READINESS OF THE HEARTS@CERN FACILITY FOR SPACE ELECTRONICS HIGH-ENERGY HEAVY-ION TESTING*

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Abstract

The HEARTS@CERN activity in the framework of the HEARTS (High-Energy Accelerators for Radiation Testing and Shielding) EU project is targeted at enhancing Europe's high-energy (hundreds of MeV/n) heavy ion electronics irradiation capability through the development of an irradiation beam combining unique penetration and ionization characteristics. These types of tests are essential for exploiting commercial electronics in space. Throughout 2024, the HEARTS@CERN efforts have focused on achieving and demonstrating compliance with the space user radiation effects testing requirements. This includes being able to offer a wide range of energies, linear energy transfer (LET) values, and fluxes, with a high level of accuracy and a rapid change between parameters. Moreover, large homogeneous beams are necessary for enabling the test of multiple electronic components in parallel, and for performing board level testing. This work presents requirements for high-energy heavy ion testing along with the level of compliance achieved, as demonstrated during the November 2024 HEARTS@CERN user run, with a focus on the beam related parameters.

INTRODUCTION

The European infrastructure for radiation-effects testing contains facilities for total ionizing dose (TID) testing using radioactive sources emitting gamma radiation, single-event effects (SEE) testing facilities, e.g., proton accelerators mainly operated for other research or radiotherapy, or cyclotron-based facilities accelerating heavy ion beams providing wide ranges of linear energy transfer (LET) values, and more, providing valuable beam time for users [1].

In terms of SEE testing, less common are facilities providing high-energy heavy ions with beam energies above 100 MeV/n. This type of facility is highly useful (sometimes necessary) for certain types of tests or for testing certain types of components. The high energy of the ions is associated with a long penetration range in the tested device, and is an attractive beam parameter for radiation-effects testing of modern complex electronic components, which sometimes are thick (e.g. 3D stacked devices), and often difficult to de-lid (i.e. remove the protective packaging layers to be able to access the Si die and sensitive volumes of the device). The projectile ranges of commonly utilized heavy-ion testing facilities with energies around 10–20 MeV/n are limited to be on the order of hundreds of µm in Si [2, 3], while particle ranges of the high-energy heavy ion facilities, such as HEARTS@CERN [4], instead can be many mm or cm [5]. This facilitates the possibility of testing components for SEEs, either at all, or at least without having to de-lid them, and provides confidence of potentially using high-performance commercial-off-the-shelf (COTS) for applications in radiation environments, such as in space or around particle accelerators.

Development of heavy-ion irradiation capabilities have been ongoing at CERN for many years, with the CHIMERA project [6], irradiations using beams from the Super Proton Synchrotron (SPS) at the SPS North Area with very high energies [7,8], and the developments of irradiation capacities using ions slow-extracted from the Proton Synchrotron (PS) at the PS East Area, where the current HEARTS@CERN test location is situated [9–12].

THE HEARTS@CERN ION BEAMS

Beam Parameters

The ion beams for HEARTS@CERN are slow-extracted [12] from the CERN PS accelerator over a certain energy range. So far, only beams composed of Pb-ions have been used (as Pb beams are produced for collisions in the Large Hadron Collider (LHC)), and this will be the only ion species referred to in this paper unless otherwise specified. Currently, the utilized extraction energies are 1 GeV/n and 500 MeV/n. The beam energies can be further modulated close to the position of the device under test (DUT) using sheets of polymethyl methacrylate (PMMA) of various thickness, resulting in the (for the 2024 run) energies and LET values at DUT as seen in Table 1. The reported energy and LET values have been calculated using the FLUKA Monte Carlo code [13–16], while the range values have been obtained using SRIM [17].

The highest energy, 908 MeV/n at DUT, is the non-degraded 1 GeV/n beam, which loses energy on its path towards the DUT location through the T08 beamline. The HEARTS@CERN test location is hosted down the T8 beam line in the IRRAD facility. The energy is lost in air gaps in the beam line, vacuum windows, as well as in the air column between the beam exit window and the DUT location, as the irradiations are performed in air [16]. All other energies are achieved using the beam with 500 MeV/n extraction energy, and the energy 387 MeV/n at DUT is reached without PMMA degraders. All lower energies are obtained

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Table 1: Properties of the HEARTS@CERN Pb ion beam in 2024. These are parameters valid at the DUT surface with a spread within ±10 %, with LET and Range values for Si.

Energy (MeV/n)	**LET (MeV/(mg/cm^2))**	**Range (mm)**
908	12.3	50.0
387	16.5	14.5
210	22.2	6.0
153	26.6	3.5
113	31.7	2.3
88	36.3	1.5

using 13.0–19.5 mm of 1.19-g/cm^3 PMMA in the path of the 500-MeV/n beam.

The vacuum pipes in T08 will be extended for future runs to cover some of the present air gaps of the beam line, so the energy loss of the ions would be reduced. Further lower extraction energies (below 500 MeV/n) from the PS are also under development, which would result in a smaller degrader thickness needed to achieve beams with high LETs. This, along with reduced air gaps in the beamline would improve the beam quality by reducing the energy and LET spread at the DUTs with less straggling and fewer fragments [18].

The current range of LET values in Table 1 spans from 12.3–36.3 MeV/(mg/cm^2). A further increase in the energy would only provide a small decrease in LET (e.g., going from 387 to 908 MeV/n only a reduction of 4 MeV/(mg/cm^2) is achieved), and the higher limit of LETs could potentially be pushed through lower extraction energies from the PS, as mentioned. The current maximum LET in Table 1 is however already close to 40 MeV/(mg/cm^2), which is commonly discussed as the maximum necessary LET value needed for the *new space* community [19].

The beam area is defined by 3-cm thick tungsten collimator masks with square openings. Three collimators are available, with side lengths of 2.5, 5, and 7.5 cm respectively of the beam windows. These can be remotely moved in and out of the beam, as can the PMMA degraders, so the beam energy and size can be quickly changed by the facility operators. The DUTs are fixed on a separate movable stage, with remote horizontal and vertical translation possible, as well as rotations around the vertical axis. The degraders, collimators, and DUT stage are shown in Fig. 1.

As the beam is extracted from the PS, the time structure of the beam is such that the irradiation is delivered in spills. Each spill is about 1 s long, as achieved through the process of slow extraction [10], and normally around four to five spills are delivered every minute. The ion flux is tunable, so that around 10^2–10^5 ions/cm^2/spill (i.e. also ions/s during the one second spill) can be delivered, with some variations depending on the extraction energy and degrader thickness that is used. There is a variability in the spill intensities extracted from the PS, that is dependent on (among other things) the destinations of the beams in the CERN complex preceding the ones delivered to HEARTS@CERN. The temporal pattern of beam destinations, repeating every 1–2 minutes, is called the super cycle, and thus the relative position of the spills destined for HEARTS@CERN within the super cycle is important for the spill-to-spill variability due to e.g. magnet hysteresis. This variability is targeted to be kept within a factor of 2.

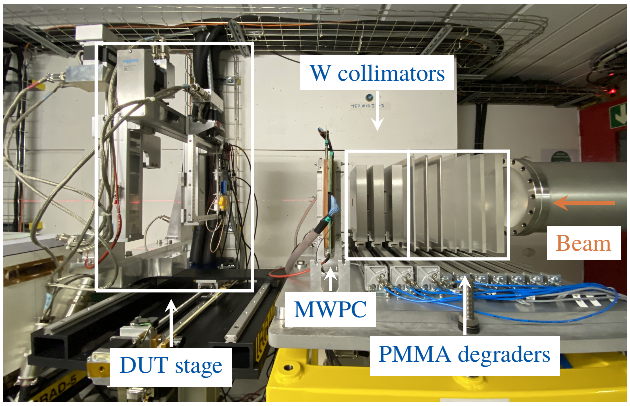

Figure 1: The DUT area of HEARTS@CERN, with the movable stage for the DUTs, W collimator masks, PMMA degraders, as well as the multi-wire proportional chamber (MWPC) beam-profile monitor.

Beam Dosimetry

The values of the beam energy and LET are as mentioned reliant on FLUKA simulations [16], but are also cross calibrated, measured, and validated using measurements with a Si diode detector [18, 20]. These parameters are not continuously monitored during operation, but fixed by the machine and degrader settings. As is discussed in e.g. [18], an increase in material budget, including PMMA degraders, increases the spread in the energy and LET distributions at the DUT location. Each value listed in Table 1 has therefore an associated statistical spread around it, which is targeted to being within ±10 % of the listed value.

The vertical and horizontal profiles of the beam are measured, and continuously monitored with a Multi-Wire Proportional Chamber (MWPC). The MWPC is constantly in place in the beam, and is displayed in Fig. 1 after the collimators in the beam direction. The resolution (wire spacing) of the MWPC is 6 mm, and examples of measured beam profiles are shown in Fig. 2. The MWPC provides beam profile projections in the vertical and horizontal directions, which are in Fig. 2 displayed for the three different collimators introduced in the 908 MeV/n beam.

The beam flux is monitored through secondary emission chamber (XSEC) and ionization chamber (XION) [21] beam instruments, constantly kept in a fixed location in the beam. The output signals of these instruments are proportional to the beam intensity, and these signals have been calibrated against absolute count rates measured by Si diode detectors at the DUT position, for each beam energy setting. The utilized XSEC and XION instruments were located 5–6 m upstream of the DUT position. These specific instruments were named XSEC70 and XION71, and the Si-diode calibration measurement for the XSEC70 is exemplified in Fig. 3 for

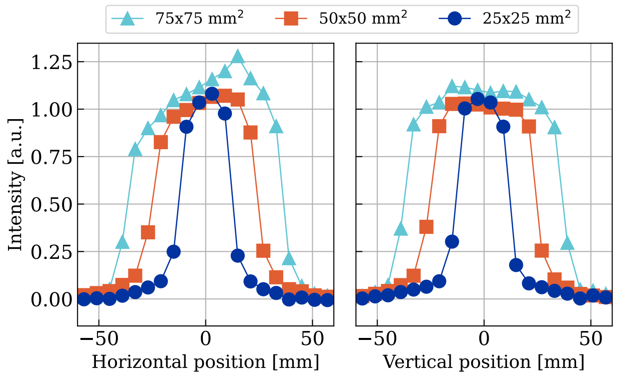

Figure 2: Examples of the horizontal and vertical beam profiles measured by the MWPC, for the 908-MeV/n beam.

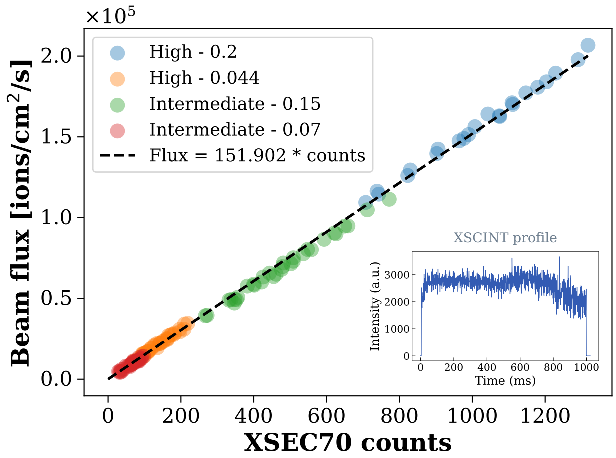

Figure 3: Example of the flux calibration of the beam instrument XSEC70, for various beam intensity settings. The normalized (by instrument gain) XSEC counts are calibrated against the number of ions detected by a Si diode detector, normalized by the diode area. The inset figure to the lower right shows an example of the longitudinal spill profile measured by the XSCINT scintillator detector.

the primary beam energy 500 MeV/n from the PS, without PMMA degraders (corresponding to 387 MeV/n at DUT). The flux on the DUT can be tuned through a radio-frequency knock-out (RFKO) extraction scheme [10], which controls the gain of the voltage that kicks particles out of the PS (with settings corresponding to the numbers 0.044–0.2 in the legend of Fig. 3), as well as through a flux tag setting, corresponding to *intermediate* and *high* in the figure legend, where different horizontal tune shifts through low energy quadrupoles are applied [10]. For the flux tag, also *low* is available providing ion fluxes down towards 10^2 cm^2/s/spill.

The longitudinal profiles of the ion spills from the PS are also monitored, with the intensity over the spill duration recorded using a scintillator detector (XSCINT). An example of these measurements is shown in the inset of Fig. 3 for a high intensity beam, corresponding to machine settings of the blue dots in Fig. 3. With this one can monitor that the beam intensity is kept constant over the spill duration.

THE 2024 USER RUN

In the HEARTS@CERN pilot user run at the end of 2024, ten user groups participated. These users were both internal to the HEARTS collaboration, as well as from external institutions and companies, with participants from industry as well as academia. Twelve days were devoted to providing beam time for these users outside of CERN [22], after a period of six days of beam calibrations, verification, and operational tests with the ion beam directed to HEARTS@CERN.

The facility was operating 24 h per day during the user run, continuously staffed by HEARTS operators. Typically the user groups started their beam times in the mornings, after one night of buffer time since the end of the previous users beam time. Thanks to this, all users managed to complete their allocated beam times despite occasional short beam interruptions for some users, which were compensated in the short term (i.e. typically the same day) through the aforementioned buffer time. In total 168 h of beam time was provided for the users in the 2024 pilot run.

In the user run 2024, improvement potentials were identified in the DUT alignment system, as this was done with a portable laser mounted on a tripod. This tripod was for the alignments placed in the beamline behind the mounted DUTs in the beam direction, illuminating the backside of the DUT boards with a cross marking the beam center. The laser had to be removed during irradiation, and re-placed in position again for each alignment. For the HEARTS@CERN run in 2025, this system will be upgraded to a fixed, wall-mounted alignment system, that will illuminate the DUTs from the front side where the beam will hit. This will provide a faster and more reliable DUT alignment.

CONCLUSION

The pilot user run in 2024 that was performed at HEARTS@CERN confirmed that the beams delivered at the irradiation area with comparatively large LET values and long ranges are of high interest to the community. The facility was able to integrally deliver the scheduled beam time hours for the users, with valuable experience gained from the pilot run to apply for the operation over the coming years. This pilot run was also successful in confirming the ability of HEARTS@CERN to act and perform as a radiation-effects testing facility for the user community.

The beam parameters, their monitoring, and the operation of HEARTS@CERN for the user run in 2024 was described herein. Most of this information will be valid in principle also for the continuing operation in 2025 and beyond, however the selection of beams in terms of the available values of energies and LET values at the DUT location might differ. The beam quality, beam line layout and related instrumentation and its performance are items continuously under development, which for future runs will result in improved beam homogeneity in the irradiation window as well as likely larger available beam window sizes, with a targeted smaller fluence variability across the spills.

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