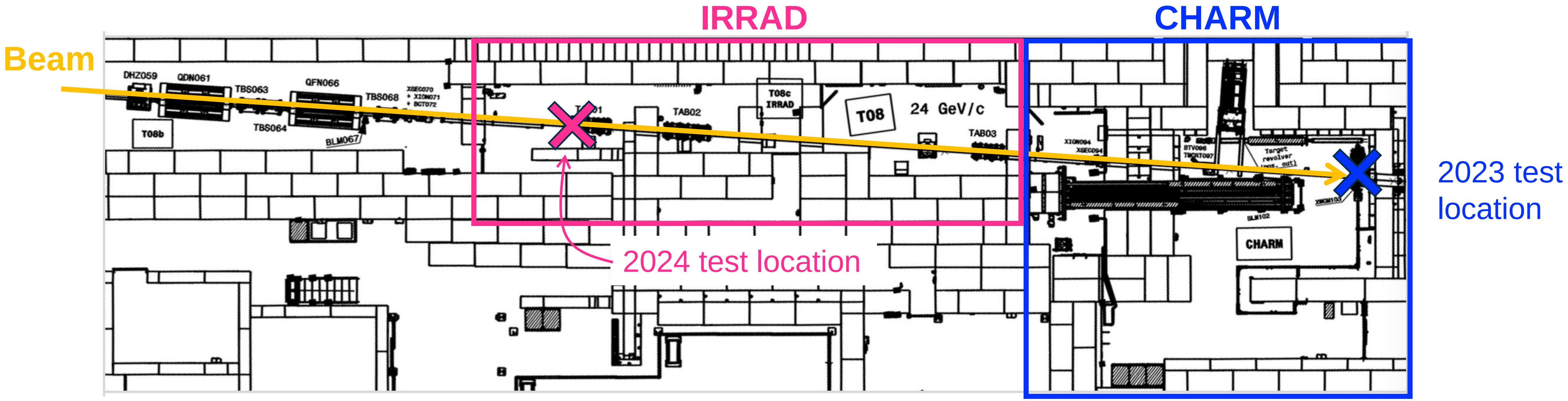
Introduction and Motivation

- Heavy ion irradiation of electronics is necessary for the qualification of space (and accelerator!) semiconductors against Single Event Effects
- Tests are typically performed at cyclotron facilities, with energies (ranges) in the 10-20 MeV/n (100-200 µm in silicon) interval
- Testing at larger energies and ranges, of >100 MeV/n and >1 mm in silicon respectively, is highly advantageous for state-of-the-art microelectronics architectures
- Linked to this interest, since 2021 (and even 2017, in more exploratory mode) the development of high-energy heavy ion testing of electronics at CERN has been supported first by ESA and then by the European Commission, through the **HEARTS EU project**)

Where? Slow-extracted PS heavy ions to East Area

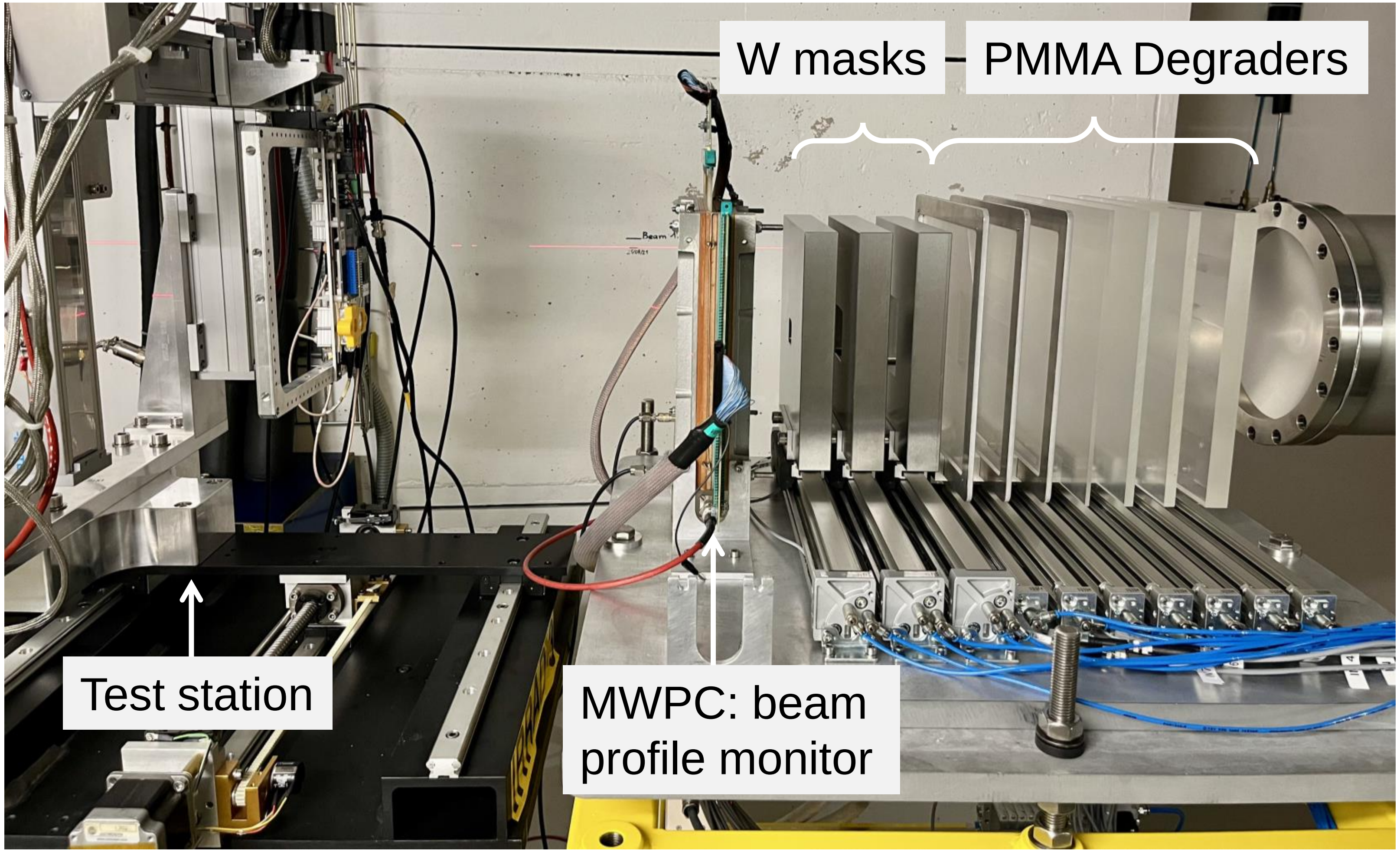


Where? HEARTS 2024 migration upstream



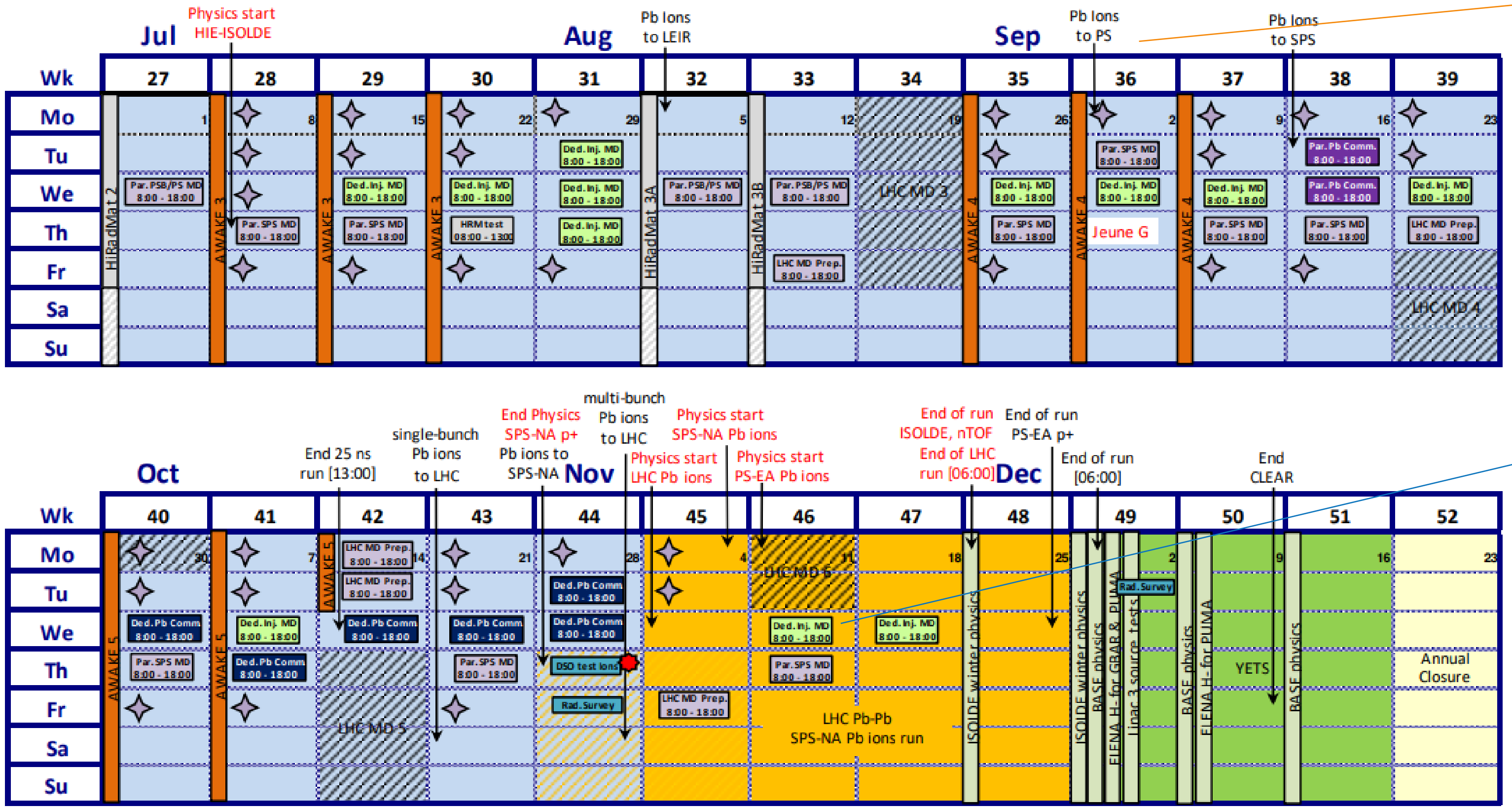
- From 2024, HEARTS at CERN is relocated 30m upstream from CHARM to IRRAD facility
- Beam taken at the exit of the vacuum pipe ⟶ improved beam quality, lower energies
  ⟶ several upgrades needed

Where? HEARTS at IRRAD 2024



BEAM

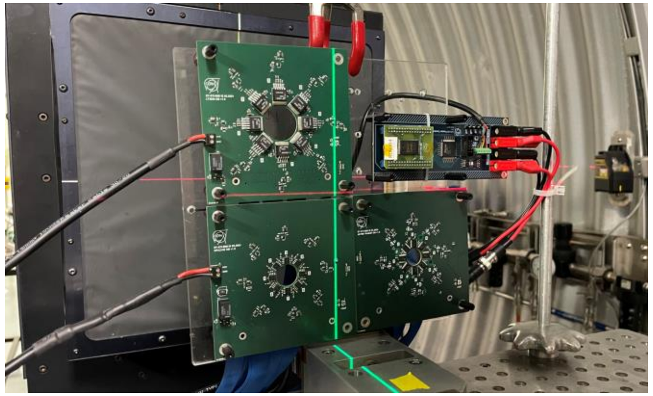
When? Schedule considerations



Start of PS HEARTS MDs to East Dump (i.e. in parallel with protons to T8), plus T8 time during proton cool down (Tue-to-Wed nights)

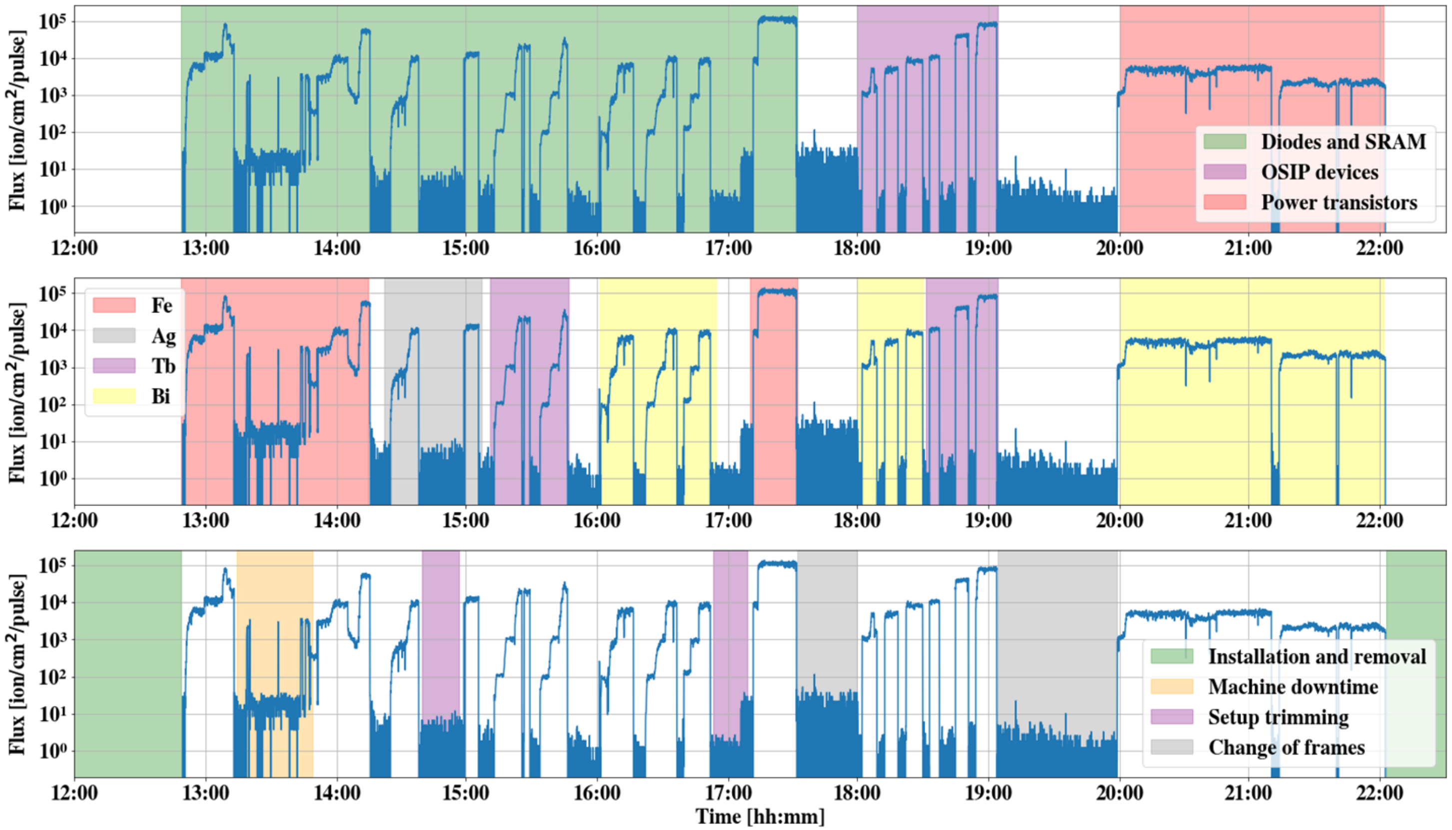
Actual dedicated run from Nov 13th to Dec 2nd; first beam commissioning, calibration and validation and then, as of Nov 19th, pilot user run

How? Example of high-energy heavy ion testing at NSRL in BNL

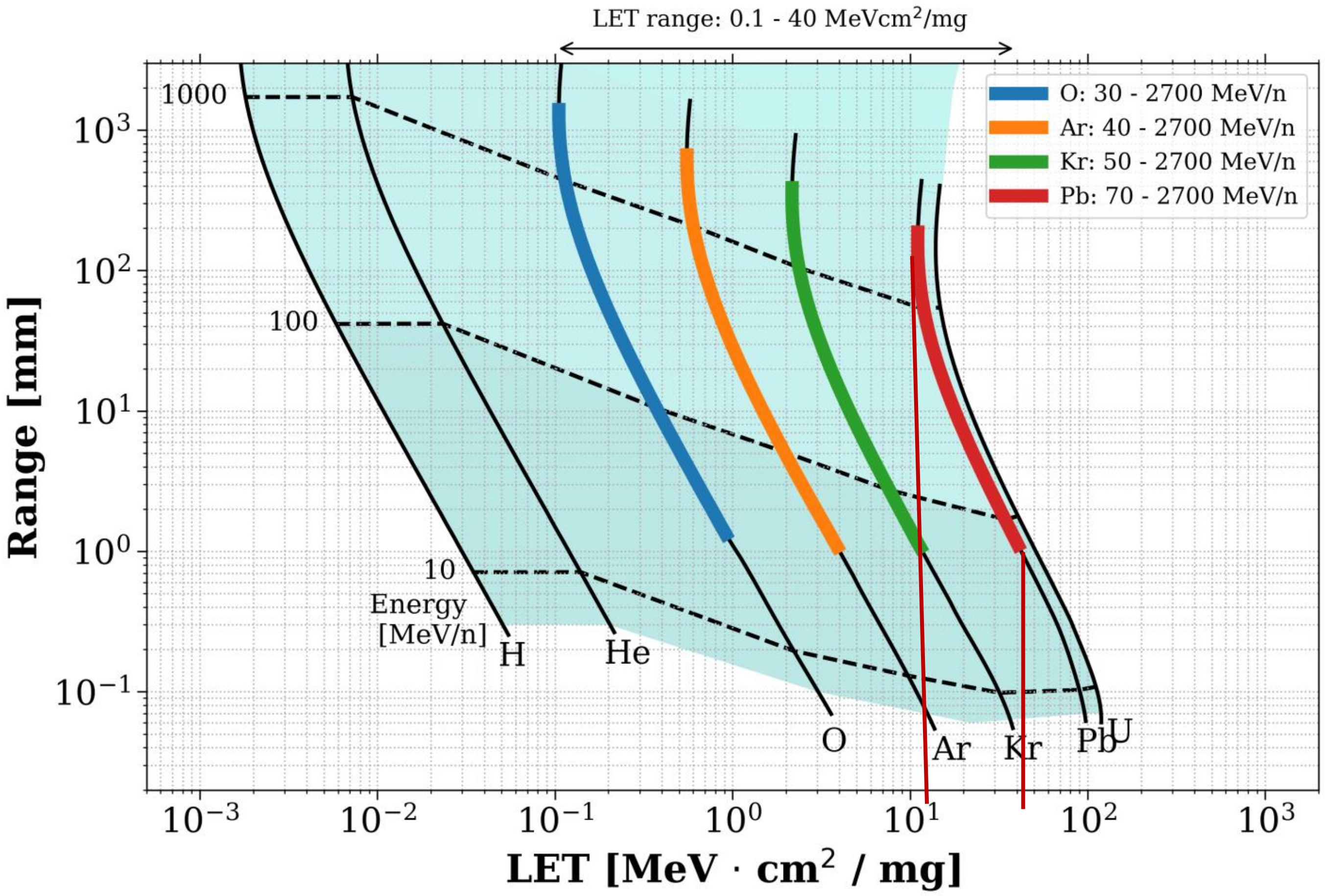


Usual SEE tests: fast switching of flux, LET and setup

Real-time device response, very dynamic experience!



How? Different LETs through different lead energies



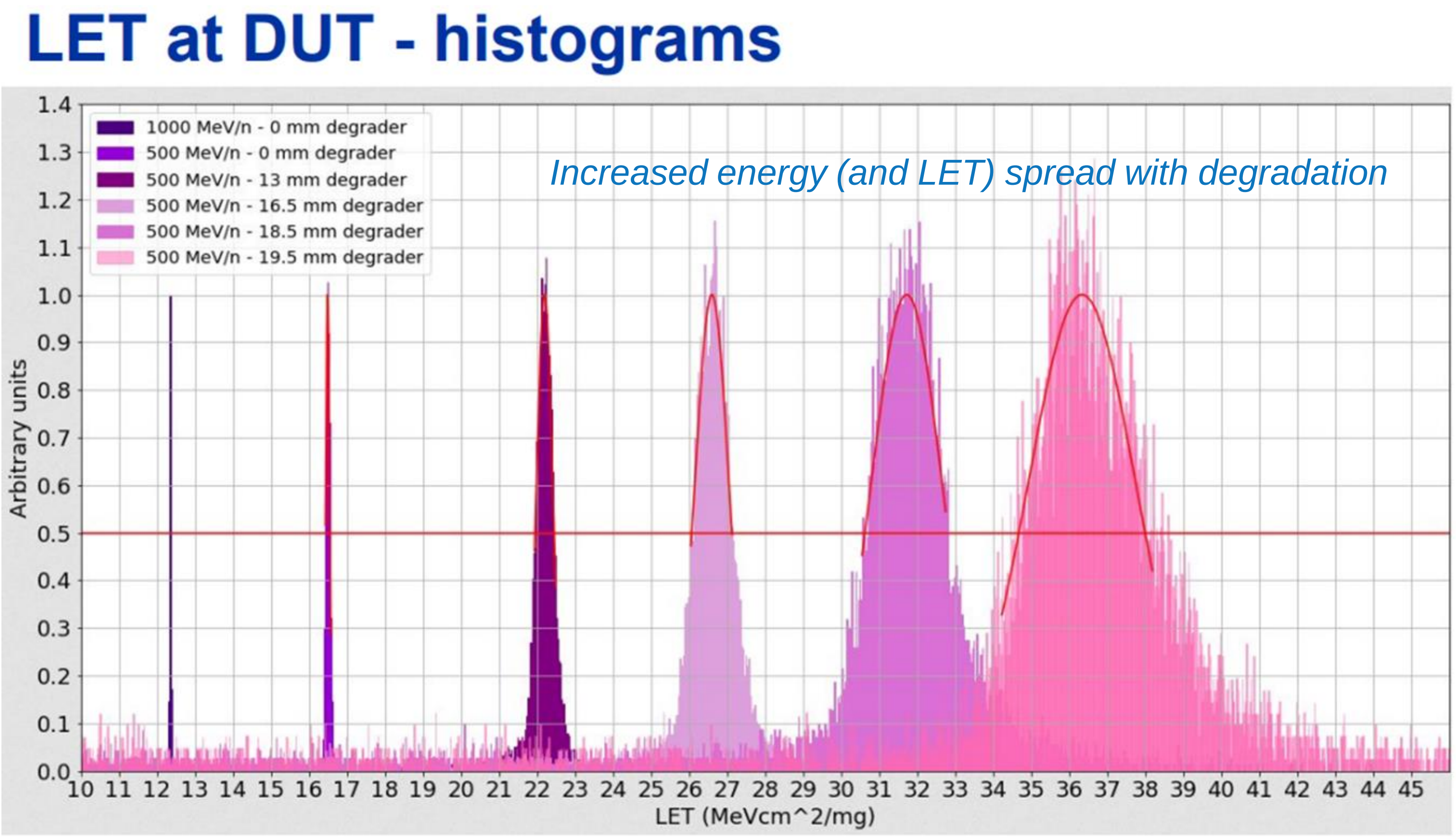
Typical for cyclotrons: constant energy per nucleon; change of LET through change of ion species

At HEARTS@CERN: single ion species, and change in LET done through energy, achieving a ~12-37 MeVcm^2/mg coverage (ideal: 0.1-60 MeVcm^2/mg)

How? Different LETs through different lead energies

$^{208}_{82}Pb^{82+}$		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

How? Different LETs through different lead energies

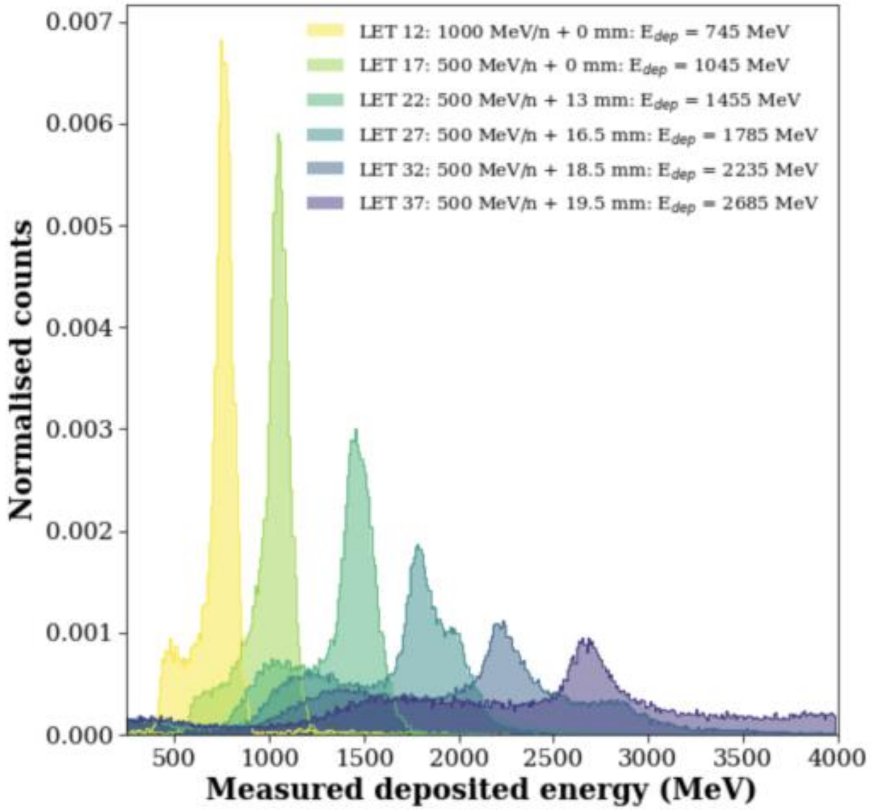


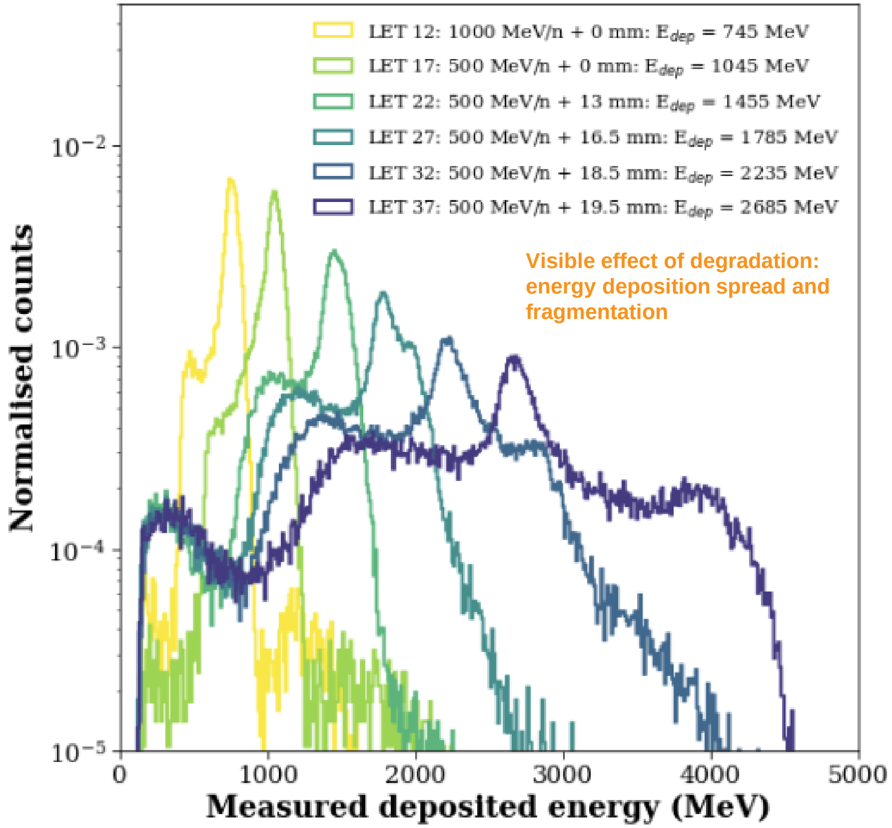
HEARTS

CERN SY Accelerator Systems

CERN Knowledge Transfer Accelerating Innovation

How? Different LETs through different lead energies

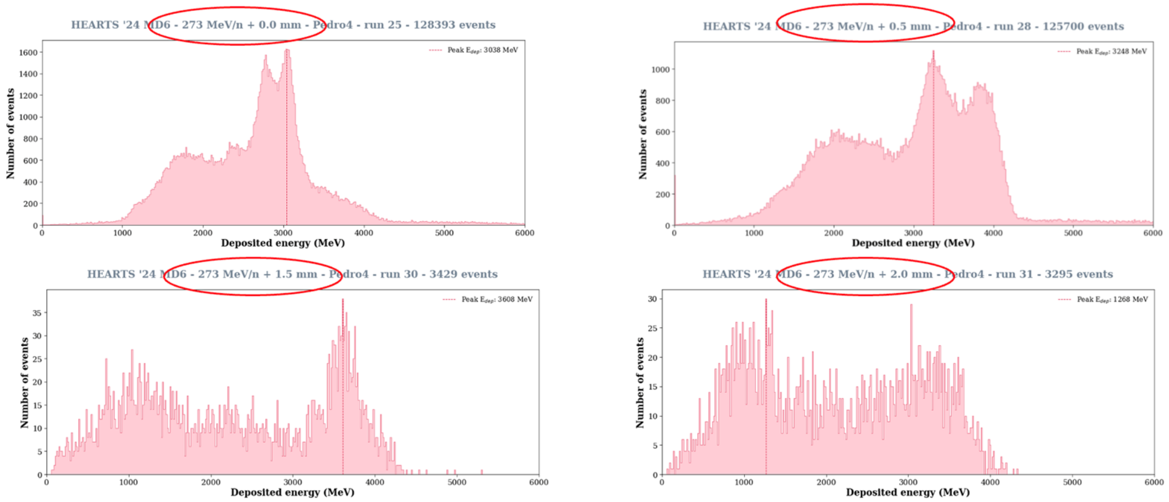


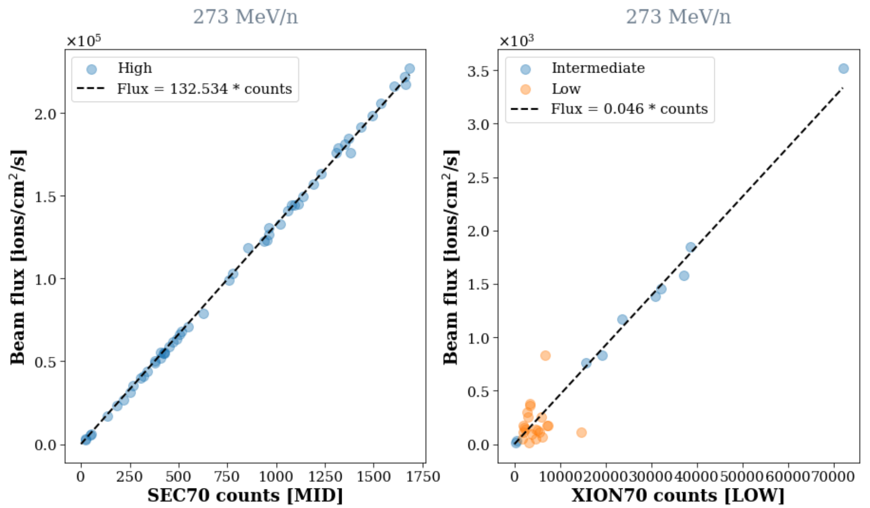


“Bonus beams” (maybe for 2025?)

- Two additional energies developed and calibrated: 350 and 273 MeV/n
- Optimal primary and degraded energy combination to be re-evaluated for 2025

273 MeV/n + degraders

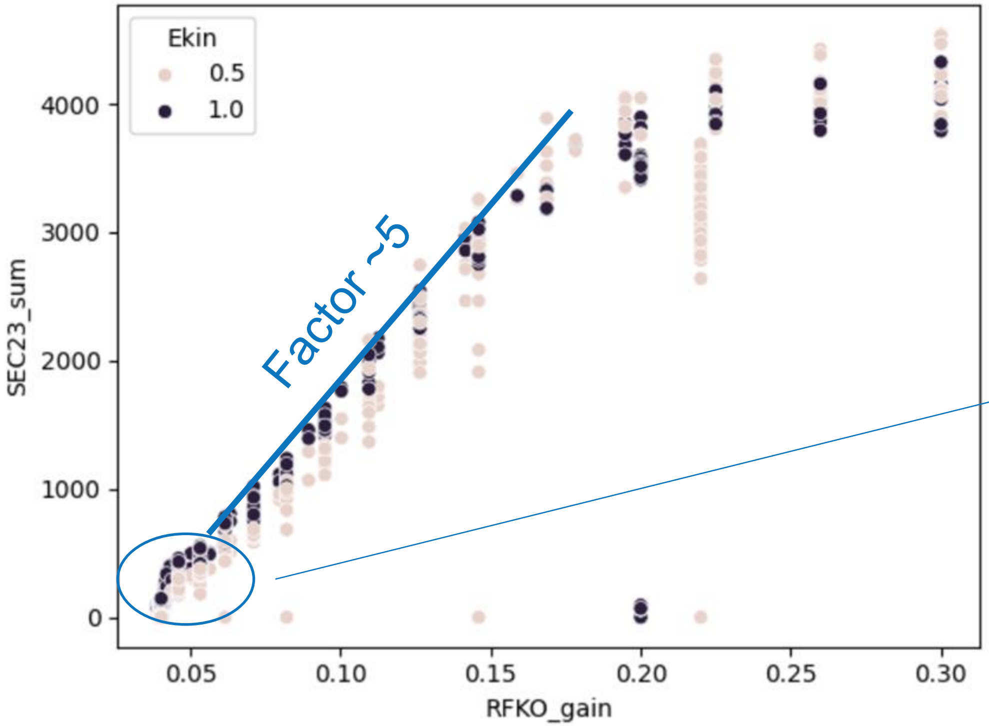


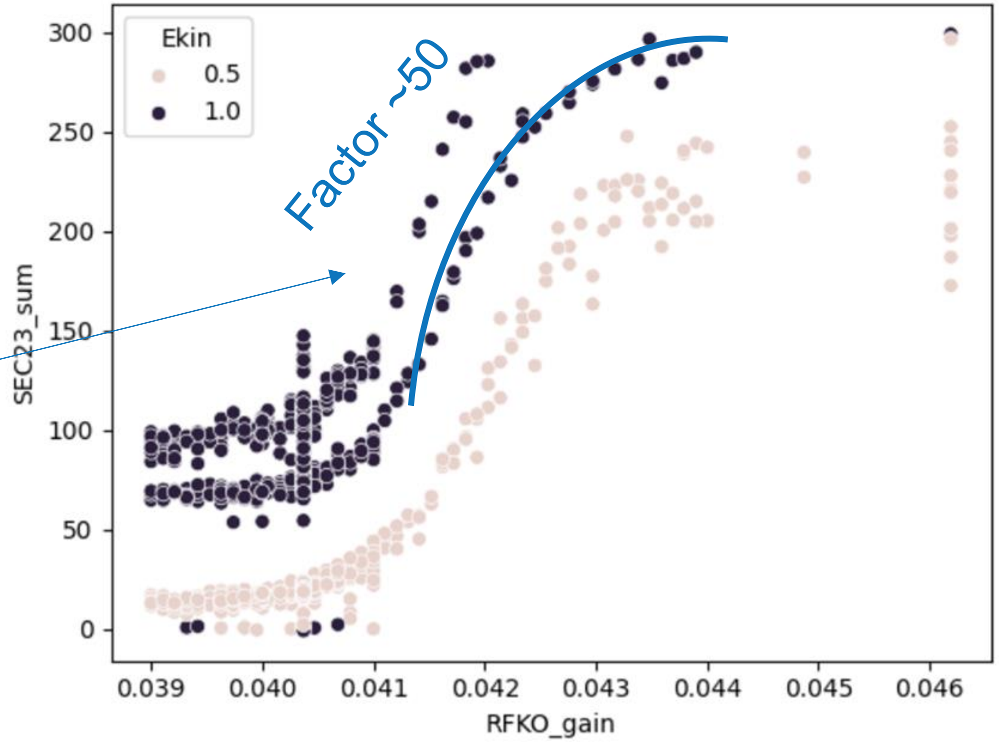


Challenge for lower energies: energy loss in the beam line is not linear, and increases significantly (in relative terms) for lower energies, impacting transmission, position, etc.

How? Requirement: flux control over 3 orders of magnitude

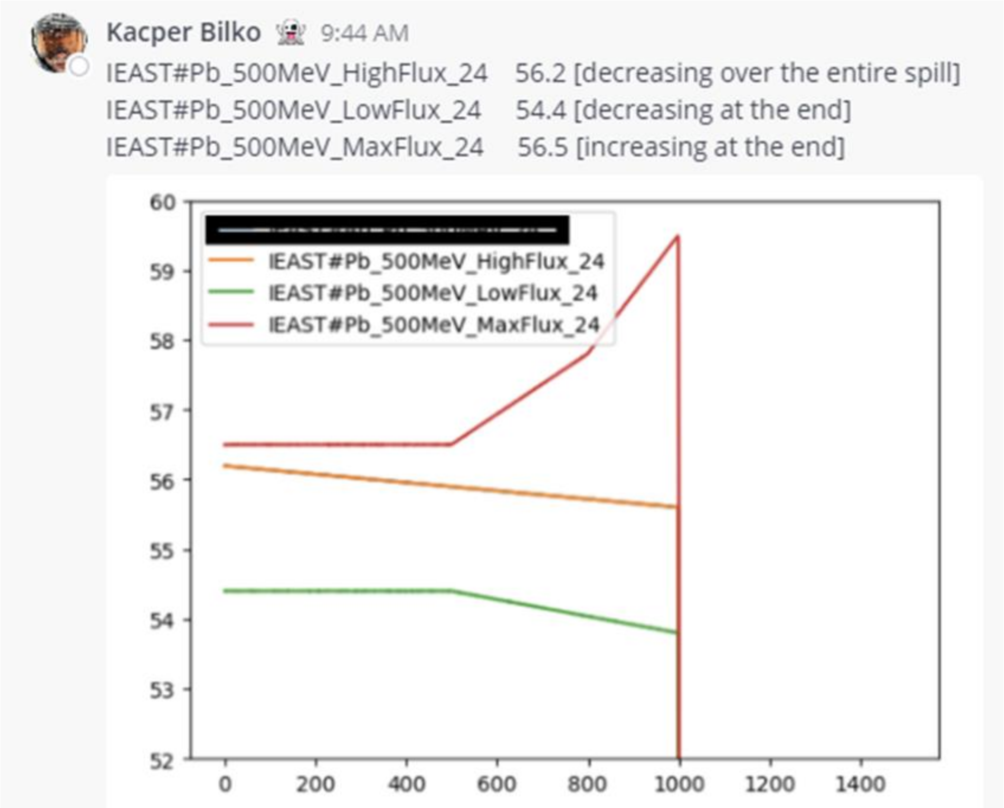
By varying the RFKO gain, we achieved a factor ~5 in the linear regime, and a factor ~50 if we considered also the region of stronger intensity dependence with RFKO

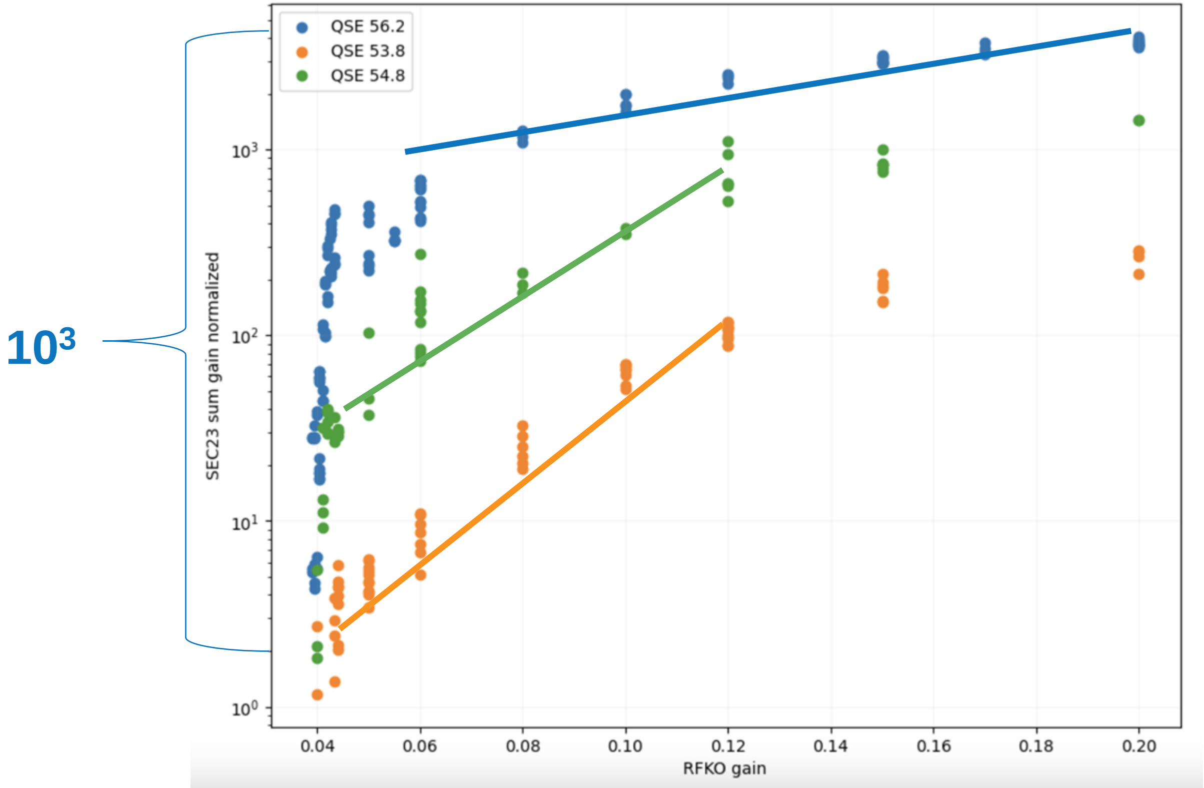




How? Requirement: flux control over 3 orders of magnitude

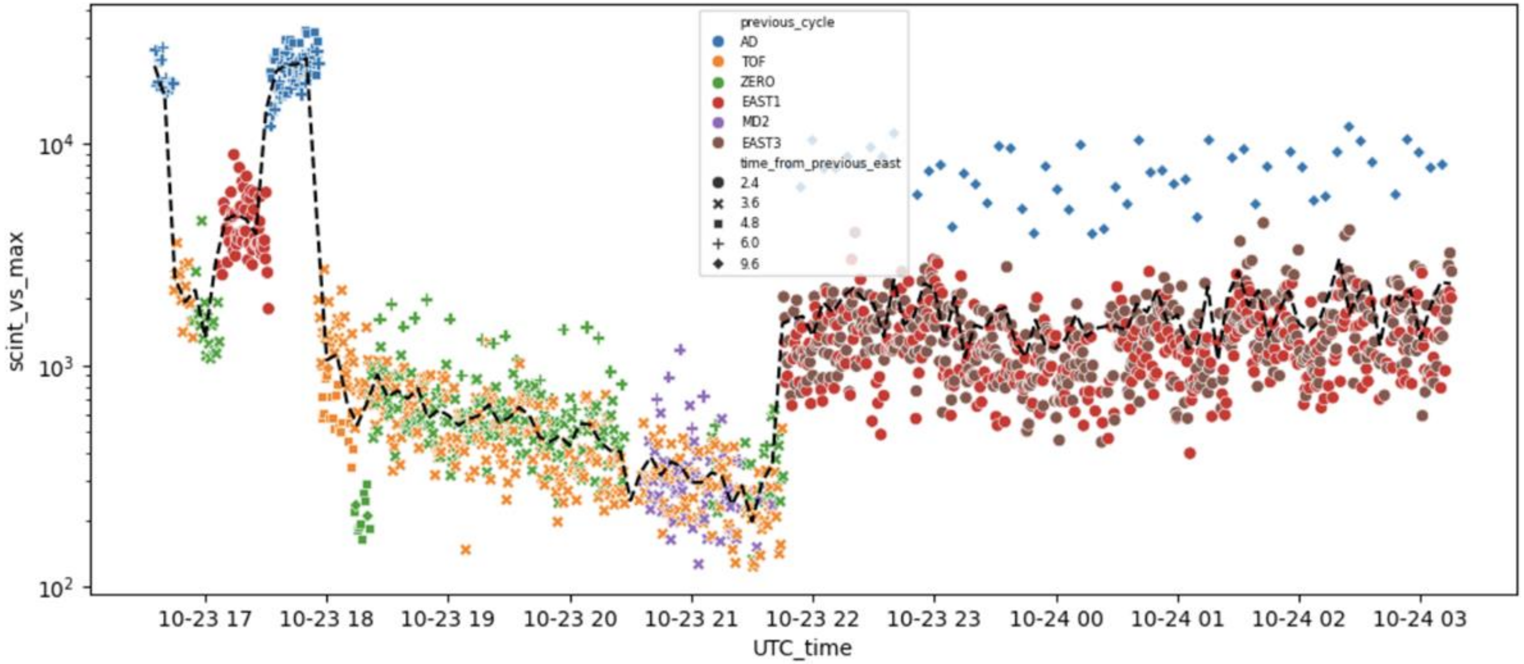
Extra knob used in combination with RFKO: QSE current → achievement of necessary flux range, with required level of control

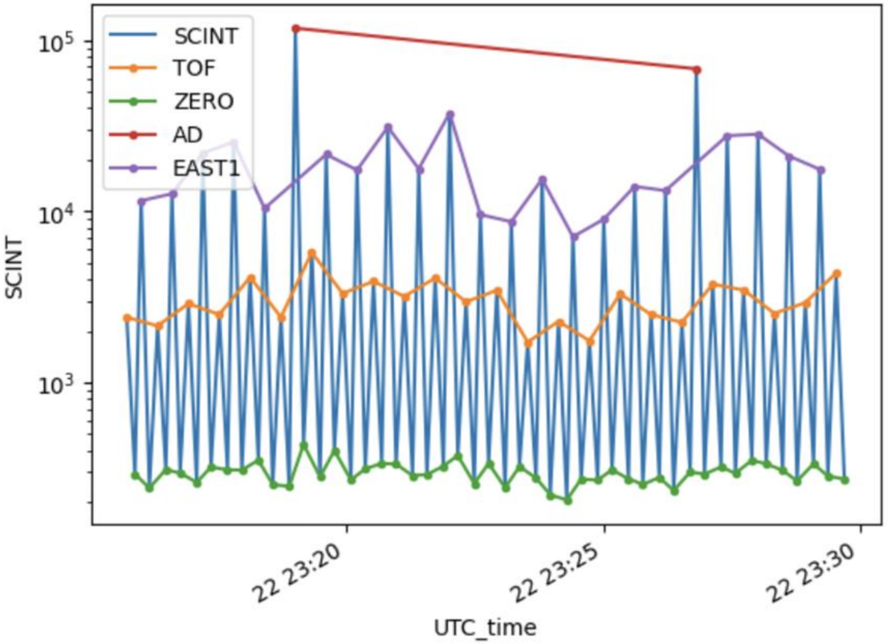




How? Requirement: flux control over 3 orders of magnitude

Challenge: very strong dependence of flux with super-cycle composition



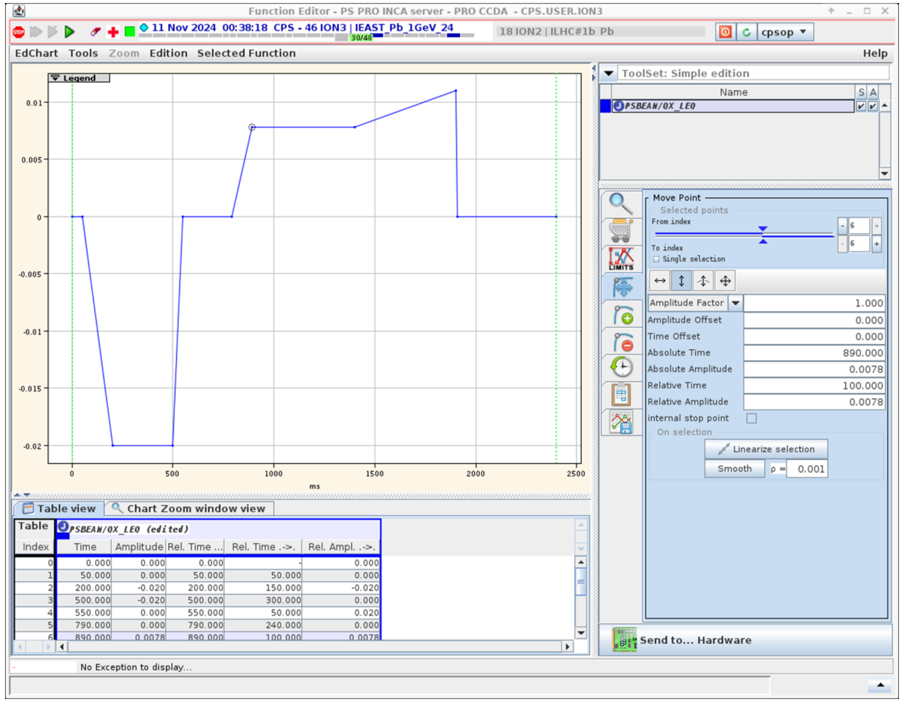


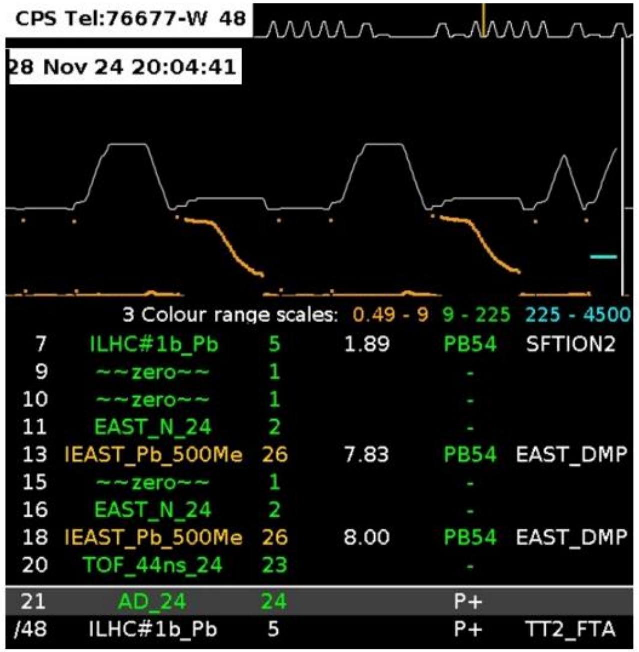
SY Accelerator Systems

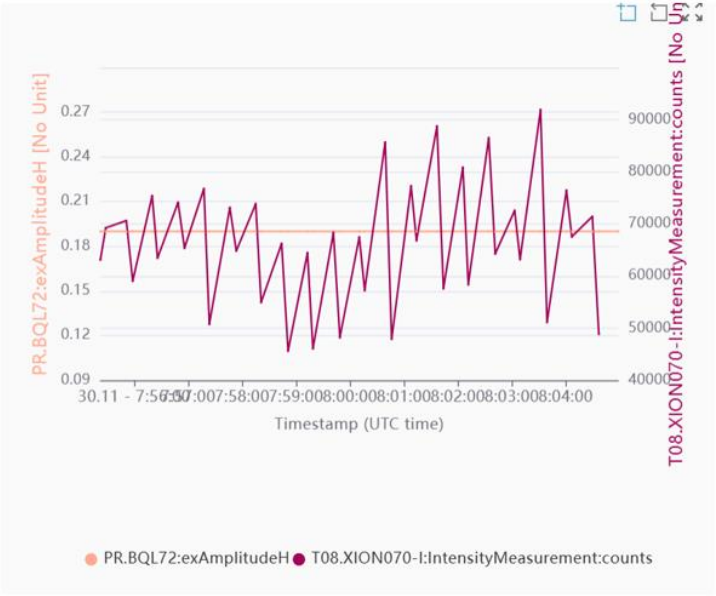
Knowledge Transfer
Accelerating Innovation

How? Requirement: flux control over 3 orders of magnitude

Solution: LEQ knob instead of QSE, plus more regular placement in super-cycle (ideally behind another EAST) → factor ~2 spill-to-spill variability, which is not great for users, but still acceptable







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Maximum flux

Table 8: Maximum flux (i.e. corresponding to full intensity extraction and maximum relative transmission) during the HEARTS@CERN 2024 run per beam type.

PS Energy (MeV/n)	Energy@DUT (MeV/n)	LET@DUT ($MeVcm^2/mg$)	Maximum flux (10^5 ions/cm^2/spill)
1000	908	12.3	8.7
500	387	16.5	2.3
	210	22.2	2.0
	153	26.6	1.6
	113	31.7	1.4
	88	36.3	0.8

Transmission loss with PS energy (to be further analyzed and, if possible, improved)

Transmission loss due to impact of degraders

Minimum flux and flux (intra and inter-spill) uniformity

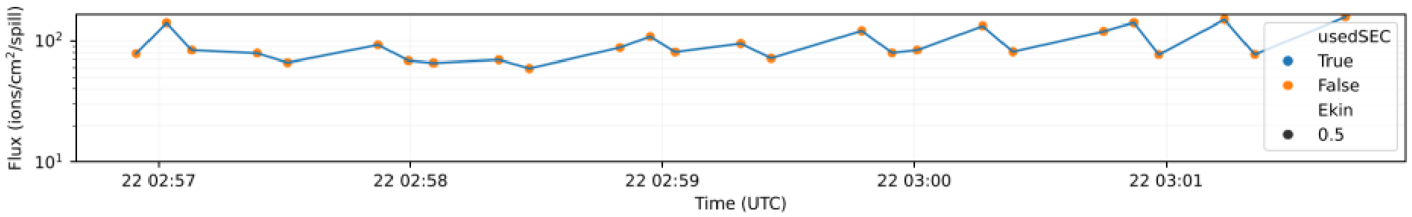

Figure 8: Flux evolution during Run 68 of 2024 User C, as provided to the users in their dosimetry logs. The run consisted of 26 spills with a total run fluence of 2.48×10^3 ions/cm^2.

← *Example of minimum flux and **spill-to-spill** flux stability*

*Example of **intra-spill** intensity uniformity* →

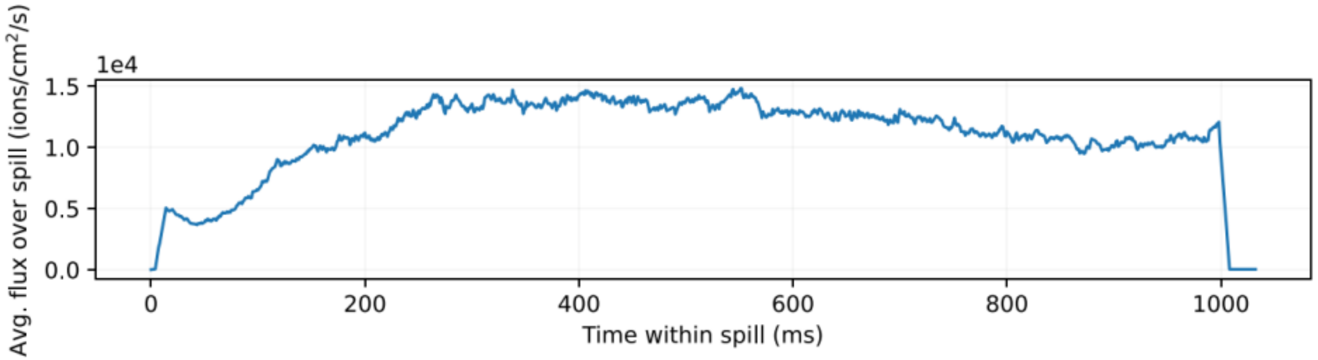

Figure 9: Example of spill profile, corresponding to Run 44 of User C. The maximum spill flux (considering a time binning of 10 ms) is roughly 1.5×10^4 ions/cm^2/s, while the average spill flux is 1.16×10^4 ions/cm^2/s (or per spill, as the spill duration is 1 s.

Beam profile – broad beam without scanning

- OK for up to 7.5 x 7.5 cm^2 (with a skew in the horizontal direction we will try to improve in 2025)
- 10 x 10 cm^2 seems possible (albeit with a flux reduction) but going beyond that is in principle incompatible with the beam line optics and aperture restrictions

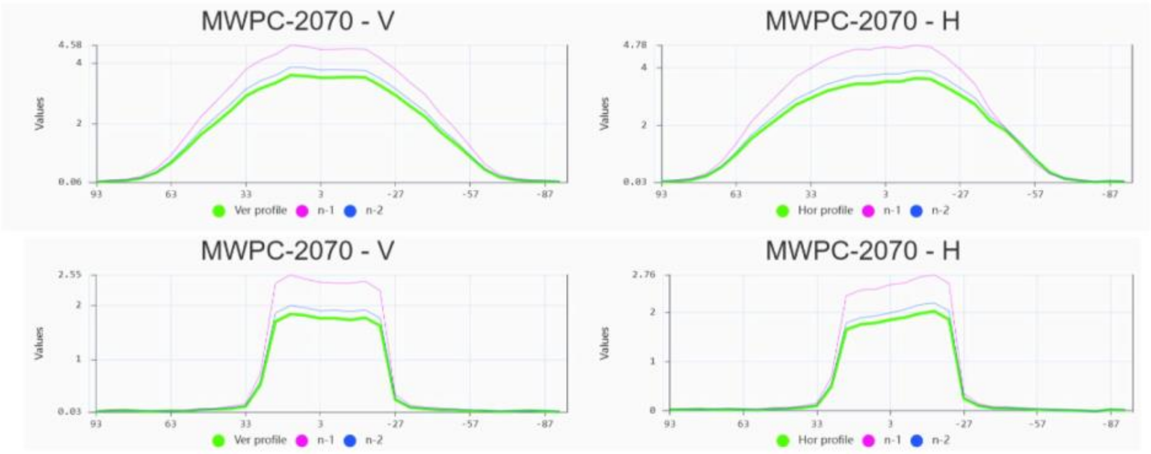

Figure 10: Effect of the 5×5 cm^2 mask (bottom) on broad Gaussian beam (top). The green trace corresponds to the most recent spill, whereas the pink and blue one correspond to the two previous spills.

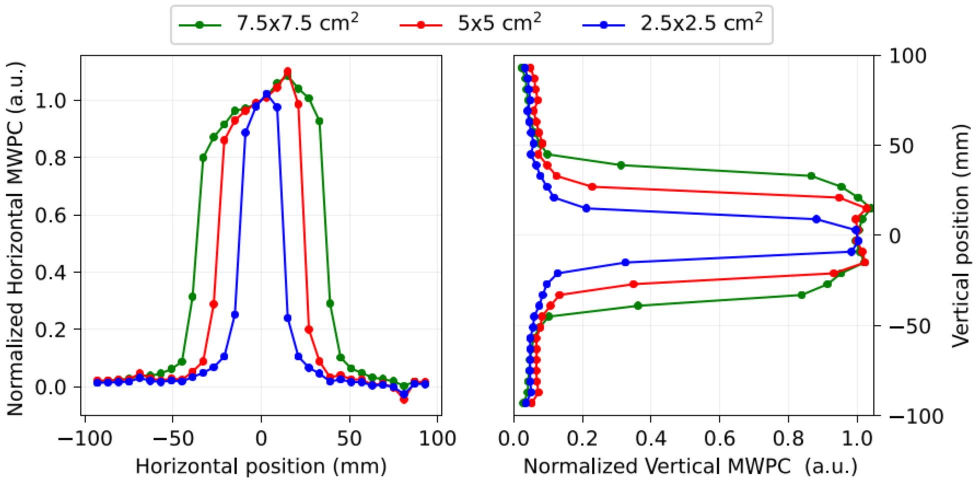

Figure 11: Beam profiles with the three different mask options during the HEARTS@CERN 2024 user run.

Beam related objectives for 2025 (and beyond)

- Beam energy:
  - Requirements already met in 2024 to a very large extent
  - Likely having more than 2 PS energies (e.g. 3-4), extending to lower energies (~250 MeV/n) will be useful to improve beam quality
- Beam spatial profile:
  - 7.5 x 7.5 cm^2 seems already at the limit of what can be reasonably achieved with the necessary homogeneity and maximum flux, and also meets user requirements to a large extent
- Beam flux:
  - Spill-to-spill intensity stabilization will be a priority
    - We plan to work on this (and other beam aspects) already with "ion-equivalent" low energy proton cycles
  - Checking if there is margin to improve spill rate (without impacting other PS users)
- Some prospects beyond LS3 (very conceptual and hypothetical at this stage!):
  - More beam time (presently very constrained) → dedicated beam line and facility
  - Fast (~15min) switches between ions → synergies with Ion Complex Upgrade (ICU)

Thanks for your attention!
Questions?

Funded by the European Union

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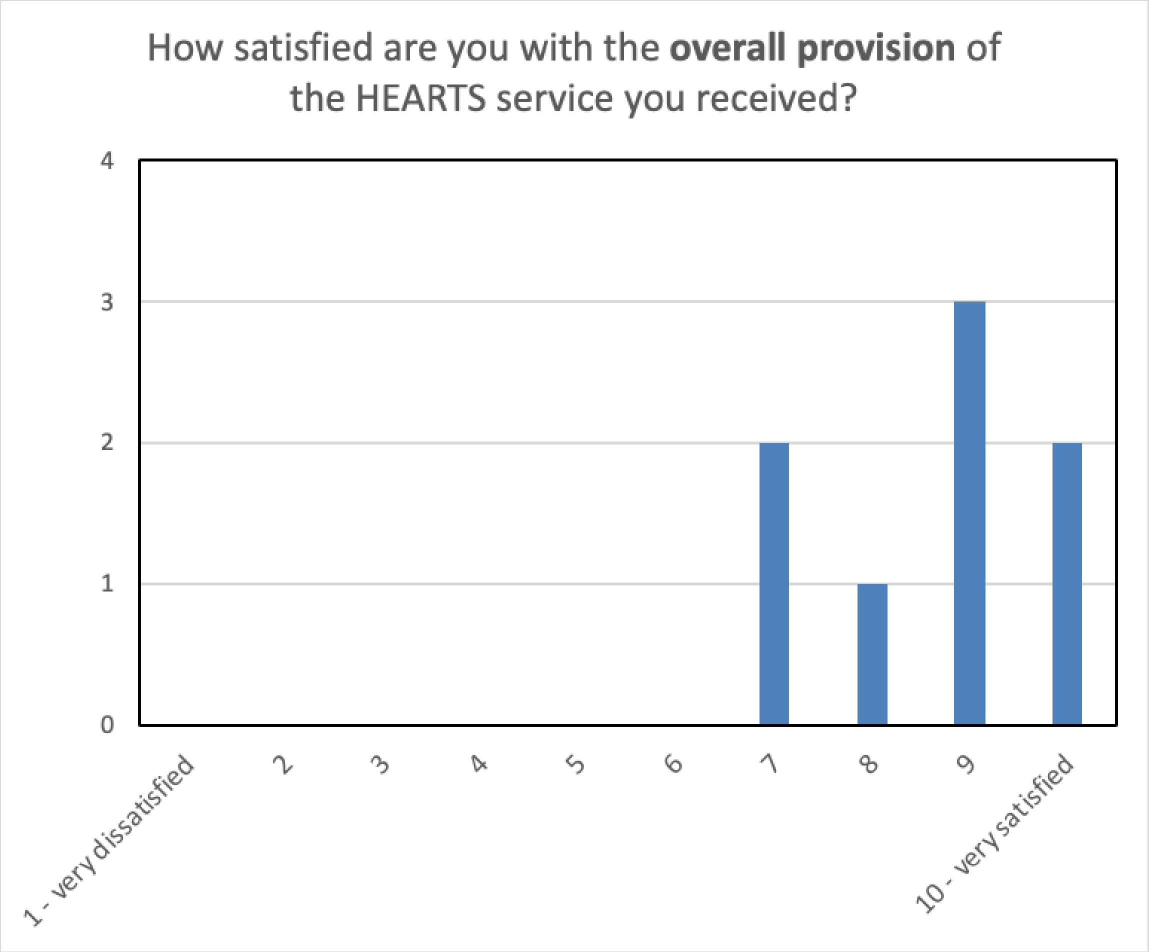
HEARTS

Extra Slides

Preliminary Results from Electronic Survey

Electronic Survey:
- Completely anonymized
- 32 questions (7 are open-end)

- 8 surveys completed and evaluated



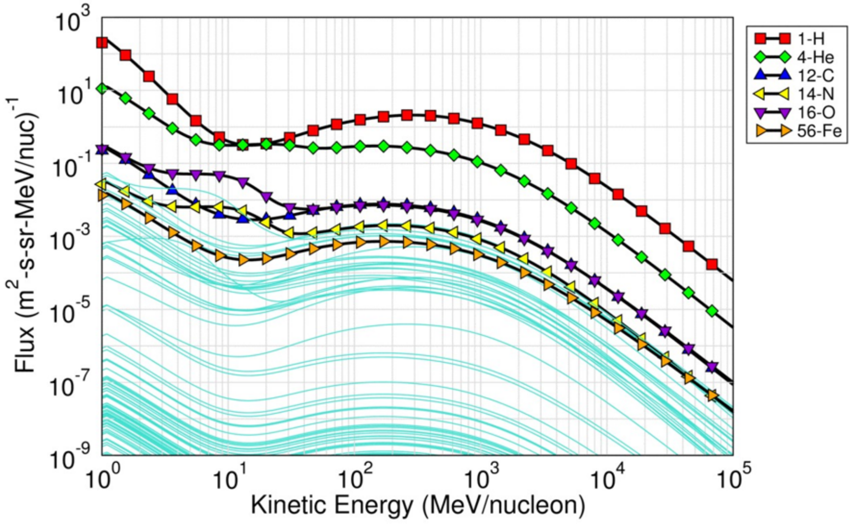
Motivation: Why radiation effects testing?

- Radiation effects are critical for high-reliability/availability applications in radiation exposed areas, such as space, avionic, accelerator, or even ground level (automotive, medical…) applications
- Radiation effects testing is a key pillar of electronics Radiation Hardness Assurance, along with modeling (at many different physical levels), radiation environment characterization, radiation hardening by design (also at multiple levels), etc.
- Radiation effects testing is important both for rad-hard (i.e. built with the requirements of resisting certain levels of radiation) and commercial (i.e. no radiation tolerance requirement) parts
- Radiation effects are divided in cumulative and stochastic – this presentation focuses on stochastic, Single Event Effects, which are those that can impact a system at any moment of their mission (and hence typically dominate the overall risk) and which require access to high-energy accelerator infrastructure for testing

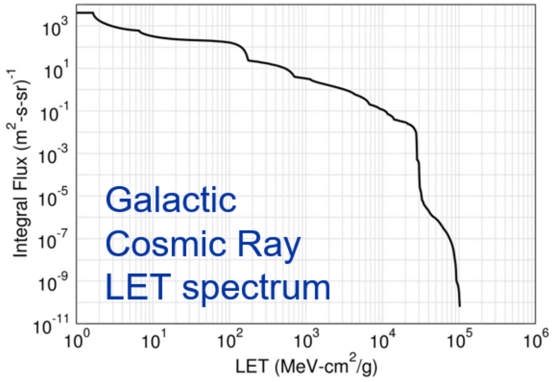
Motivation: why heavy ions?

- The Linear Energy Transfer (or dE/dx) is the key figure-of-merit for SEE induction
- Heavy ions are needed to reach large LET values, which in turn are needed for component qualification for space applications, as per the related test standards
- This is mainly motivated by the presence of high-energy, high-LET heavy ions in space, as part of the Galactic Cosmic Rays and (to a lesser extent) solar particle events
- Heavy ions are not present in the high-energy accelerator environment (at least in areas of interest for electronics operation) but provide a worst-case test opportunity with respect to the constituents of the accelerator mixed-field, composed (from an SEE-induction perspective) of neutrons, protons and pions

Motivation: why heavy ions?



Galactic Cosmic Ray energy spectra



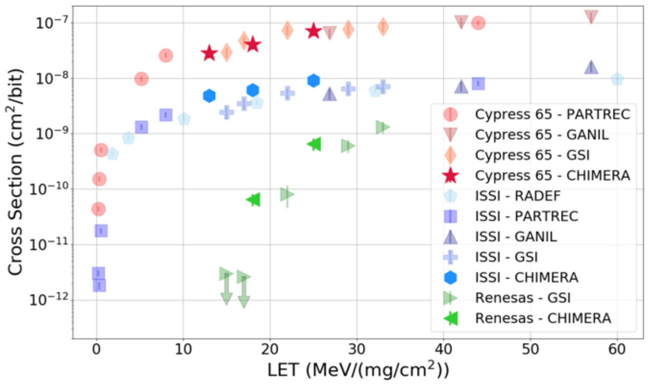


Fig. 8. SEU cross section as a function of ion LET of three SRAMs measured at CHIMERA and compared to other European heavy-ion facilities.

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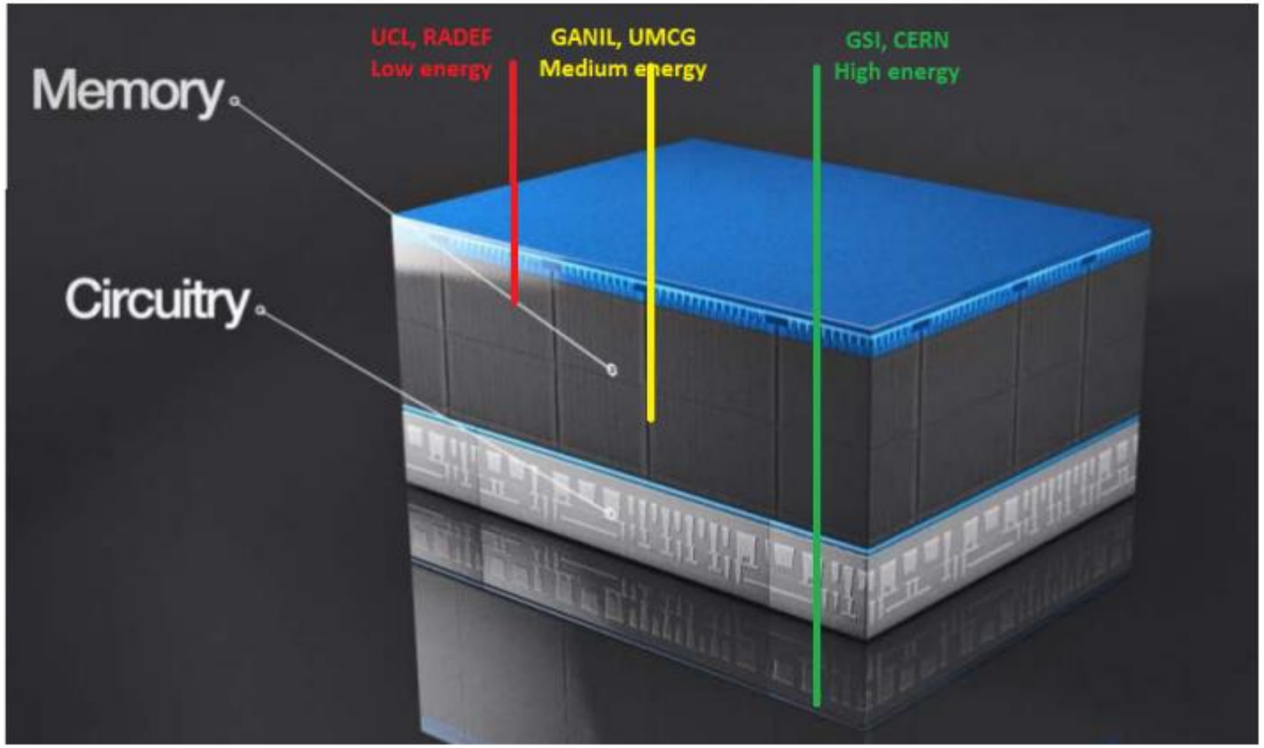
Motivation: why high-energy heavy ions?

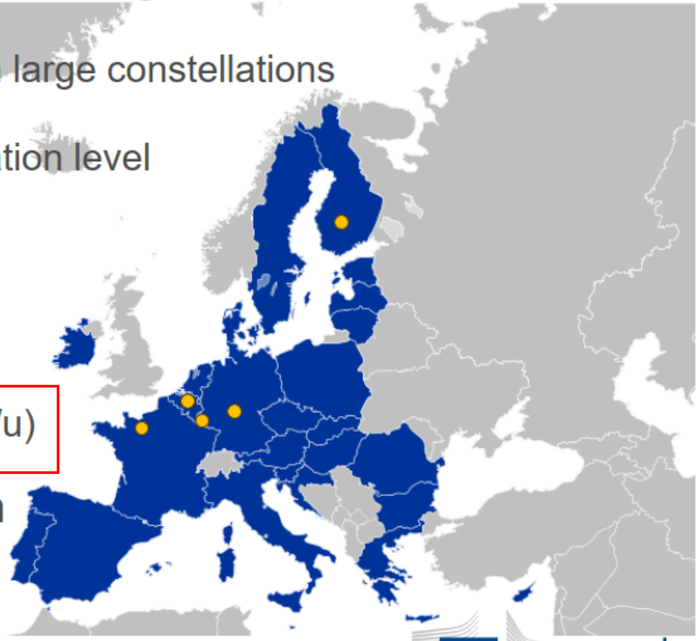
- Standard heavy ion facilities provide energies up to ~10-20 MeV/n, which pose practical constraints related to their limited range in matter and need for testing in vacuum
- Testing at larger energies and in air, as could be offered at is an additional plus to an already very heavily demanded beam type



Motivation: European Commission

Current radiation testing facilities in EU

- Demand for heavy-ions radiation testing is increasing due to several factors:
  - Increase use of COTS components combined with large constellations
  - Increase complexity of EEE parts with high integration level
- The available irradiation facilities in Europe:
  - Do not satisfy the demand for beam time
  - Do not cover high energy (from 100MeV/u to GeV/u)
- Available non-EU irradiation facilities do often prioritize national demand



European Commission

Part of Fabio Vitobello's (European Commission) RADECS 2024 Invited Talk

Motivation: ESA

COTS EEE components

esa

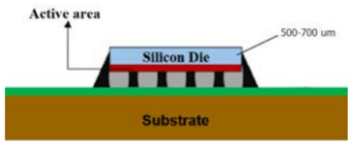
One common particularity of EEE COTS components is the dense packaging

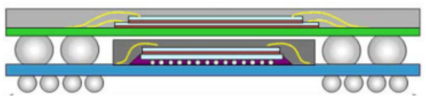
Examples:

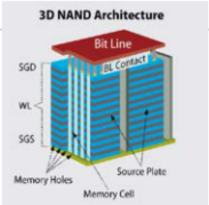
- Multi chip modules
- Flip chip construction
- Hybrids
- Plastic package with Cu bondwires

The exposure of either the dies of such packages is eiter impossible or difficult,
And there is the risk to modify the device response.

need of more enegetic particles to have more range
(despite lower LET)







Flip chip:	System in package:	Dense structure:
Active area facing package Backside irradiation -> die thinning to ~200 um	Test separately	Higher beam penetration range

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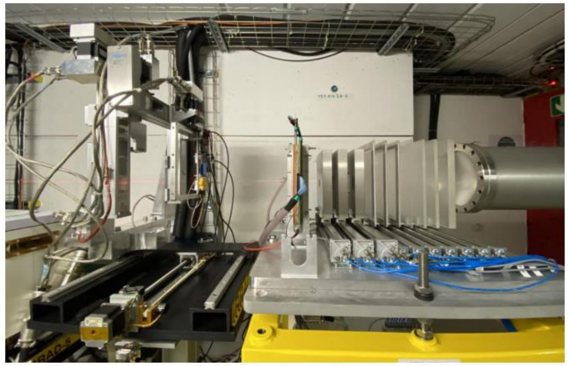
ESA | 07/11/2019 | Slide 20

European Space Agency

Complementarity with GSI

HEARTS@CERN

Facility information



The HEARTS@CERN facility during the November 2024 run. (Image: CERN)

General facility parameters

	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

HEARTS@GSI

Facility information

The HEARTS@GSI facility / Cave A showcasing a sample setup for electronics irradiation (left) and the current electronics target station (right). In the left picture the beam traverses from the left to right, exiting the vacuum exit window, through the beam monitors until it hits the devices under test. In the right picture the beam points towards the viewer. (Image: GSI)

General facility parameters

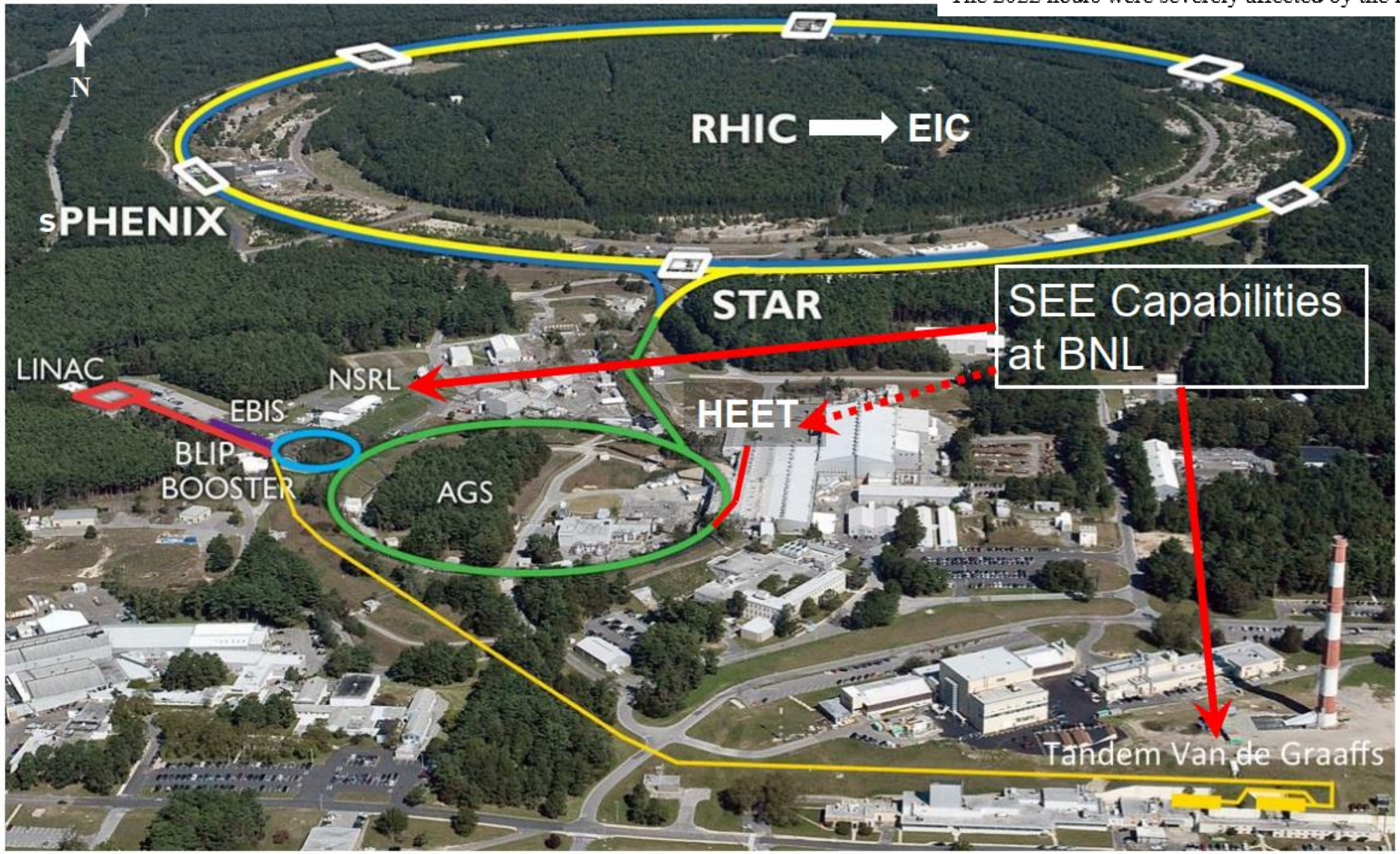
	Typical value	Extra information
Ion species	U	
Beam flux	$10^2 – 10^5$ ions/cm^2/s	Higher values are also possible.
Spill timing	5s length with 2s pause	The spill length is adjustable between 0.2 – 10s in length.
Beam delivery	Raster scanning	For more information see links below.
Beam size	adjustable up to 5×5cm^2	The size is freely adjustable, as magnetic raster scanning is used.
Uniformity	better than ±5%	
LET range	17 – 40 MeV·cm^2/mg	

- Commitment at different GSI levels to offer industrial access (and related service) to **industrial users**
- Would very nicely complement CERN's offer, especially in terms of having two high-energy heavy ion irradiation slots per year in Europe (i.e. waiting times of 6-8 months instead of 12 months – or more, depending on shutdowns)

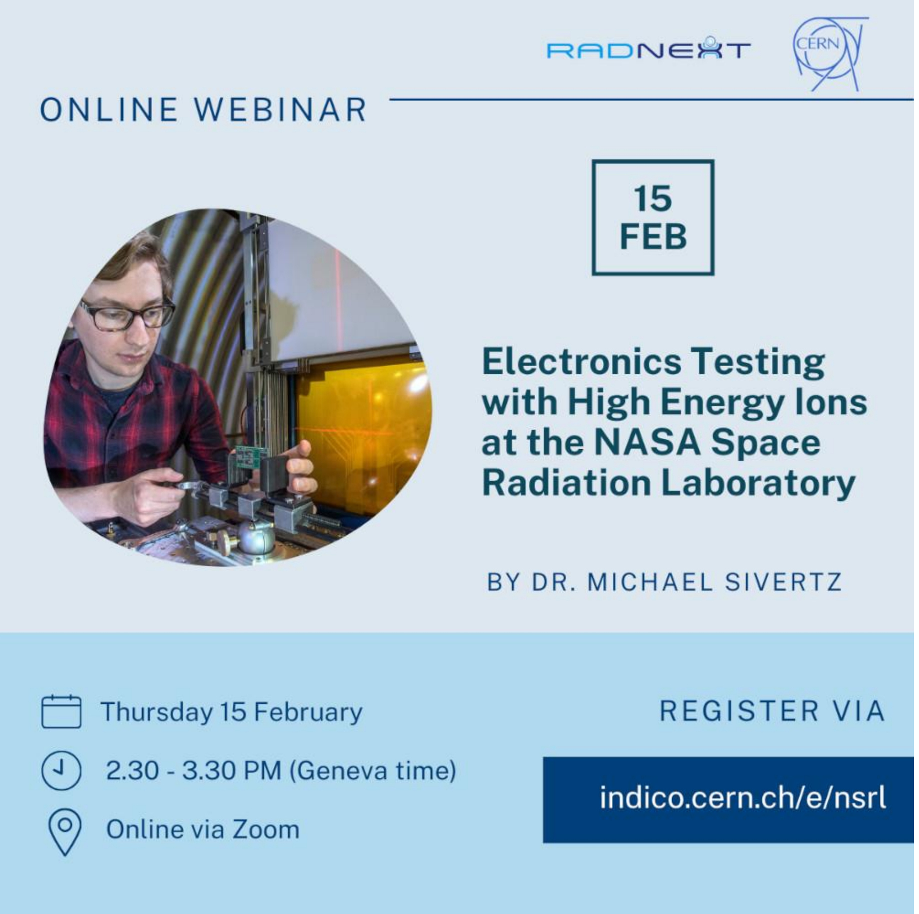
BNL: present (NSRL) and future (NSRL + HEET)

Here are the numbers for the last few years:
2024: 1826 hours of electronics testing
2023: 1522
2022: 713
2021: 935
2020: 213
2019: 401
Note, the 2020 and 2021 hour were severely affected by COVID restrictions.
The 2022 hours were severely affected by the long shutdown to upgrade the EBIS ion source.

@Mike Sivertz (BNL)



BNL online available seminars on NSRL and HEET



R2E seminar: Proposed High Energy Single Event Effects Facility at BNL

  16 February 2024 00:56:18

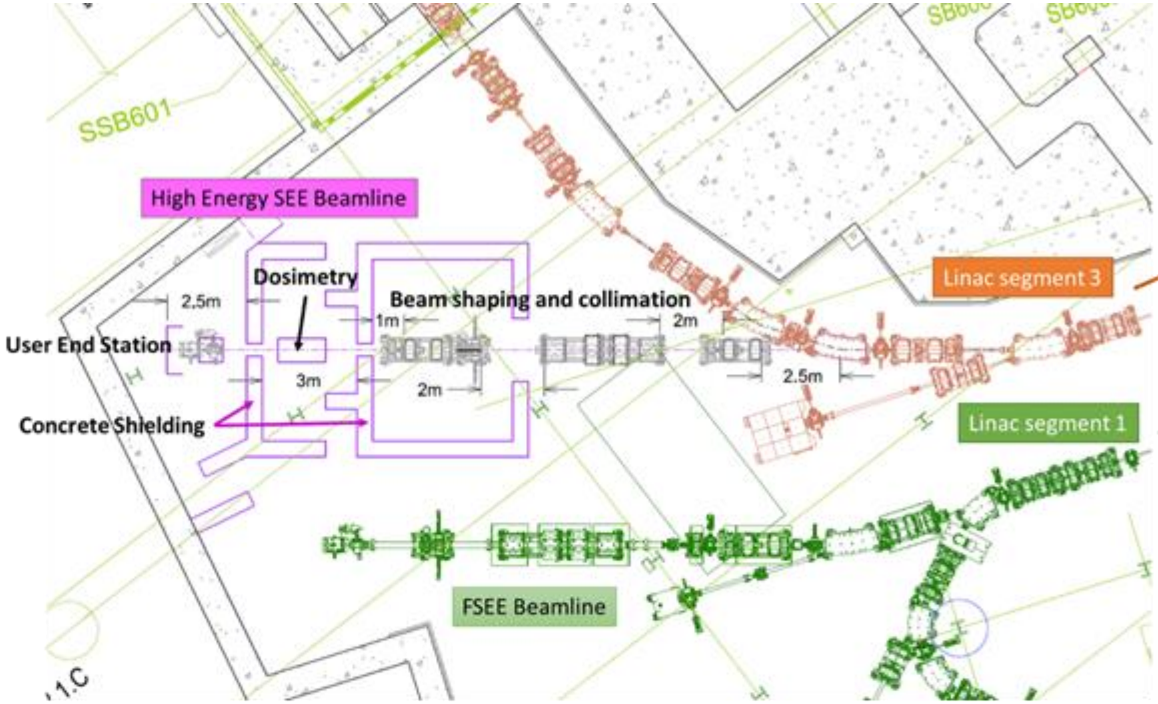
Abstract:
In this talk I will describe the status and plans for building a high energy effects testing facility (HEET), designed for single event effects testing, at BNL off the AGS. The purpose of the facility is to simulate space weather by producing suites of particle beams (ion species at various energies to simulate galactic cosmic ray and solar particle events). The demand for such a capability is high, as we deploy more systems into the space environment. The demand will only grow as space exploration expands and becomes more commercial. In the talk I will describe the motivations, the proposed facility, the status of the proposal in the US funding process, and how we imagine the facility will be operated.

About the speaker:
Kevin A. Brown is a Physicist at BNL and an adjunct Professor in the Electrical and Computer Engineering Department at Stony Brook University. He is leading the design and development of the proposed BNL HEET facility.

https://videos.cern.ch/record/2299807

https://youtu.be/LvpEddIUjf0?si=zihjqs1yUJQhwbmY

MSU/FRIB: present and future



At the moment, we only have a concept for the facility (see drawing to the left) and a rough cost estimate (~$4.5M) and schedule (~18 months).

This facility would operate in a similar fashion to the FSEE facility, which is that it runs complementarily to the nuclear physics program that has the ultimate priority at this time. In this context, we provide up to 2000 hrs per year of SEE testing from the linac-based facility. I would anticipate that the majority of those hours would be devoted to these higher energy studies, while the recommissioned K500 cyclotron facility will service the lower energy SEE users (at 4000-6000 hrs per year).

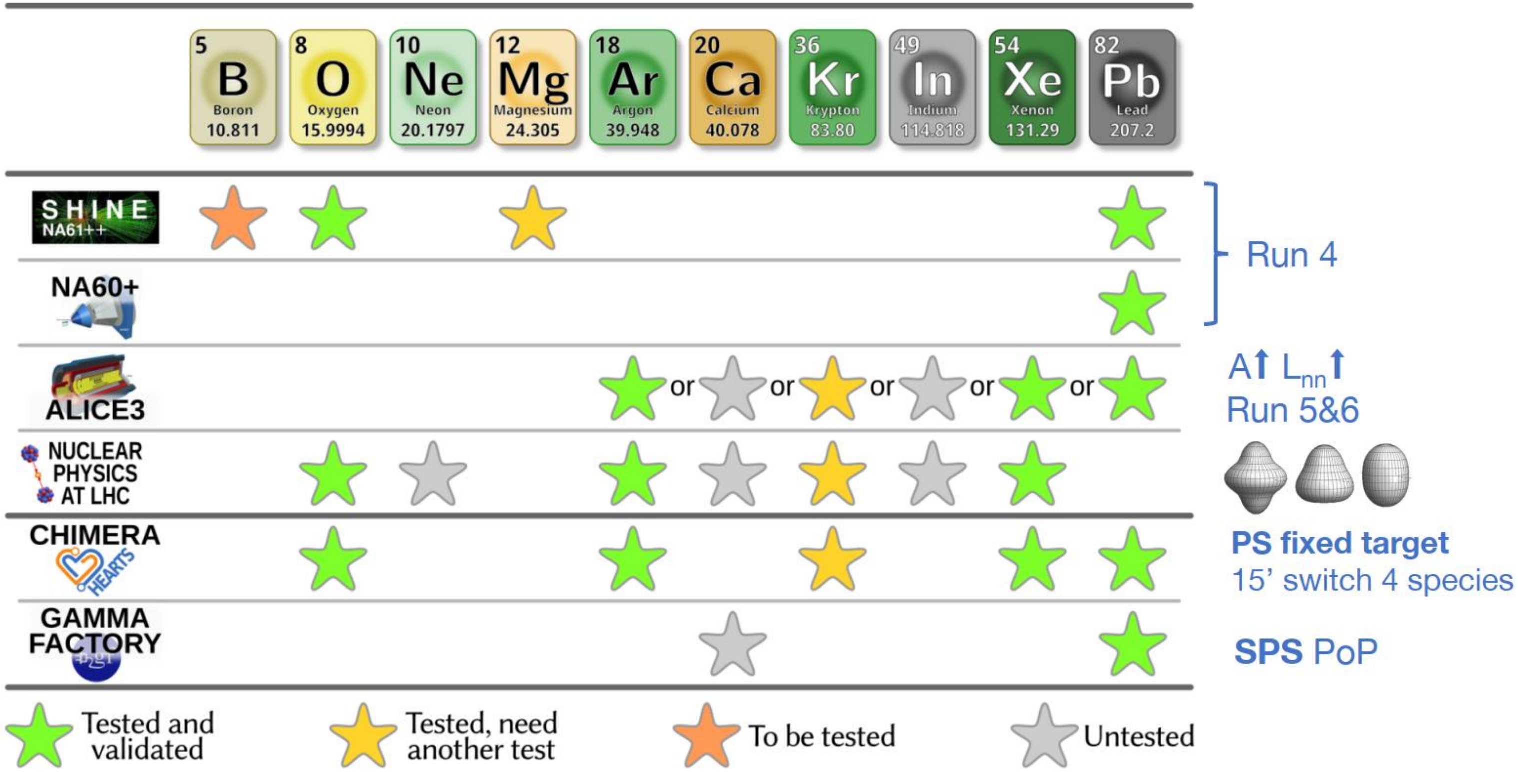
For FSEE usage, I have not done the final tabulation, but we have averaged ~1500 hrs/year in user experiments for the past 2 years

@Steve Lidia (MSU FRIB)

Looking further ahead: ICU for fast ion species changes

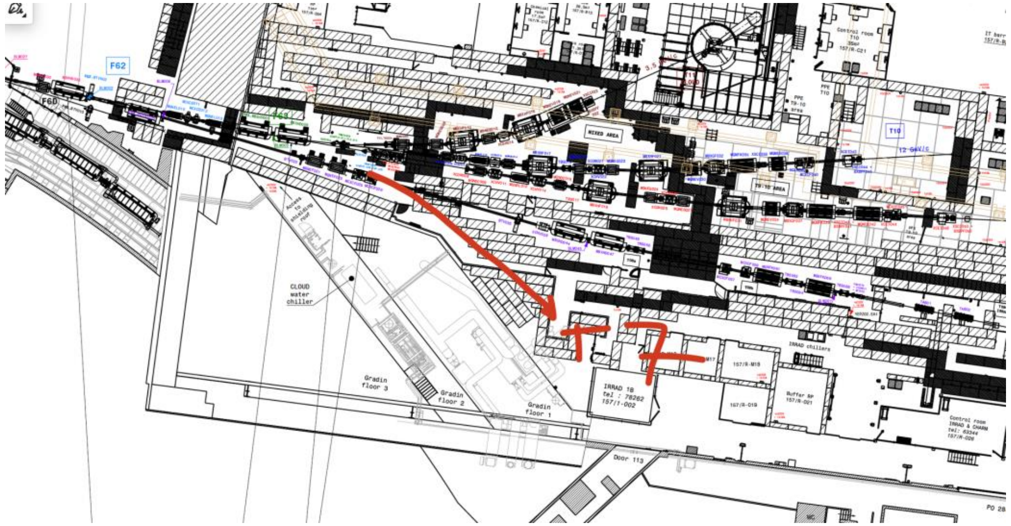
CERN Ion Complex Upgrade Proposal

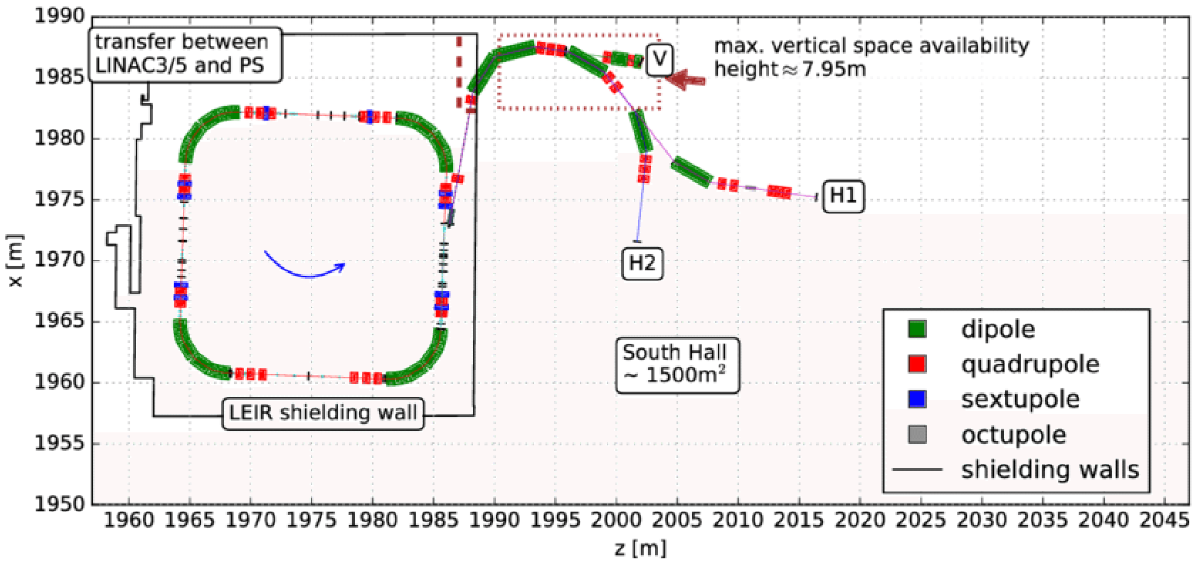
Reyes Alemany Fernández



Looking further ahead: dedicated beam line and experimental facility

- Main overall constraint: very limited (~150h/year) beam time, mainly due to the fact of sharing the beam line and facility with high-energy, high-intensity protons in T8 (critical for detector and accelerator electronics and sensor radiation testing)
- Possible solution: dedicated beam line and facility → Conceptual Design Study (including feasibility, costing estimate…) to be carried out in 2025





SY Accelerator Systems

Knowledge Transfer Accelerating Innovation

Thoughts beyond the facility and service: guidelines

Single-Event Effects (SEE) Symposium
Military and Aerospace Programmable Logic Devices (MAPLD)
Combined Workshop

SEE MAPLD

The Use of High Energy Heavy Ion Facilities for Single Event Effects (SEE) Testing: A Perspective on Return on Investment (ROI)

Kenneth A. LaBel, SSAI, Inc. work performed for NASA-GSFC kenneth.a.label@nasa.gov
Jonathan A. Pellish, NASA-GSFC
Thomas L. Turflinger, The Aerospace Corporation

Conclusions

- The bottom line is that both standard piece part level testing and high-energy heavy ion testing will be needed in the future
- This presentation made the argument that there are scenarios where the ROI for high-energy makes sense for large field tests and large sample size tests
- There are also unique capabilities where a high energy source is required to sufficiently test complex devices

Opinion

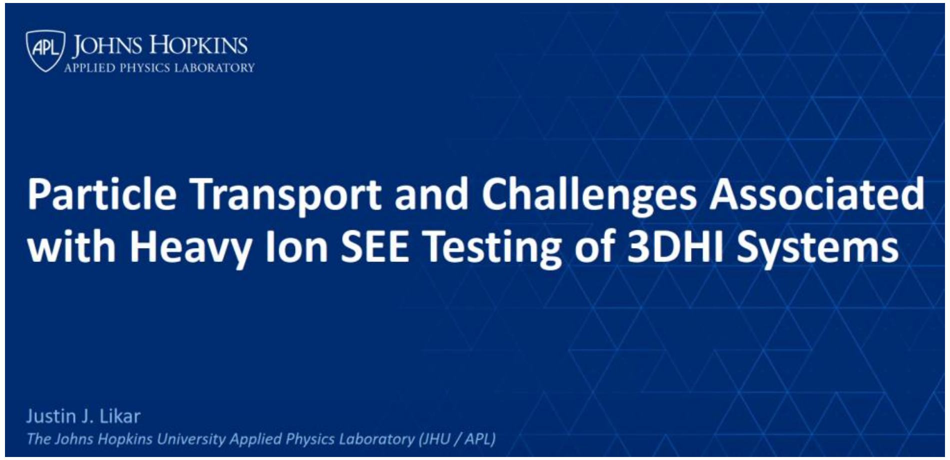
Guidelines should be developed on best practices for high energy SEE testing

2021 SEE Symposium / MAPLD Workshop 17

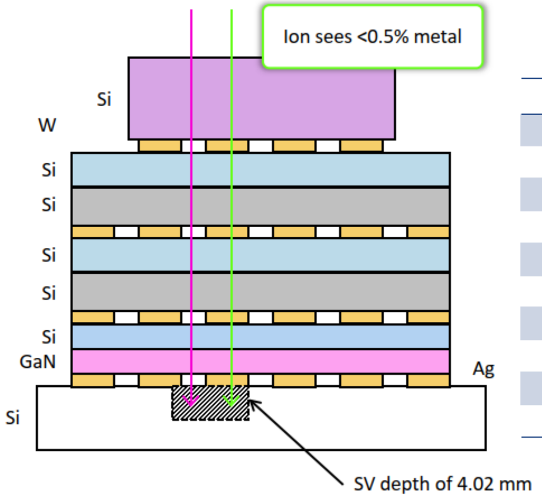
Thoughts beyond the facility and service: modeling

NASA Electronic Parts and Packaging Program

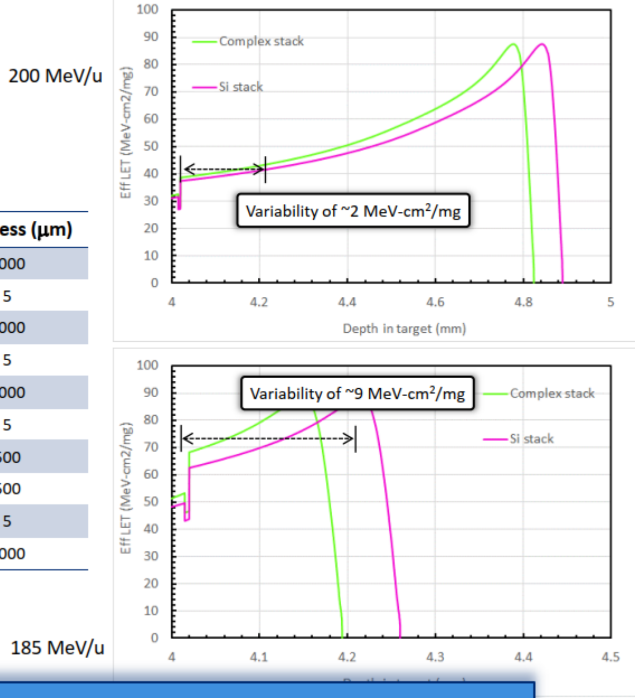
2024 Electronics Technology Workshop



Ta beam into notional stack



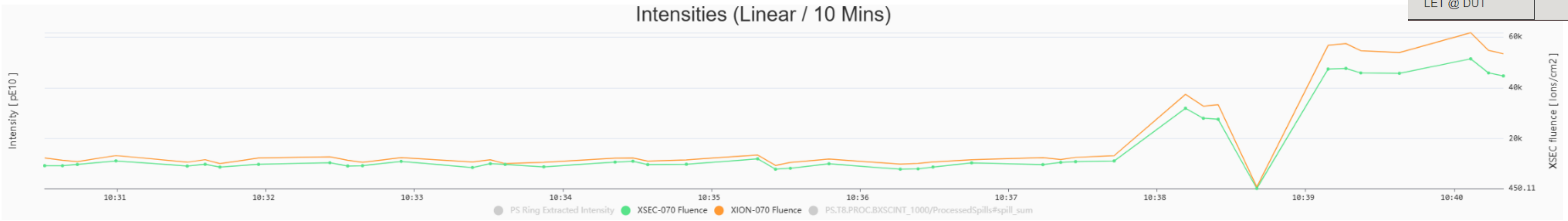
Material	Thickness (µm)
Si	1000
W	5
Si	1000
W	5
Si	1000
W	5
Si	500
GaN	500
Ag	5
Si	1000

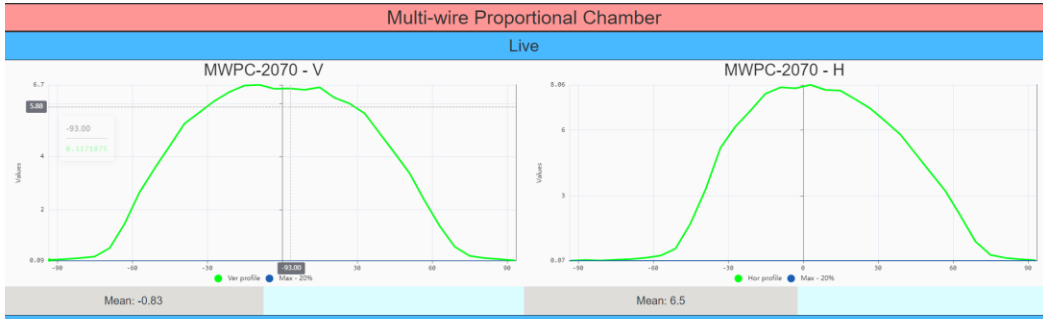


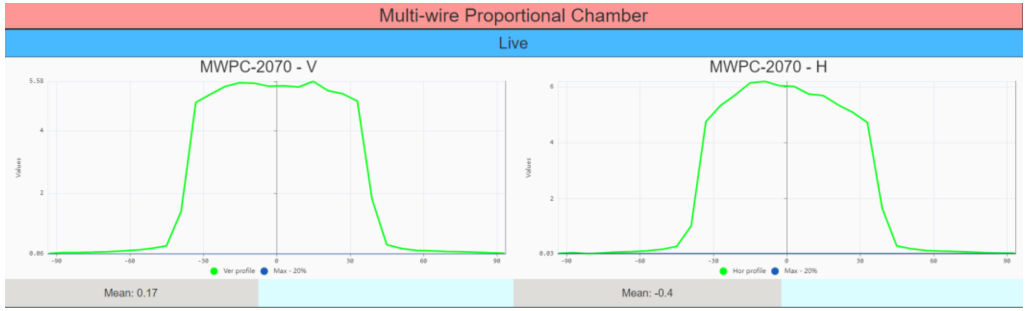
Very simple example; on-going studies of LET range in SV during mono-energetic irradiation

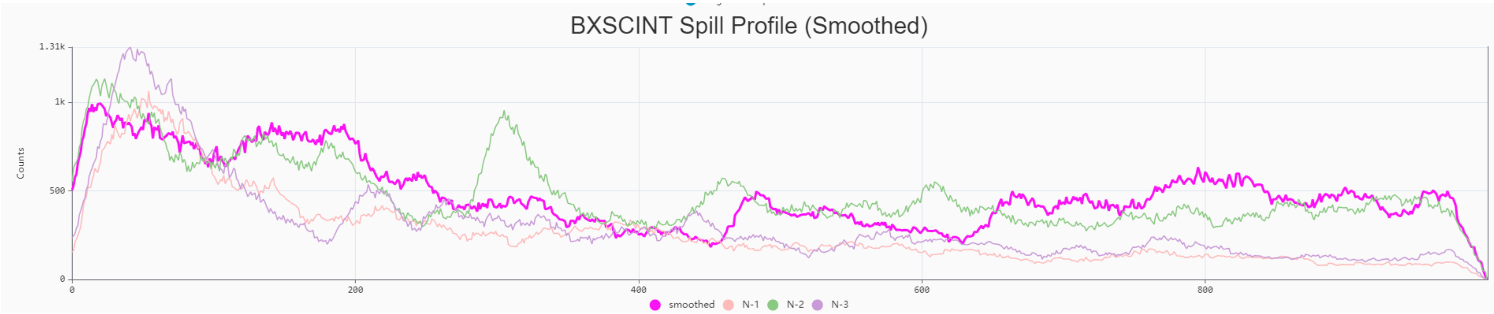
WRAP USER:	CPS.USER.ION3
Cycle name:	IEAST_Pb_1GeV_24
Flux tag:	Low Flux
MeV @ PS:	1000.21
MeV @ DUT	908
LET @ DUT	12.3

The Beam: control and monitoring









For 2025: focus will by on COSYLAB solution for beam control and monitoring

How? Requirement: flux control over 3 orders of magnitude

- Maximum (~10^5 - ~10^6 ions/cm^2/spill) and minimum (~100 ions/cm^2/spill[*]) flux values were compatible with user requirements
- Same applies to spill-to-spill intensity stability [*] and intensity uniformity within spill
  - A factor ~2 was targeted as spill-to-spill intensity stability, and was met throughout most of the runs, but periods with larger variability (typically linked to changes in the super-cycle composition) were difficult to avoid
- The achieved average spill rate (one spill every ~12-15s for standard operation, ~20s for LHC filling) was however below the target of ~10s
  - Also, spills rates are provided in average, but they are not uniformly distributed, which typically would be the preference for users

[*] A good fraction of the beam development and commissioning efforts were devoted to reaching very low fluxes in a controlled manner and stabilizing the spill-to-spill intensity

(note: written independently of user feedback collected by Gerd – more about that later in the presentation)

Communication

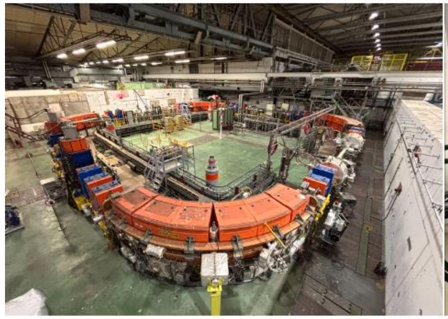
Fabio Vitobello • 1st 2d •••
Space Policy Officer - EEE Components & Critical Space Technologies at Euro...

Very well to all of you! I'm glad to see that #HEARTS is advancing very fast responding to the #EuropeanCommision, #DG-#DEFIS strategy in the area of #EEE for #space. We are implementing this project with the intention to make available very high energy radiation facilities to all EU industry developing space EEE components. This is becoming a reality, thank you all the team for the great job!

Matthew Gill • 1st •••
Radiation Consultant - Former Nuclear Engineer turned Rocket Scientist
17h •

Last week I had the pleasure of smashing some ~1 GeV/n lead ions into a mixture of electronics at CERN. Thanks to HEARTS@CERN team for doing an amazing job at bringing this facility online for industry users - it's a beautiful facility with an incredible capability for #space #radiation testing.

I highly recommend for anyone looking for high-LET, high-penetration heavy ions :)



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HEARTS •••
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❤️ Two weeks, 150+ irradiation hours, 10 teams from global companies and institutions – the HEARTS user run at CERN 2024 comes to a successful close.

🚀 The goal of the pilot run was to demonstrate CERN's IRRAD facility's capabilities in providing high penetration, heavy ion #radiation testing of #electronic components and modules destined for use in #space.

👀 Based on the positive feedback from the users, it has been a great success and marks an important step forward for space #electronics qualification in #Europe. Keep an eye out for more results, user testimonies and data that will be available soon.

🙌 A huge thank you to the users, the CERN technicians, operators, engineers and scientists, and the HEARTS team for all your dedication and hard work.

🎉 We go into 2025 full of optimism

Find out more about HEARTS - https://hearts-project.eu/

#innovation #HorizonEurope #EUfunded CERN Innovation Partnerships

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