HEARTS P1 Review Meeting

25 September 2024

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

S. Gerardin - UniPD

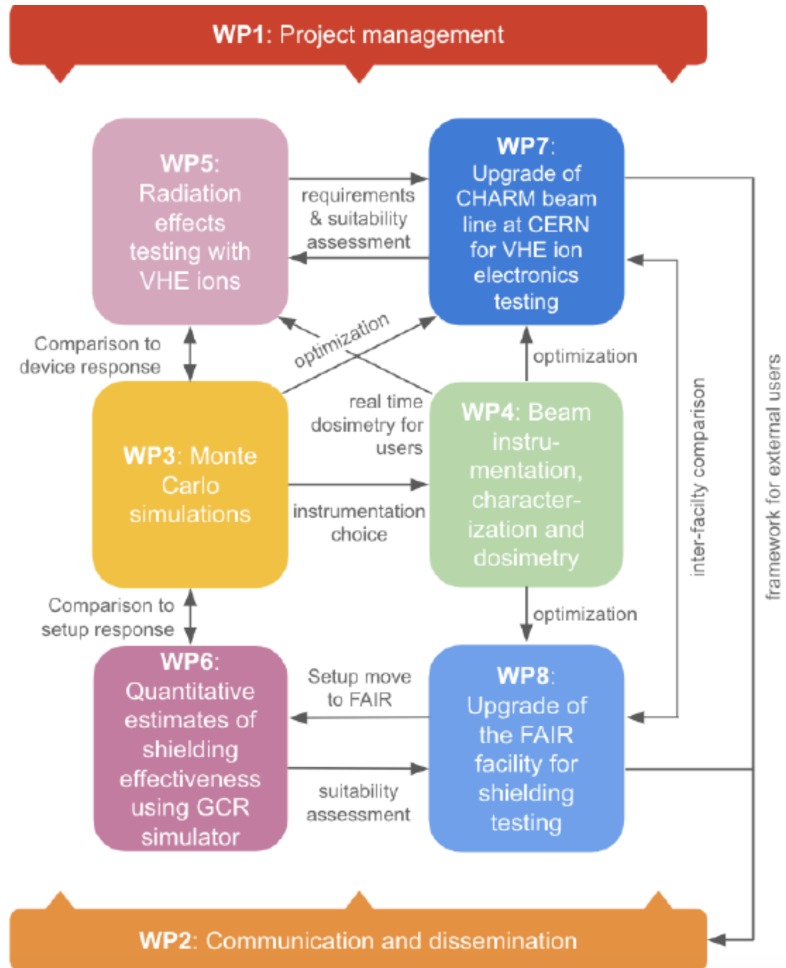
Funded by the European Union

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

Tasks & Objectives

- Project goal is to provide **>100 MeV/n heavy ion beams to space users**, to mimic the effects of Galactic Cosmic Rays (GCR) at ground level
  - penetration levels large enough to enable electronics testing in air, without the need of special preparation and at board and box level
  - essential for the exploitation of high-end microelectronics technology in space, for e.g. onboard Artificial Intelligence or Big Data processing applications
- Purpose of WP5: study of **radiation effects induced by VHE heavy ions** on a set of **technologies representative of current state-of-the-art COTS electronics**
  - Comparison with standard-energy heavy ions.
  - A hierarchical approach, based on three levels of complexity, will highlight different levels of details

WP5 in the Project



- WP5 is strongly interconnected with the other work packages
  - WP3: comparison with simulation results
  - WP4: beam dosimetry
  - WP7: facility development

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WP5 Key Personnel

- Airbus DS/TESAT:
  - R. Mangeret, M. Rostewitz
- TAS:
  - R. Mancini, S. Francola
- UniPD:
  - M.Bagatin, UniPD project leader
  - S. Gerardin, WP5 leader
- CERN:
  - M. Sacristan Barbero

Work package number	5.	Lead beneficiary	UNIPD	
Work package title	Radiation effects testing with VHE ions			
Participant number	1	3	4	5
Short name participant	CERN	ADS	TAS	UNIPD
Person-months per participant	2	19	4	16
Start month	M1	End month	M48	

WP5 Tasks

5.1 Final review of VHE ion beam requirements for SEE testing COMPLETED

5.2 Analysis of ionization response in a PIN diode for beam quality assessments IN PROGRESS

From 1st year

5.3 Suitability of the proposed VHE ion beams for 3D integrated device structures IN PROGRESS

5.4 Validation of the VHE ion beams for industrial use with TRL 6-7 achievement IN PROGRESS

From 2nd year

5.5 Qualification of high-complexity devices IN PROGRESS

5.6 Board-level testing

From 3rd year

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WP5 Timeline

Year	1												2												3												4												
Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	
WP5 Radiation effects testing with VHE ions																																																	
Task 5.1: Final review of VHE ion beam requirements for SEE testing						D5.1																																											
Task 5.2: Analysis of ionization response in a PIN diode for beam quality assessments																								D5.2																									
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Task 5.4: Validation of the VHE ion beams for industrial use with TRL 6-7 achievement																																				D5.4	**M5.1, M5.2**												
Task 5.5: Qualification of high-complexity devices																																																D5.5	**M5.3**
Task 5.6: Board-level testing																																																D5.6	**M5.4**

Task 5.1 - Final review of VHE Ion Beam Requirements for SEE Testing: Description of Work

- Partners: UNIPD, ADS, TAS, CERN   M1-6
- Academic and industrial partners will review the goals in terms of **VHE ion beam parameters** to be reached with the CHARM and GSI-FAIR upgrade (WP7-8)
- Other than parameters such as ion type, energy, LET and and range (and related accuracy), **beam time availability** (facility usable/bookable with reasonable delays) and **commercial conditions of access** (competitive with respect to European standard-energy ion facilities) will be included. Optimal trade-offs will be identified and submitted to the facilities

DELIVERED

D5.1 (M6) Beam Requirements

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Deliverable 5.1: Structure

D5.1 FINALISED LIST OF BEAM PARAMETER REQUIREMENTS CONCURRING TO ESTABLISH A TRL 6-7 FOR THE HEARTS FACILITIES

- 2. SOURCE
  - 2.1. HEAVY-ION BEAMS
  - 2.2. BEAM FLUX, FLUENCES AND TEMPORAL STRUCTURE
  - 2.3. BEAM SIZE AND SPATIAL UNIFORMITY
  - 2.4. SAMPLE HOLDER AND USER SETUP
- 3. CONDITIONS FOR ACCESS

- The document is organized as a set of requirements and reflects users' perspective!

Deliverable 5.1: Beam Requirements

D5.1 FINALISED LIST OF BEAM PARAMETER REQUIREMENTS CONCURRING TO ESTABLISH A TRL 6-7 FOR THE HEARTS FACILITIES

SOURCE

- Req. 2.1.a: the LETs of the available beams shall range from ~ **0.1 to >= 60 MeV · mg^{-1}** · cm^2

  […] **Low-LET** beams are very important, because the long range of very-high energy heavy-ion facilities will be used to test advanced components with low LET threshold, and because of the abundance of low-LET particles in space.
- Req. 2.1.d: the particle range shall exceed **500 µm** in Silicon for the full LET range. In addition, several use cases require significantly longer ranges [heat spreader > 3 mm].
- Req. 2.2.a: the heavy ion accelerator shall be capable of delivering ions with variable flux ranging **from a few (10) ions/cm^2/s to at least 10^6 ions/cm^2/s** on the device under test.

Deliverable 5.1: Access Requirements

D5.1 FINALISED LIST OF BEAM PARAMETER REQUIREMENTS CONCURRING TO ESTABLISH A TRL 6-7 FOR THE HEARTS FACILITIES

CONDITIONS FOR ACCESS

- Req. 3.a: a schedule with weeks of beam time availability should be ready 6 months before the first testing period. The user should have the possibility of giving the **final confirmation 3 weeks in advance**.
- Req. 3.b: the cost for beam should be less than **3000€ per hour**. The invoiced time should include only hours that can be effectively used (beam preparation should not be included, but ion energy changes should be).

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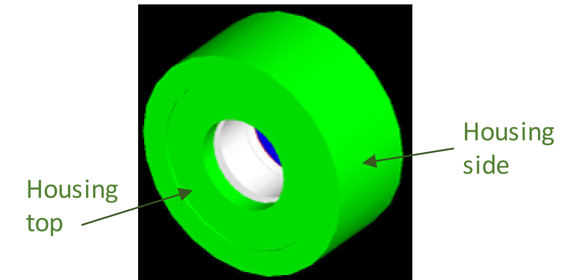
Task 5.2 - Analysis of Ionization Response in a PIN diode for Beam Quality Assessments: Description of Work

- Partners: UNIPD, M1-24
- **PiN diode**: simple and effective structure to study heavy ion beams. It provides precise measurements of energy deposition in semiconductor materials. Diagnostic tool to assess the quality of the provided beam in terms of purity and energy straggling (e.g. with degraders)

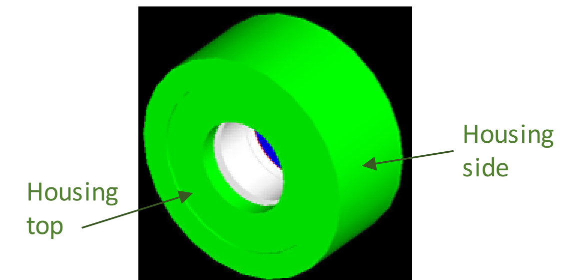


D5.2 (M24) Beam Quality

D5.5 (M48) Impact of beam energy in SEE testing

Task 5.2 - Analysis of Ionization Response in a PIN diode for Beam Quality Assessments: Status and Plans

- UniPD has defined the experimental setup and procured the material
  - ESA involvement is no longer foreseen
  - Mirion diodes, CAEN charge amplifier and multi-channel analyzer have been procured
  - Measurements in second half November 2024
- **Large experimental data set is available** with standard energy heavy ion beams, mostly collected with the ESA experimental setup
  - **Monte Carlo model** of the diode is **available** (see also WP3)
- **TCAD simulations** using Sentaurus are being carried out by UniPD to study the transient currents induced by the heavy ions (see also WP3)

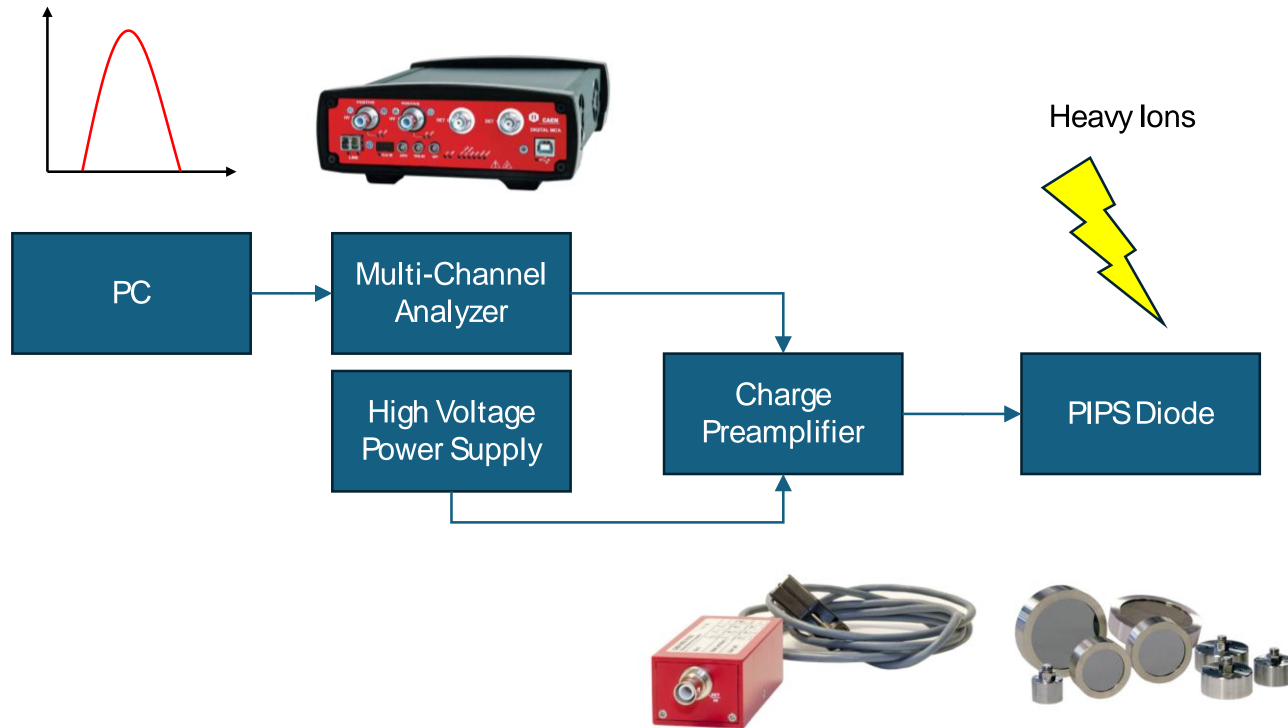


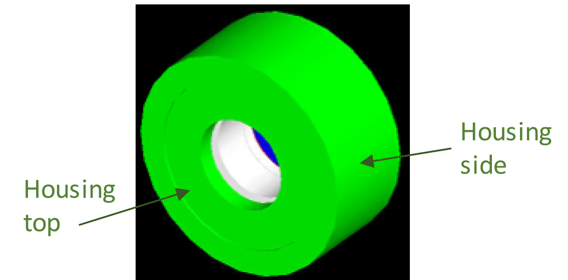
D5.2 (M24) Beam Quality

D5.5 (M48) Impact of beam energy in SEE testing

Task 5.2 - Analysis of Ionization Response in a PIN diode for Beam Quality Assessments: Status and Plans

- UniPD experimental setup: currently being tested and debugged in the lab



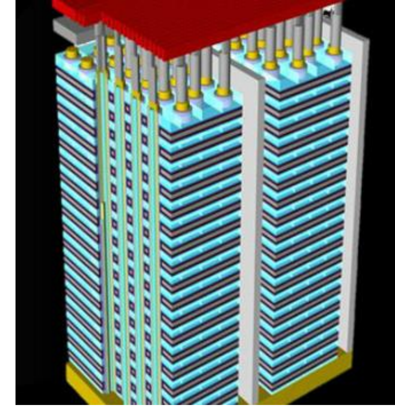


D5.2 (M24) Beam Quality

D5.5 (M48) Impact of beam energy in SEE testing

Task 5.3 - Suitability of the Proposed VHE Ion Beams for 3D Integrated Device Structures: Description of Work

- Partners: UNIPD, M12-36
- **3D NAND Flash memories,** the first and most successful example of 3D integration in the semiconductor industry, are an ideal test vehicle
- Devices with **hundreds of layers** are now available and increasing, reaching tens of microns of thicknesss.
- VHE heavy ions are extremely useful for these technologies



D5.3 (M36) Beam suitability for 3D structures

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

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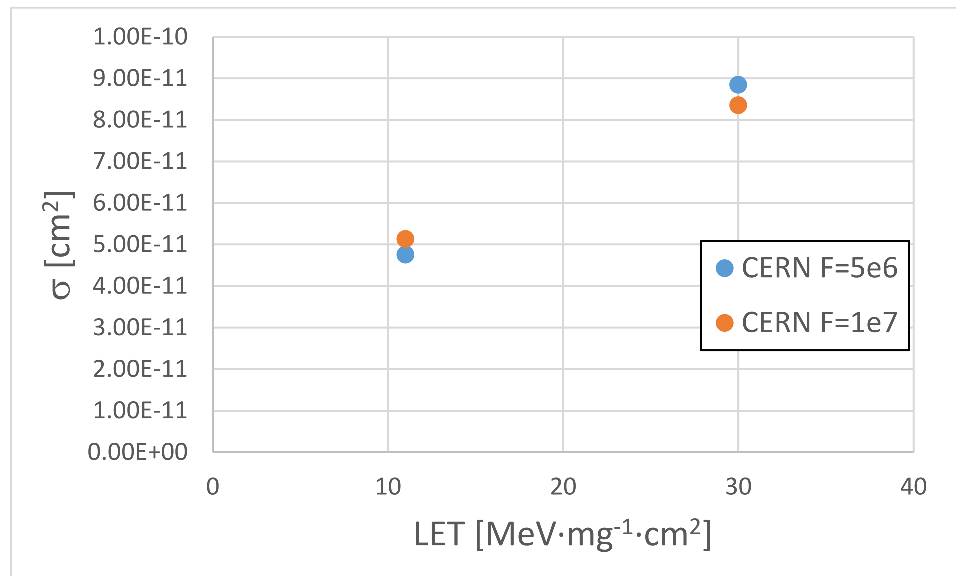
Task 5.3 - Suitability of the Proposed VHE Ion Beams for 3D Integrated Device Structures: Status

- **Four 3D NAND FG devices have been irradiated at CERN in October/November 2023**
  - Exposure in passive mode, possible thanks to the non-volatility of the memories

Device S/N	Energy	LET [MeV/(mg/cm²)]	Fluence [ions/cm²]
MS33	2GeV/n	11	5E6
MS34	2GeV/n	11	1E7
MS35	750 MeV/n + 15 mm PMMA degradation	30	5E6
MS36	750 MeV/n + 15 mm PMMA degradation	30	1E7

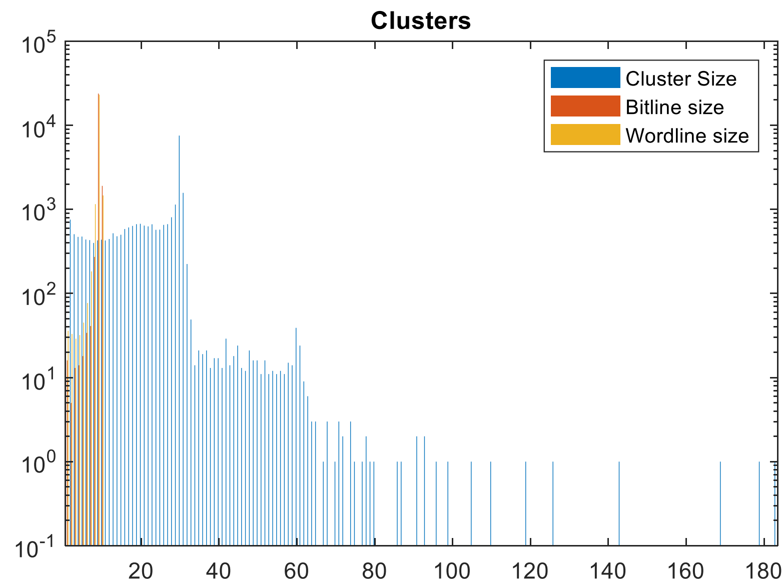
Task 5.3 - Suitability of the Proposed VHE Ion Beams for 3D Integrated Device Structures: Status

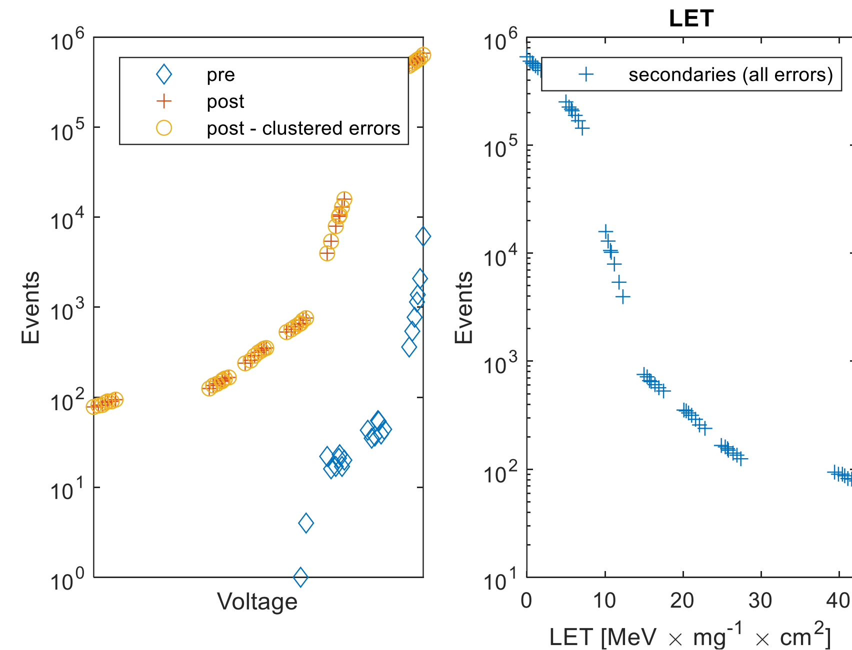
- **Four 3D NAND FG devices have been irradiated at CERN in October/November 2023**
  - Cross section consistent with previous measurements
  - Good linearity with fluence (errors bars smaller than symbols)



Task 5.3 - Suitability of the Proposed VHE Ion Beams for 3D Integrated Device Structures: Status (2)

- **Four 3D NAND FG devices have been irradiated at CERN in October/November 2023**
  - Large clusters are visible and secondaries information extracted. Monte Carlo simulation of secondaries for calibration/comparison ongoing.





Task 5.3 - Suitability of the Proposed VHE Ion Beams for 3D Integrated Device Structures: Plans

Next steps

- Complete analysis on irradiated FG 3D NAND devices and compare experimental results with simulations (see WP3)
- Carry out a full irradiation campaign in second half of November 2024
  - 3D NAND Devices with Floating gate and Replacement Gate Technologies will be used
  - Both passive and active irradiations
  - Exposure to different LETs

Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement: Description of work

- Partners: Airbus DS/TESAT, CERN, M-12-36
- **VHE SEE testing on devices which have already been characterized** by the ADS or CERN **at standard-energy heavy ion test facilities** (e.g., UCL, RADEF)
- Previous tests carried out according to ESCC 25100 (package lid removal)
- Broad range of technologies have been tested or will be tested:
  - Benchmark SRAMs
  - High power diodes (Silicon or SiC)
  - High power MOSFETs (Silicon or SiC)
  - A stacked memory
    - all the dies will be tested as opposed to only the top die as customary with standard energy ions
  - High-complexity device

D5.4 (M36) Verification of beam parameter requirements

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

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Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

CERN used a wide range of energies/LETs by means of the continuous tunability of the beam extraction energy and the LET booster (PMMA degrader).

Primary LETs from 10 to 24 MeV·cm^2/mg and enhanced LETs up to 52 MeV·cm^2/mg.

Contribution to NSREC 2024 Data Workshop with the SEE measurements (SEU, SEL, SEB).

TABLE I
BEAM ENERGY CONFIGURATIONS USED IN THE SEE TESTS.

Extraction energy [MeV/n]	Degrader PMMA thickness [mm]	LET@DUT [MeV·cm^2/mg]
2000	0	10.2
1500	0	10.7
1250	0	11.4
1000	0	13.1
900	0	14.3
850	0	15.2
800	0	16.3
750	0	17.5
700	0	20.1
650	0	23.5
650	2	26.2
650	4	30.4
650	6	38.9
650	7	51.8

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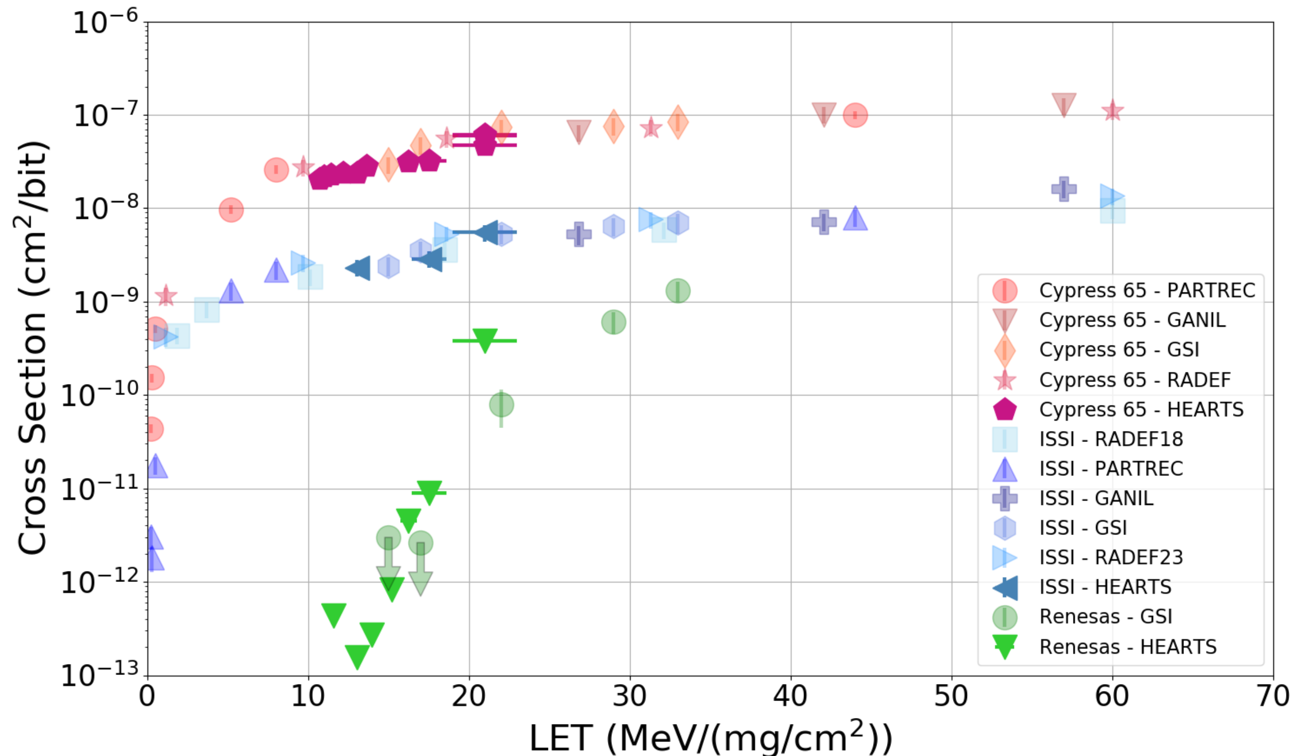
Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans



CERN measured the SEU cross section of three benchmark SRAMs from Cypress, ISSI, and Renesas during the October 2023 run

A large amount of experimental data at other facilities is available for these samples

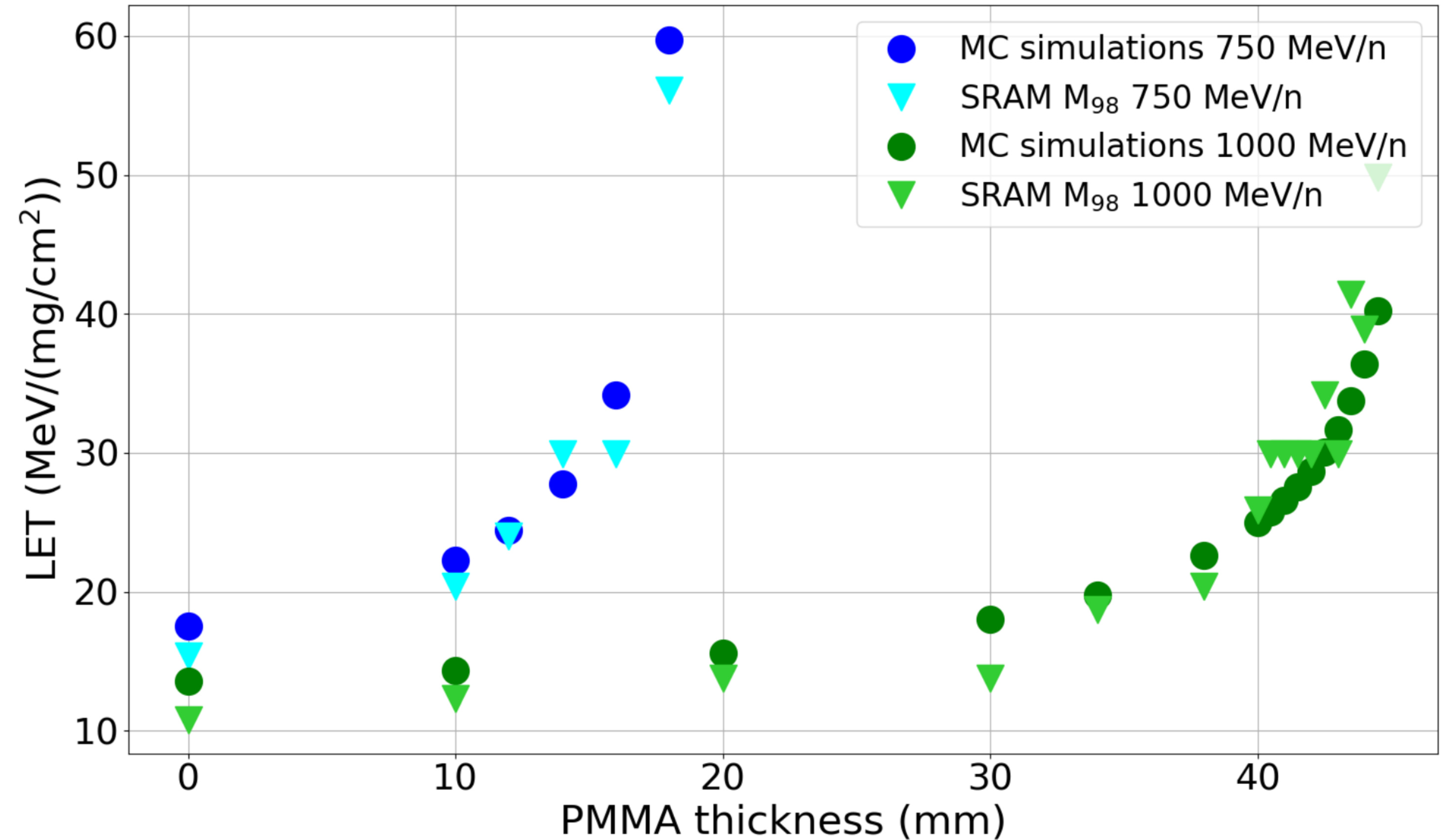
The data taken at HEARTS include only primary beam energies and no degradation runs.

Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

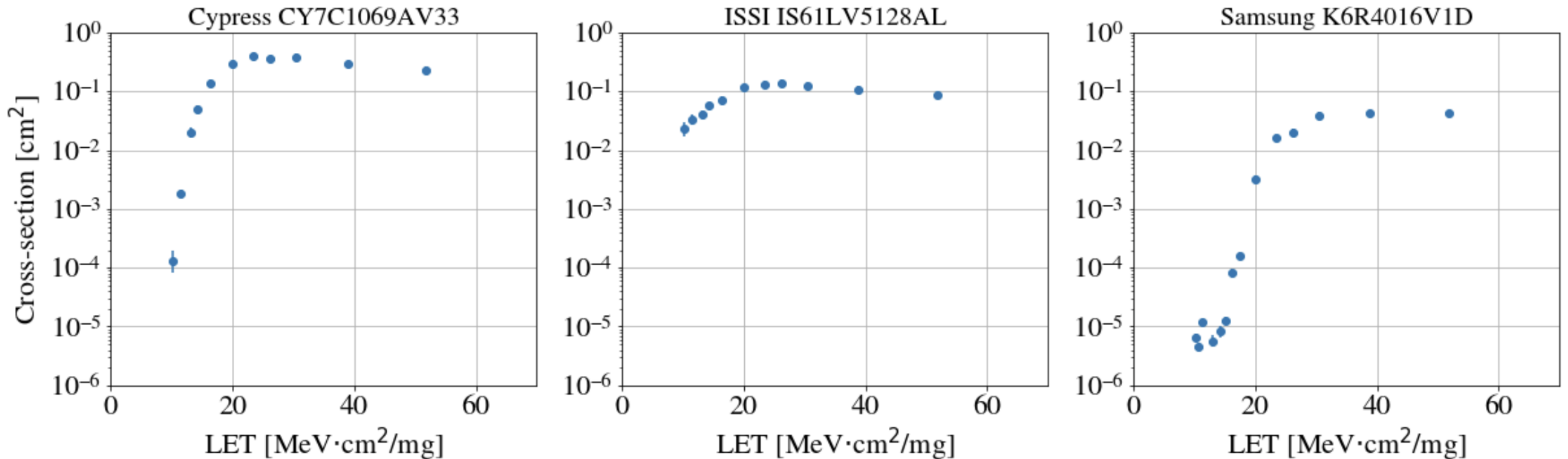
MCU clustering algorithms allow correlating multiplicity distribution and beam LET.

Good correlation between degraded LETs obtained via MCU multiplicity study and FLUKA MonteCarlo simulations.

Contribution for RADECS 2024.



Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans



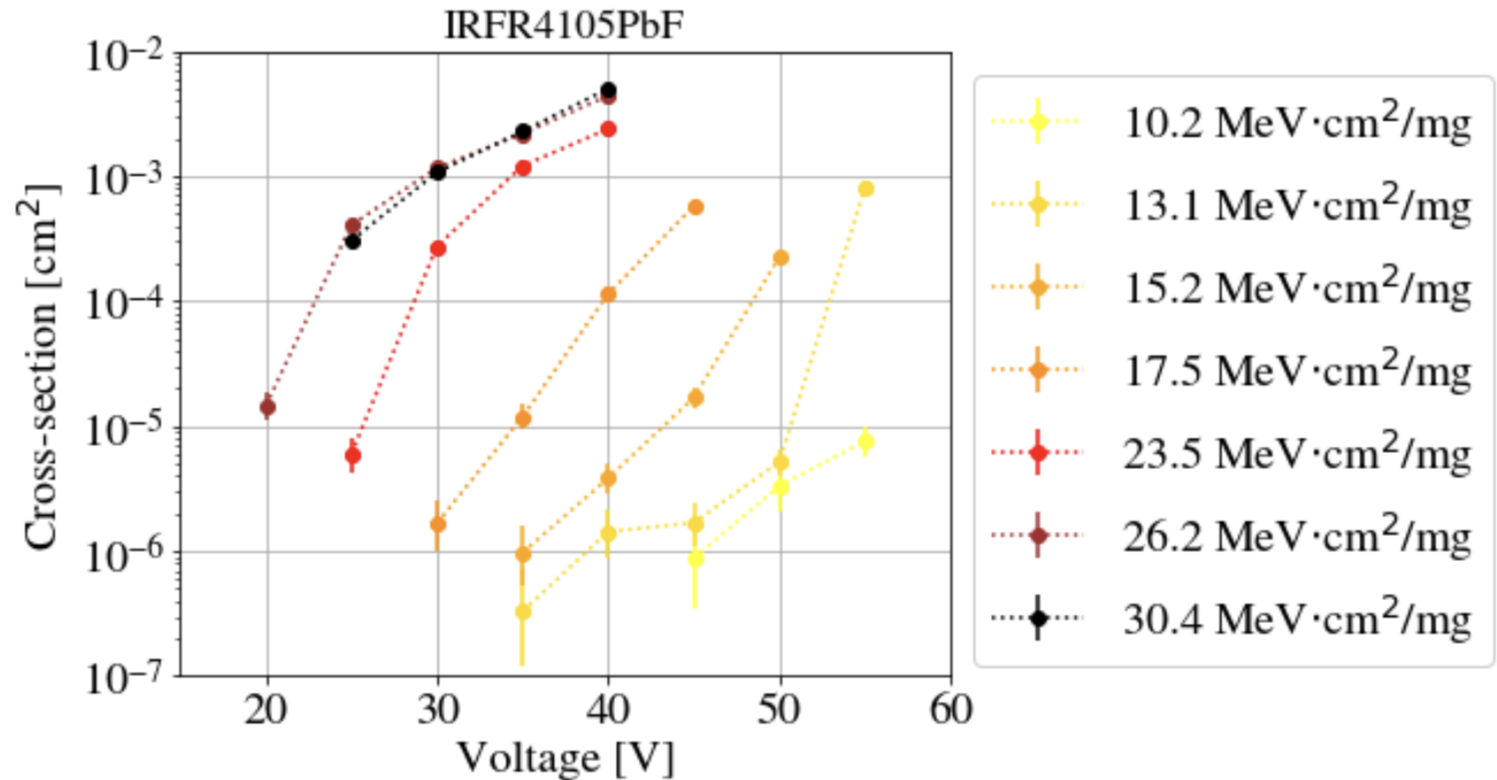
Single Event Latchup has been measured as well for three 3 SRAMs (Cypress, ISSI and Samsung) during the same test campaign

Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

Single Event Burnout of power MOSFETs (Infineon IRFR4105PbF 55V max.).

Increasing SEB cross-section as a function of LET and drain voltage.

Higher LET features lower voltage SEB onset.



Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

- Device types are to be selected according to HEARTS objectives, and, both heritage testing and device stock availability at Airbus DS and TESAT.
- Device type selection aims at
  - Covering different families, different Single Event Effect natures and different potential issues
  - Allowing test results comparison between high energy and traditional SEE test facilities
  - Allowing testing of "untestable" device reference
  - Supporting test analysis guideline
- Multiple test campaigns will be needed

D5.4 (M36) Verification of beam parameter requirements

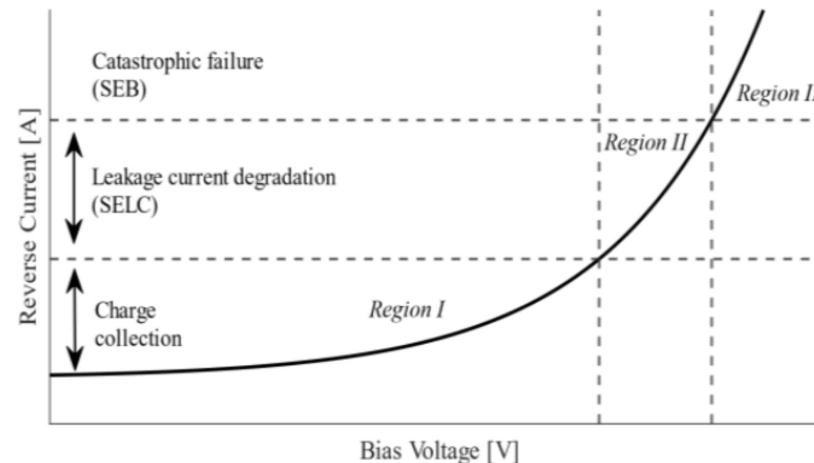
D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

- First "family" will address power devices and SEB/SEGR
  - Two different power device types and SEE mechanisms are planned to be tested
    - SiC Diode (e.g. SiC Schottky C3D02060E from Wolfspeed)
    - Si/SiC Power Mosfet
  - SiC diode is of particular interest

  since exhibiting a very specific behavior under HI exposure



D5.4 (M36) Verification of beam parameter requirements

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

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Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

- Second “family” is memory
- NAND flash MT29F256G08AUCAB

- Different type of SEE to be investigated since those devices exhibit sensitivity to multiple SEE
  - SEL, SEU, MBU, row event, column event, SEFIs, stuck/weak bits

D5.4 (M36) Verification of beam parameter requirements

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

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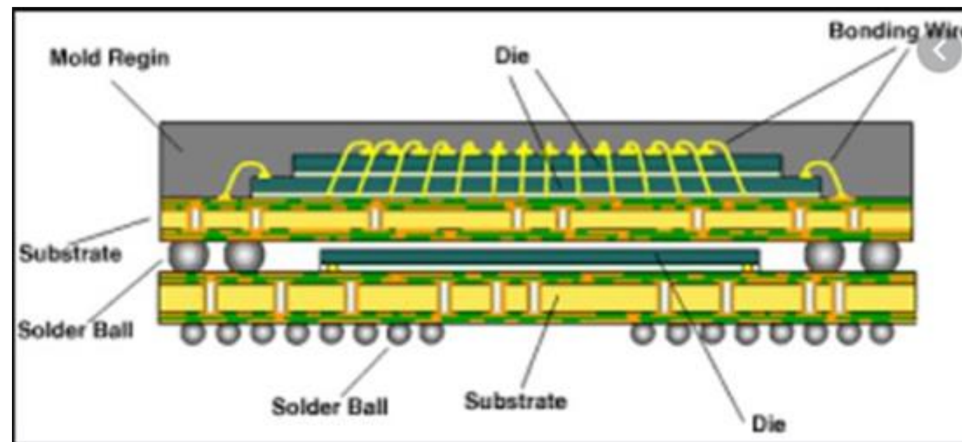
Task 5.4 - Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement : Status and Plans

- Third “family” prone to a different approach
- Device type will be selected according to the Airbus DS project needs (and stock availability)
  - Device won’t necessarily benefit of previous SEE testing
  - Device selection of interest w.r.t. beam specificities



D5.4 (M36) Verification of beam parameter requirements

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

Task 5.5 - Qualification of High-complexity Devices: Description of Work

- Partners: UNIPD, TAS, M24-48
- **Graphical Processing Units** (GPUs) and **Field Programmable Gate Arrays** (FPGAs) are two key enablers for on-board **artificial intelligence**
- Heavy-ion SEE qualification is very complex because of the very high power-consumption (standard energy ions require in-vacuum irradiations) -> in air irradiation is key
- UNIPD will perform a test campaign on a GPU
- TAS will perform a test campaign on a FPGA
- The results will be used together to compile recommendations and guidelines about SEE testing with very high energy ion beams

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

Task 5.5 - Qualification of High-complexity Devices: Status and Plans

- UNIPD has selecting a suitable platform and has performed preliminary test campaigns (using neutrons)
  - NVIDIA Jetson line of AI accelerators appears as the most promising candidate
    - CPU + GPU in one chip, with full framework for AI computing
  - Preliminary tests carried out at ChipIr (UK) on some Jetson Nano boards

Jetson Nano board

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

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Task 5.5 - Qualification of High-complexity Devices: Status and Plans

- Device is to be chosen according to the need and availability of TAS projects.

- Trade-off is between:
  - High performance System-On-Chip (backside irradiation with fan-based cooling system).
  - Optoelectronics that cannot be «opened» in the traditional way to be tested.

- Device will be chosen during the next months

D5.5 (M48) Impact of beam energy in SEE testing

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

Task 5.6 - Board-level testing: Description of Work

- Partners: TAS, M24-48
- Board-level testing can enable the qualification of several devices by irradiating them simultaneously under the same beam.
- In some cases, and thanks to the properties of VHE ion beams, it can even be envisaged to test more complex systems that are made of a few electronic boards stacked on top of one another.
- The task will consist of testing electronic boards enabling power conditioning functionalities, which may be particularly sensitive to radiation.
- The objective of the task will be that of defining a methodology for testing these kinds of boards with a VHE ion beam that will be integrated in the guideline.

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

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Task 5.6 - Board-level testing: Status and Plans

- Device under trade-off for testing are DC/DC converters.
- DC/DC converter with high power density w.r.t. footprint are not so common in the space market.
- On the other hand they are a need in payload architecture where the same module type is implemented recursively to build large structures (like SAR for earth observation).
- The first choice for this application are commercial DC/DC converters available in TAS.

D5.6 (M48) SEE qualification guidelines for high complexity devices and board level testing

Conclusions

Task	Status
5.1: Final review of VHE ion beam requirements for SEE testing	Beam requirements have been discussed. Task has been completed with deliverable D5.1.
5.2: Analysis of Ionization Response in a PIN diode for Beam Quality Assessment	In progress.PIN diode setup has been defined.
5.3: Suitability of the Proposed VHE Ion Beams for 3D Integrated Device Structures	In progress. First set of high-energy heavy ion experiments on 3D NAND Flash have been carried out.
5.4: Validation of the VHE Ion Beams for Industrial use with TRL 6-7 Achievement	In progress. Experiments have been carried out with benchmark SRAM devices and power devices. Additional experiments have been planned and are being prepared for the next campaigns.
5.5: Qualification of High-complexity Devices	Initial study and experiments on GPUs using wide spectrum neutrons.
5.6: Board-level testing	Will start later as planned

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