HEARTS P1 Review Meeting

25 September 2024

https://indico.cern.ch/event/1411185

L.S. Esposito, A. Waets / CERN

on behalf of all WP3 members and contributors

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.

WP3 members

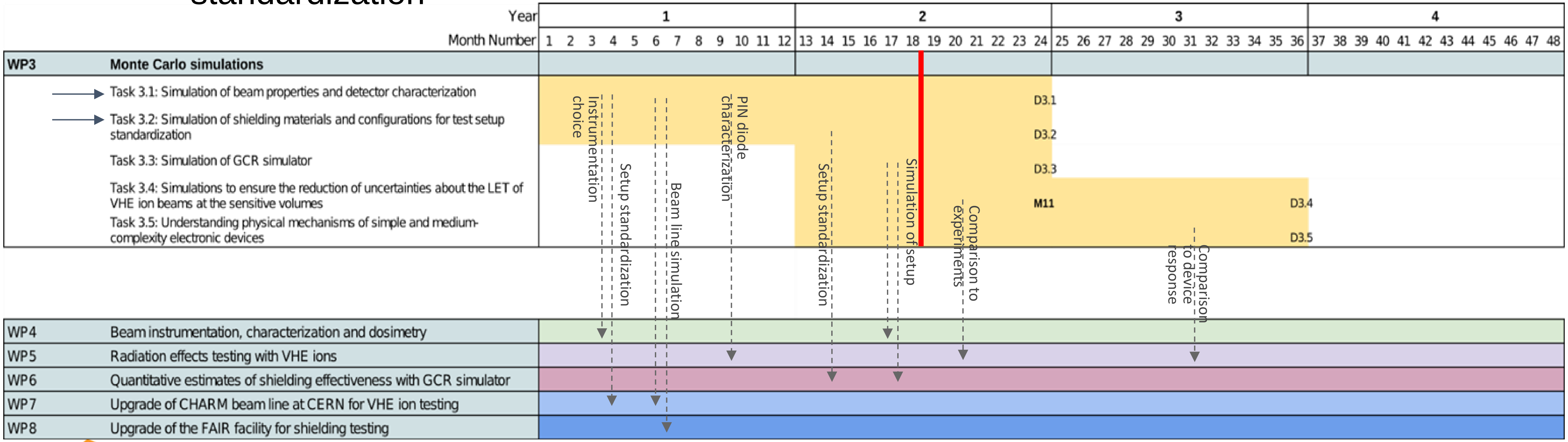
- CERN
  - Luigi Salvatore Esposito
  - Rubén Garcia Alia
  - Karolina Klimek
  - David Lucsanyi
  - Andreas Waets
- GSI
  - Christoph Schuy
- UNIPD
  - Marta Bagatin
  - Simone Gerardin
  - Alessandro Paccagnella
- TAS
  - Luca Bocchini
  - Claudio Cipriani

Outline

- W3 timeline
- Upcoming Deliverables & Milestones
- Task status and progress
- Risk assessment
- Follow-up of recommendations from previous review
- Conclusions

WP3 timeline

- Activities in WP3 span over the first 3 years (M1 - M36) of the project
- Transversal work package providing support and deliverables to WP4-8
  - Characterization of beam conditions, feeding into instrumentation choice, setup standardization



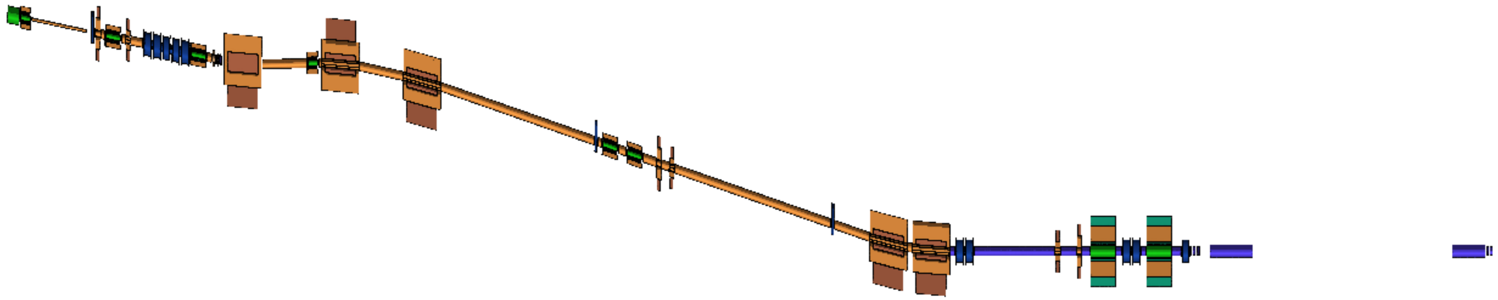
Upcoming Deliverables & Milestones

Deliv. No.	Deliverable name	Due date	Status
D3.1	Numerical characterization of the CHARM beamline and of detector response	2024-12-31	Pending
D3.2	Modelling of shielding materials and configurations for test setup standardisation	2024-12-31	Pending
D3.3	GCR/SPE simulator optimizer software	2024-12-31	Pending
D3.4	Demonstration of LET uncertainty reduction from simulations as a complement to experimental measurements	2025-12-31	Pending
D3.5	Modelling of medium-complexity devices and response to different ion beams	2025-12-31	Pending

Milest.No.	Milestone name	Due date	Status
M11	Release of G4SEE VHE ion tool	2024-12-31	Pending

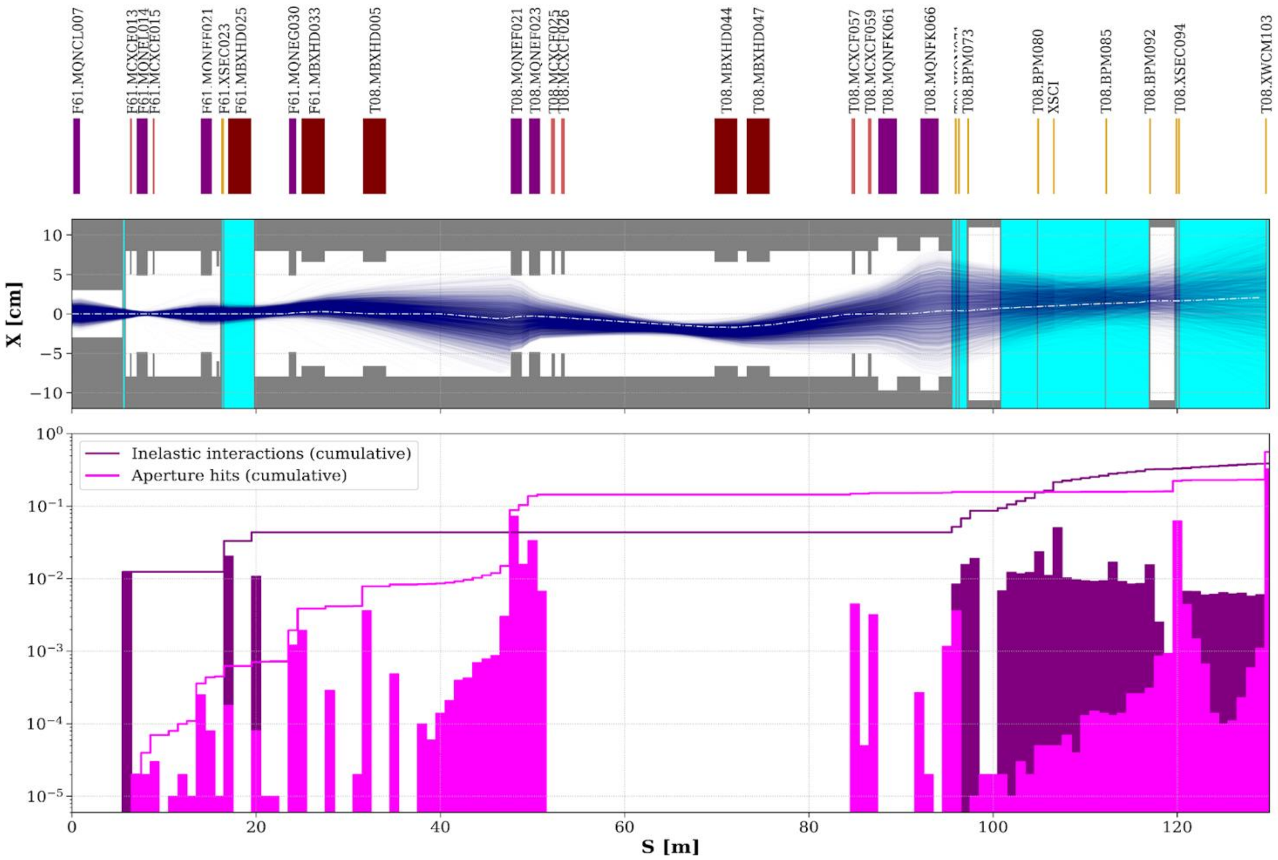
No deliverables or milestones were due in P1

Task 3.1: Simulation of beam properties and detector characterization (CERN)



- Detailed Monte Carlo simulations of the VHE ion beam transport through the T08 beam line at CERN were carried out
- A dedicated geometry of the T08 beam line was constructed relying on the optics settings used during operation, dimensions from technical drawings and in-person inspections
- Using **FLUKA**, a more fundamental and **in-depth description of the beam and radiation environment** was obtained and multiple configurations and related optimizations in parallel could be explored (directly feeding into WP7)
- The properties determining the **beam quality** are:
  - beam line transmission
  - beam profile
  - beam energy and spread of energy distribution
  - LET and spread of LET distribution

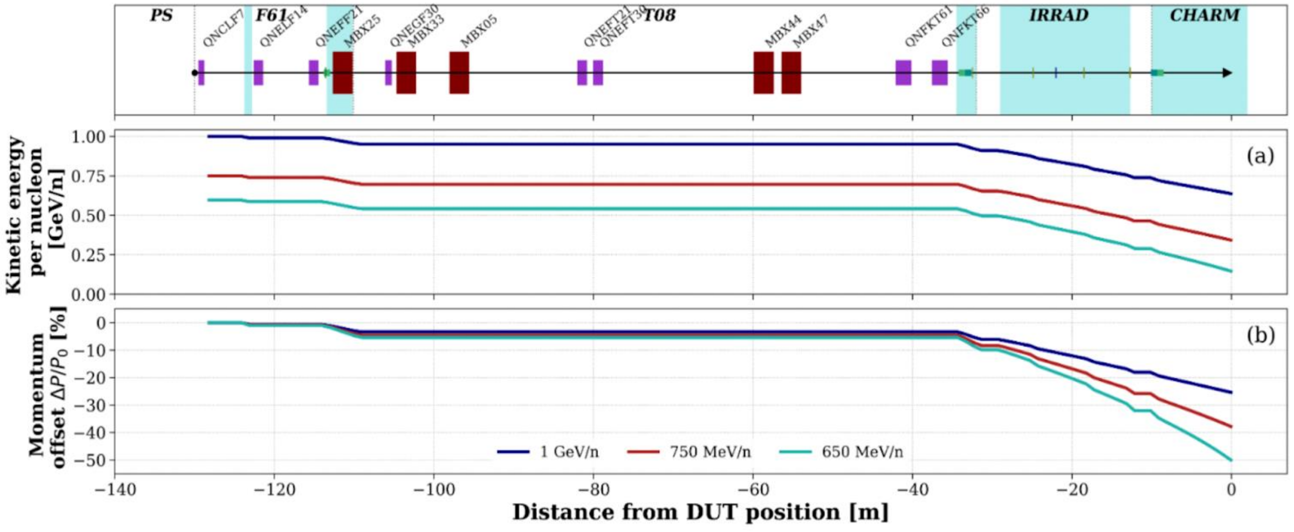
Task 3.1: Simulation of beam properties and detector characterization (CERN)

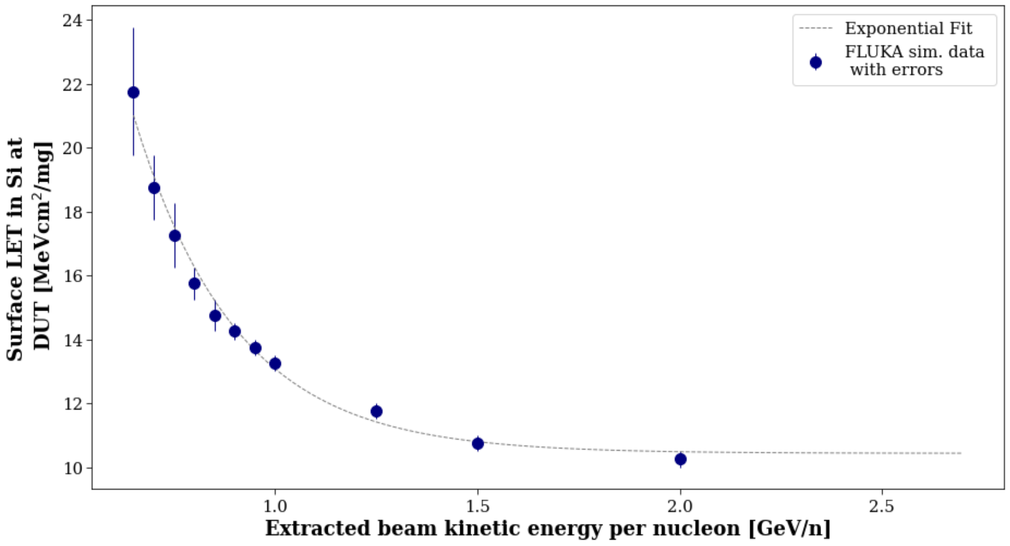


- "Loss maps" give insight into the physical processes that determine the **resulting radiation field** at the DUT
- Aperture hits are prevalent where:
  - the beam is defocused by the quadrupole magnets
  - non-vacuum sectors (scattering)
- Inelastic interactions causing the primary beam to fragment and generate lower-LET ions and other secondary particles:
  - Non-vacuum sectors (including beam instrumentation and vacuum windows)

Task 3.1: Simulation of beam properties and detector characterization (CERN)

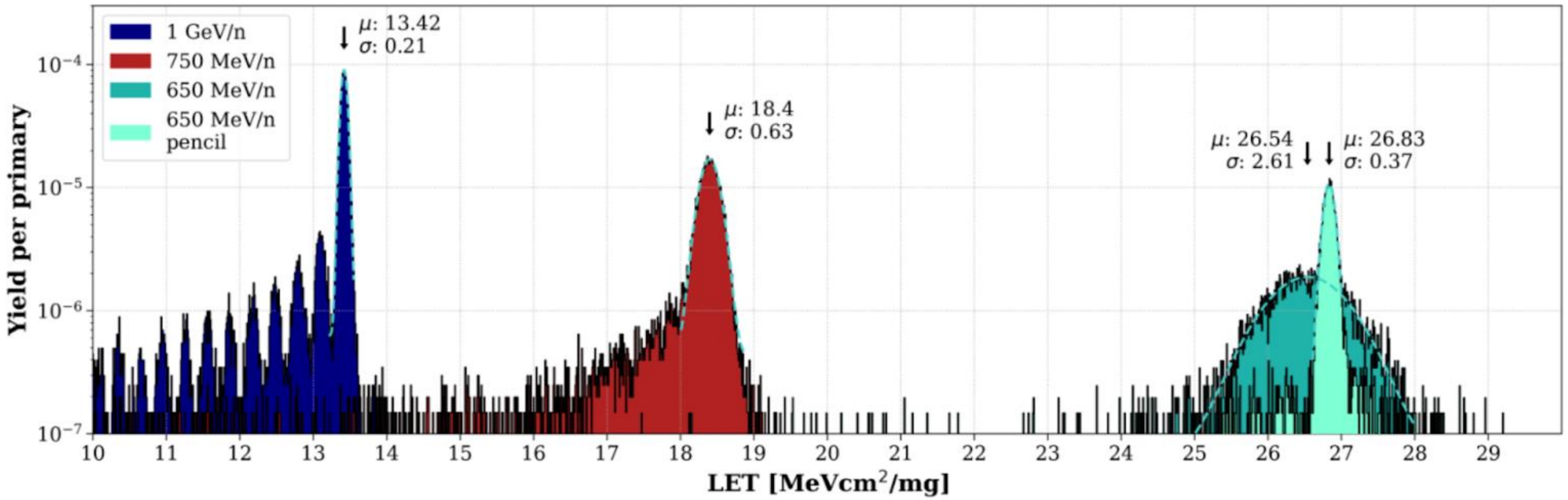
- Material budget in the beam line causes a significant amount of **energy straggling**: the beam extracted from the Proton Synchrotron at a certain energy will arrive at the DUT position at a **significantly reduced energy**
- Minimum energy limit for extraction and transport to CHARM set to 650 MeV/n





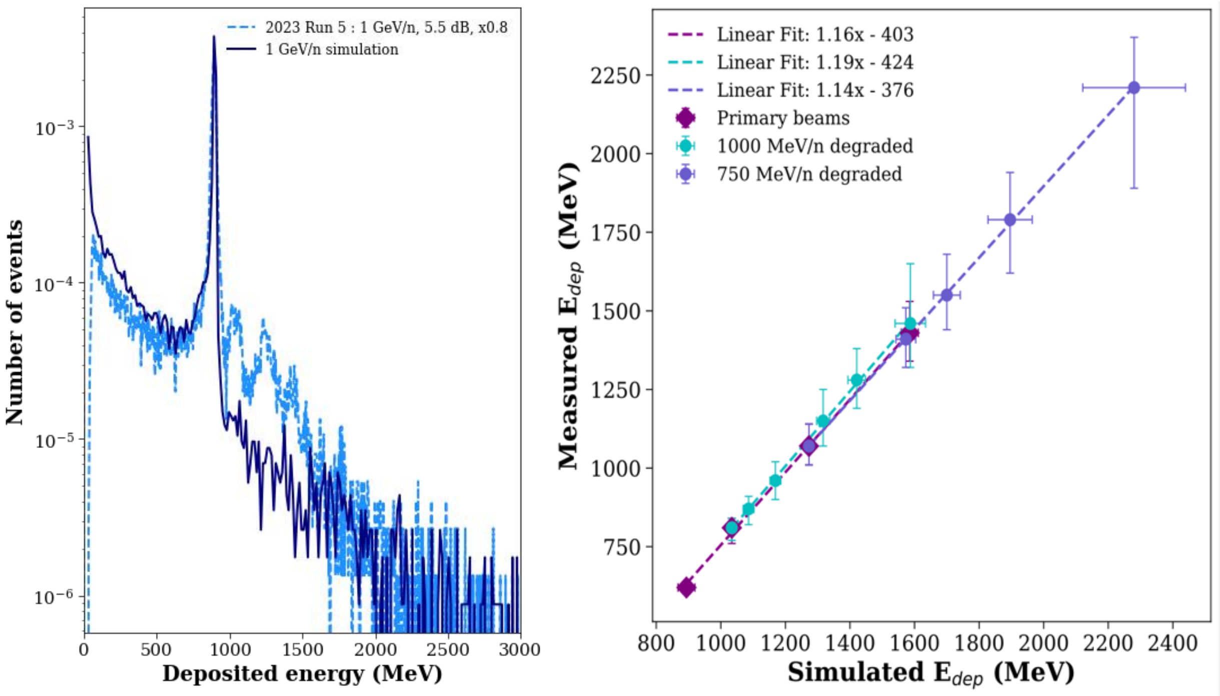
Task 3.1: Simulation of beam properties and detector characterization (CERN)

- **Spread** of the primary beam **LET distribution** is an important **dosimetric information for the users** who are generally used to a single LET value in standard energy heavy ion facilities
- Deviations from the desired LET value of the DUT radiation field result from ion fragments and other secondary particles present in the beam

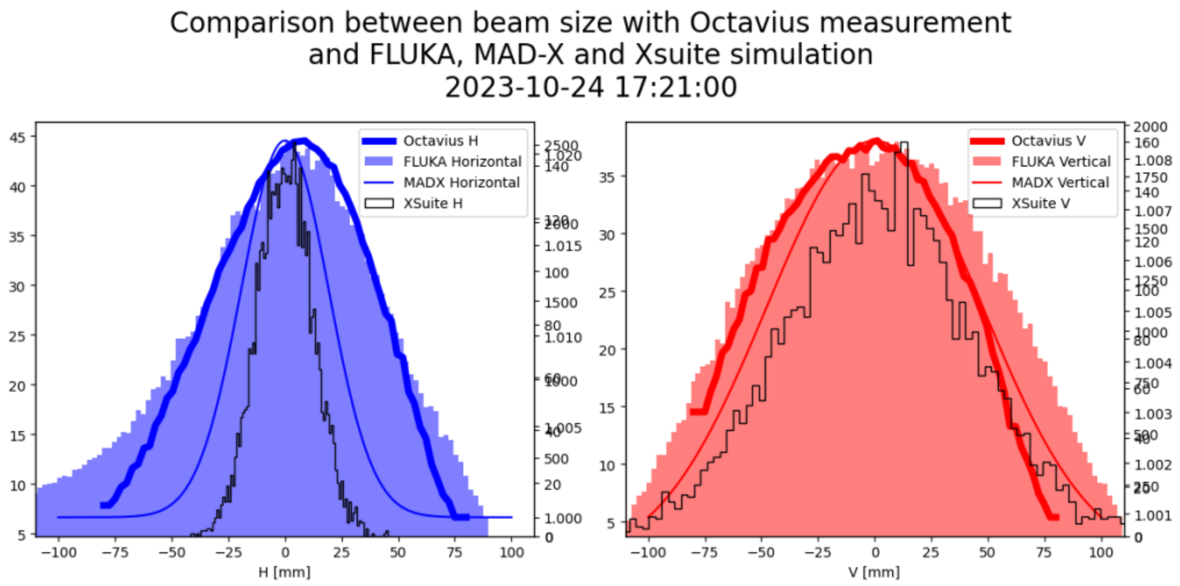


Task 3.1: Simulation of beam properties and detector characterization (CERN)

- A good agreement between the simulated and measured energy deposition spectra is observed
- Energy deposition only offers an indirect indication of the beam LET, However, this agreement offers sufficient confidence that the silicon **diode in combination with FLUKA** simulations **can determine the LET** as one of the key dosimetric quantities
- **Comparison between simulated and measured peak energy deposition values show an excellent agreement.** This correlation also serves as a calibration of the instrument



Task 3.1: Simulation of beam properties and detector characterization (CERN)

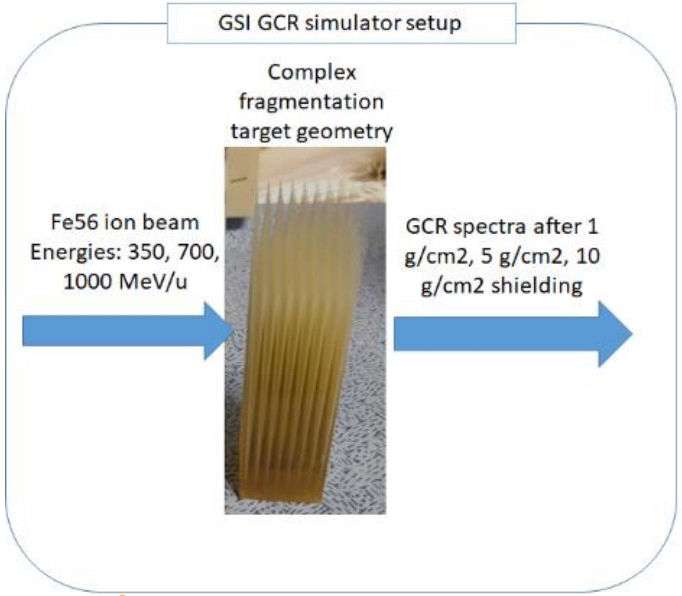


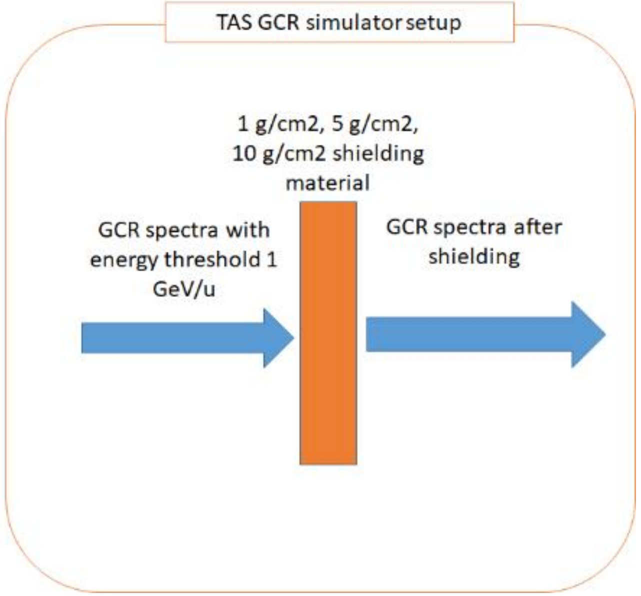
- Excellent agreement between
  - FLUKA
  - PTW Octavius array
  - Multi-Wire Proportional Chamber
- In conclusion, **the FLUKA simulation model and workflow** has been shown to be an **excellent tool for the numerical characterization of the beam line**

Task 3.2: Simulation of Shielding Materials (TAS-I)

GRAS and Geant4 Monte Carlo preliminary simulations have been performed to:

- identify a suitable set of **relevant parameters** to be considered in the **standardized setup definition** for **shielding materials testing**
- prepare a simulation setup to include the **GPS source** provided by GSI, representative of the **GCR simulator**



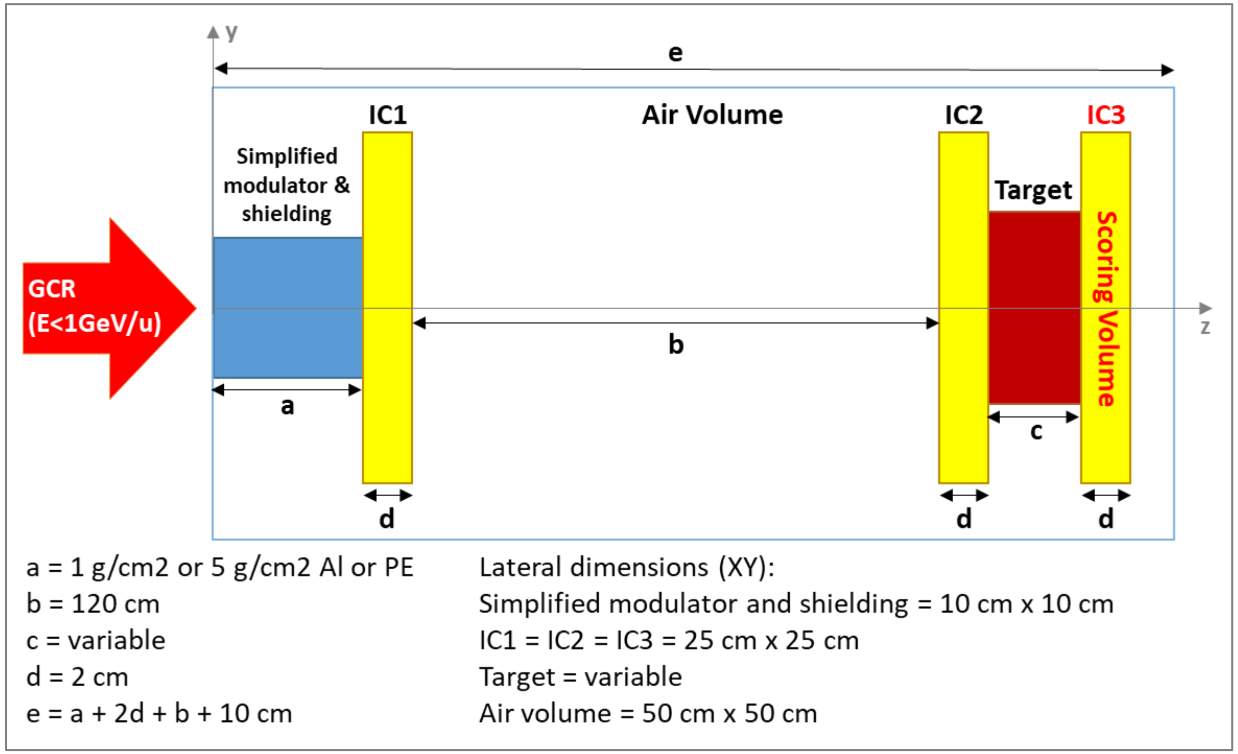


Simulation cases summary

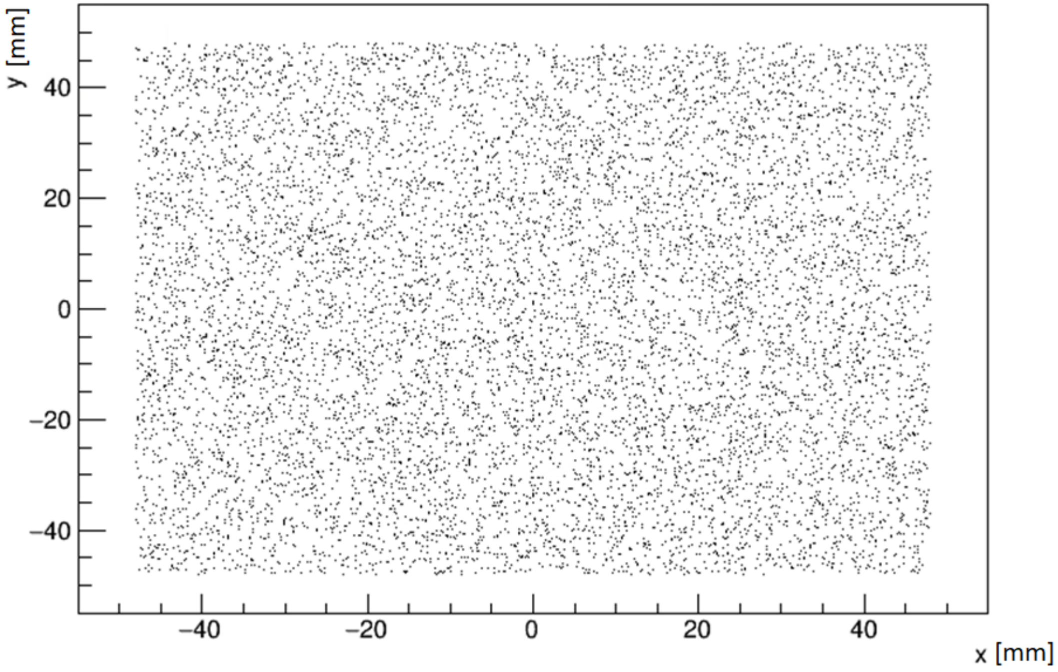
GCR Modulator Shielding material	GCR Modulator Shielding Material thickness	Target Lateral Dimensions [cm]	Target Thicknesses [cm]
Aluminium	$1\ g/cm^2$	10 cm x 10 cm	1, 2, 3, 4, 5, 7, 10, 20
		20 cm x 20 cm	1, 2, 3, 4, 5, 7, 10, 20
		30 cm x 30 cm	1, 2, 3, 4, 5, 7, 10, 20
		40 cm x 40 cm	1, 2, 3, 4, 5, 7, 10, 20
Aluminium	$5\ g/cm^2$	10 cm x 10 cm	1, 2, 3, 4, 5, 7, 10, 20
		20 cm x 20 cm	1, 2, 3, 4, 5, 7, 10, 20
		30 cm x 30 cm	1, 2, 3, 4, 5, 7, 10, 20
		40 cm x 40 cm	1, 2, 3, 4, 5, 7, 10, 20
Aluminium	$10\ g/cm^2$	10 cm x 10 cm	1, 2, 3, 4, 5, 7, 10, 20
		20 cm x 20 cm	1, 2, 3, 4, 5, 7, 10, 20
		30 cm x 30 cm	1, 2, 3, 4, 5, 7, 10, 20
		40 cm x 40 cm	1, 2, 3, 4, 5, 7, 10, 20
Polyethylene	$1\ g/cm^2$	10 cm x 10 cm	1, 2, 3, 4, 5, 7, 10, 20
		20 cm x 20 cm	1, 2, 3, 4, 5, 7, 10, 20
		30 cm x 30 cm	1, 2, 3, 4, 5, 7, 10, 20
		40 cm x 40 cm	1, 2, 3, 4, 5, 7, 10, 20
Polyethylene	$5\ g/cm^2$	10 cm x 10 cm	1, 2, 3, 4, 5, 7, 10, 20
		20 cm x 20 cm	1, 2, 3, 4, 5, 7, 10, 20
		30 cm x 30 cm	1, 2, 3, 4, 5, 7, 10, 20
		40 cm x 40 cm	1, 2, 3, 4, 5, 7, 10, 20
Polyethylene	$10\ g/cm^2$	10 cm x 10 cm	1, 2, 3, 4, 5, 7, 10, 20
		20 cm x 20 cm	1, 2, 3, 4, 5, 7, 10, 20
		30 cm x 30 cm	1, 2, 3, 4, 5, 7, 10, 20
		40 cm x 40 cm	1, 2, 3, 4, 5, 7, 10, 20

Task 3.2: Simulation of Shielding Materials – Geometry (TAS-I)

Simplified simulation setup used in TAS-I simulations



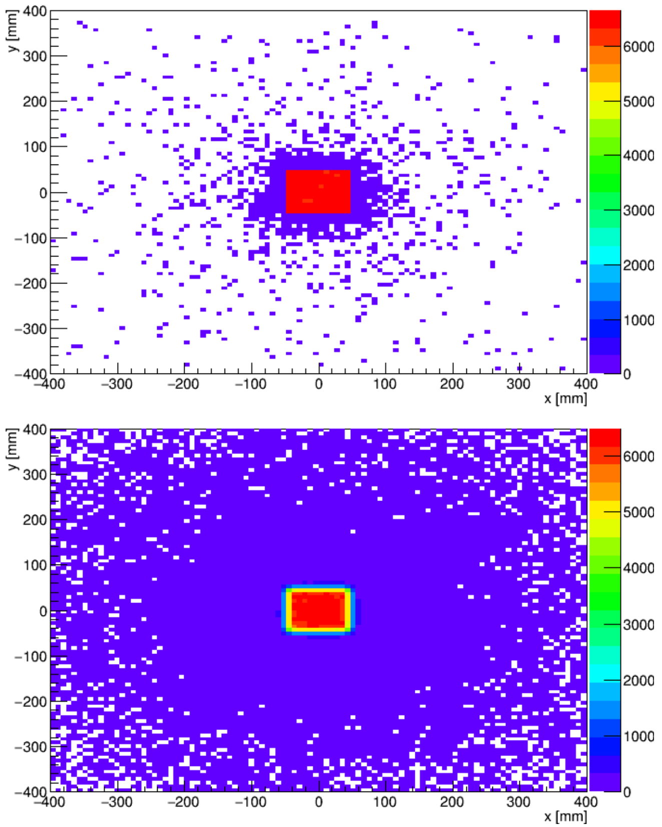
Source Sampling Geometry



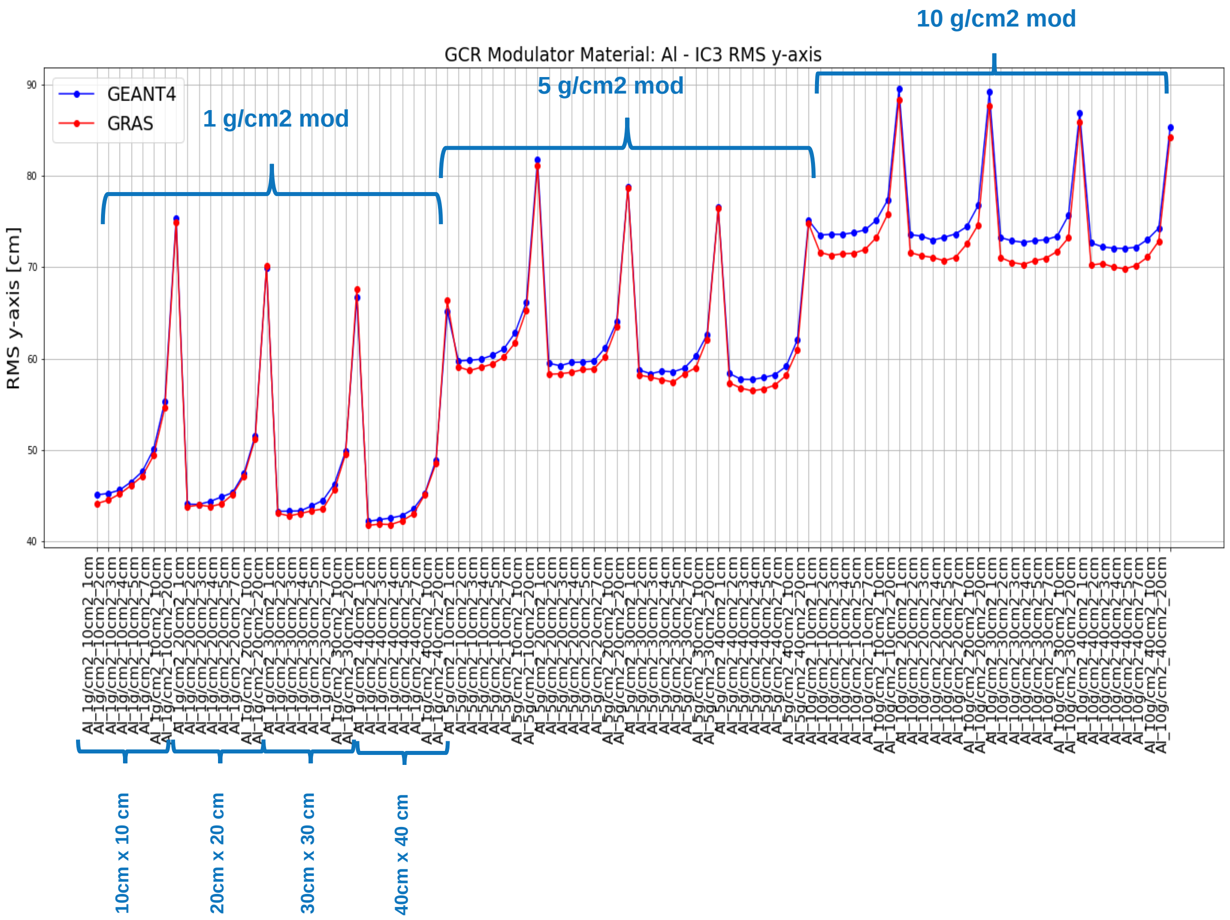
Task 3.2: Simulation of Shielding Materials – Setup (TAS-I)

- **GCR spectra**
  - CREME96 model as particle source
  - Energy <=1 GeV/n (imposed by the GSI accelerator facility)
  - All particle species from H to Fe56 simulated
- **Results evaluation parameter**
  - To evaluate the **lateral scattering** induced by the target dimensions and modulator thickness and material, the **RMS** of the particle position distribution has been calculated (results briefly summarized in the following charts)

Upstream and downstream ionization chambers particle distribution



Task 3.2: Simulation of Shielding Materials – Results & Future Work (TAS-I)



QBBC_EMY Physics list is used

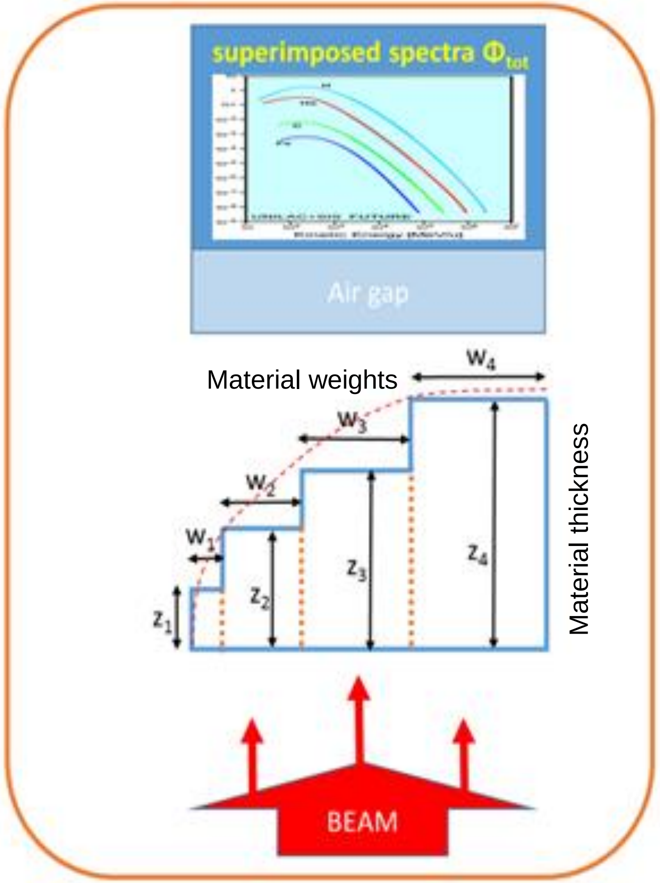
The Geant4 (v4.10.05p01) and GRAS (v3.3) results show good agreement

Similar results are obtained for PE modulator

Upcoming activities

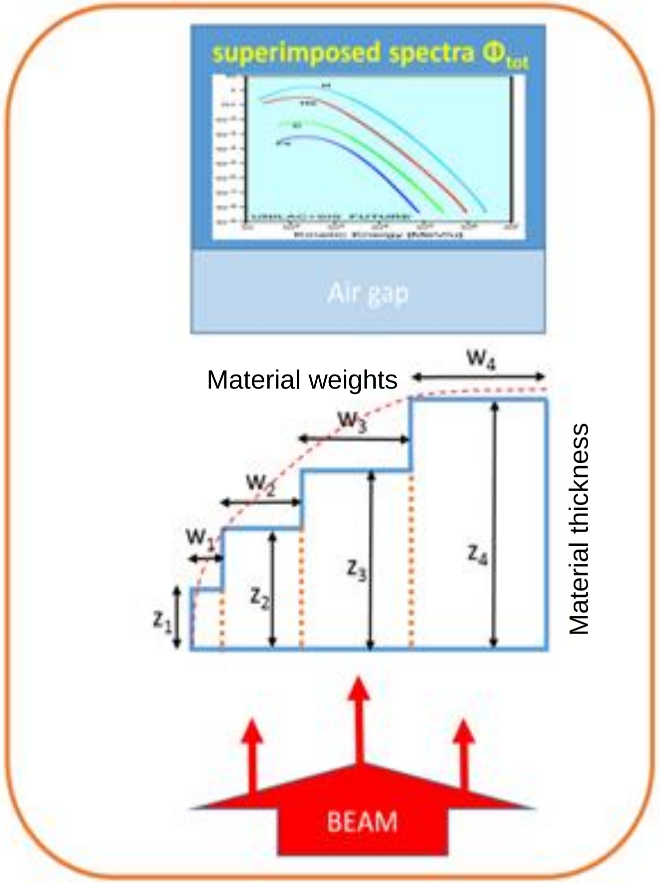
- Benchmark simplified TAS-I setup vs GSI GPS (phase space file), done in close collaboration with GSI
- Preliminary dose reduction simulations of selected shielding/spacecraft materials in a simplified setup
- Modelling of realistic experimental setup to establish a representative standardization approach, in close collaboration with GSI

Task 3.3: Simulation of GCR/SPE simulator (GSI)



- **Objective:**
  - Enhance simulation capabilities of the GCR/SPE simulator, which aims to find material weights for given material thickness to reproduce target function
- **Key Focus Areas:**
  - Development of templates and standards for modulator base data and full setup geometry simulations
  - Simplified simulation strategies like providing a GSI-GCR phase space
  - Standardized interaction with GSI's HPC cluster
  - New Python-based optimization tool (instead of the original approach based on C++ and ROOT)

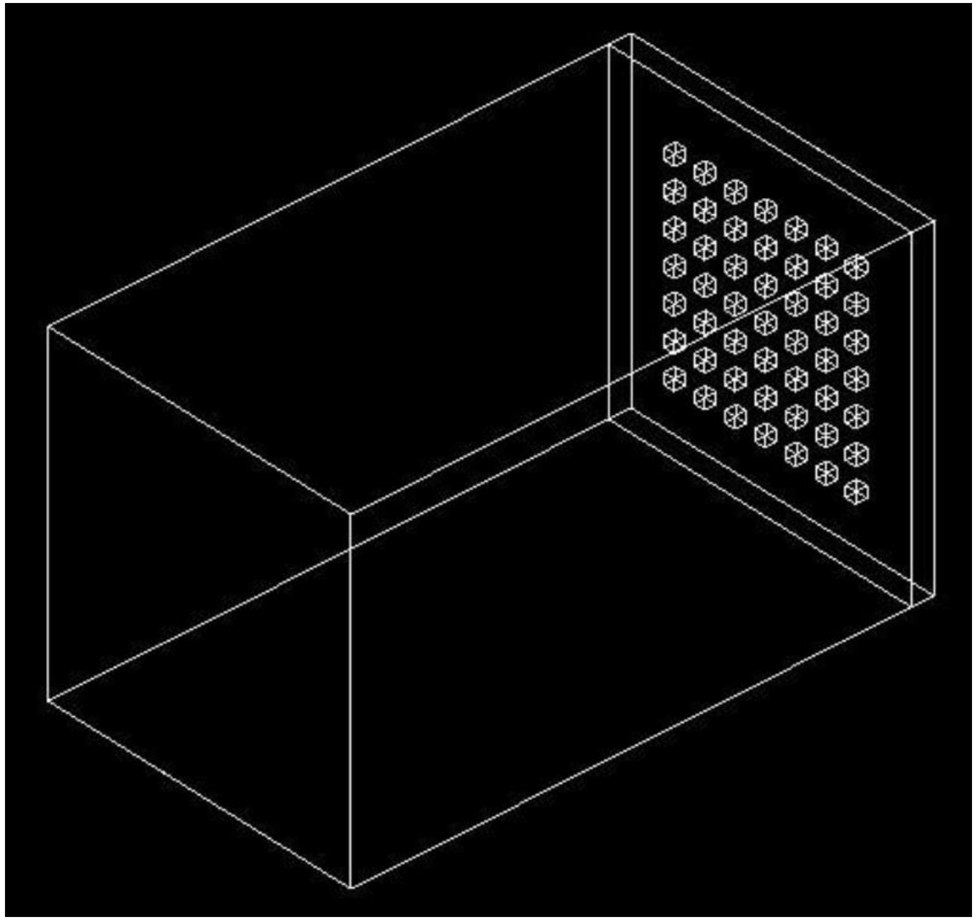
Task 3.3: Simulation of GCR/SPE simulator (GSI)



- **Optimization Tool Benefits:**
  - Ease of use (no compilation, Jupyter notebook compatibility)
  - Access to external libraries for agile development
  - Broader potential contributor base due to Python usage
- **Next Activities:**
  - Test, finalize and evaluate new tools
  - Open internal development Git repositories to the external users (wherever possible and reasonable)

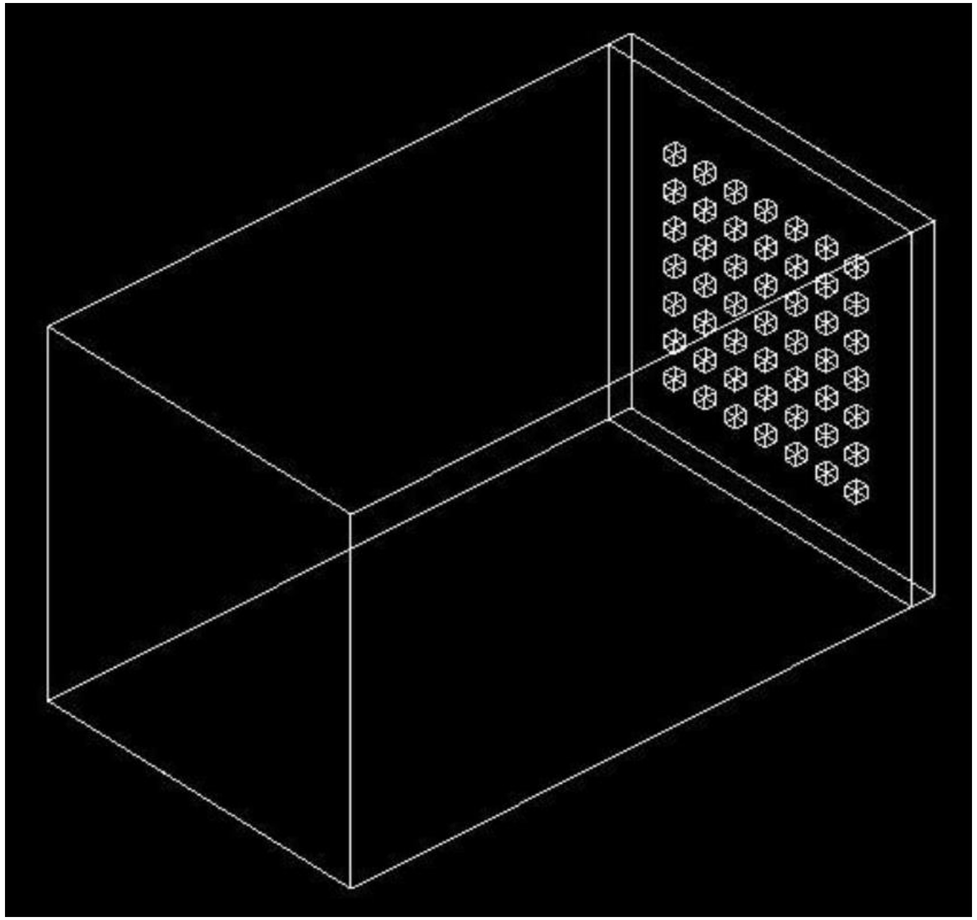
Task 3.4: Simulations to Reduce LET Uncertainties (UniPD)

- **Objective:** Study uncertainties in energy deposition and LET for VHE ions impacting small sensitive volumes
- **Model:** UniPD has developed a simple but effective model using Geant4
- **Key Features:**
  - Array of small silicon cubes representing sensitive volumes (reversed-biased –n junctions,
  - Configurable parameters (size, pitch, overlayer material and thickness)
  - GDML description for easy import into Geant4 codes



Task 3.4: Simulations to Reduce LET Uncertainties (UniPD)

- **Current Focus:**
  - Simulations to compare energy deposition and LET uncertainties between VHE ions and particles from commonly used accelerators and HEARTS
- **Future Work:**
  - Analyse simulation results to gain insights into LET uncertainties
  - Develop strategies to reduce these uncertainties for VHE ion testing
  - Explore synergies with G4SEE



Task 3.5: Understanding physical mechanisms of simple and medium-complexity electronic device (UNIPD)

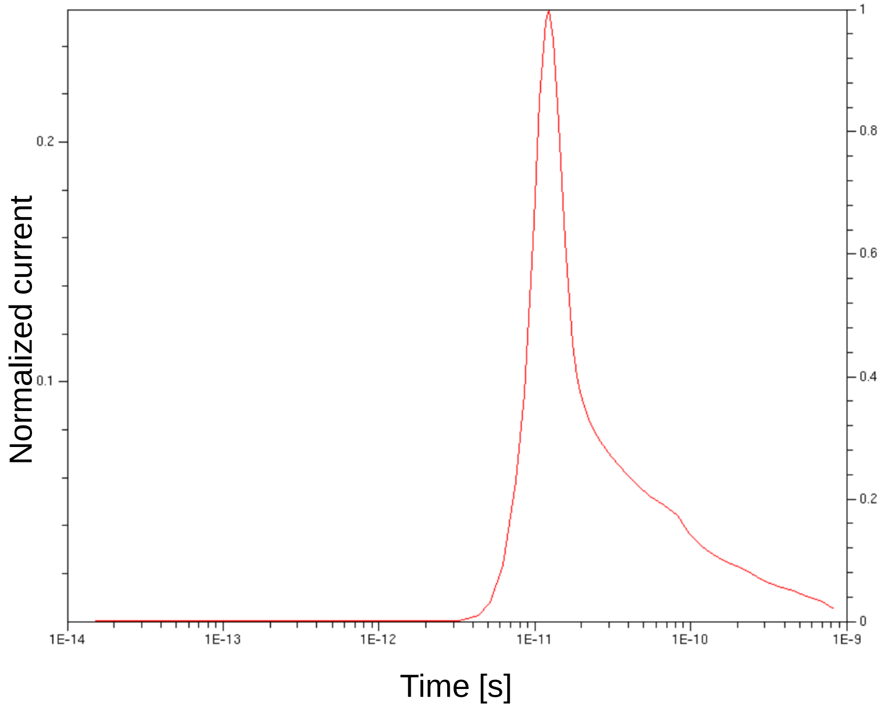
- **Objective:** Elucidate physical mechanisms underlying the response of electronic devices to VHE heavy ions
- **Test devices:**
  - pin (p-intrinsic-n) diode (simple) and 3D NAND Flash memories (medium complexity)
  - Physical devices are or will be available for a direct comparison with experimental data

- **Models:**
  - TCAD model of a pin diode (developed using Synopsys Sentaurus device simulator) is currently being calibrated
  - GDML descriptions of pin diode and 3D NAND Flash memories for Geant4 simulations

Task 3.5: Understanding physical mechanisms of simple and medium-complexity electronic device (UNIPD)

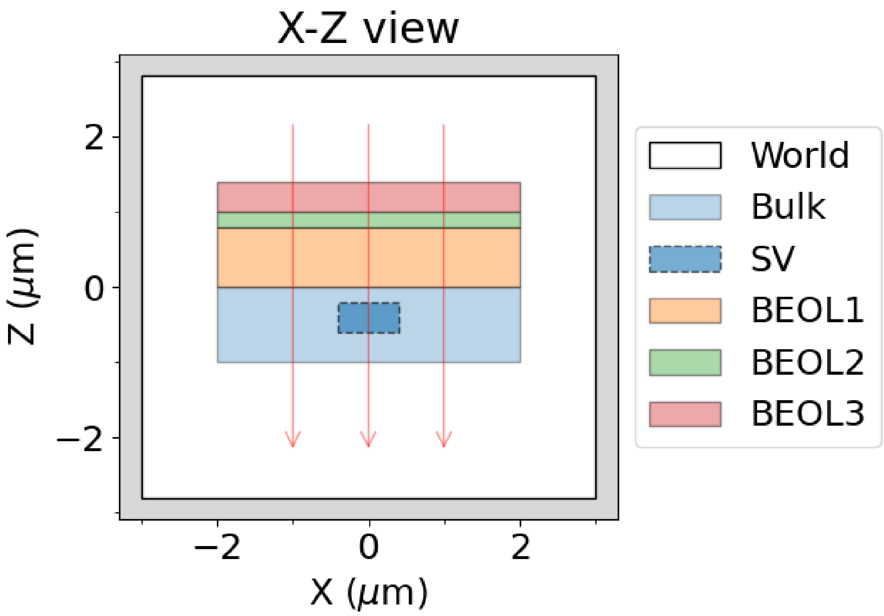
- **Current Focus:**
  - Preliminary transient simulations of pin diode at various biases, akin to Mirion pin diodes (to be tested at CERN and GSI)
  - Development of Python script to change dimensions and materials in 3D NAND Flash memory models
- **Future Work:**
  - Compare simulation results with experimental data from CERN and GSI campaigns
  - Investigate variability in measured energy deposition and charge losses
  - Gain insights into the physical mechanisms influencing device responses to VHE ions

Transient waveform simulated with TCAD software in a pin diode



Milestone 11: G4SEE VHE Ion Tool

- **Achievement:** Successful development of G4SEE, a Geant4-based Single Event Effect simulation toolkit
- **Motivation:** Lack of open-source SEE simulation tools and limited access to proprietary tools
- **Key Features:**
  - Physics-based Monte Carlo particle transport in microscopic volumes
  - Dedicated event-by-event energy deposition scoring
  - Released as free and open-source code



Multi-layer, micro-metric geometry used in a G4SEE simulation to obtain energy deposition in Sensitive Volume (SV) inside Bulk and below Back End Of Line (BEOL) layers

Milestone 11: G4SEE VHE Ion Tool

- **New Features for HEARTS and VHE Ion Simulations:**
  - LET scoring of individual particles
  - Energy deposition per nuclear reaction scoring
  - Capability to run non-analog Monte Carlo simulations for heavy ions
- **Upcoming Release:**
  - G4SEE VHE ion tool to be released in December 2024
  - Includes all new features, updated documentation, and simulation examples/tutorials
  - Will be publicly available on the G4SEE repository

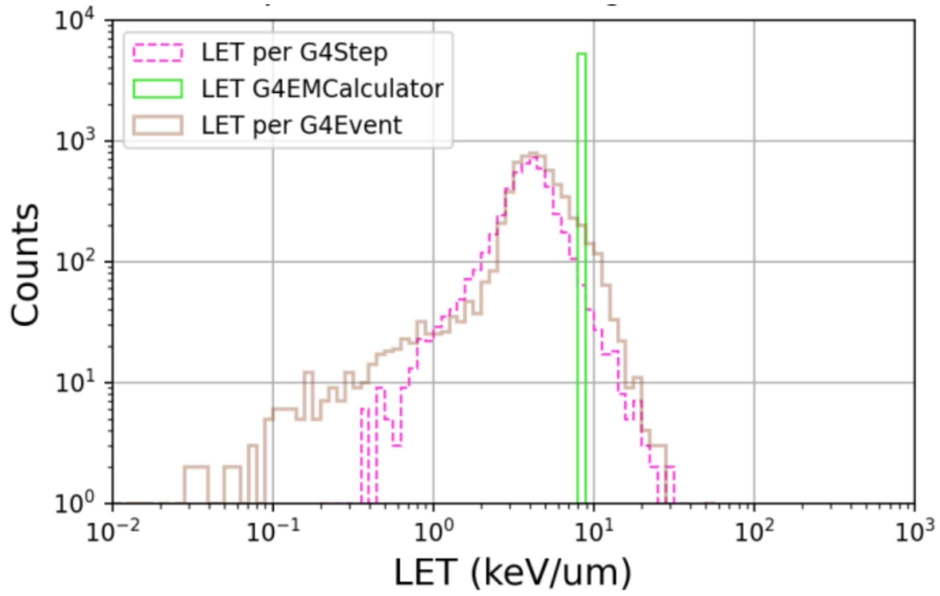


Figure 15. Comparison of LET scorings with G4SEE.

G4SEE website: cern.ch/g4see
Open-source repository: gitlab.cern.ch/g4see
Open-access publication: 10.1109/TNS.2022.3149989
User forum: g4see-forum.web.cern.ch

Risk Assessment

- **No Delays:** All tasks are progressing as planned, with no anticipated delays in achieving the deliverables and milestones.
- **No Critical Risks Materialized:** The identified critical risks in the Grant Agreement have not materialized during P1.

Follow-up of recommendations from previous review

- Development of a user-friendly tool for calculating the incident LET based on the component's material composition and beam path
- **Progress:**
  - Development of a dedicated HEARTS tool has been initiated
  - Thanks to the collaboration with NSRL, they have now incorporated lead as a primary ion in their stack-up tool (released on 9th August 2024)

Conclusion

- **Significant progress** has been made all tasks in developing and validating simulation models and tools for beam characterization, shielding material assessment, and understanding the effects of VHE ions on electronic devices.
- **Deliverables 3.1, 3.2 and 3.3, and Milestone 11 are on track to be completed in due time (31.12.2024)**

Thank you for your attention. Questions?

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.

HEARTS