CHIMERA - Facility activities overview and updates

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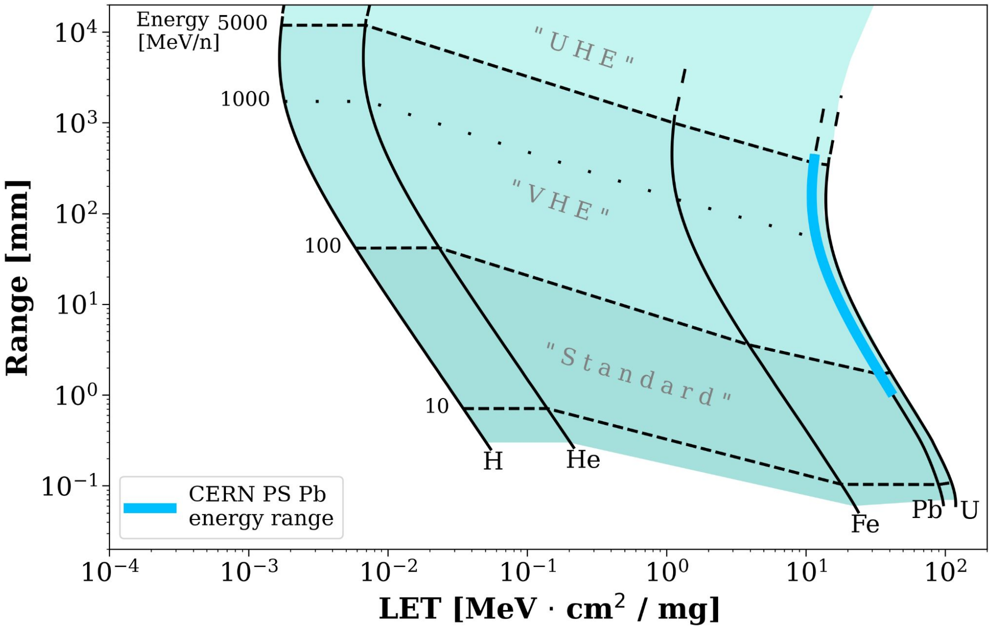
Outline

- Introduction to CHIMERA
  - ➔ Motivation, objectives, ESA support

- Facility overview
  - ➔ CERN accelerators, beam line and CHARM facility
- Progress timeline (2021 - 2023)
- Facility commissioning milestones and results
  - Primary beam energy and intensity adjustment, dosimetry, spatial profile, user support

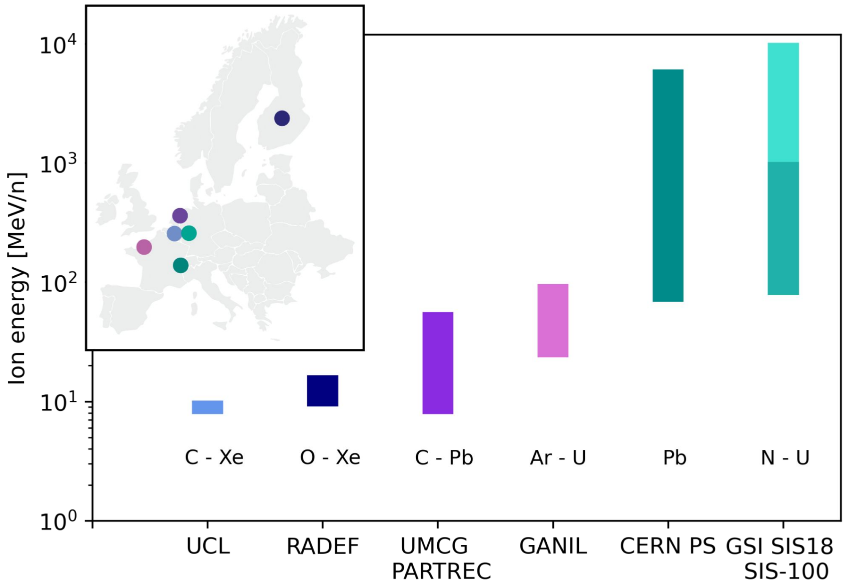
- Outlook on future
- Conclusions

Motivation (1)



- Radiation effects on electronics are an important **engineering constraint** for critical (high reliability and availability) applications in which electronics operates in e.g. space or accelerator environments.
- State-of-the-art microelectronics has evolved to 3D, complex structures.
- **CERN** can offer a "**sweet spot**" solution to a physical trade-off: **high LET** (> 30 MeVcm^2/mg) combined with a **high range** (>1 mm) beams at the CHARM user facility in the PS East Area using **high energy (>100 MeV/n), heavy ions (VHE)**
- **"CHIMERA": Charm Heavy Ions for MicroElectronics Reliability Assurance**

Motivation (2)



- **Current availability** of very high energy (VHE), heavy ion beams **is scarce**, even though there is a great interest
- The CHIMERA activity is driven by **collaboration agreement between CERN and ESA** on key priorities, including high-penetration, heavy ion tests to assess EEE components and modules (COTS) (https://home.cern/news/news/knowledge-sharing/cern-and-esa-forge-closer-ties-through-cooperation-protocol)
- **Contracts with ESA for CHIMERA funding** + funding through ESA's Open Science Innovation Platform
- Project benefits from collaboration with space community partners (e.g. CNES, Airbus, TAS, through RADSAGA/RADNEXT EU projects, HEARTS, etc.)

Requirements and objectives

Upgrades are needed in the CHARM facility and beam line in the PS East Area to render infrastructure suitable for space electronics qualification using high-energy, high-penetration ions:

- Tuning **ion energy** in the "high LET variability" range
  - **70 MeV/n - 2 GeV/n**

- Tuning the **ion flux** in a large dynamic range with ± 10% uncertainty
  - **10^2 - 10^5 ions/cm^2/s**

- Tuning the **beam size** for board level testing
  - up to **~ 20 x 20 cm^2**

- Possibility to achieve an operation mode that is **compatible** with the rest of CERN's physics programme, the other users of the PS, East Area and T08 beam line users.

Proton Synchrotron

CHARM facility

ESA contract framework

- ESA statement of work for contracts with CERN initiated in June 2021
- Focusing on two main activities: demonstration of energy tuning capability + adequate beam characterization

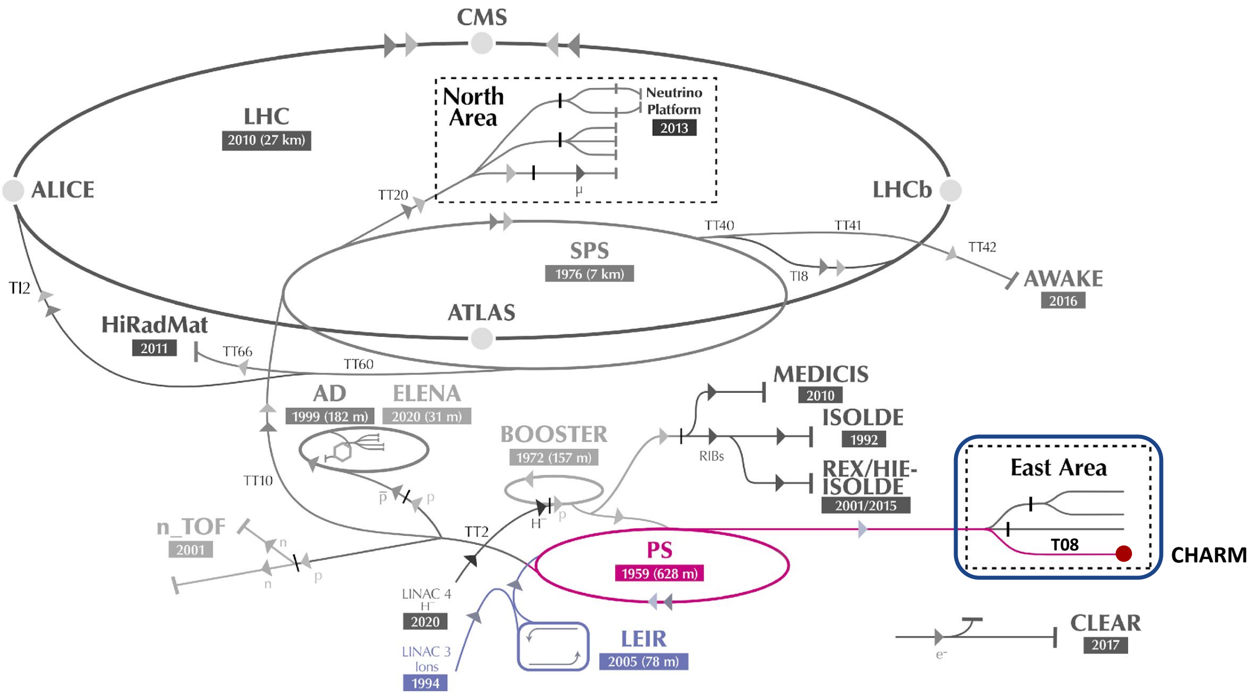
- Development studies all year long + dedicated machine development sessions + yearly 2-week experimental campaign
- ESA TEC-QEC delegation participated in 2022 experimental campaign as users

  → Technical notes and reports are currently being circulated between ESA and CERN

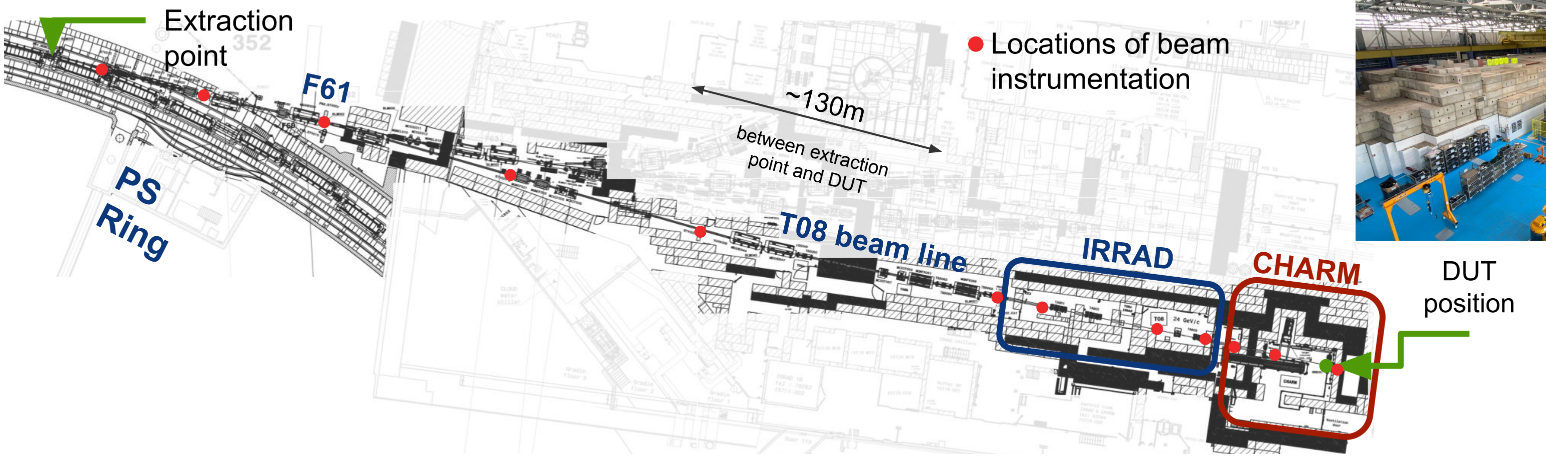
Contract name	Contract number - ESA	Contract number - CERN	Tasks
Development of High Energy Beam (range and LET) for Radi-ation Tests of Highly Integrated Electronics components	4000134554 /21/NL/KML/rk	KM5174 /KT/SY/273A	Task 1: CERN CHARM ion beam energy reduction Task 2: Beam calibration and dosimetry
High Energy Beam Intensity Adjustment for SEE tests of COTS EEE Components	4000136601 /21/NL/KML/rk	KM5450 /KT/SY/276R	Task 1: Primary beam intensity adjustments Task 2: Beam calibration and dosimetry Task 3: Preparation of test execution process for industry

CERN accelerator complex

- **CERN's accelerator complex operation is driven by Large Hadron Collider (LHC) physics programme**
  - p-p collisions
  - Pb - Pb or p-Pb collisions restricted to several weeks per year (Oct-Nov)
- Injector chain used: Linac3 → LEIR → **Proton Synchrotron** (24 GeV/c protons) → T08 transfer line → CHARM
- The PS is key in the operation of the complex, delivering beams to different destinations in parallel (supercycle).



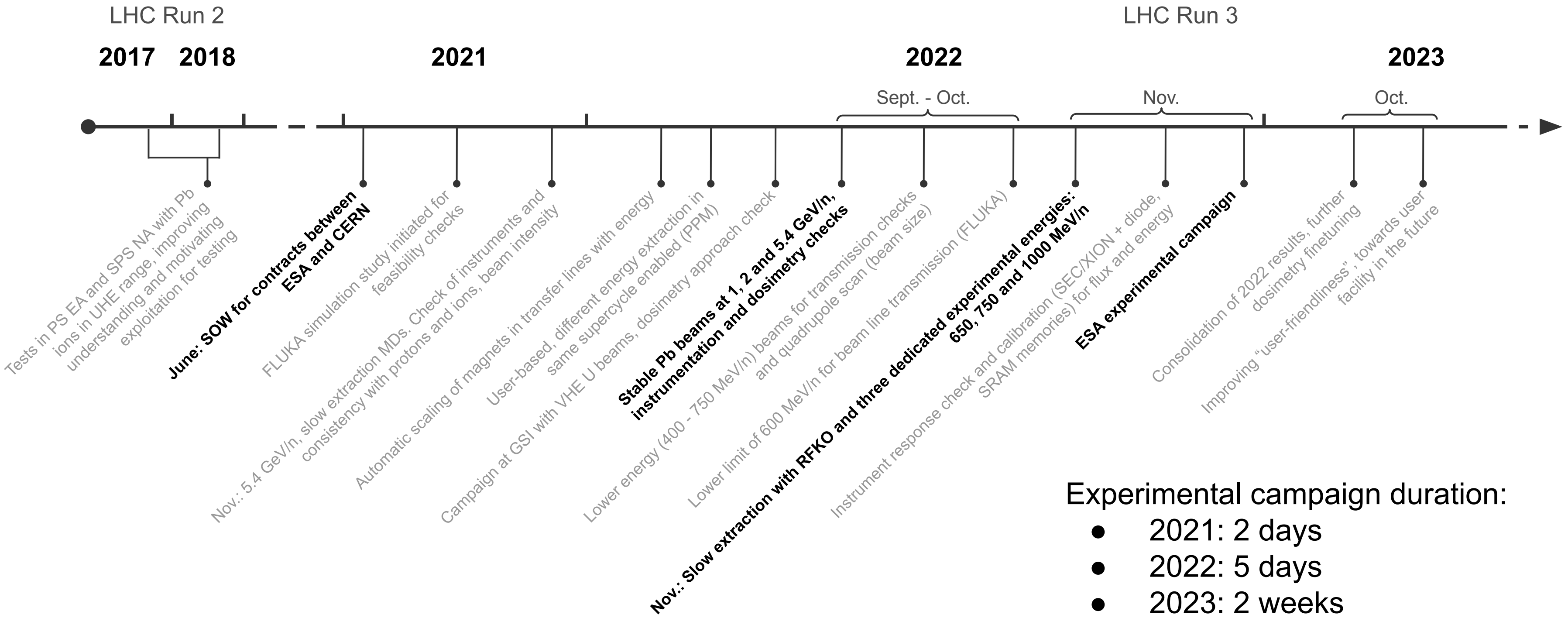
PS and T08 transfer line



PS East Area hall

- T08 transfer line operation and instrumentation are **tailored for delivering top energy protons** to IRRAD and CHARM user facilities
  - High intensity proton beams at 24 GeV/c → low (variable) intensity, heavy ion beams at different energies
- Safe, parallel operation with other beam lines in East Area hall needs to be ensured
- Sections of the beam line are non-vacuum, i.e. VHE heavy ion beams see a significant amount of material budget before reaching the DUT position in **CHARM** (existing infrastructure for electronics testing).

Progress timeline



Experimental campaign duration:

- 2021: 2 days
- 2022: 5 days
- 2023: 2 weeks

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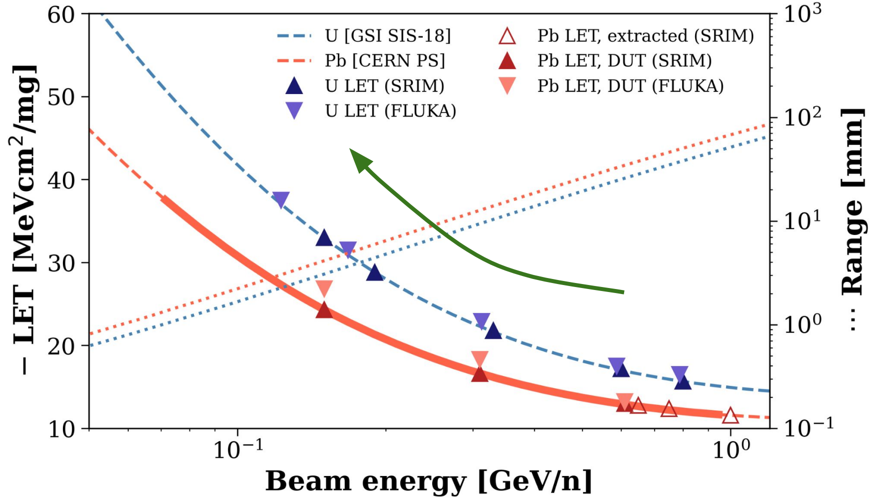
Primary beam energy reduction (1)

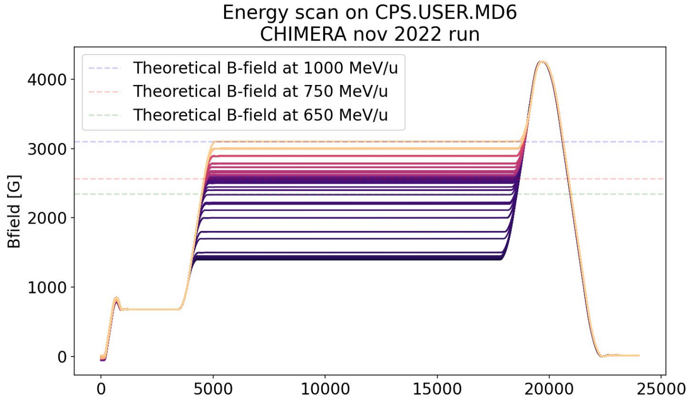
- Changing the energy across a relatively broad value range is crucial to achieving substantial variability in Linear Energy Transfer (LET)
- The **variation of the beam energy was achieved by scaling the magnetic field in the Proton Synchrotron** (PS)
- Automatic scaling of T08 line magnets, allowing for seamless transition between energies down to 15 seconds
- For the 2022 CHIMERA run, three primary kinetic energies were selected: **1000, 750, and 650 MeV/n**

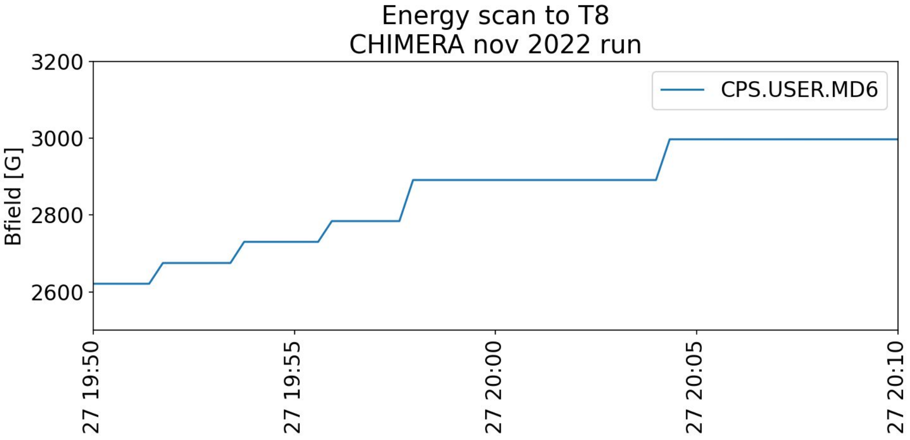


Primary beam energy reduction (2)

- Erroneous swap of pre-programmed supercycles in control centre during ESA experimental run

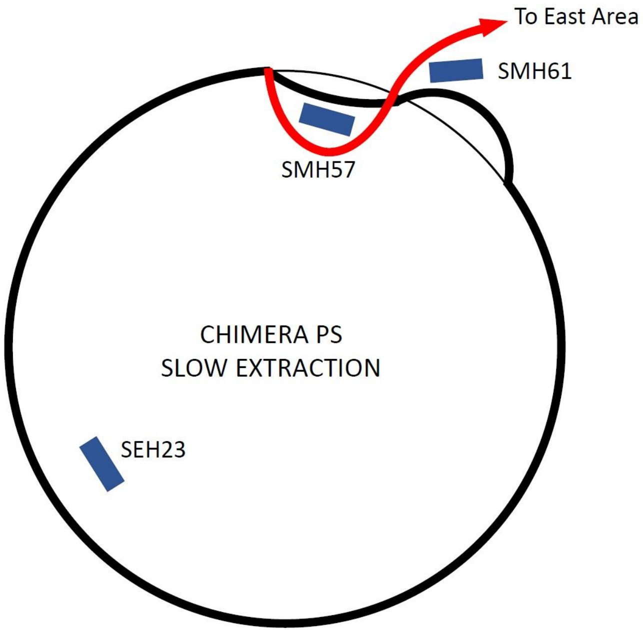
- **Solution**: have a single ion cycle and implement an automatic script to adjust the energy. This approach was tested later during the campaign with a single “user” ranging between 775 and 950 MeV/n
  - ➔ will prove useful for future beam characterization activities.





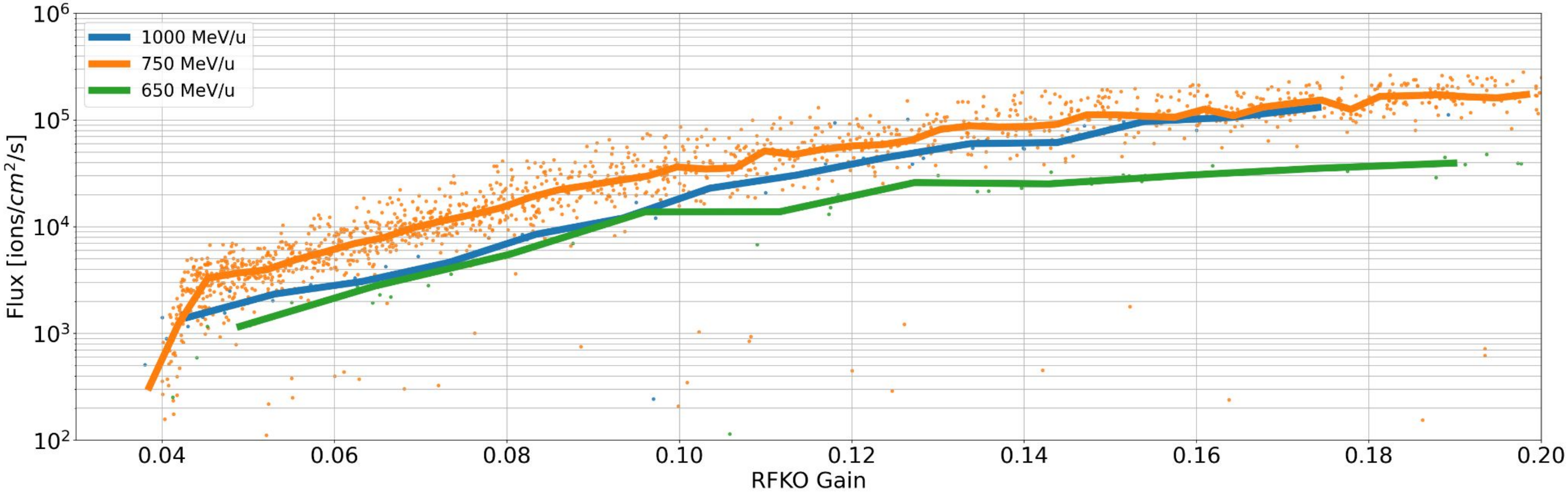
Primary beam intensity adjustment (1)

- Use of septum magnets to extract the beam to the East Area
- **Radiofrequency Knock Out** (RFKO) adopted during the 2022 November run to improve the control of the beam intensity at different energies.
  - Beam is **slow extracted** due to emittance growth
  - Beam intensity can be controlled mainly by adjusting the amplitude and duration of the applied RF field
- **Note**: Reproducibility of beam parameters is subject to careful optimization of the supercycle in the accelerator complex, i.e. the supercycle composition is essential to beam production.



Primary beam intensity adjustment (2)

- **Easy and reproducible intensity control** by dialing a “single button”: gain = voltage between RFKO plates
- Demonstrated for the three selected CHIMERA primary kinetic energies 650, 750, 1000 MeV/n



VHE ion beam dosimetry

- **Accurate dosimetry** of particle beams is **essential** for radiation effects testing in an accelerator facility
- Resulting dose on test device: $D(E, \Phi) = LET(E) \times \Phi$
  - The SEE response of an electronic component under test is determined as function of the **LET** [$MeVcm^2/mg$]
  - The number of recorded SEEs in a device under test is proportional to the **fluence** [$ions/cm^2$]
- Both the LET and the fluence are affected by the transport of the beam along the T08 transfer line: accurate determination of both quantities during testing at the DUT position is indispensable

LET

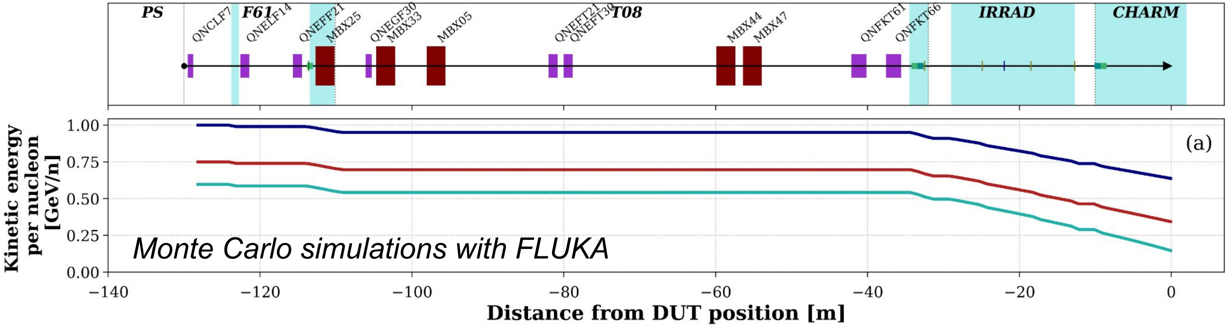
- FLUKA beam transport simulations through T08, extracting energy and LET
- Experimental energy deposition measurements with a silicon diode exposed to VHE beams

Fluence

- Present T08 in-beam monitoring instrumentation
- Silicon diode measurements
- SRAM memory measurements

VHE ion beam dosimetry: energy and LET (1)

- The **primary beam energies are degraded significantly** before reaching the CHARM testing location
- As a result, the mean LET values at the DUT are 13.4, 18.4 and 26.5 MeVcm^2/mg respectively (range above 4mm in Si) with a conservative error of ± 1 MeVcm^2/mg.
- The theoretical max. LET can be reached at the DUT (98.3 MeVcm^2/mg) using degraders, at the expense of the range which drops below 1 mm.

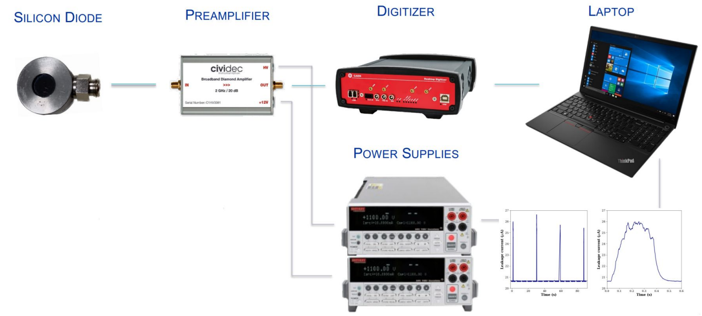


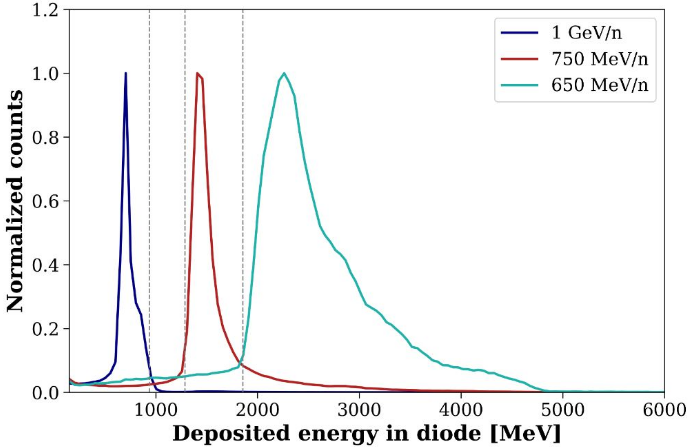
	USER		CPS.USER .EAST4	CPS.USER .EAST3	CPS.USER .MD5
EXTRACTED FROM PS	Total momentum [GeV/c]		351.92 (2.47)	291.15 (2.04)	265.79 (1.86)
	Kinetic energy per nucleon [MeV/n]		**1000.0** (10.51)	**750.0** (8.20)	**650.0** (7.12)
AT CHARM DUT LOCATION	Kinetic energy per nucleon [MeV/n]		**610.09** (11.76)	**308.78** (10.92)	**155.93** (13.00)
	LET [MeVcm^2/mg]	FLUKA	**13.42** (0.10)	**18.40** (0.32)	**26.53** (1.33)
		SRIM	13.43	17.77	25.67

Mean (FWHM)

VHE ion beam dosimetry: energy and LET (2)

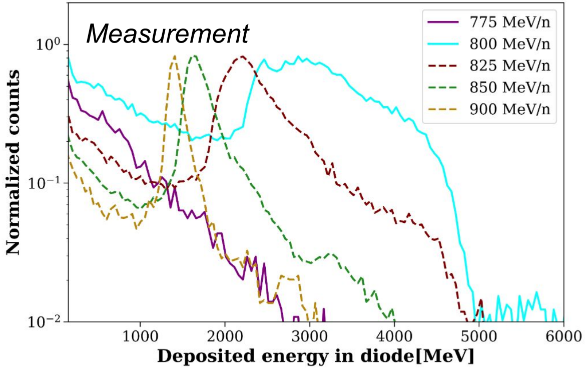
- Experimental validation using diode monitor at DUT position
- **Indirect measurement of the LET** by extracting the amount of deposited energy by the beam particles within a sensitive silicon layer of known thickness.
- **First-order approach** to calculate the expected deposited energy in the 300 µm sensitive layer: $\varepsilon_{dep} = LET_{Si} \times \rho_{Si} \times t_{Si}$, three distinct primary energy peaks are expected from simulated LET = observation with the Si diode

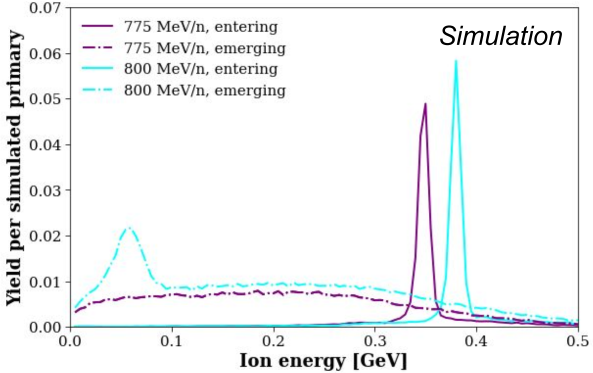




VHE ion beam dosimetry: energy and LET (3)

- **Energy scan**
  - between 775 and 900 MeV/n in 25 MeV/n steps
  - diode behind a 21.6 mm PMMA degrader plate
- Diode measurements showed
  - 775 MeV/n: only fragments
  - 800 MeV/n: degraded beam
- **Confirmed by FLUKA simulations** scoring particle fluence and energy entering and emerging from PMMA plate
- ⟶We can determine the beam energy with an accuracy of 25 MeV/n at the DUT independent of diode calibration/signal attenuation. Future energy scans will be carried out with steps down to 1 MeV/n

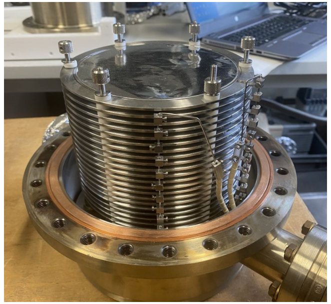




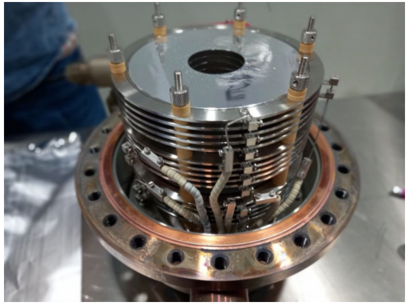
VHE ion beam dosimetry: flux and fluence (1)

- Similar approach adopted as used at GSI and NSRL: the dose at the test location is measured by using a **calibrated, point-like detector** which in turn is used to calibrate **large ionization chambers** that remain in the beam during exposure.
  - Diode at DUT position: measures energy deposition on event-by-event basis: total amount of counts in spill
  - Secondary emission chamber/ionization chambers upstream in the T08 beam line: always in the beam
    - Secondary emission chambers: suspected energy dependent response and beam intensity between SEC and DUT
    - Argon ionization chambers: higher sensitivity at very low fluxes

Diode



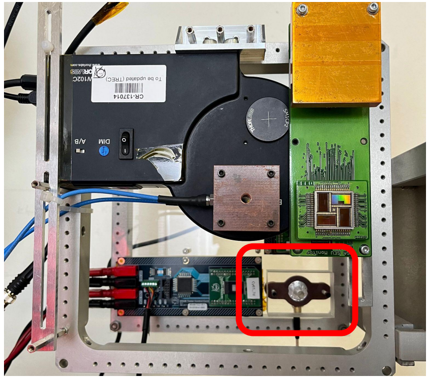
XION Argon ionization chamber

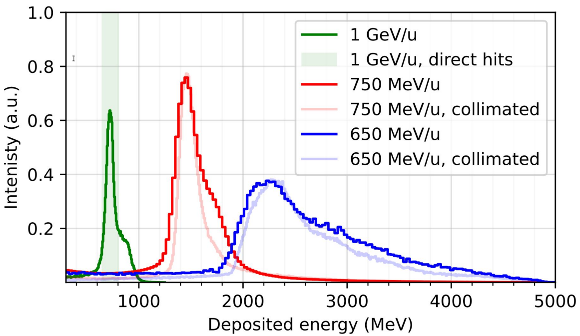


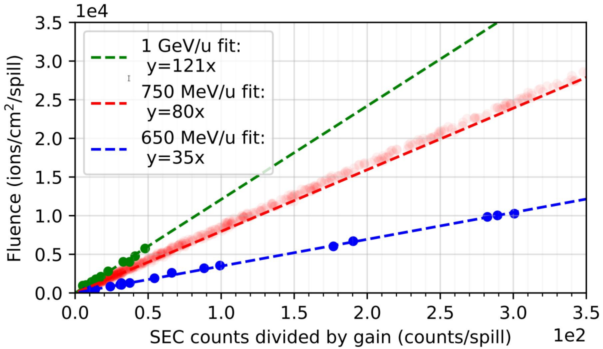
XSEC secondary emission chamber

VHE ion beam dosimetry: flux and fluence (2)

- Two main limitations to this approach:
  - Active surface of the diode is partially covered by a case ➡ Solution: PMMA collimator allowing to identify hits only through uncovered Si surface area by comparing energy deposition spectra shapes
  - For the higher fluxes the buffer of the digitizer saturates ➡ Solution: optimisation of the digitizer settings, focusing on event rate and neglecting analogue pulse shapes
- Based on the obtained calibration curves (for each energy) and over the experimental irradiations, the delivered fluence per spill spanned between **10^2 and 10^5 ions/cm²/spill**
- Spill duration of ~350 ms and good quality independent of energy or intensity setting

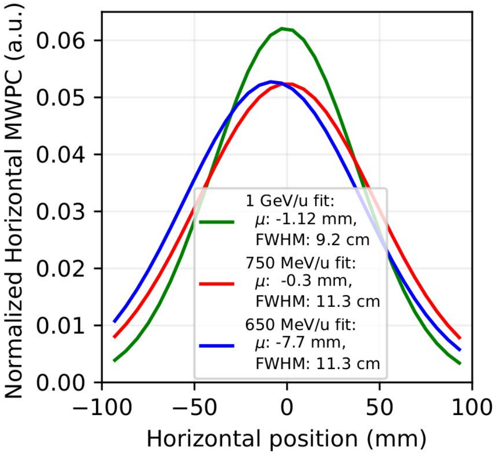


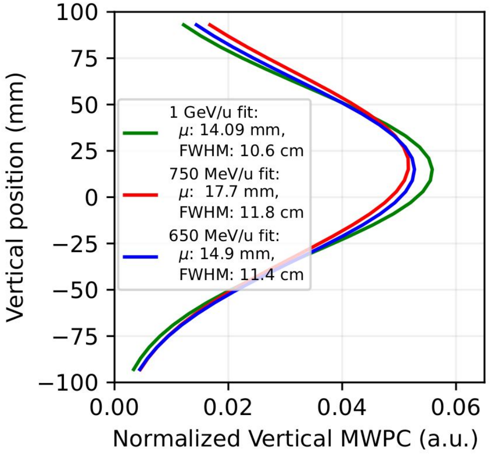


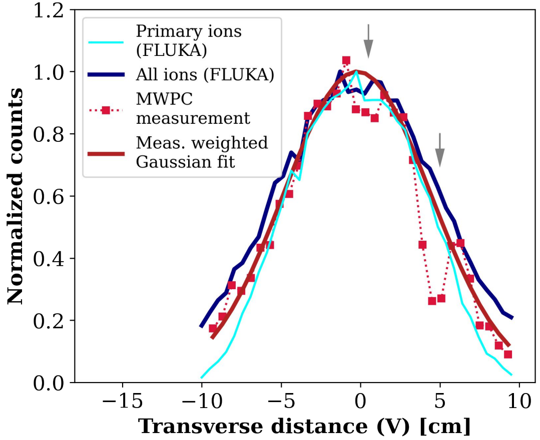


Beam profile

- Experimental measurements with Multi-Wire Proportional Chamber (MWPC) located in CHARM directly behind DUT position.
- Each energy has a Gaussian, 10 cm FWHM beam profile (beam size largely dominated by air scattering in IRRAD/CHARM)
- In very good agreement with FLUKA simulations, also predicting a similar beam size independent of the extracted energy
- Different beam line optics under study which can further enlarge the beam for board level testing (+mask)

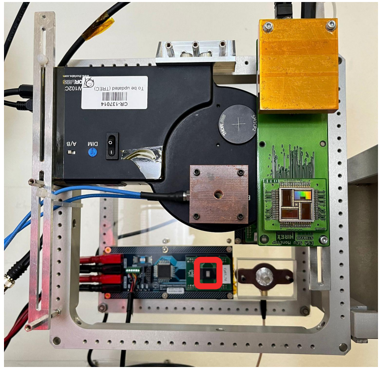


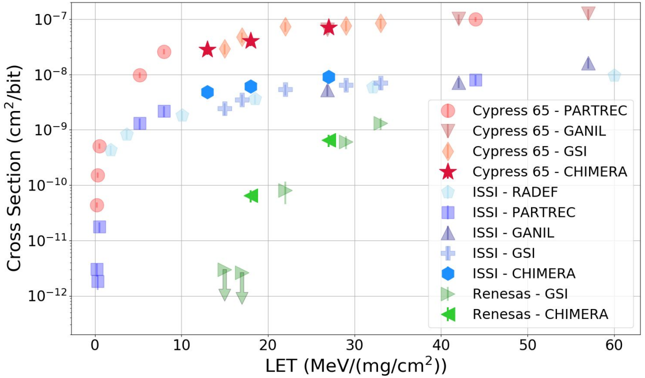




Testing components in CHIMERA: SRAMs

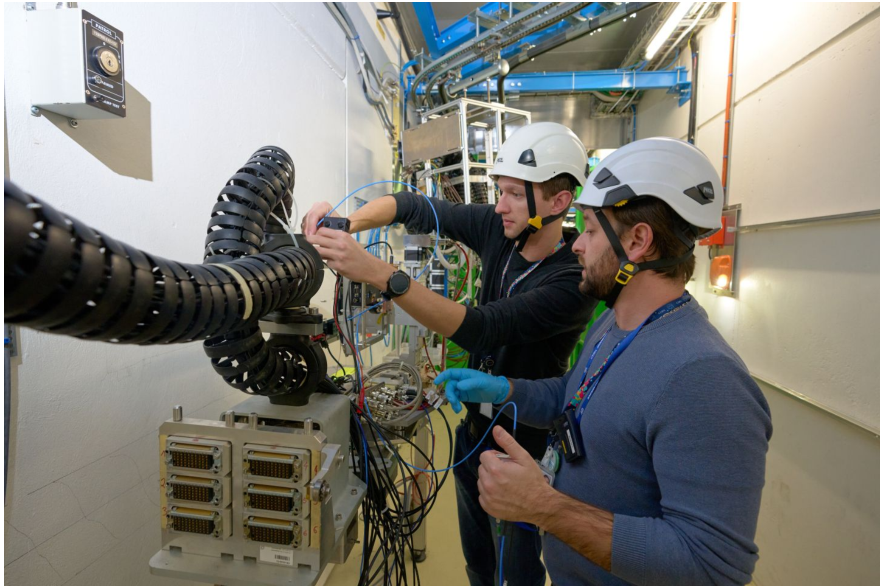
- Use of SRAM (in CHIMERA: Cypress, ISS, Renesas) can be considered to have a **dual purpose**:
  - actual **SEU experiment** that can be compared to other European heavy ion facilities (e.g., RADEF, GANIL, PARTREC and GSI) which provide ions at different energies (from 10 MeV/n to almost 1 GeV/n), but with similar LET range [0-60 MeV/(mg/cm^2)] → $\sigma_{SEU} = N_{SEU}/(\Phi N_{bits})$
  - use the SRAMs as radiation monitors that can allow to measure the flux/fluence delivered by the facility, provided an independent measurement of the LET by the facility and a proven independence of the cross section wrt the beam energy → $\Phi = N_{SEU}/(\sigma_{SEU} N_{bits})$





- ➔ Good agreement for all 3 SRAMs
- ➔ Based on LET estimate from FLUKA/diode, the flux calculated from the SEU cross sections is within a factor 2 of the beam instrumentation measurements.

External user support

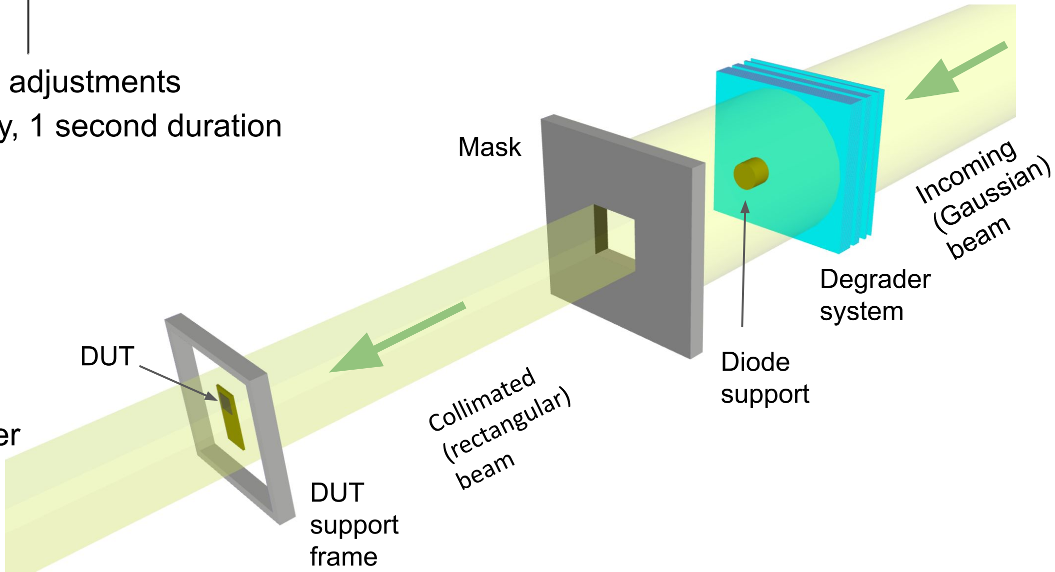


- The November 2022 CHIMERA campaign welcomed **TEC-QEC as users of the facility**
  - Opportunity for ESA to review progress in the facility development
  - Opportunity on CERN side to streamline access for external users
- Continued efforts to improve user access:
  - Beam time preparation (planning, access to CERN sites, required courses, equipment, …)
  - Integration of setups in CHARM
  - Real time visualisation of data during beamtime + logging for post-processing
  - Communication with CERN’s control centre
- Discussions ongoing that will further improve user autonomy in the future
  - Less strict constraints on facility access where possible (RP) or remote operation
  - Beam ON/OFF button, irradiation up to a certain fluence

Outlook

- Some **prospects** in the near and longer term future: final goal is to become a **user facility**
- Consolidation of 2022 experimental results:
  - Optimization of beam dosimetry method
  - Beam characterization at DUT
- Beam operation
  - Further automation of energy, intensity adjustments
  - Spill quality improvements: flat intensity, 1 second duration
- Infrastructure
  - Extended vacuum sections in T08
  - Octupole magnets for beam shaping
  - Remotely controlled PMMA degrader + mask system

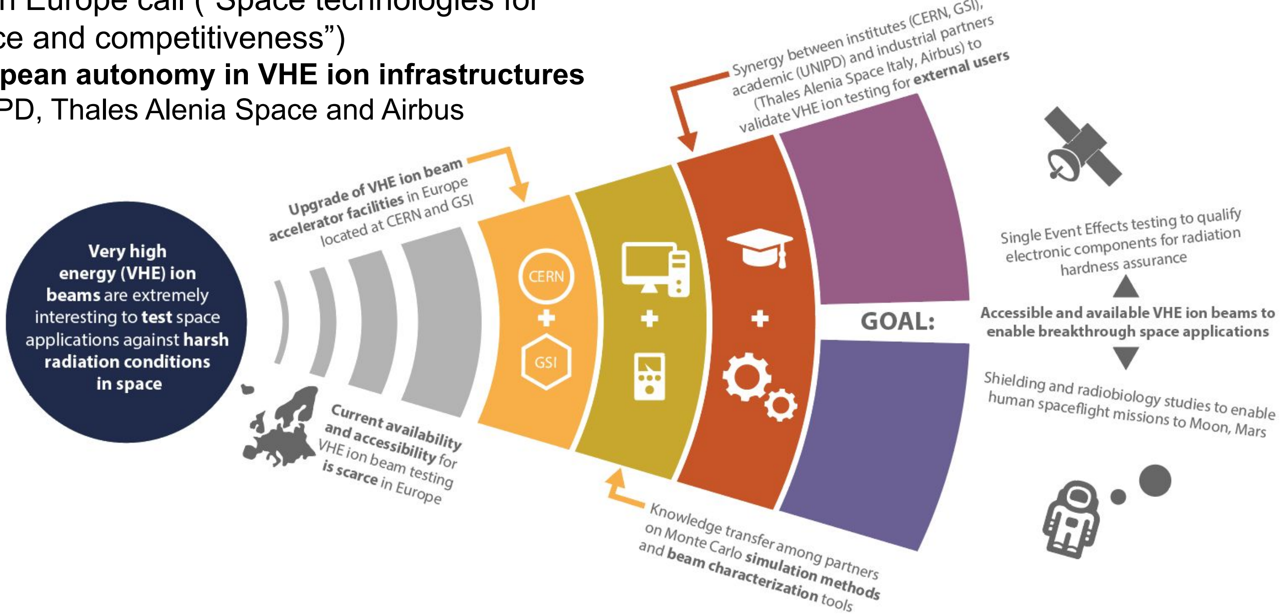
- Developments benefit from knowledge transfer with GSI and NSRL as reference facilities



HEARTS

https://hearts-project.eu/

- **HEARTS (High Energy Accelerators for Radiation effects Testing and Shielding)** is the ongoing EU Commission funded project in which the CERN VHE ion activity is embedded.
- It answers specific Horizon Europe call ("Space technologies for European non-dependence and competitiveness")
- In particular: **increase European autonomy in VHE ion infrastructures**
- In partnership with GSI, UniPD, Thales Alenia Space and Airbus



Conclusions

- **CHIMERA activity at CERN answers testing needs in Europe for space electronics qualification using VHE, heavy ions**
- Commissioning of the facility is ongoing with dedicated experimental run each year, working towards user facility
- Support from ESA is essential in the development of this facility (reports currently under circulation between CERN and ESA)
- Revisiting the **CHIMERA objectives:**

Objective	Status
Tuning **ion energy** in the "high LET variability" range	Effective solution for beam energy control and extraction in PS, 10 - 30 MeVcm^2/mg LET range experimentally verified after MC simulations, dosimetry to be optimized further
Tuning the **ion flux** in the **10^2 - 10^5 ions/cm^2/s** range	Achieved by RFKO slow extraction technique and calibrated dosimetry method, good spill quality
Tuning the **beam size** up to **~ 20 x 20 cm^2**	10 cm FWHM Gaussian beams to be further manipulated by improved beam optics

Thank you for your attention!

References

[1] E. Petersen, *Single Event Effects in Aerospace*, Wiley IEEE Press (2011)
[2] As published on: https://www.eetimes.com/micron-leapfrogs-to-176-layer-3d-nand-flash-memory/ Image courtesy of Micron Technologies, Inc.
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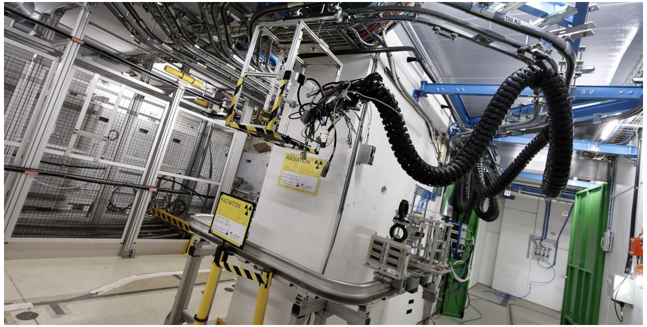
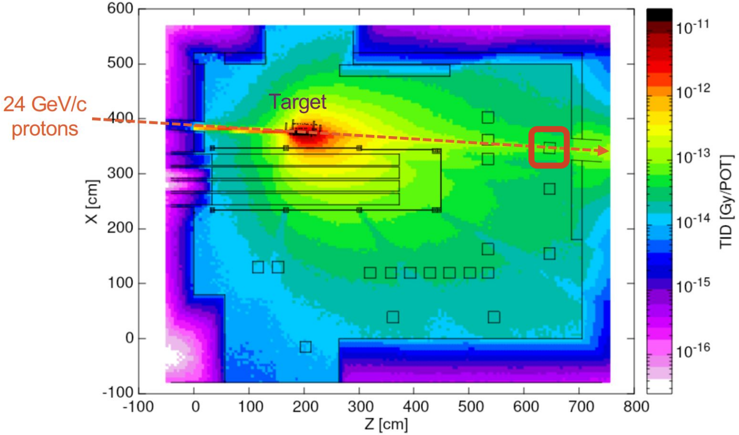
Internal reports shared between CERN and ESA.

Extra slides

CHARM facility

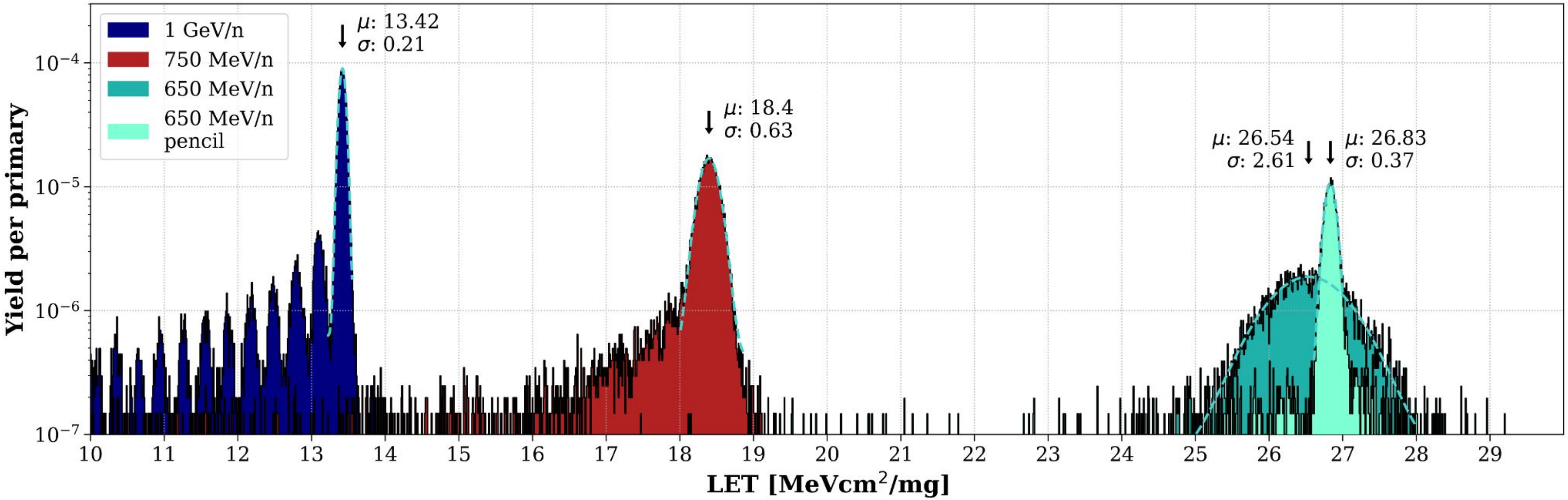
- **CHARM = CERN High-energy AcceleRator Mixed field**
- Is a radiation test facility at CERN used to qualify electronic components and systems against harsh radiation environments, mainly for LHC accelerator applications.
- The radiation field is generated through the interaction of a 24 GeV/c proton beam from the PS with a metallic target (requires cool down time).
- The mixed-field environment resembles that present in the vicinity of a high-energy accelerator and can be adapted to the application conditions by selecting different test configurations/locations.
- **Existing infrastructure for electronics testing** is very interesting for CHIMERA.
- In CHIMERA, test objects are placed in the primary ion beam (no target)





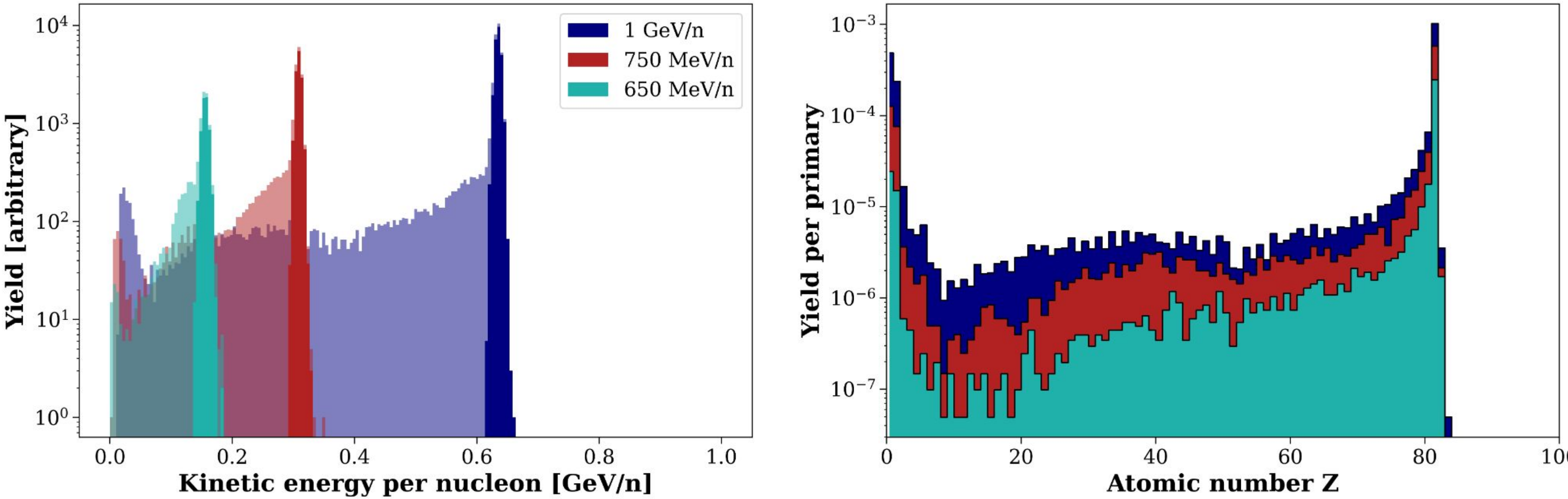
Prelipcean et al., "Benchmark Between Measured and Simulated Radiation Level Data at the Mixed-Field CHARM Facility at CERN," https://ieeexplore.ieee.org/document/9762483

Primary beam LET



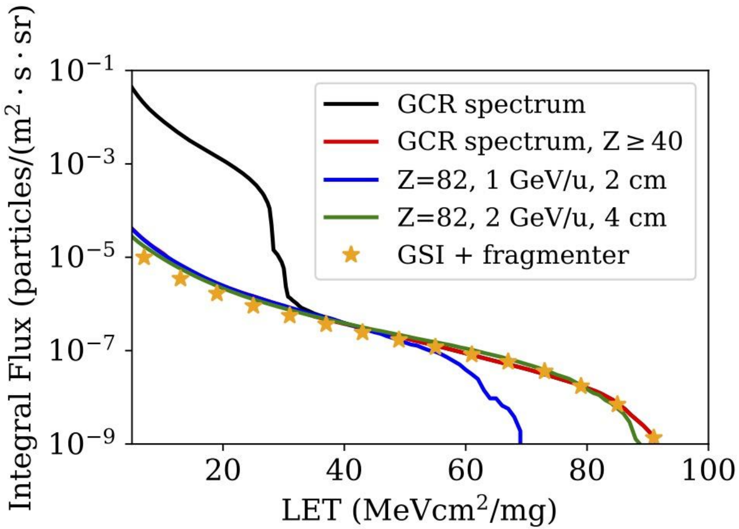
Beam fragmentation

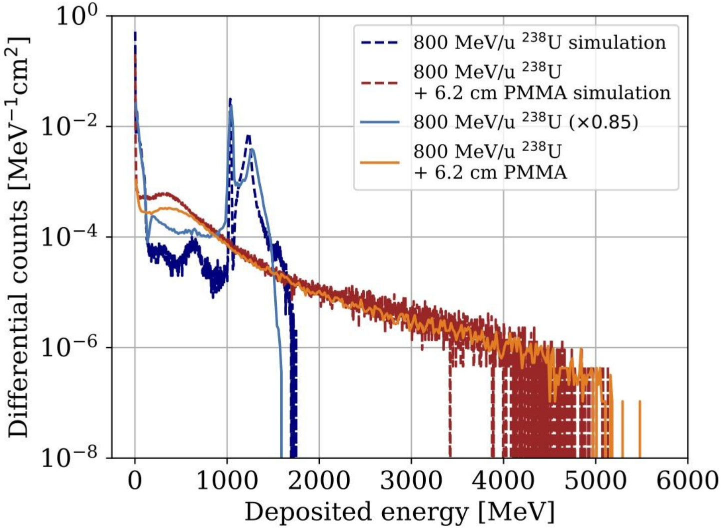
- For each energy, the ratio of primary ions/secondary fragments reaching the DUT is between 60% and 65%



Fragmented heavy ion beams

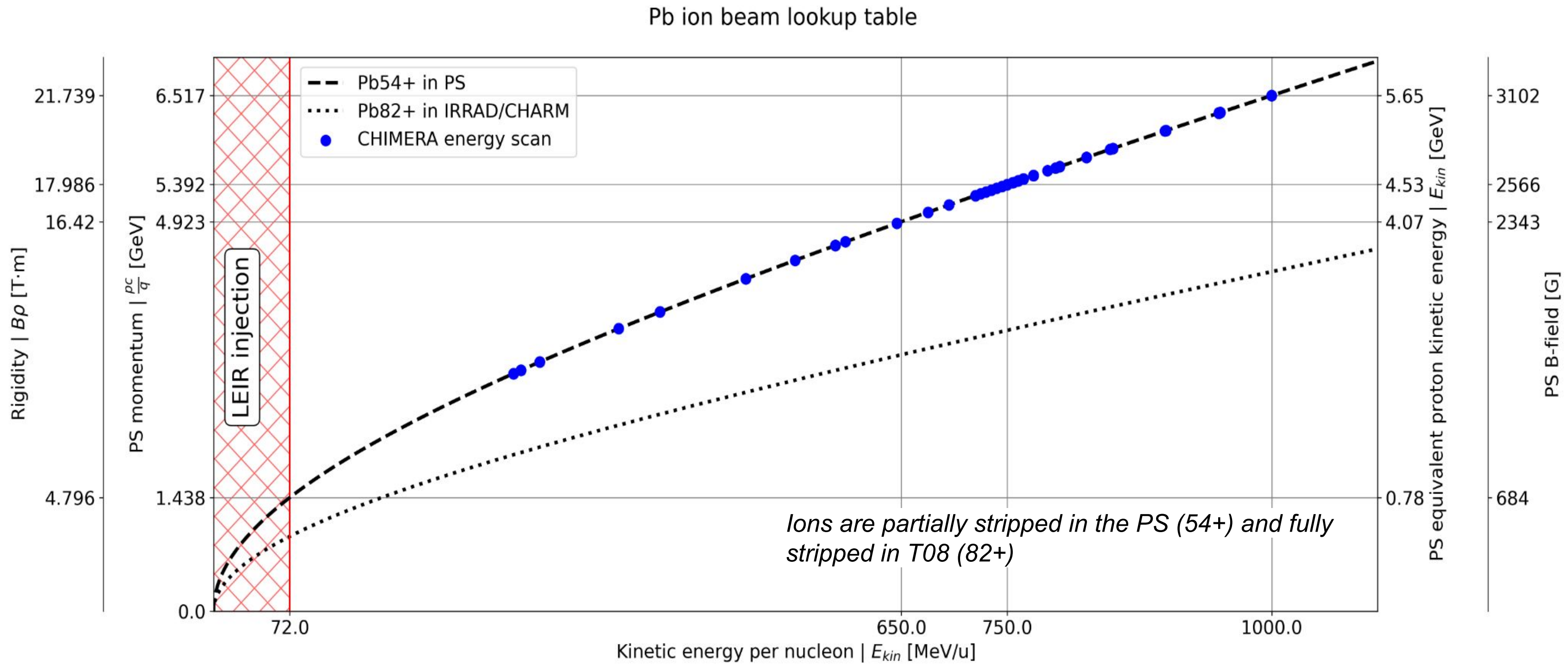
R. G. Alía *et al.*, "Fragmented high-energy heavy ion beams for electronics testing," in *IEEE Transactions on Nuclear Science*, 2022, doi: 10.1109/TNS.2022.3210403.





- Proof-of-concept of using a fragmenter with thickness larger than range of primary beam → only (potentially high LET) fragments remain!
- 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.

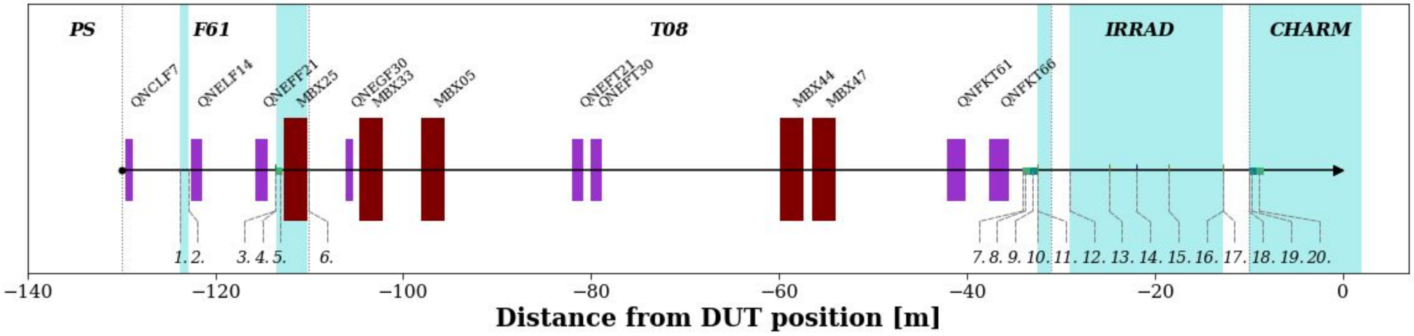
PS energy lookup table



Ions are partially stripped in the PS (54+) and fully stripped in T08 (82+)

VHE ion beam dosimetry: energy and LET

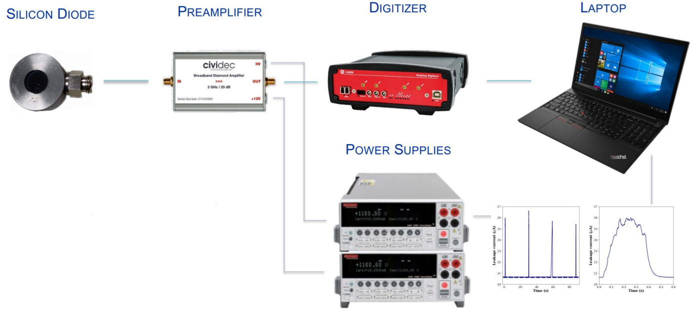
- The T08 transfer line and IRRAD, CHARM user facilities contain a **significant amount of non-vacuum** regions (~30m in total, cumulative surface density: 5.4 g/cm^2):
  - In-beam instrumentation
  - Sections of air (70%)
- The present material budget affects the beam quality through
  - Electronic stopping power
  - Inelastic nuclear interactions
- Detailed **Monte Carlo** simulations (in FLUKA) can quantify these effects, provide an in-depth description of the beam and resulting radiation environment and aid in beam line development and optimization

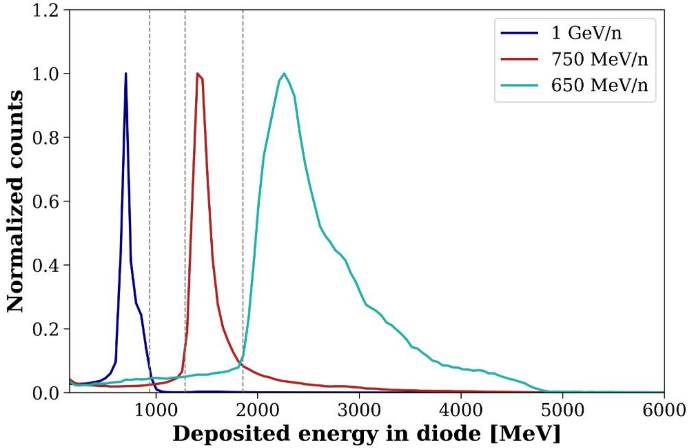


→T08 beam line geometry accurately represented by FLUKA simulation model

VHE ion beam dosimetry: energy and LET

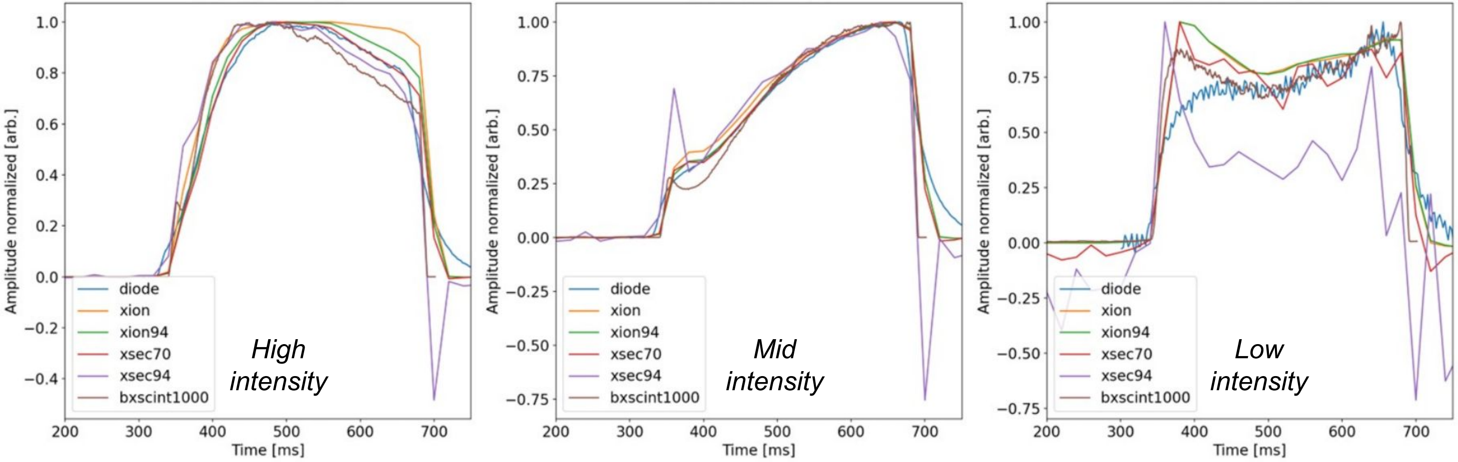
- Experimental validation using diode monitor at DUT position
- Specifications:
  - Canberra silicon diode (FD 50-14-300 RM)
  - 300 µm thickness of active layer
  - 0.5 cm^2 exposed surface
  - Operated at full silicon depletion using a reverse bias
- Cividec C1-HV0089 20 dB preamplifier + 6dB attenuator
- CAEN digitizer (DT5751) →pulse analysis using WaveDump software
- **Indirect measurement of the LET** by extracting the amount of deposited energy by the beam particles within a sensitive silicon layer of known thickness. **First-order approach** to calculate the expected deposited energy in the 300 µm sensitive layer: $\varepsilon_{dep} = LET_{Si} \times \rho_{Si} \times t_{Si}$, three distinct primary energy peaks are expected from simulated LET = observation with the Si diode





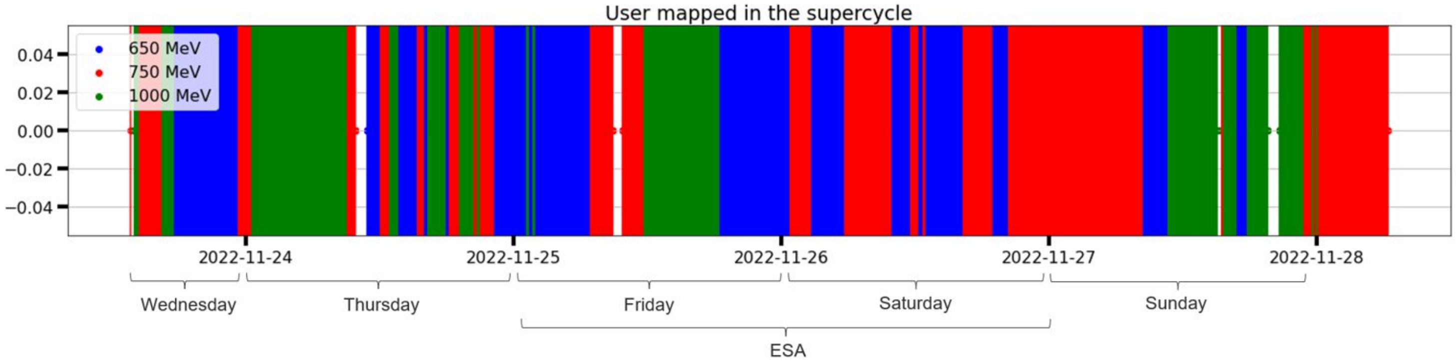
Spill quality

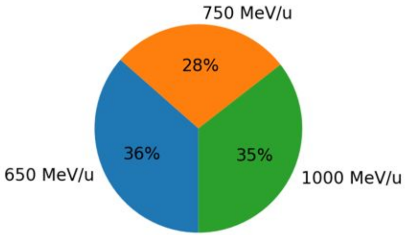
- Excellent agreement between spill time profiles measured by various T8 beam instrumentation units, i.e., diode at DUT position, secondary emission chambers (SECs), ionization chambers (XION) and gaseous scintillator (BCGAA/XSCINT).
- **350 ms** spill duration was **independent** of the beam **energy** (thanks to the RFKO) and **intensity**.
- Future studies could benefit from using a signal generator to modify the excitation voltage during the spill, enabling extraction of a constant beam intensity + a longer spill duration of around 1 second.



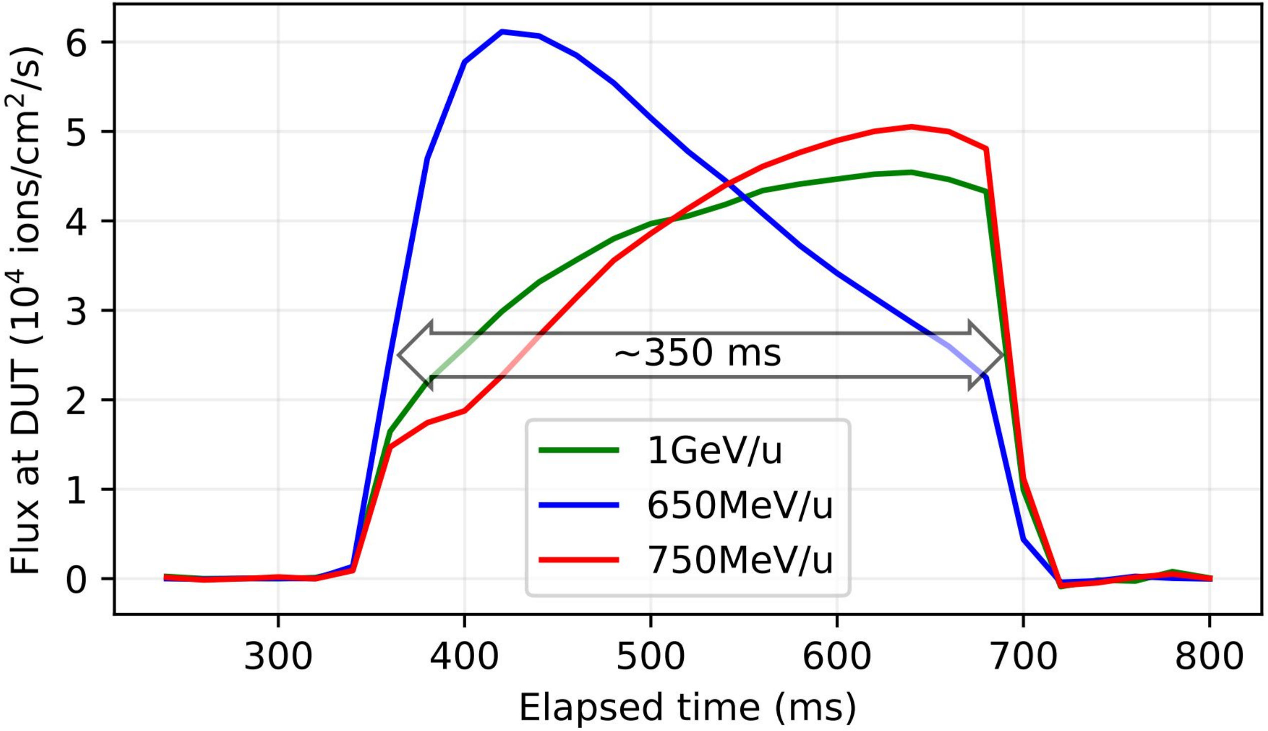
Flux November 2022 run

User mapping timestamps





Spill shape as function of energy



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