HEARTS Follow-up Annual Meeting 2025: WP3

February 20th, 2025

https://indico.cern.ch/event/1500292/

A. Waets, L.S. Esposito / 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
  - Enrico Pierobon
  - Luca Lunati
- UNIPD
  - Marta Bagatin
  - Simone Gerardin
  - Alessandro Paccagnella
- TAS
  - Luca Bocchini
  - Claudio Cipriani

Outline

- **WP3 timeline**
- **Overview of Deliverables & Milestones**
- **Task status and progress**
  - Deliverables 3.1, 3.2 and 3.3, Milestone 11
- **Outlook on 2025**

WP3 members

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

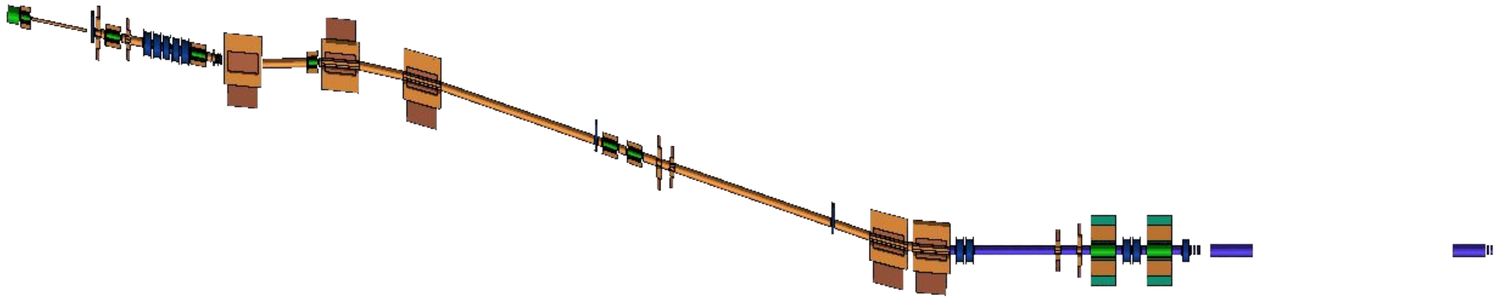
Upcoming Deliverables & Milestones

- (Transversal) activities in WP3 span over the first 3 years (M1 - M36, 2023 - 2025) providing support and deliverables to WP4-8.

Deliv. No.	Deliverable name	Due date	Status
D3.1	Numerical characterization of the CHARM beamline and of detector response	2024-12-31	**Completed**
D3.2	Modelling of shielding materials and configurations for test setup standardisation	2024-12-31	**Completed**
D3.3	GCR/SPE simulator optimizer software	2024-12-31	**Completed**
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	**Completed**

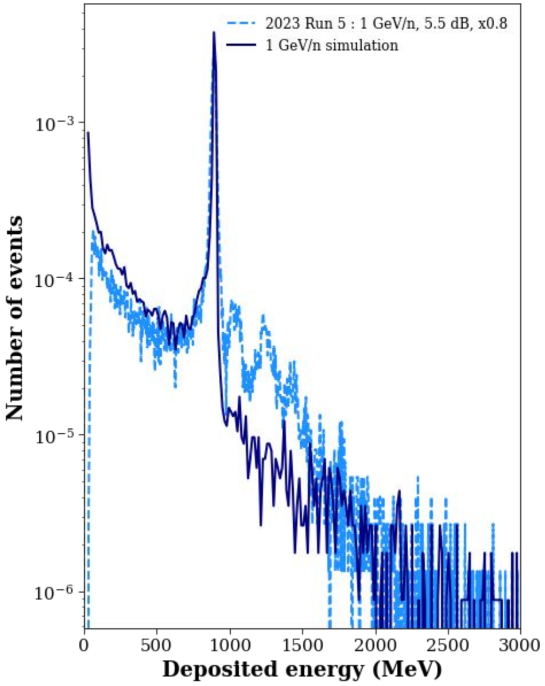
Task & Deliverable 3.1: Simulation of beam properties and detector characterization (CERN)

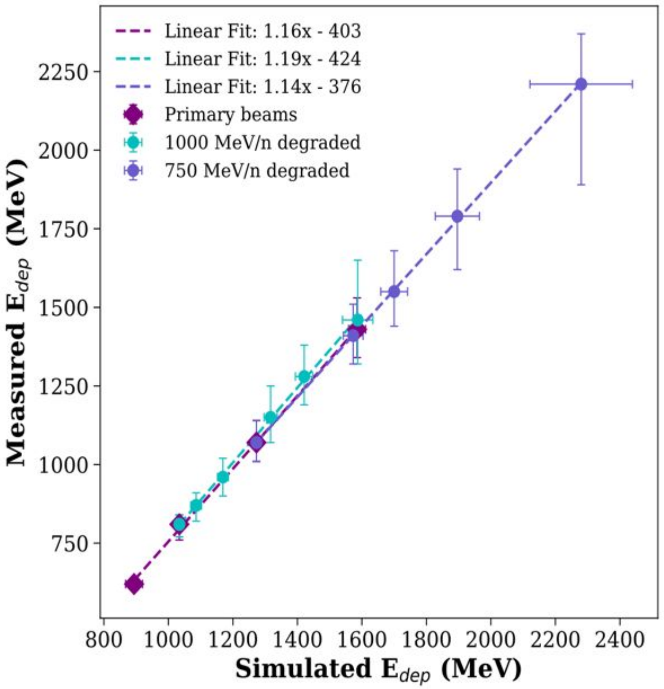


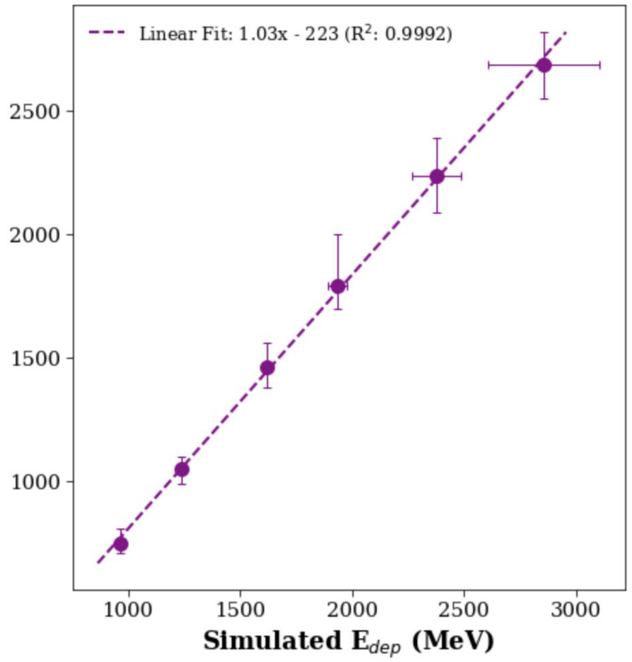
- Detailed Monte Carlo simulations of the VHE ion beam transport through the T08 beam line at CERN were carried out
- A dedicated geometry of the T08 beam line was constructed relying on the optics settings used during operation, dimensions from technical drawings and in-person inspections
- Using **FLUKA**, 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 & Deliverable 3.1: Simulation of beam properties and detector characterization (CERN)

- Minimum energy limit for extraction and transport to CHARM set to 650 MeV/n.
- Beam path correction which allowed a 273 MeV/n beam to be extracted to the IRRAD facility.
- “Loss maps” give insight into the physical processes that determine the **resulting radiation field** at the DUT.
- 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
- 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

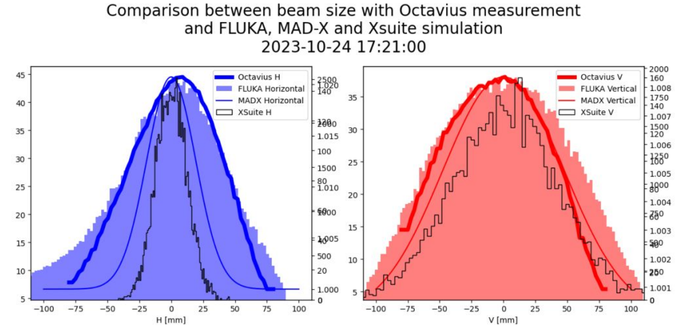




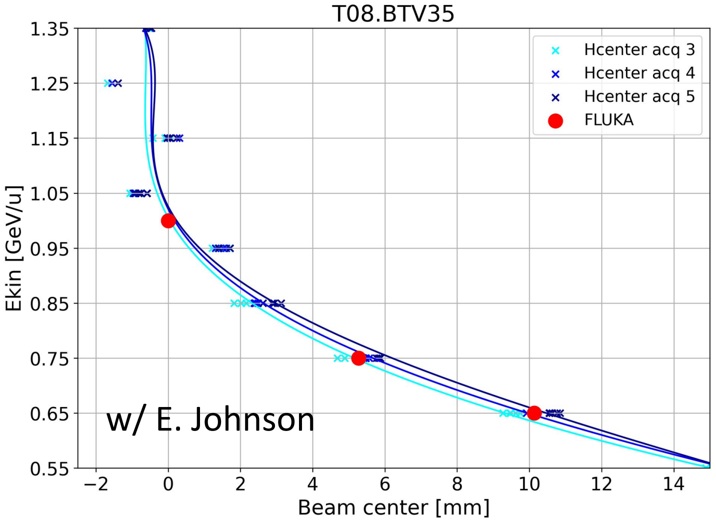


Task & Deliverable 3.1: Simulation of beam properties and detector characterization (CERN)

- In conclusion, **the FLUKA simulation model and workflow** has been shown to be an **excellent tool for the numerical characterization of the beam line**
- In correspondence with other tools, instruments and measurements
- Beam line changes can be readily updated in the simulation geometry/configuration

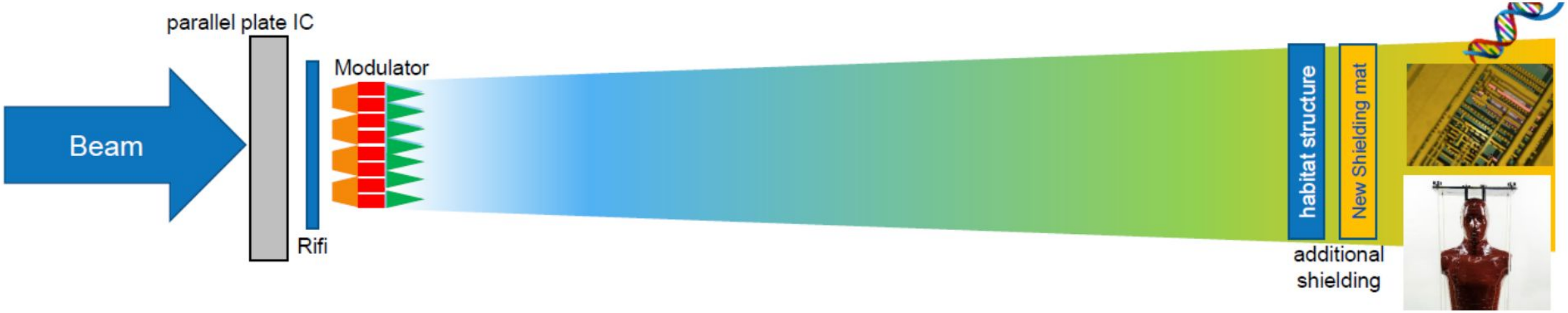


Beam screen measurement vs sim.



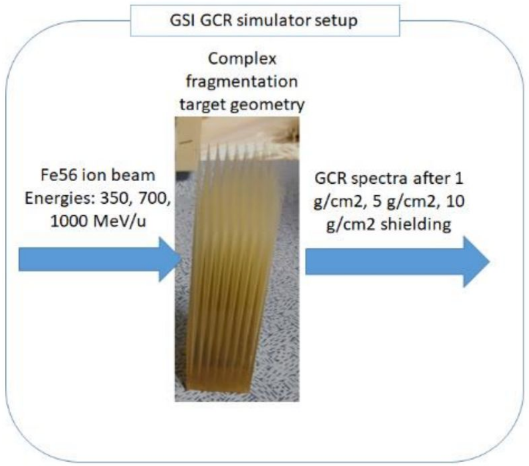
Task & Deliverable 3.2: Simulation of Shielding Materials (TAS-I)

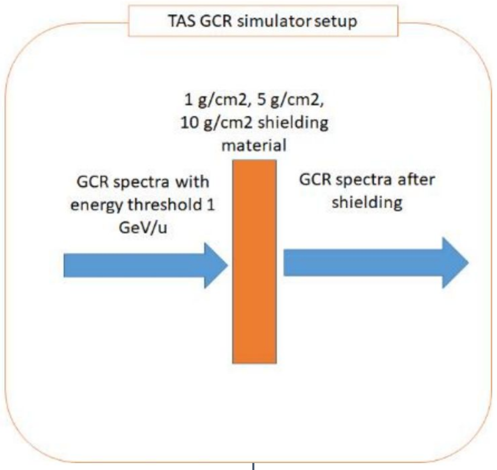
- Selection of different **shielding configurations**
  - Validating compatibility with GSIs cave A GCR simulator setup
  - Selected configurations cover all relevant mission scenarios
- Development of an **in-house tool** (Cave A GCR simulator phase space simulation)
  - Empower users to run in-silicon tests for experiment preparation
  - Minimizes the complexity (difficulties, high computational demands) for users
  - Making comparison of experimental data to Monte Carlo simulations easier
  - Compatibility of the tool with GRAS (Geant4 Radiation Analysis for Space) was validated.



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

- **Preliminary materials identification** including materials and material configurations that can be used in shielding effectiveness evaluation:
  - Aluminum alloys, Titanium, CFRP, thermal protection materials, glass, ceramics, polyimide, ISRU
  - Reference cases as passive shielding materials (Polyethylene)
- **Parametric simulation study** conducted to evaluate main parameters for setup standardization (mainly test sample size)
- In agreement with GSI, TAS used a simplified geometry for this study





a simplified experimental setup has been developed to study the influence on lateral scattering effects due to setup shielding material, assessing the maximum lateral dimension of the target.

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 & Deliverable 3.2: Simulation of Shielding Materials (TAS-I)

- **Cave A GCR simulator phase space tool**
  - Monte Carlo simulations of Galactic Cosmic Radiation (GCR) are inherently computationally intensive and resource-hungry.
  - In addition, the geometric complexity of the modulators is very high
  - **Goal**: match a well-defined MC code particle source to the complex radiation field generated by the GCR simulator → **simulations can start directly with the GCR-simulator field as radiation source**.

In the process of opening our internal repositories and releasing all simulations and tools under an open-source license to the public. This will empower all users of GSIs GCR simulator to perform traceable, computationally optimized and validated in-silico studies.

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

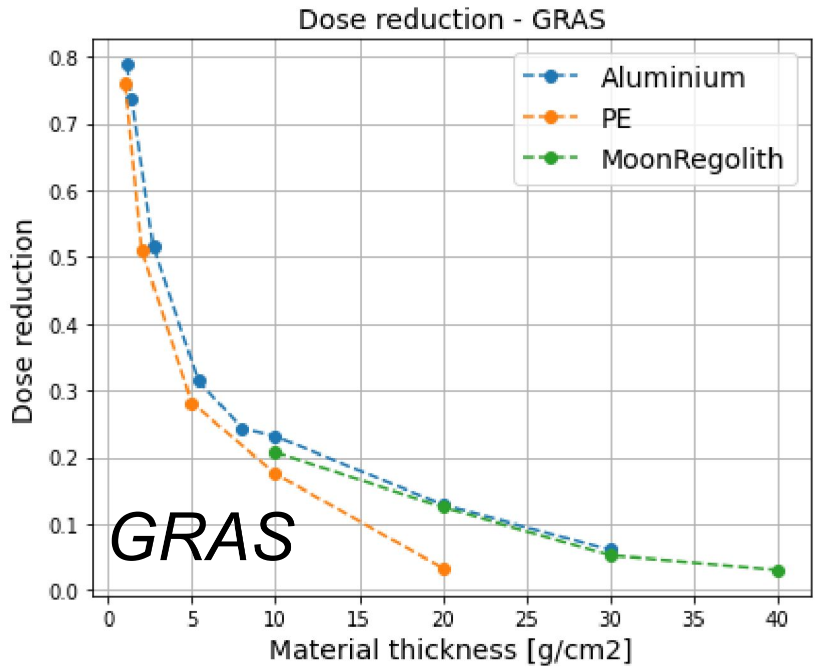
- **Validating compatibility with standard tool: GRAS & Geant4**

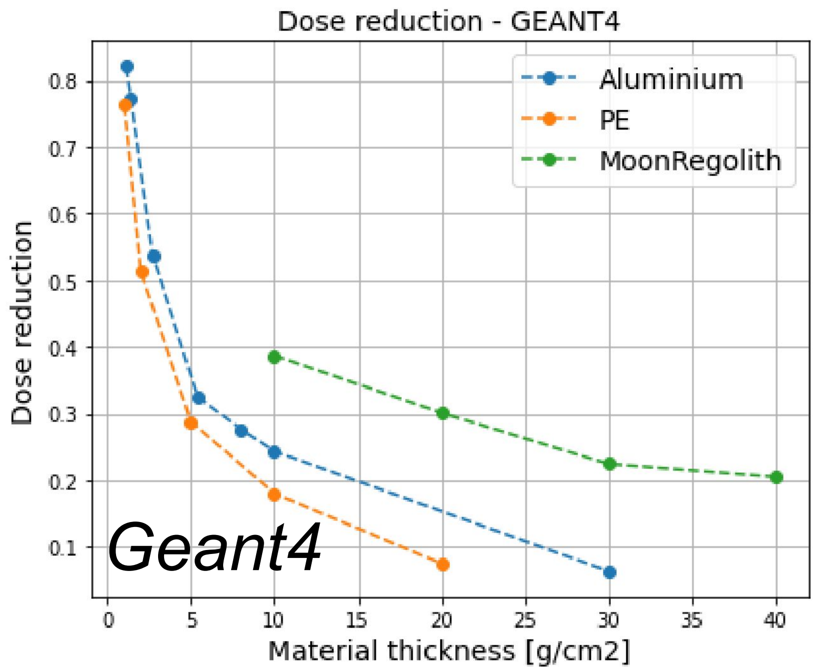
Dose reduction $\frac{D_2}{D_1} = \frac{Q_2/Q_1}{Q_{2,no\ target}/Q_{1,no\ target}}$

Where:

Q_2 is the total dose calculate in IC2

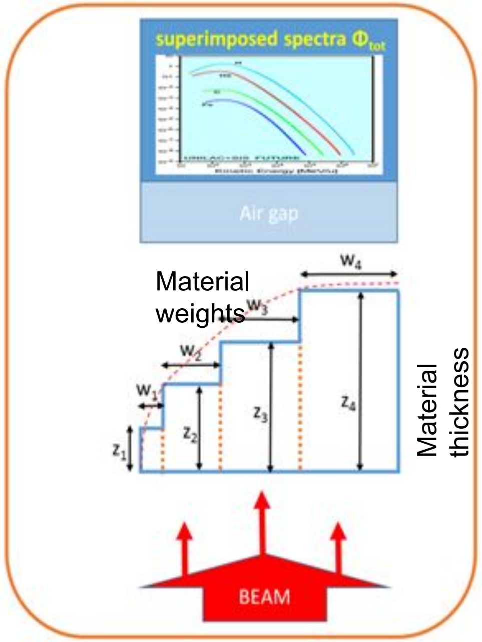
Q_1 is the total dose calculated in IC2





Very similar results for Al and PE, less good agreement for regolith samples which is under investigation

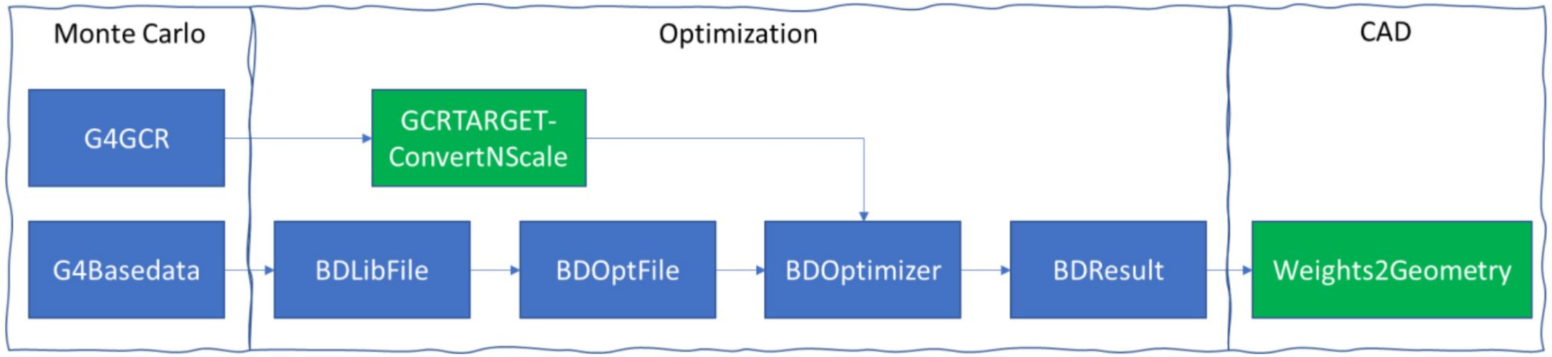
Task & Deliverable 3.3: GCR/SPE Simulator Optimizer software (GSI)



- **Objective:**
  - Develop a software toolchain and workflow developed for the optimization of GSIs GCR simulator
  - GCR simulator is a hybrid active-passive system: employing passive beam modulation and active ^{56}Fe beam changes.
- **Key Focus Areas:**
  - Optimizing the complex interplay of energy loss, nuclear fragmentation and scattering inside highly structured modulators/targets directly to reach a specific target distribution poses a serious challenge, due to the high number of free parameters.
  - Description of primary (e.g., basedata simulations, optimizers, …) and auxiliary software (e.g., interaction with GSIs cluster, converters, …)
  - Provides the rationale for the development of a new optimizer generation.
  - New software stack is currently under development based on lessons learned

Task & Deliverable 3.3: GCR/SPE Simulator Optimizer software (GSI)

- **Current toolchain:**
  - **Pre-simulated base data** in combination with an **analytical optimizer** is used to find material weights of modulator/target geometries.
  - Optimizer relies on open-source software:
    - ROOT + Minuit 2 for data handling + support
    - Geant4 for MC simulations
    - FreeCAD for weights to geometry conversion
    - uproot, numpy, scipy and matplotlib for interfacing C++/ROOT and python and for the generation of target functions



Task & Deliverable 3.3: GCR/SPE Simulator Optimizer software (GSI)

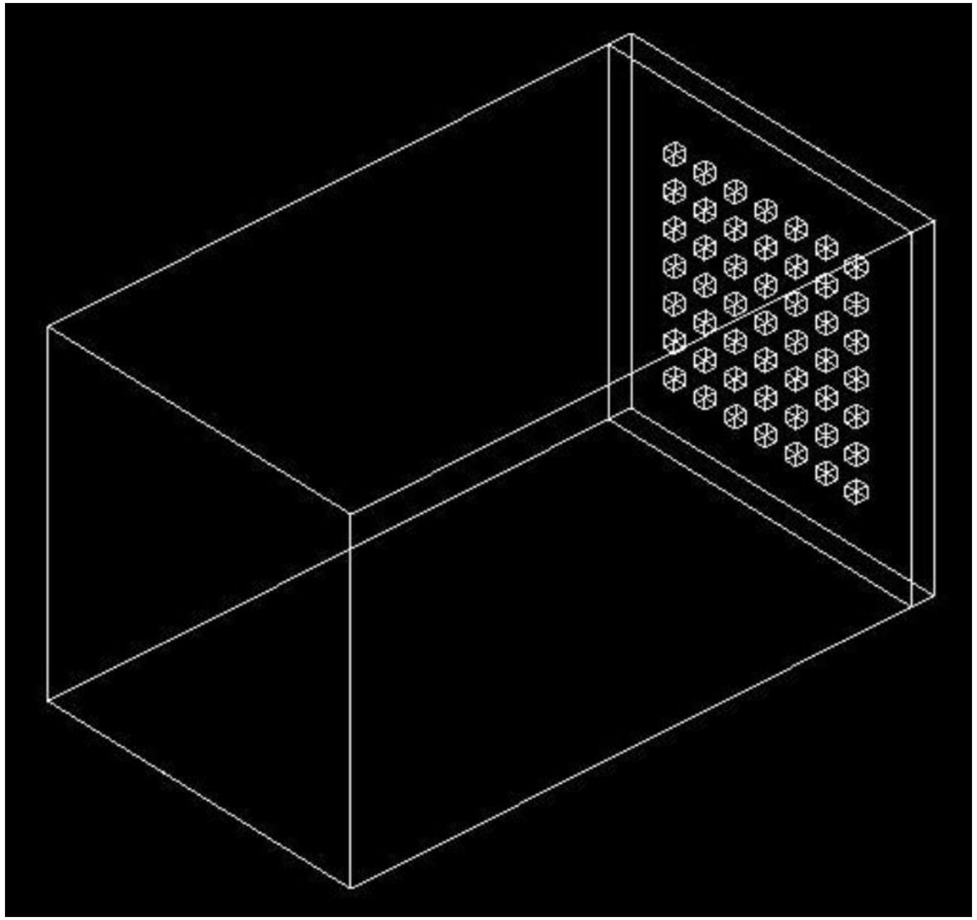
- **Next generation**
  - FAIR: No magnetic scanning available →synchronized scanning of target
  - Extremely high penetration depth of 10 GeV/u ^{56}Fe

    →necessary to **extend all available tools and add additional optimization options** as well as geometry generation options to facilitate the design of the higher energy GCR simulator. **New Python optimizer package** was developed, used to reoptimize the slab targets for the Cave A GCR simulator showing promising results
- **Future plans**
  - rewriting the optimizer toolchain based on current toolchain and **lessons learned** (Extremely demanding MC simulations, set of optimization rules, find suitable material machining processes, optimization of overall system)

    1. Achieve feature parity between the new and the current toolchain
    2. additional functionality necessary for the design of the higher energy GCR simulator for FAIR will be implemented → WP8

Task 3.4: Simulations to Reduce LET Uncertainties (UniPD)

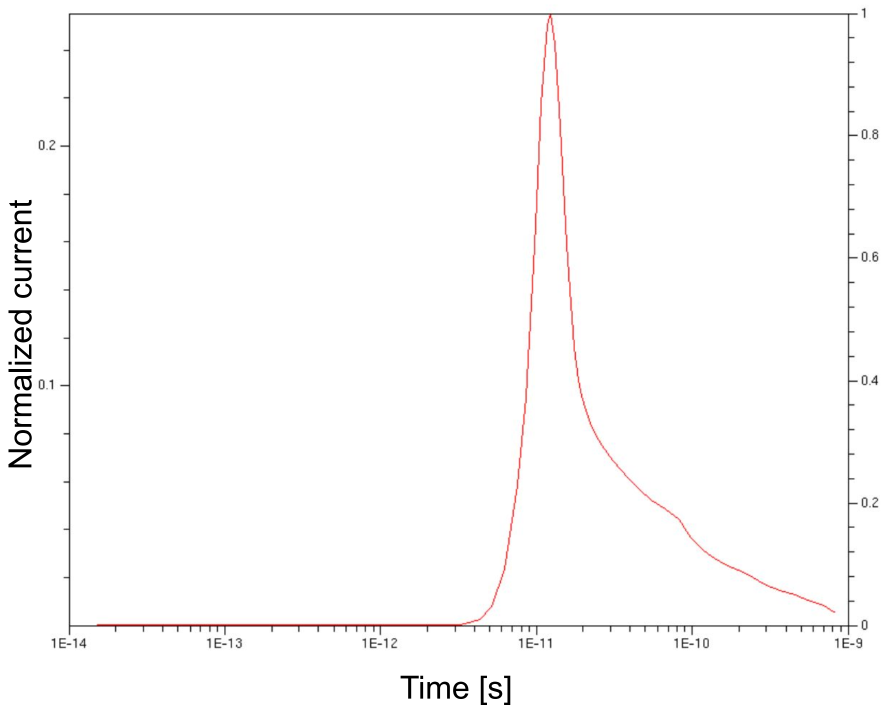
- **Objective:** Study uncertainties in energy deposition and LET for VHE ions impacting small sensitive volumes
- **Current Focus:**
  - Geant4 simulations to compare energy deposition and LET uncertainties between VHE ions and particles from commonly used accelerators and HEARTS
- **Future Work:**
  - 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)

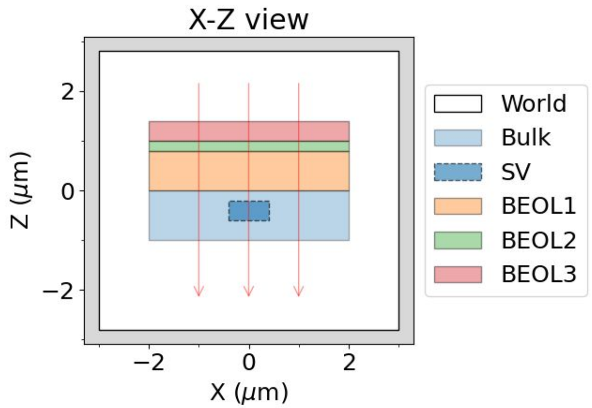
- **Objective:** Elucidate physical mechanisms underlying the response of electronic devices to VHE heavy ions
- **Test devices:**
  - pin diode and 3D NAND Flash memories
- **Models:**
  - TCAD model of a pin diode (developed using Synopsys Sentaurus device simulator) is currently being calibrated
  - GDML descriptions of diode and 3D NAND Flash memories for Geant4 simulations
- **Current Focus:**
  - Preliminary transient simulations of pin diode
  - Development of Python script to change dimensions and materials in 3D NAND Flash 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

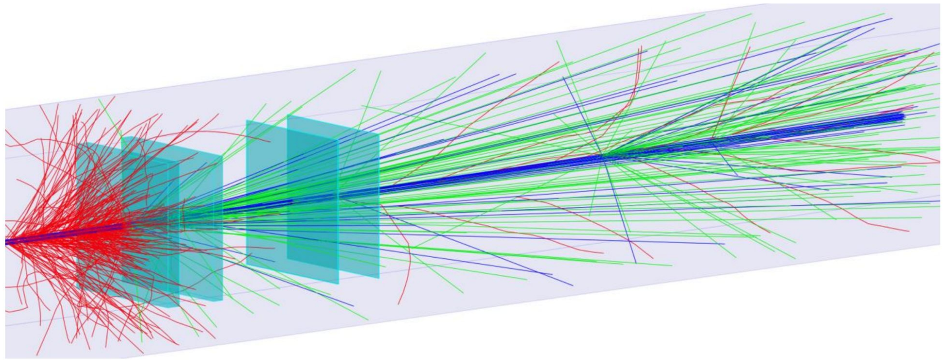
Transient waveform simulated with TCAD software in a pin diode



Milestone 11: Release of the G4SEE VHE ion tool

- **The G4SEE toolkit**
  - Within HEARTS WP3, the **focus** is on very **high-energy (VHE) heavy ion simulations**.
  - Release of G4SEE VHE ion tool in December 2024
  - New Features including LET scoring of individual particles.
  - Demonstration and testing the VHE heavy ion simulation and LET scoring capabilities of G4SEE based on 2024 HEARTS@CERN November run.
  - G4SEE scoring features are being progressively integrated into FLUKA v5, G4SEE itself will be maintained in parallel.
  - Open-source repo: https://gitlab.cern.ch/g4see/g4see
  - Online docs: https://g4see-docs.web.cern.ch





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 were delivered in due time (31.12.2024)**
- Deliverables 3.4 and 3.5 expected for 31.12.2025.

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