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Characterisation of degraded very-high-energy heavy ion beams using the HEARTS LET booster

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***Abstract*—Very-high-energy (VHE) heavy ions are particularly relevant for single event effects (SEE) testing due to their unique combination of high linear energy transfer (LET) and substantial penetration depth in electronic components, removing the need for vacuum testing and component delidding. The HEARTS project addresses the growing demand for these types of beams by leveraging the CERN accelerator complex and its use of heavy ions for physics studies and adapting it to radiation testing of electronics. To this end, a detailed characterisation of primary and degraded very-high-energy heavy ion beams has been performed at CERN, using a combination of silicon diode energy measurements and Monte Carlo simulations, to demonstrate their suitability for SEE testing.**

***Index Terms*—Very-high energy heavy ions, primary beams, degraded beams, single event effects (SEEs), silicon diode, energy spectra, Monte Carlo simulations, FLUKA, CERN, HEARTS**

I. Introduction

The space radiation environment outside of the protection of the Earth's magnetic field is characterised by the presence of galactic cosmic rays (GCR), composed of high-energy, ionising particles originating from energetic sources in outer space. Although the GCR spectrum is predominantly composed of protons and light nuclei [1], the less prevalent heavy nuclei pose a specific hazard. Their combination of high charge (Z) and high energy can cause them to have a large penetration range in matter and deposit a high amount of energy [2]. A single GCR particle can therefore trigger a single event effect (SEE) in mission-critical, on-board electronics.

Radiation hardness assurance of electronics is key to mitigate risks and enhance spacecraft resilience in deep space. It can be carried out using very-high-energy (VHE) heavy ions, which can mimic the effects of GCR radiation. The key advantage of VHE heavy ion beams is the ability to reach high linear energy transfer (LET) values while maintaining large penetration range. The large range in Si ($< 1\,\mathrm{mm}$) is desirable to ensure that the beam penetrates all layers of the device with a constant LET. The higher LETs can be obtained in two ways, either by lowering the energy of the primary beam done through the accelerator settings or by keeping the same settings but using passive energy degraders locally [3].

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This paper discusses both approaches and presents the dosimetry of primary and degraded VHE heavy ion beams used at CERN within the High-Energy Accelerators for Radiation Testing and Shielding (HEARTS) project for radiation hardness assurance purposes, in particular for space applications. Accurate dosimetry of these type of beams is essential for beam quality control during electronics testing. However, it can be particularly challenging because of the energy straggling and beam fragmentation when the beam interacts with material in the beam line [4]. The presented dosimetry method is relying on solid state detector measurements in correlation with Monte Carlo simulations. This dosimetry approach was benchmarked using U ions in GSI [5] and applied to Pb ion beams at CERN used for SEE testing.

The paper is organised as follows: Section II describes the HEARTS project and the associated testing infrastructures at CERN, Section III presents the detector setup used for beam characterisation measurements and the obtained energy spectra, Section IV correlates the obtained energy deposition measurement results with simulations and provides the associated LET values, Section V discusses the implications on flux and finally the conclusion and outlook are provided in Section VI.

II. Testing infrastructure

The HEARTS project [6, 7] addresses the increasing demand for VHE heavy ion beams in Europe. This 4-year project kicked off in January 2023 is funded by the European Union (EU). It aims at further developing and expanding the European radiation testing infrastructure by providing research and industrial access to high-quality, high-energy heavy ion facilities tailored for space users and applications. The project features two high-energy heavy ion accelerator infrastructures: CERN, in Switzerland and GSI, in Germany. It also involves the University of Padua as academic partner, and Thales Alenia Space and Airbus Defence and Space as industrial partners, all of which have ample experience in the radiation effects domain. Cosylab also joined HEARTS thanks to additional EU funding and will contribute by providing its expertise in control system protocols and user interface tools.

The CERN branch of HEARTS, previously known as CHIMERA [8], is working on improving the existing CERN infrastructure to optimise it for radiation effects testing [9]. Lead ion beams (^{208}Pb) can be accelerated to an energy of interest for radiation testing, i.e., within the range of 100 to $1000\,\mathrm{MeV/n}$ by the Proton Synchrotron (PS) [10], which is the third largest accelerator in the CERN accelerator complex. The ion beam is then slow extracted [11] and transported

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though the T08 beam line to the East Area (EA) test hall where it can be used for radiation testing in IRRAD [12] and CHARM [13, 14] facilities. The HEARTS ion run in 2023 was performed in CHARM, taking advantage of the existing electronics testing infrastructure.

Since the ion beam extracted from the PS is propagated through air (about $30\,\mathrm{m}$), vacuum windows, and beam instrumentation along the beam line, it arrives at the device under test (DUT) location in CHARM with a significantly reduced energy than what was extracted. This puts a lower limit on the extracted energy that can be transported through the beam line down to CHARM and therefore also limits the range of achievable LETs.

A solution for this is to extract a higher energy and degrade the beam locally [15], just upstream of the DUT using lightweight, low Z, and low-density degraders, typically plastic. Within HEARTS, this is achieved with a so-called ”LET booster”; a remotely-controlled system allowing to move different degraders independently in or out of the beam.

The HEARTS LET booster, shown in Fig. 1, is composed of eight polymethyl methacrylate (PMMA) plates with different thicknesses, mounted on pneumatic actuators enabling a two-position movement using compressed air. The PMMA degraders used in this work were $24 \times 24\,\mathrm{cm}^2$ large and with thicknesses of 0.5, 1, 2, 4, 8, 10, 20 and $40\,\mathrm{mm}$ but can easily be exchanged based on specific user needs.

Two additional stronger actuators were added to the LET booster, downstream of the degraders, hosting two beam masks. The masks were made of copper blocks, $20 \times 20\,\mathrm{cm}^2$ large and $3\,\mathrm{cm}$ thick, with a square cutout at the centre, used to fully stop the tails of the Gaussian beam profile and obtain a uniform square-shaped beam spot. In this work, two masks were used, one with $5 \times 5\,\mathrm{cm}^2$ opening and the other with $10 \times 10\,\mathrm{cm}^2$.

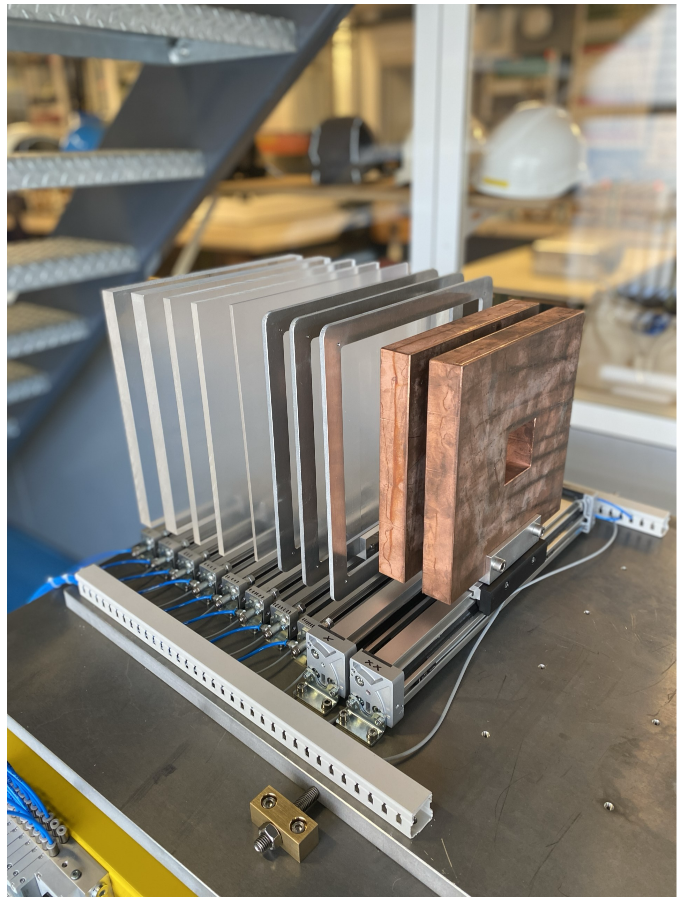

Fig. 1. HEARTS LET booster: a remotely-controlled system enabling to place PMMA degraders with different thicknesses in or out of the beam. It also features beam shaping masks.

III. Solid state detector measurements

A. Test setup

The solid state detector used for the beam characterisation was a fully depleted p-n junction silicon diode manufactured by Micron Semiconductor Ltd. (model MSX002 (SS) 300 2M/2M). The square diode is $4 \times 4\,\mathrm{mm}^2$ large, with an active area of $2 \times 2\,\mathrm{mm}^2$, and $300\,\mu\mathrm{m}$ thick. It is mounted on a ceramic PCB, connected with wire-bonds to an SMA connector and protected by an aluminum housing, as shown in Fig. 2. The detector assembly was wrapped with a $20\,\mu\mathrm{m}$-thick aluminum foil during the measurements to shield it from light and electromagnetic noise.

The signal induced in this diode by the HEARTS VHE heavy ion beams was large enough, hence no signal amplification was needed. The diode was connected to a Cividec D1 Bias-Tee enabling to split the bias voltage and signal line. The detector was biased with a reverse bias of $80\,\mathrm{V}$. The signal was sampled and acquired by a CAEN DT5751 digitizer with $1\,\mathrm{GHz}$ and 10-bit resolution and $50\,\Omega$ input impedance.

The data acquisition (DAQ) was done using the CAEN WaveDump software. The detector was used in self-triggered pulse mode, recording the full analogue waveform for each particle generating an event signal above a given threshold. The threshold in these measurements was set to a higher value to remove the low energy peak in the energy deposition spectra, due to secondary protons and light fragments, which are not of direct interest and would saturate the DAQ chain.

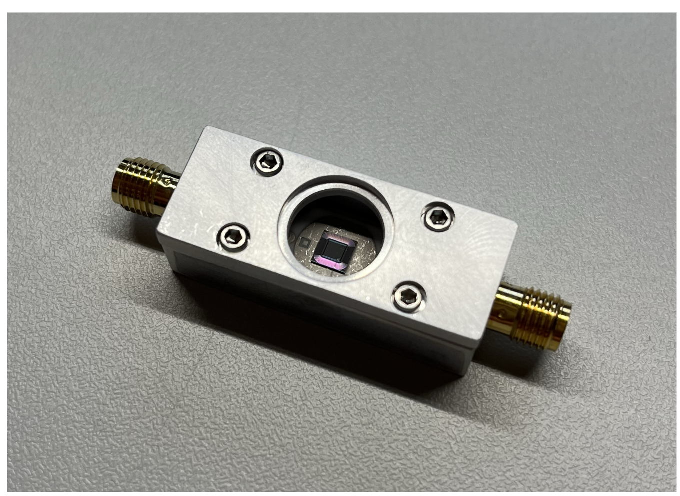

Fig. 2. Silicon diode used for beam characterisation measurements during the HEARTS 2023 ion run.

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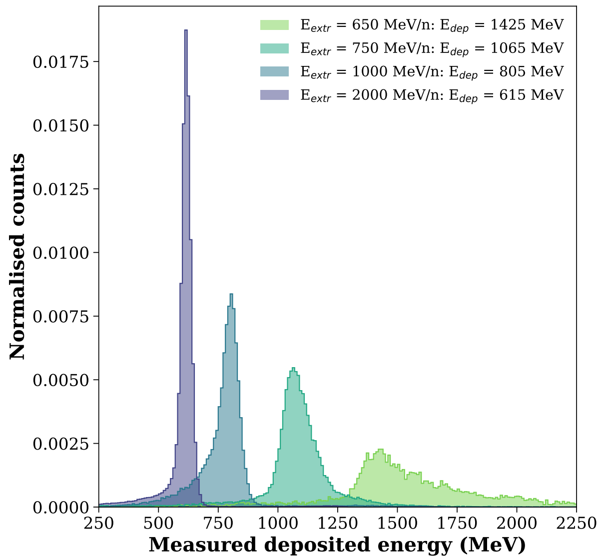

Fig. 3. Event-by-event energy deposition spectra measured by the silicon diode for four selected primary beams of the HEARTS 2023 ion run at CERN.

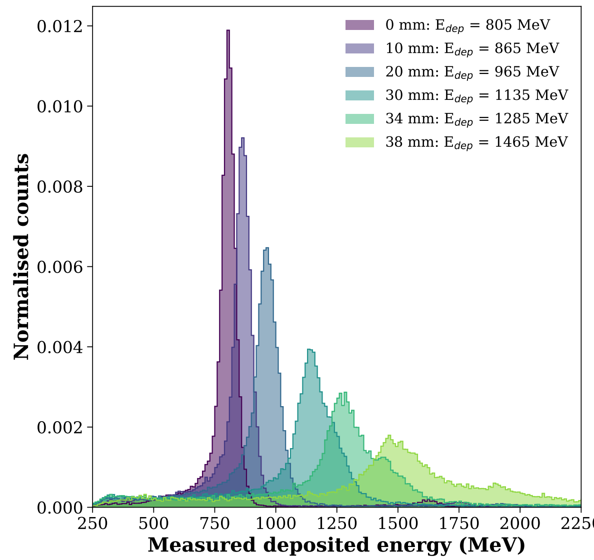

Fig. 4. Event-by-event energy deposition spectra measured by the silicon diode for the $1000\,\mathrm{MeV/n}$ beam degraded with PMMA degraders of different thicknesses.

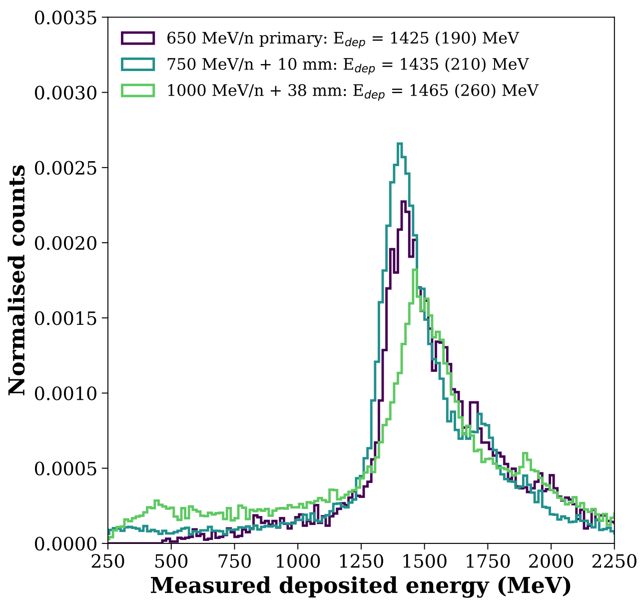

Fig. 5. Comparison of event-by-event deposition spectra measured by the silicon diode for the primary beam of $650\,\mathrm{MeV/n}$ and beams degraded from higher extracted energies but depositing a similar average energy.

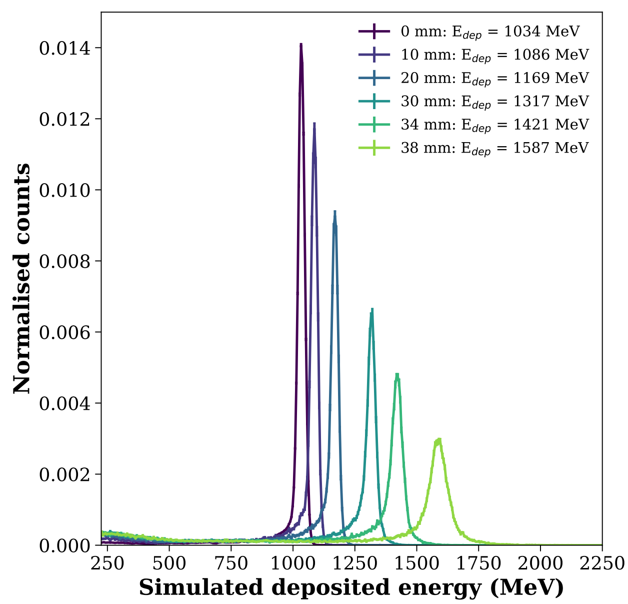

Fig. 6. Event-by-event energy deposition spectra obtained from FLUKA simulation of the $1000\,\mathrm{MeV/n}$ beam degraded with PMMA degraders of different thicknesses.

The single event deposited energy was extracted as a value proportional to the integral of the signal pulse, under the assumption that the charge-to-energy conversion is $3.6\,\mathrm{eV}$ per e/h pair and gain equals to one since no amplification was used. A deposited energy spectrum for each measured configuration was then obtained by binning these integral values with sufficient statistics. More details about the measurement method is provided in [16, 17, 18], for similar test setups.

B. Energy spectra of primary and degraded beams

During the 2023 HEARTS heavy ion run at CERN, four primary beam energies were selected, implemented and extensively characterised: $650\,\mathrm{MeV/n}$, $750\,\mathrm{MeV/n}$, $1000\,\mathrm{MeV/n}$ and $2000\,\mathrm{MeV/n}$. These are the energies extracted from the PS which were selected to cover the available LET range.

The event-by-event energy deposition spectra of these four selected primary beams measured by the silicon diode are shown in Fig. 3. As expected, the lower the beam energy, the higher the LET and hence the higher the energy deposited in the active volume of the diode. Indeed, when lowering from

TABLE I
SUMMARY TABLE OF THE MEASURED AND SIMULATED HEARTS AT CERN HEAVY ION BEAM CONFIGURATIONS.

Beam energy extracted [MeV/n]	Degrader thickness [mm]	Total material budget [g/cm^2]	FLUKA Beam energy at DUT (FWHM) [MeV/n]	FLUKA Surface LET (FWHM) [MeVcm^2/mg]	SRIM Range in Si (FWHM) [mm]	FLUKA E_{dep} simulation (FWHM) [MeV]	Silicon Diode E_{dep} measurement (FWHM) [MeV]
2000	0	5.53	1665 (21)	11.4 (0.1)	108.4 (1.7)	893 (53)	615 (40)
1000			660 (13)	13.4 (0.1)	31.4 (0.9)	1034 (33)	805 (60)
750			361 (14)	17.0 (0.2)	12.9 (0.7)	1273 (32)	1065 (130)
650			223 (14)	21.7 (0.7)	6.1 (0.6)	1585 (53)	1425 (190)
1000	10	6.70	558 (15)	14.2 (0.1)	24.7 (1.0)	1086 (33)	865 (70)
	20	7.88	450 (18)	15.5 (0.2)	18.0 (1.1)	1169 (34)	965 (110)
	30	9.06	331 (21)	17.7 (0.5)	11.3 (1.1)	1317 (41)	1135 (160)
	34	9.53	279 (23)	19.3 (0.7)	8.7 (1.1)	1421 (54)	1285 (160)
	38	10.00	220 (26)	21.8 (1.2)	6.0 (1.1)	1587 (94)	1465 (260)
750	10	6.70	226 (18)	21.6 (0.8)	6.3 (0.8)	1573 (61)	1435 (210)
	12	6.94	194 (19)	23.4 (1.1)	4.9 (0.8)	1700 (83)	1575 (280)
	14	7.17	159 (22)	26.1 (1.8)	3.7 (0.8)	1896 (137)	1785 (382)
	16	7.41	120 (26)	30.8 (3.5)	2.4 (0.8)	2280 (318)	2240 (595)

an extracted energy of $2000\,\mathrm{MeV/n}$ down to $650\,\mathrm{MeV/n}$, the peak energy deposited in the diode increases by more than $800\,\mathrm{MeV}$, i.e., a 132% increase.

This demonstrates that lowering the energy extracted from the machine allows to obtain higher LETs interesting for SEE testing. However, when increasing the beam LET this way the beam energy spread also increases, as it can be observed from the broadening of the energy deposition spectra. The integral of each spectrum is normalised to one, which allows to better visualise the peak broadening.

Then the predefined $1000\,\mathrm{MeV/n}$ primary beam was degraded with progressively thicker PMMA degraders of the LET booster. The obtained energy deposition spectra measured by the diode are presented in Fig. 4. As expected, when the degrader thickness increases, the average energy deposited in the diode increases as well due to an increased LET. For instance, $1000\,\mathrm{MeV/n}$ beam degraded by $30\,\mathrm{mm}$ of PMMA results in an average energy deposited in $300\,\mu\mathrm{m}$ silicon similar to the average energy deposited by the primary beam extracted at $750\,\mathrm{MeV/n}$. Similarly, the $38\,\mathrm{mm}$-thick degrader allows to increase the average deposited energy to up to $1465\,\mathrm{MeV}$, which is equivalent to the energy deposited by the primary beam with extracted energy of $650\,\mathrm{MeV/n}$.

For a better comparison between the two methods to increase the LET, the energy deposition spectra measured by the silicon diode with the primary beam of $650\,\mathrm{MeV/n}$ is reported in Fig. 5 in comparison with the $750\,\mathrm{MeV/n}$ beam degraded with $10\,\mathrm{mm}$ of PMMA and $1000\,\mathrm{MeV/n}$ beam degraded with $38\,\mathrm{mm}$ of PMMA. All three distributions peak at roughly the same value pointing out to a very similar LET of these beams. All three deposited energy spectra exhibit the same shape, although the configuration with the thicker degrader results in slightly greater dispersion than the one with the thinner degrader. This indicates that while degraders effectively increase the LET, using thicker degraders comes at the cost of increased dispersion, and thus, their use must be carefully optimised to avoid compromising beam quality.

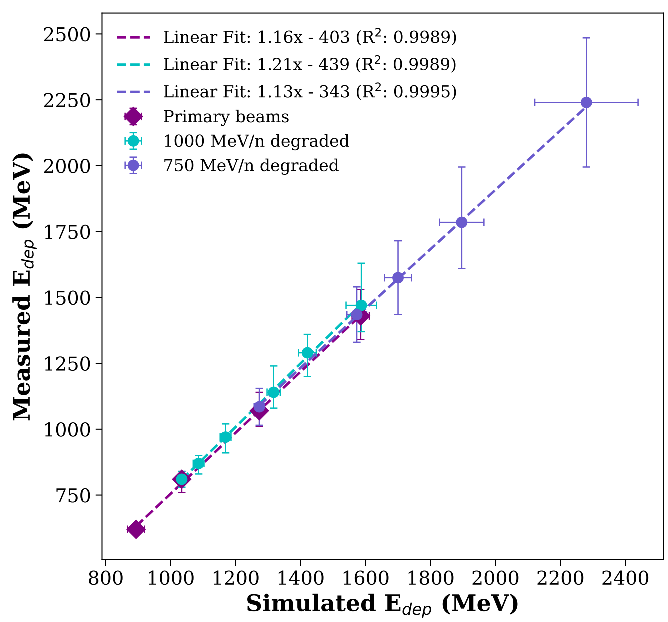

Fig. 7. Correlation between the measured and simulated energy deposition in the silicon diode for the four predefined primary beams and beams obtained by degradation from $1000\,\mathrm{MeV/n}$ and from $750\,\mathrm{MeV/n}$.

IV. COMPARISON WITH SIMULATION AND LET EXTRACTION

All values of the measured deposited energies and the associated spread (expressed as full width at half maximum (FWHM)) are reported in the right most column of Table I. The primary and degraded beam configurations measured using the silicon diode as described above were also simulated using the FLUKA Monte Carlo transport code [19, 20, 21] building on the method described in [5].

The primary beam energy characteristics were calculated as result from transport calculations through the T08 beam line and experimental facilities in the PS East Area [22], relying on an accurate material budget seen by the beam (provided in Table I) and FLUKA's benchmarked heavy ion

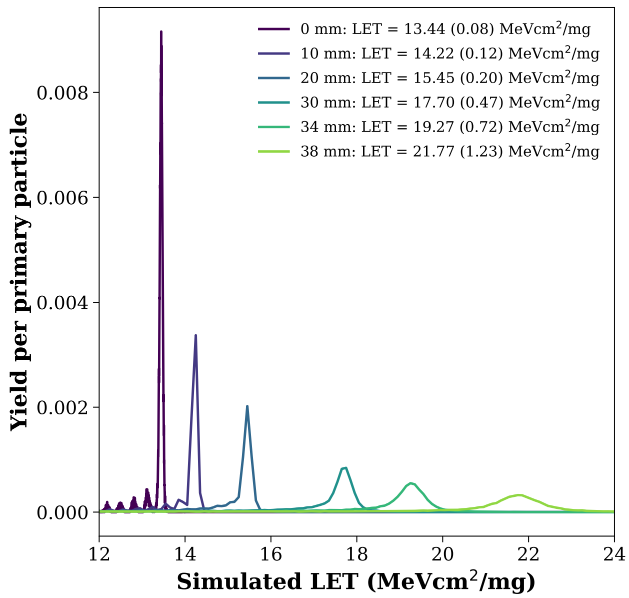

Fig. 8. LET distributions at the front surface of the sensitive volume of the $1000\,\mathrm{MeV/n}$ beam degraded with PMMA degraders of different thicknesses obtained from FLUKA simulations.

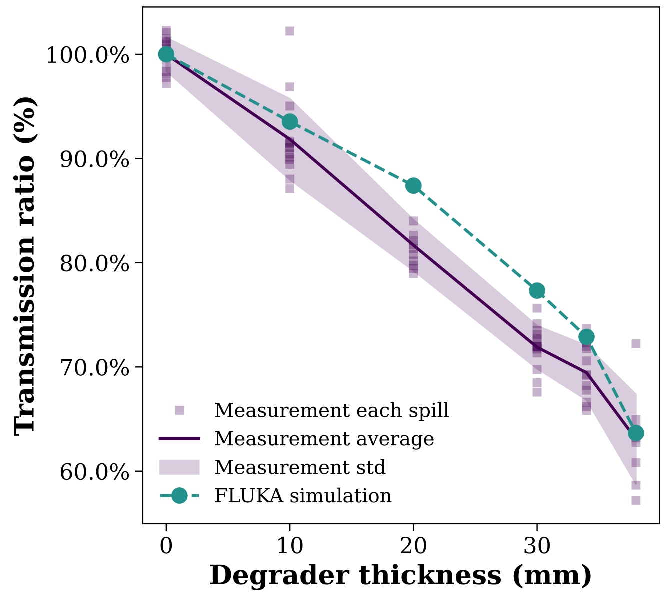

Fig. 9. Flux transmission ration of the $1000\,\mathrm{MeV/n}$ beam as a function of the degrader thickness counting only particles in the main energy deposition peak.

interaction models [23, 24]. The beam properties were then loaded into a more detailed geometric model comprising only the LET booster and the silicon diode placed roughly $1.5\,\mathrm{m}$ downstream, corresponding to the configuration adopted during the measurements.

The requested simulated quantities consisted of the beam energy at the DUT location (i.e., the diode), the LET distribution arriving to the front surface of the diode and the event-by-event energy deposition spectra in the $300\,\mathrm{\mu m}$-thick active volume of the diode. These are all affected by beam-material interactions, most notably electronic stopping (dE/dx), scattering through Coulomb interactions and inelastic collisions resulting in nuclear fragmentation [8]. All obtained values are provided in Table I along with their respective FWHM spread. Based on these results the associated range in silicon and its FWHM was extracted using SRIM [25] and is also included in Table I to demonstrate that a very large penetration range is preserved even after degradation. Indeed, a typical electronic component is on the order of hundreds of microns thick plus it may have a $1\,\mathrm{mm}$ package on top, while the beams studied in this work have a range larger than a couple of mm.

An example of the energy deposition spectra obtained from the FLUKA simulation of the $1000\,\mathrm{MeV/n}$ beam, primary and degraded with different degraders, are presented in Fig. 6. It can be directly compared to the corresponding beam/degrader configurations measured by the silicon diode shown in Fig. 4. FLUKA reproduces the same trend as observed in measurements, i.e., when the degrader thickness increases the deposited energy increases and the distribution broadens. The simulated energy deposition spectra are generally narrower then the measured ones, which can be primarily attributed to the finite resolution of the detector, not taken into account in simulation, and which induces additional dispersion. The simulated spectra are also peaking at a higher deposited energy than the measured data (on average about $200\,\mathrm{MeV}$ higher). This can be attributed to the attenuation of the diode current transients propagated as analogue signal through $40\,\mathrm{m}$ of coaxial cable to the control room before being digitised and recorded by the acquisition software. Such attenuation is usually removed by applying a calibration, however in this work no calibration was applied to the diode setup, given that conventional low-energy calibrations are not applicable to the energy range considered in this study.

Our dosimetry approach consists in correlating the diode response to VHE heavy ions with FLUKA simulations [5], rather than calibrating the detector with low-energy radiation sources or at standard energy facilities, as such calibrations may not be reliably extrapolated to very high energies. The correlation between the simulated and measured energy depositions in the diode is presented in Fig. 7. The data points correspond to the peak value of the obtained energy spectra and the error bars represent the FWHM. They are asymmetric for the measurements since the spectra generally present a larger tail towards higher energies, as it can be seen, e.g., in Fig. 5, while they are rather symmetric for the simulations. An excellent linearity between simulations and measurements is observed for the primary beams as well as for the degraded ones. All linear fits result in a very similar slope and intercept, confirming the applicability of this dosimetry method.

This confirms that we can rely on FLUKA simulations not only to calibrate the measured quantities, but also to extract other ones that are not directly accessible through measurements, as for instance the LET of the beam. The LETs of all studied beam/degrader configurations obtained from simulations are provided in Table I along with their FWHM. The simulated LET distributions of the $1000\,\mathrm{MeV/n}$ beam, primary and degraded with PMMA degraders of different thicknesses are shown in Fig. 8. The oscillations visible on

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the lower LET tail of the primary beam distribution are due to ion fragments, where the LET peaks correspond to integer values of the atomic number Z. They are less and less visible when thicker degraders are used, because they are smeared out. This plot further illustrates that the LET of the beam can be increased by employing passive degraders, albeit with a corresponding degradation in resolution. In this measurement, the LET of the primary beam of about $13\,\mathrm{MeVcm^2/mg}$ was increased up to almost $22\,\mathrm{MeVcm^2/mg}$ using degraders.

In fact, as can be seen from Table I, the three configurations, presented in Fig. 5, i.e., $650\,\mathrm{MeV/n}$, $750\,\mathrm{MeV/n}$ + $10\,\mathrm{mm}$ and $1000\,\mathrm{MeV/n}$ + $38\,\mathrm{mm}$, give a resulting LET between 21.5 and $22\,\mathrm{MeVcm^2/mg}$, demonstrating that the same higher LET can be obtained by three different beam/degrader configurations. Even though an increasing amount of degrader thickness also introduces a higher FWHM of the LET distribution, this remains below $\pm10\%$, which is complying with the radiation testing standards [26]. It is also noteworthy from Table I, that these three beam configurations, achieving an LET of almost $22\,\mathrm{MeVcm^2/mg}$, are capable of penetrating slightly more than $6\,\mathrm{mm}$ in silicon and the beam configuration leading to the highest LET of this study ($30.8\,\mathrm{MeVcm^2/mg}$) has still a penetration range above $2\,\mathrm{mm}$. This characteristic makes these beams particularly valuable for radiation testing of electronics, eliminating the need for vacuum testing or delidding of components.

V. Degrader impact on flux

Finally, another critical consideration when using degraders is their impact on the beam flux. Degraders do not only impact the beam energy and LET but also reduce the count rate due to scattering and fragmentation processes. Since the silicon diode can record the energy deposition of each individual particle, it can also function as a flux counter. This capability was utilised to assess the flux transmission as a function of degrader thickness. The result for the $1000\,\mathrm{MeV/n}$ beam is shown in Fig. 9.

The flux of the HEARTS heavy ion beams arriving to the irradiation area is monitored using secondary emission chambers (SECs) installed along the beam line. These beam instruments are calibrated with the silicon diode for various beam energies at the start of the ion run [8]. In this study, the calibrated SEC counts served as a reference for the flux measurement before the degrader, while the silicon diode measured the flux at the DUT position, after the degrader. The transmission ratio is then calculated as the ratio between these two measurements and expresses the percentage of particles transmitted through the degraders to the diode. Primary ions are identified by selecting events with deposited energies within the main peak of the energy deposition spectra. This selection was based on energy values with an occurrence greater than 10^{-3}, after normalising the integral of the spectrum to unity. As shown in Fig. 9, we assume the transmission to be 100% for the primary beam with no degrader.

The HEARTS heavy ion beams at CERN are accelerated by a synchrotron and are hence pulsed, unlike continuous beams from cyclotrons. They arrive in so-called "spills" with no beam in between. Therefore, the measurement data points, indicated in Fig. 9 by square markers, correspond to the flux transmission of each measured spill. Several spills were measured for the primary beam as well as for each degrader thickness. The results show some spill-to-spill variation, but the average is indicated by the solid line and the standard deviation is also provided.

The measurement was compared to FLUKA simulations. Primary ions were identified based on the same occurrence method as applied to the measurements. Only particles that deposit an energy above $500\,\mathrm{MeV}$ in the sensitive volume of the diode were taken into account to correct for the detector threshold effect. The simulation result, shown in green in Fig. 9, follows the same trend as the measurements. For some degraders, the transmission from FLUKA is slightly higher, but overall the agreement stays within $\pm10\%$. The agreement between measurements and simulation could be further improved in the future by collecting more statistics, i.e., recording more spills per degrader configuration.

As expected, when thicker degraders are used the flux transmission decreases, because more and more particles scatter or fragment. When the beam is degraded with $10\,\mathrm{mm}$ of PMMA, on average 90% of primary particles are transmitted through the degrader. With the thickest degrader used in this study, i.e., $38\,\mathrm{mm}$, the average transmission ratio (i.e., the ratio with respect to $0\,\mathrm{mm}$ degrader thickness) decreases down to only 60%. This is a critical consideration in the use of degraders, as thicker degraders do not only extend the time required to achieve the target fluence but also necessitate precise characterisation of the transmission ratio to accurately account for fluence in the SEE measurements. The FLUKA simulations reveal that the amount of scattering and fragmentation increases for increasing degrader thickness. For reference, the inelastic scattering length of $1000\,\mathrm{MeV/n}$ Pb ions in PMMA is $36.9\,\mathrm{mm}$. The fragments themselves can also significantly impact the SEE test outcome [27].

VI. Conclusion and outlook

This study presents an extensive characterisation and dosimetry of primary and degraded very high-energy heavy-ion beams used at CERN within the HEARTS project for radiation testing of electronics. The use of passive degraders as a means of boosting the LET of these types of beams was demonstrated. Locally degrading the beam was shown to provide the same LET values as varying the extracted primary beam energy. An excellent correlation between energy depositions measured by a silicon diode detector and values from Monte Carlo simulations was obtained, confirming the suitability of this dosimetry method to quantify the beam LET and its spread. The use of large degrader thicknesses increases the LET spread but this nevertheless stays within the margins of radiation testing standards. The beam flux attenuation due to the use of degraders was quantified using both measurements and simulations, allowing to correct the primary beam flux to achieve the desired fluence during SEE testing. However, some caution is required when using these types of beams for SEE testing, because of the high-energy-deposition events caused by ion fragments, seen in diode measurements but not necessarily considered in simulations. They can have a big effect on SEE testing, especially for destructive testing like SEGR and SEB and could be quantified by a dedicated SEE experiment using well-known parts.

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