Characterization of Fully Fragmented High-Energy Heavy-Ion Beams for SEE Testing Through Measurements and Simulations

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***Abstract*— Fully fragmented, very-high-energy (VHE) heavy-ion beams offer interesting possibilities for radiation hardness assurance testing of electronic components exposed to the Galactic Cosmic Ray (GCR) space environment. In this article, we perform the dosimetry of these fully fragmented ion beams through a combination of silicon solid-state detector measurements and detailed Monte Carlo (MC) simulations in FLUKA focusing on the interaction between the beam and the device under test. The tested experimental configurations highlight the challenges of implementing this method in VHE ion facilities. The MC simulations offer further insights into the optimization of this approach.**

***Index Terms*— Alternative radiation hardness assurance (RHA), CERN, FLUKA, Geant4, GSI, Monte Carlo (MC) simulations, nuclear fragmentation, silicon detector, single-event effects (SEEs), SRIM.**

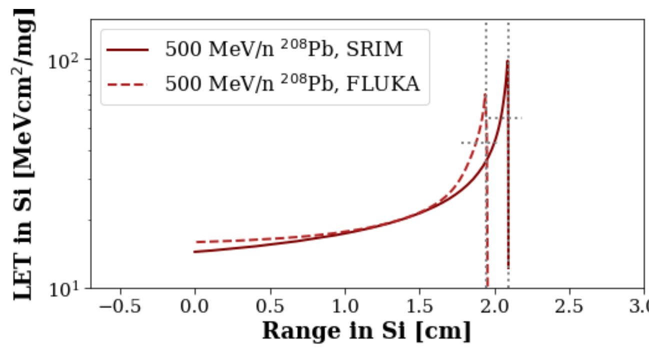

Fig. 1. LET as a function of range in silicon calculated for Pb (lead) ions using SRIM and FLUKA for 500 MeV/n kinetic energy. The LET values from FLUKA are approximated by scoring the energy deposition in 100 μm slices of Si.

I. Introduction

In recent years, the radiation effects testing community has taken great interest in using very high-energy (VHE, between 100 and 5000 MeV/n kinetic energy), heavy-ion beams for qualifying electronic components. The motivation for using these beams is twofold: first, high-energy heavy ions are an important part of the space radiation environment as a component of the Galactic Cosmic Ray (GCR) spectrum [1] where they can cause single-event effects (SEEs); second, the combination of high linear energy transfer (LET) and high range of these ions in matter is attractive for testing modern (micro-) electronics structures with a complex 3-D architecture and for board-level testing. A penetration depth above 1 mm in silicon is desirable to make sure that all sublayers of a device under test (DUT) see the same beam LET. This also removes the need for de-lidding components as is required in so-called standard energy test facilities which use ions around 10 s of MeV per nucleon kinetic energy. The European Union-funded high-energy accelerators for radiation testing and shielding (HEARTS) project aims to improve the current availability of high-energy, heavy-ion beams in Europe for radiation effects testing; the study presented in this article is carried out under this project. Despite the clear advantages of using VHE ion beams for space application testing, there are also a number of inherent challenges to this approach.

1) To ensure that each layer sees the same LET, a VHE beam for which the LET does not significantly vary over mm or even cm of matter that can be used, but this comes at the cost of using absolute LET values that are too low for most qualification purposes.
2) The high LETs of interest ($\geq$40 MeV·cm^2/mg) for qualification purposes are obtained at the end of the particle range. In modern electronics packages under test, the composition and thickness of the different sublayers are typically unknown. Moreover,

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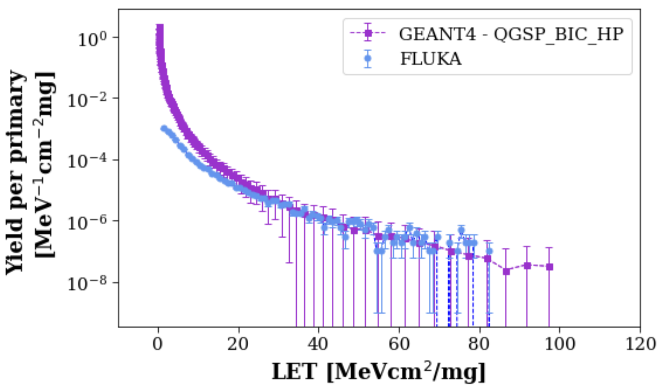

Fig. 2. Comparison of the LET spectrum generated by a 1-GeV/n Pb ion beam on an 11-cm PE target between GEANT4 and FLUKA.

sensitive volumes can be located at different depths within the component. This makes an accurate determination of the LET at the exact location of the sensitive volume very difficult. Given an unknown composition, it is also possible that beam particles range out before reaching the component layer of interest.

3) Test facilities can tune the ion energy in the accelerator or use passive degrader material to scan different LET values. Combined with any material budget (e.g., air, vacuum windows, or beam instrumentation) in the facility, energy straggling and fragmentation cause the device under test to see a distribution of LETs. This distribution can be simulated and verified experimentally but induces an inevitable spread around the desired LET value.

4) Monte Carlo (MC) simulations are crucial to extract the beam LET as a key dosimetric quantity, complement experimental results, and perform SEE rate predictions. The inevitable uncertainties in component layer composition and thickness propagate into the accuracy of simulation results. In addition, different simulation codes can yield different results given the same input as shown in Fig. 1 for FLUKA and SRIM [2]. Given the exact same energy (500 MeV/n), the same silicon material, and density (2.329 g/cm^3), the resulting particle range is 1.5 mm apart. For both code results, 50% of the LET variation (taken as the difference between the LET at the surface and the maximum LET) happens within the final 1 mm of range before stopping at a depth of around 2 cm.

The first two limitations led to the proposal of a test condition that simultaneously ensures a high LET as well as high penetration with a constant LET profile. This can be achieved through the nuclear fragmentation of a high-energy heavy-ion beam and was detailed as a proof-of-concept in [3]. The method entails placing a slab of material with a thickness that is larger than the range of the primary beam. The resulting beam is dominated by fragmentation products created by nuclear inelastic interactions. Common materials used to degrade or fully fragment ion beams are polyethylene (PE) or polymethyl methacrylate (PMMA) plastics with densities of 0.94 and 1.19 g/cm^3, respectively. Thus, instead of a single LET, a continuous distribution of LETs is seen by the DUT which bears an excellent similarity to the LET spectrum of GCRs in the space environment, especially at an LET $>$ 40 MeV·cm^2/mg when using beams of Pb or U. This beam can penetrate the device layers without substantially modifying the intensity and LET spectrum, a finding that was the result of MC simulations of fully fragmented beams which also showed an excellent agreement with experimental measurements as shown in [3] and [4]. It is to be noted that different simulation codes can yield different results given the exact same input. An example is shown in Fig. 2 which compares the resulting LET spectrum generated behind an 11-cm-thick PE target by a 1-GeV/n ^{208}Pb ion beam (range in PE of 10.7 cm according to SRIM) of 1 cm^2 surface area, calculated by MC codes FLUKA [5], [6], on the one hand, and Geant4 [7], [8], [9] on the other hand. The model was implemented in FLUKA and converted to a Geant4 input through the Moira tool [5]. In the Geant4 input, the "QGSP_BIC_HP" Binary Cascade model physics list [10] was chosen for its applicability in radiation protection, shielding, and medicine. The agreement between the two cases is good with two notable exceptions; at low LETs, the particle yields are predicted to be much higher through Geant4 which could have important consequences for calculating the total ionizing dose (TID) [3] or SEEs in components with low LET thresholds. Above 40 MeV·cm^2/mg, both codes predict yields within error bars from each other with slightly higher particle yields predicted by FLUKA. Differences in results may stem from the different physics models used and their implementation. At energies considered in this study (100 MeV/n–GeV/n), the chosen physics list in Geant4 relies on the Binary Cascade model, whereas for FLUKA, an extensively modified Relativistic Quantum Molecular Dynamics (RQMD) model [11], [12], [13] is used. The parameters in the precompound and de-excitation models used in both codes are tuned differently and can explain the large discrepancies at low LETs shown in Fig. 2. Despite the good agreement between the two codes, experimental validation of the LET spectrum through energy deposition measurements is needed to yield a proper physical understanding of the fully fragmented beams. In a follow-up to the aforementioned works, this article describes the first attempts at dosimetry of these fragmented beams by comparison of energy deposition spectra obtained from solid-state detector measurements to those obtained from simulations. This dosimetry is then applied to extract SEE rates from static random access memory (SRAM) response measurements taken in the same configuration and are detailed in a separate contribution submitted to the NSREC 2024 Radiation Hardness Assurance session. In Section II, the irradiation facilities and solid-state detector measurements carried out therein are summarized. In Section III, the FLUKA simulation settings are detailed before the measurements and simulations are compared in Section IV. In Section V, the interaction of the fragmented radiation field with test devices is further explored using dedicated simulations. A summary and outlook are provided in Section VI.

TABLE I
FULLY FRAGMENTED BEAM CONFIGURATIONS USED FOR DOSIMETRY STUDIES

Facility	Ion	Energy [MeV/n]	Energy at DUT [MeV/n]	Primary fluence [$\times 10^5$ cm^{-2}]	Range in PMMA (SRIM) [mm]	Inelastic scattering length in PMMA (FLUKA) mm	Degrader thickness [mm]
GSI	^{238}U	800	800	5	61	35	62
CERN	^{208}Pb	1000	660	270	50	38	47
CERN	^{208}Pb	750	350	5	20	39	21.6

II. SOLID-STATE DETECTOR MEASUREMENTS IN VHE ION FACILITIES

A key challenge for fragmented VHE ion testing is the related beam characterization and dosimetry. As opposed to testing scenarios where a single energy and corresponding LET are desired, for fragmented beams, one requires the characterization of the full distribution in terms of particle species, LET, and fluence. This deconvolution is possible using MC codes which can show differing results depending on the nuclear physics models included and their implementation. As highlighted in [14], measuring the resulting energy deposition spectra is very important since these spectra are directly determined by the fragmentation physics models. As a function of the particle energy, the PMMA thicknesses were chosen to be slightly above the range of the particles in this material (calculated using SRIM [2]), ensuring that no primary beam particles can traverse the stack. An overview of the different test setups is given in Table I. Note for the CERN configuration, a degrader thickness lower than the projected range in PMMA from SRIM for that particular energy was chosen. This was the result of preceding experimental work which indicated that this degrader thickness is sufficient to fully fragment the beam. As will be shown and further detailed below in Section IV, experimental verification is necessary due to the uncertainties in simulation codes which calculate the particle range, in addition to the uncertainty of the particle energy after traversing a certain material budget. Uncertainties in degrader thickness, composition, and density will always be present such that even with perfect simulation codes experimental validation is always necessary.

A. Irradiation Test Facilities

The groundwork for this method was carried out in 2022 at the GSI facility in Germany, where ^{238}U ions at 800 MeV/n kinetic energy were sent from the SIS-18 accelerator to the dedicated high-energy irradiation Cave A, shown in Fig. 3. A proof-of-concept experiment was carried out which placed a 62-mm thickness stack of PMMA plates in the beam path with the silicon diode (further detailed below) placed roughly 50 cm downstream [3]. Further validation measurements of this approach were carried out at CERN, where beams at different energies were extracted from the Proton Synchrotron (PS). Transport through the T08 beam line causes energy straggling before the beam arrives with degraded energy at the DUT position in the CERN high-energy accelerator mixed field facility (CHARM). The characterization of the radiation field was the subject of extensive beam line calculations also carried out in FLUKA and detailed in [15] and [16]. The T08 beam line features beam instrumentation, vacuum windows, and air sections and has a cumulative material budget of 5.55 g/cm^2. In the last 30 m of the transfer line, the beam traverses mostly air which spreads out the spatial profile of the beam into a broad, Gaussian shape with an (energy-dependent) full-width at half-maximum (FWHM) of roughly 10 cm at the DUT position. A dedicated beam energy degrader system was installed in CHARM for the 2023 test campaign, allowing between 0.5 and 85 mm of PMMA material to be placed in the beam path which allowed for further beam energy tuning or full fragmentation if the extracted beam energy is below 1.5 GeV/n.

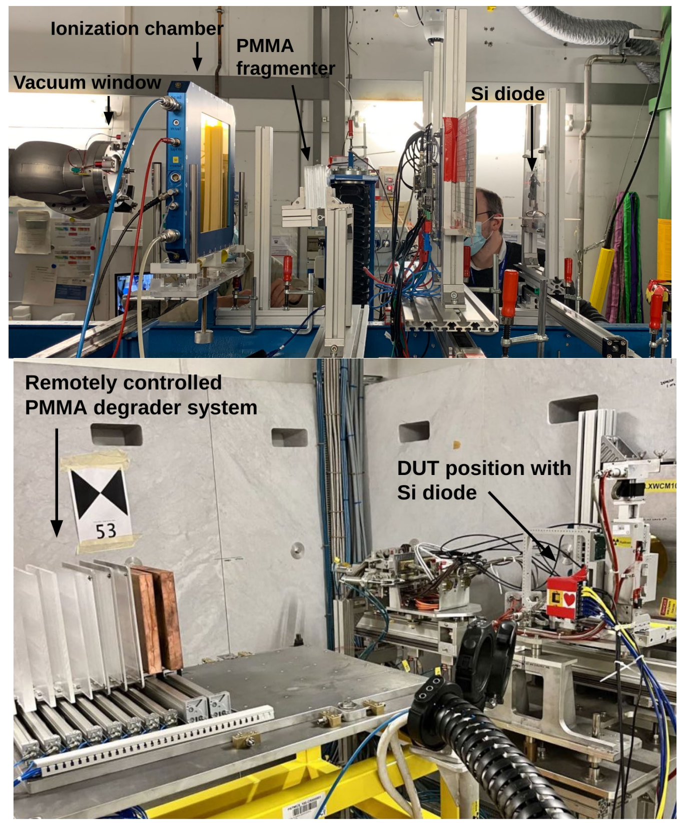

Fig. 3. Irradiation facilities where the experiments took place: Cave A in GSI (top) and the CHARM facility at CERN (bottom).

B. Experimental Solid-State Detector Setups

In this study, two different 300-μm silicon diodes were used to experimentally obtain the energy deposition spectra. As already discussed in [3], the deposited energy of each event was calculated as the integral of the measured diode current $I(t)$ over time. At GSI, a Canberra diode with 0.5 cm^2 exposed surface area was used with signal amplification by a Cividec 20 dB preamplifier in series with a 6-dB attenuator. At CERN, the Canberra diode was also used together with a Micrometer Semiconductor Technologies 2 × 2 mm^2 surface area diode with a bias T. For both these setups, calibration at low energies using alpha particles of a few megaelectronvolts is not applicable when extrapolated to very high ion energies. Comparison of measured energy deposition spectra with simulated energy deposition spectra as demonstrated in [15] yields the needed calibration in the VHE range. As detailed in the aforementioned study, the Canberra diode includes a steel casing partially covering the active silicon volume as opposed to the Micron diode which is "bare." When measuring a primary beam at a single, well-defined energy and LET, particles traveling through the case degrade in energy and fragment introducing a secondary energy deposition peak in the measurements. This feature is, however, absent when measuring fully fragmented beams where any effect from the surrounding instrument structure is not observed, both in measurements and simulation. In both cases, the data acquisition was carried out using a 1-GS/s CAEN digitizer (model DT5751), allowing to recording of the analog pulses using the CAEN WaveDump software. This way, the deposited energy for each event could be calculated as an integrated amount of charge given a certain amount of energy required to create an electron–hole pair (generally 3.61 eV/eh in silicon). The histogram of collected energy depositions can be directly compared to simulation results.

III. Simulation Settings and Geometry

In general, simulations are used to extract the beam LET value in a certain test condition as demonstrated for VHE ion beams in [4]. The physical behavior of heavy ions with matter can also be calculated with MC simulations. In light of this study, it is crucial to accurately estimate the resulting particle and LET distribution as a result of fragmentation processes. This information is essential for comparison with experimental results and to perform SEE rate predictions. The general-purpose MC code FLUKA [5], [6] is a suitable tool in this regard, regularly used in accelerator environments and extensively benchmarked on a microscopic level. In the customized simulation parameters, full ion transport was enabled. This included models for spallation processes such as fission and fragmentation, which can occur due to inelastic interactions of the primary beam with any material it encounters [17], [18]. FLUKA's heavy-ion transport and interactions have been thoroughly benchmarked against experimental data within the VHE energy range [19], [20], [21], [22]. FLUKA handles the nucleus–nucleus collisions in the VHE ion range using a significantly modified Relativistic Quantum Molecular Dynamics Model (RQMD) [11], [12], [13]. The subsequent fragment de-excitation processes (evaporation, fission, and Fermi break-up) are carried out by the cascade-preequilibrium PEANUT event generator [23]. Electromagnetic sector processes, which are computationally intensive, were activated down to 150 keV for accurate energy deposition simulation in the diode active layer. All calculated physical quantities were obtained through event-by-event energy deposition recording in material regions

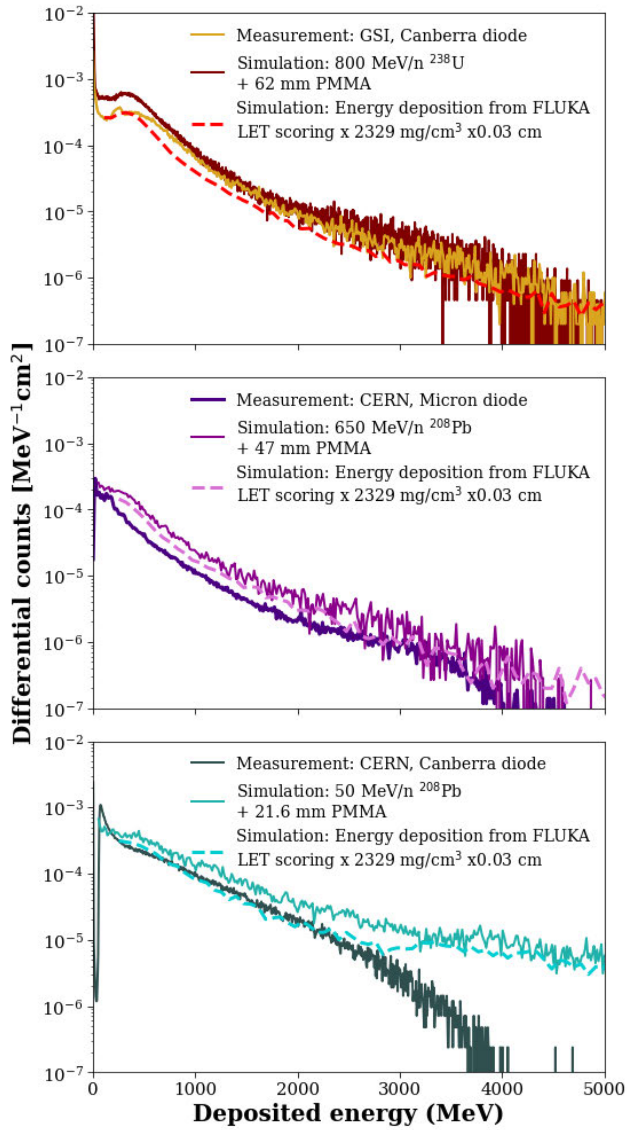

Fig. 4. Comparison of fragmented beam energy deposition spectra, comparing Si diode measurements with energy deposition scoring in FLUKA. In addition, a first-order approximation to the energy deposition spectrum is made by multiplying the LET spectrum by the density of silicon (2329 mg/cm^3) and the active layer thickness (0.03 cm).

and double-differential particle yields at region borders within the model.

As mentioned above, the beam transport through the T08 transfer line at CERN was carried out using FLUKA simulations, yielding the resulting beam characteristics at the DUT position in the CHARM facility where the tests were carried out [15], [16]. For example, this entails that a beam extracted at 1 GeV/n from the PS arrives in CHARM with on average 660 MeV/n left at the detector position with an FWHM spread of roughly 10 MeV/n.

IV. Dosimetry of Fragmented Beams Through Comparison of Measurements and Simulations

If an adequate combination of beam particle, energy, target material, and thickness is chosen, a continuous LET spectrum can be obtained. This was demonstrated at GSI with uranium ion beams and showed an excellent agreement to simulation

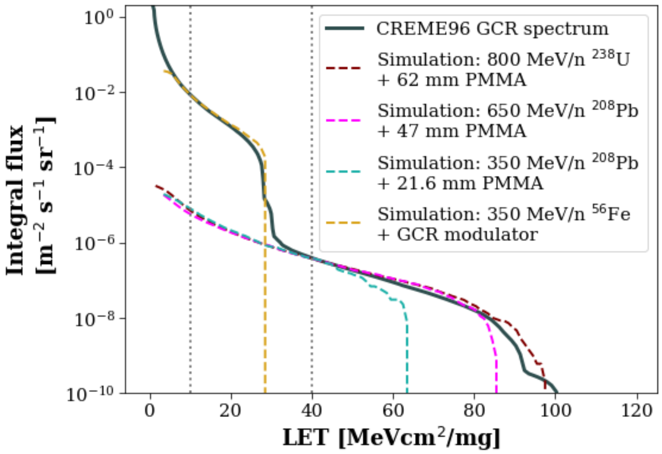

Fig. 5. Comparison of fragmented beam LET spectra at both GSI and CERN with the CREME96 GCR reverse integral flux, all normalized to the integral flux above 40 MeV·cm^2/mg, except the ^{56}Fe spectrum which was normalized to the integral flux above 10 MeV·cm^2/mg.

TABLE II
FLUKA Simulated Quantities for a 1-GeV/n Pb in a Si Target

Depth in Si [cm]	Dose per primary fluence [10^{-6} Gy cm^{-2}]	RMSE fit to GCR [10^{-8}]	Fluence above 40 MeVcm^2/mg [cm^{-2}]
4.00	0.64	/	0.000
5.00	1.43	79.7	0.467
5.09	0.30	8.22	0.035
5.17	0.17	5.29	0.012
5.21	0.15	4.44	0.009
5.27	0.13	3.75	0.006
5.40	0.10	2.59	0.004

results, as can be seen at the top of Fig. 4 when both measurements and simulations are normalized by bin width and unit primary fluence. Based on T08 beamline transport calculations in FLUKA and preceding experimental work, a combination of 1-GeV/n extracted energy (660 MeV/n at DUT) Pb beam and 47 mm of PMMA degrader was chosen to validate the approach at CERN. The resulting spectrum is shown at the center of Fig. 4 yielding an agreement within a factor of 2 between measurement and simulation. Possible explanations for this discrepancy could be a not fully accurate recording of the fluence during the measurement period (method described in [16]), MC simulation-related systematic errors, or measurement uncertainties by the diode. At the bottom of Fig. 4, the results from another attempt are shown using a beam extracted from the PS at 750 MeV/n and arriving at the DUT with an energy of 350 MeV/n. As can be noted, the agreement is fair for deposited energies up to 3 GeV. In this particular case, the discrepancy can be attributed to the combined uncertainty of the beam energy at the DUT position and the cumulative degrader thickness. In all cases, the particle LET spectrum was extracted from the same FLUKA simulation. In Fig. 5, the spectra are compared in reverse integral form to the CREME96 GCR spectrum obtained through the online CREME tool [24] using all ions up to $Z = 92$ with energies above 0.1 MeV/n, a near-Earth interplanetary orbit, solar minimum conditions, and 2.54 mm of aluminum shielding. As discussed in [3], the similarity of the resulting LET spectra with that of GCRs in the space environment is a useful advantage for testing purposes. When normalized to the fluence above 40 MeV·cm^2/mg, both the fragmented 800 MeV/n U beam at GSI, as well as the fragmented 650-MeV/n Pb beam at CERN show very close similarity to the GCR spectrum with very similar RMSE (root mean squared error) scores between the data points. However, the fragmented 350-MeV/n Pb shows much less agreement with the LET spectrum falling off sharply at 60 MeV·cm^2/mg. It is to be noted that in each facility, the beam delivery method was different: a raster scanned Gaussian beam of 7–8 cm FWHM over an area of 2 × 2 cm^2 at GSI compared to a 10-cm FWHM broad, Gaussian beam at CERN. When comparing measurements and simulations, it is more straightforward to compare raster scanned beam areas due to their homogeneity, the broad Gaussian beam profile at CERN brings an extra challenge due to the lower uniformity of the beam at the test position. As can be seen in Fig. 5, only the high LET GCR integral flux spectrum above 30 MeV·cm^2/mg can be properly replicated in a laboratory setting. As part of this study, it was investigated if the spectrum below 30 MeV·cm^2/mg can be matched in a similar fashion using a lighter ion such as iron. This is an appropriate choice given the important contribution Fe ions have to the dose in the free space GCR environment [25]. The hybrid active–passive GCR simulator at GSI uses a set of monoenergetic Fe beams between 100 s of MeV/n and 1 GeV/n with passive targets to fully replicate the GCR spectrum in terms of both composition and individual particle fluences [26]. This level of detail is generally not required for electronics testing purposes and as with the heavier ions, it is expected that a single ion with a well-chosen fragmenter material can generate an appropriate LET spectrum. A dedicated FLUKA simulation model of Cave A featuring a 350-MeV/n Fe ion beam and its tailored passive modulator was used to generate the LET spectrum shown in Fig. 5 which matches the GCR spectrum extracted from CREME96 very well. Pending experimental verification, this shows that a combination of light and heavy ions each with a dedicated fragmenter can in principle fully reproduce the GCR LET spectrum in a high-energy accelerator laboratory environment, taking into account the proper scaling by fluence of the two components. It is to be noted that each of the two configurations has its own purpose: the low-LET spectrum using an intermediate, Fe-like ions can be used to predict in-orbit SEE rates in an accelerated fashion by scaling the fluence to the expected fluence during spaceflight; the high-LET spectrum using heavy, Pb-like ions is rather used for radiation hardness assurance applications.

V. Detailed Simulations of Fragmented Beams

As shown in Section IV, the fully fragmented beam configuration needs to be chosen with care and its success is subject to the precise definition of particle fluence, beam energy, and degrader thickness. To obtain a more in-depth analysis of the interaction of fully fragmented VHE ion beams with electronic components, a dedicated FLUKA MC simulation study was carried out by launching a Pb beam onto

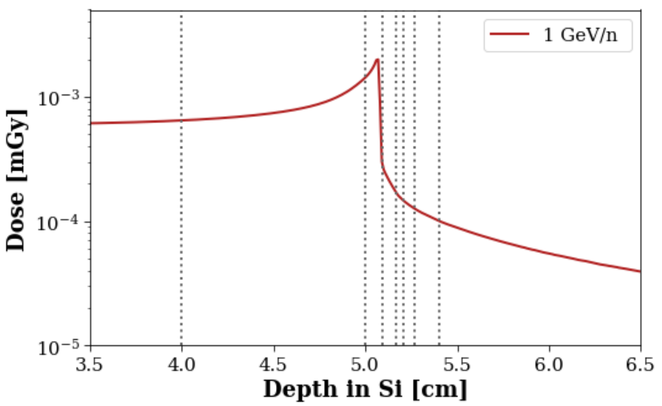

Fig. 6. Bragg peak of a 1-GeV/n Pb ion beam in a Si target extracted from FLUKA.

a silicon target. The simulation settings are identical to those used for the dosimetry comparison between measurement and simulation described above, except for using a much more simple geometry (only a long Si target), a uniform 1×1 cm^2 beam, and requesting more detailed output of simulated physical quantities. The goal of the obtained particle spectra as a function of depth in Si is to check if an optimal working point can be found that satisfies the following performance indicators.

1) A good fit to the GCR spectrum as shown previously for the GSI and CERN fragmented beam dosimetry cases.
2) An optimization of the fluence per primary particle above 40 MeV·cm^2/mg.
3) A minimization of the TID which was identified as a potential limitation of this approach in [3].

Fig. 6 shows the characteristic Bragg peak profile for a 1-GeV/n Pb ion beam in a silicon target, extracted from the FLUKA simulation by calculating energy deposition as a function of depth. The plot indicates the scoring planes for which the LET and atomic number distribution are detailed in Fig. 7. These indicate the evolution of the radiation field as a function of depth within the material and allow us to indicate at which depth a fully fragmented field is present. For each of the depths indicated, the dose, fluence above 40 MeV·cm^2/mg and fit to the GCR spectrum is detailed in Table II. The dose and fluence values are expressed per unit of primary fluence. According to FLUKA, the Bragg peak itself is situated between 5.0 and 5.1 cm in depth where also the highest doses are encountered. The atomic number distribution no longer shows any particles with $Z = 82$ at a depth of 5.09 cm, indicating that all primary particles either ranged out or underwent an inelastic interaction, yielding a distribution of exclusively secondary fragments. The dose at this depth and the subsequent ones would be on the order of Gy or 10 s of Gy when taking into account standard radiation effects testing primary fluences between 10^7 and 10^8 cm^{-2}. Over the range of nearly 3 mm between just beyond the Bragg peak and 5.4 cm, the fluence above 40 MeV·cm^2/mg drops an order of magnitude to 10^{-3} cm^{-2}. At increasing depths, the fit to the CREME96 GCR spectrum becomes better as shown by the decreasing errors. Nevertheless, maximizing

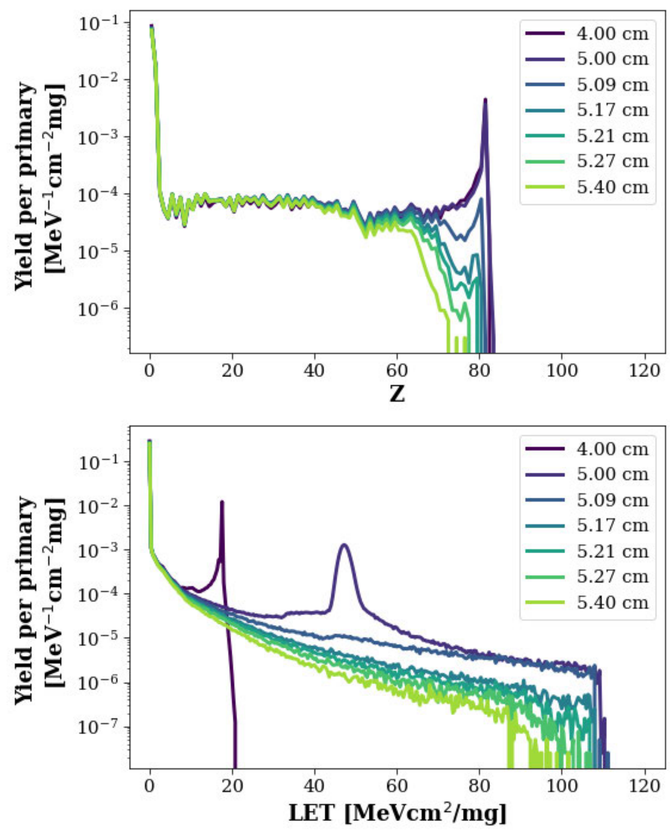

Fig. 7. FLUKA simulation results of the LET distribution (top) and atomic number distribution as a function of depth in Si material.

the fluence above 40 MeV·cm^2/mg and minimizing the dose remain far more important performance indicators for testing using this approach. Based on the values presented here, a test configuration just beyond the Bragg peak is the most desirable.

VI. Conclusion

This article explores the first attempts at dosimetry of fully fragmented VHE ion beams targeting electronics testing, using a combination of MC simulations and silicon diode measurements. Full replication of the GCR LET spectrum is technically feasible through the combination of an intermediate-mass, Fe-like ion, and a heavy, Pb-like ion beam each with a dedicated fragmenter. The challenges for implementing this approach were highlighted, including optimizing the configuration of beam energy and fragmenter material and an accurate fluence determination at VHE heavy-ion facilities. In this study, an in-depth simulation was carried out which details the physical basis of interaction between fragmented beams and a silicon target. This input can be used to optimize the SEE testing approach in terms of expected fragmented beam fluences and TID levels.

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