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HEAVY ION BEAM CHARACTERIZATION FOR RADIATION EFFECTS TESTING AT CERN USING MONTE CARLO SIMULATIONS AND EXPERIMENTAL BENCHMARKING

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Abstract

The CHIMERA† (up to December 2022) and HEARTS‡ (as of January 2023) projects aim to facilitate radiation effects testing of electronics components using heavy ion beams before deployment in harsh radiation environments such as space or high energy accelerators. The required (micro-) electronics reliability assurance testing conditions can be met by using 100 MeV/n - 5 GeV/n Pb ion beams extracted from CERN's Proton Synchrotron (PS) which have a surface Linear Energy Transfer (LET) range of 10-40 MeV cm^2/mg, >1 mm penetration depth in silicon and several cm FWHM beam size. This paper gathers the results from Monte Carlo simulations in FLUKA which were used to understand the transport of ions through the T08 transfer line in the PS East Area, focusing on key effects such as energy straggling, loss of transmission (e.g. through scattering and nuclear fragmentation) and beam size. These calculations served as input for machine development activities and allow us to characterize the radiation field at the testing location, in present and future experimental configurations. The simulation results are compared to instrumentation data obtained during an experimental campaign in November 2022. Potential future upgrades and developments are also discussed.

RADIATION EFFECTS TESTING WITH VHE IONS AT CERN

The radiation effects testing community have an increasing interest in Very High Energy (VHE, 100 MeV/u - 5 GeV/u), heavy ion beams. These particles are part of the continuous flux of Galactic Cosmic Rays (GCR) in space, but they are also present in accelerator radiation environments. Radiation Hardness Assurance (RHA) of electronic components with VHE ion beams is particularly useful due to their ability to combine high LET with a high penetration depth in silicon, allowing to test increasingly complex or multi-layered devices with micro or even nanometer-sized subcomponents. The CHIMERA (CHARM Heavy Ions for Micro-Electronics Reliability Assurance) activity is charged with studying the feasibility of performing VHE ion testing by exploiting and optimizing the present infrastructure at CERN. The activity received support from the European Space Agency (ESA) to demonstrate the provision of key testing conditions; an important milestone was the November 2022 experimental campaign fully dedicated to operating, characterizing and using the ion beams available at CERN. The activities at CERN will continue from 2023 onward as part of HEARTS (High Energy Accelerators for Radiation Testing and Shielding), a Horizon Europe project funded by the European Commission with the goal of facilitating routine access for research and industrial users, after having achieved the necessary technical and procedural readiness level. Taking benefit from the long-established LHC ion physics programme [1, 2], lead ion (Z=82, A=208) beams are available in CERN's accelerator complex for exploitation. Acceleration to energies to achieve a >1 mm range in electronics (between 100 MeV/u and 1 GeV/u) requires only part of the LHC injector chain: ion beams are extracted from the PS into the East Area experiment hall, propagated through the T08 beam line down to CHARM (CERN High Energy Accelerator Mixed-field), a facility designed as a radiation effects test station. [3]. The main focus of the heavy ion activity at CERN can be summarized in three major points:

- Tune the ion energy in the "high LET variability" range which is between 70 MeV/n and 2 GeV/n. This can be achieved by choosing the extraction energy from the PS, and/or using a degrader system.
- Tune the ion flux in a large dynamic range with ±10% uncertainty (10^2 - 10^5 ions/cm^2/s for each spill) as dictated by SEE testing standards at lower energies [4]. Different PS extraction techniques can be used[5, 6].
- Tune the beam size for board level testing up to ~ 20 x 20 cm^2, achieved by optimisation of the beam line optics.

Adjustments are needed both in CHARM and the beam line to render the infrastructure suitable for testing using high-energy, high-penetration ions. This will also involve beam characterization activities and radiation effects validation experiments. In addition, an operation mode that is compatible with CERN's physics programme, the other users of the PS, East Area and T08 beam line must be achieved.

MONTE CARLO SIMULATION SETUP IN FLUKA

An essential ingredient in this task is the use of simulations. They are a decisive tool when it comes to providing a more fundamental and in-depth description of the beam

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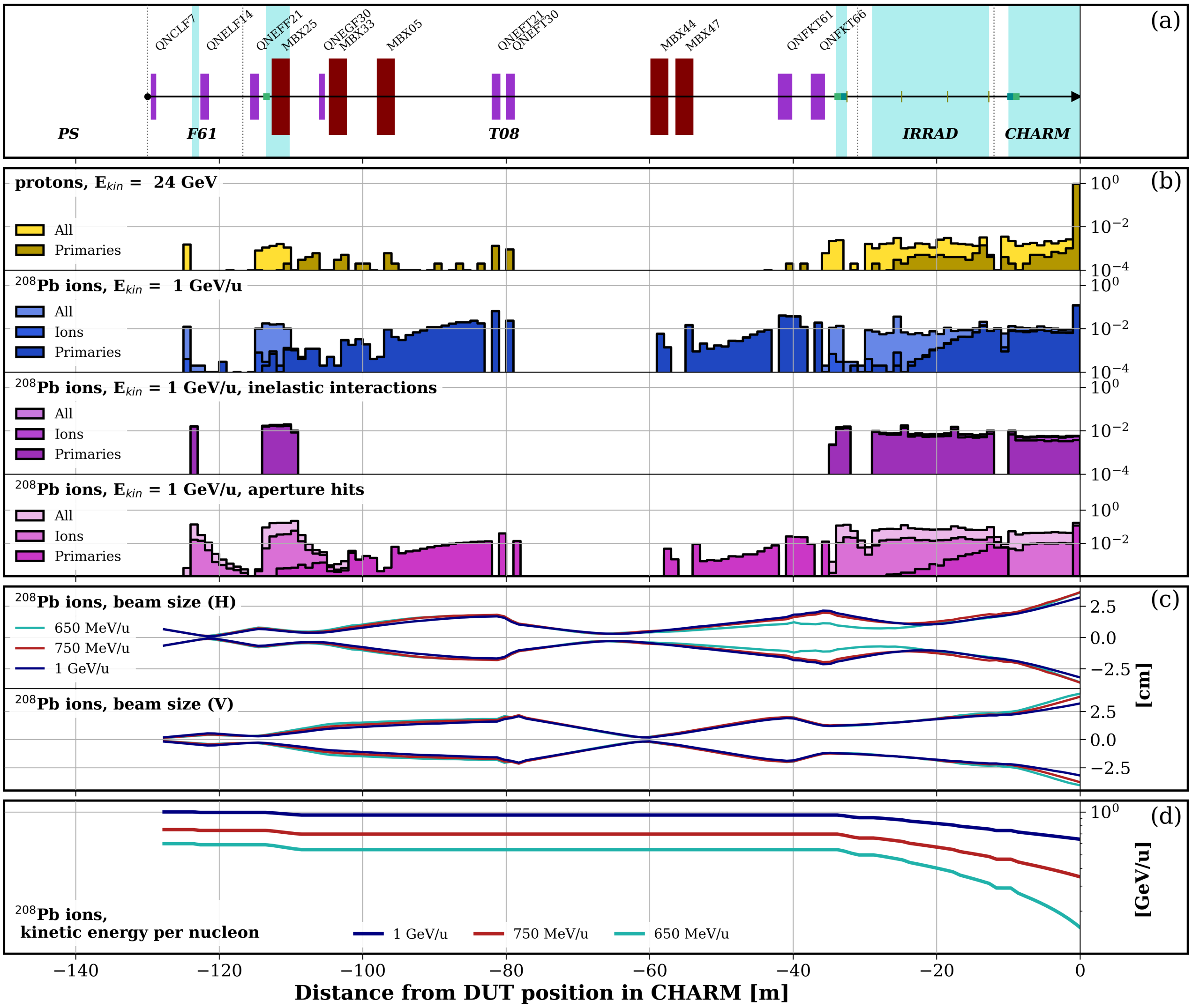

Figure 1: Summary plot of the simulation results described in this study. In (a) the beam line schematic is shown, including the dipole (brown) and quadrupole (purple) magnetic elements and air regions (cyan). In-beam instrumentation units are overlaid on the beam path (black arrow) as grey squares or lines. In (b), the longitudinal profiles are shown for respectively proton losses, 1 GeV/u Pb ion losses, their inelastic interactions and aperture hits with a 1 m spatial resolution. The distinction is made between contributions from all particles, only ions and only primary beam particles. Beam sizes in the horizontal (H) and vertical (V) transverse planes for 1 GeV/u, 750 MeV/u and 650 MeV/u Pb ions are shown in (c). For each of these energies also the kinetic energy per nucleon as function of distance from the test location is shown in (d).

and radiation environment and also allow to run multiple configurations and related optimizations in parallel; both of which are often not available experimentally. The general purpose Monte Carlo code FLUKA [7, 8] is a most suitable tool, regularly used in accelerator environments and extensively benchmarked on a microscopic level [9–11]. The simulations carried out in this study are focused on the first and third objective bullet at the end of the previous section.

Geometric Model of the T08 Beam Line

The beam characteristics under study are heavily affected by interactions with the transfer line infrastructure, including interceptive beam instrumentation (such as secondary emission chambers and the Beam Profile Monitors (BPM) in the IRRAD facility [12]), windows and sections in air; all this requires the simulation model to be as realistic and accurate as possible. The geometry was constructed using the LineBuilder python code [13], relying on chosen optics settings, dimensions from technical drawings and in-person inspections. The resulting model spans ~ 140 m from the PS extraction point to the chosen device-under-test (DUT) position located in the CHARM facility. The beam traverses the correct material budget in terms of composition, density and thickness (precision down to 100 μm) for all non-vacuum elements described above. Magnetic field strengths are implemented for the correct transport of heavy ions, corresponding to the rigidity of fully-stripped Pb^{82+} beams. A schematic of the geometry is shown in Fig. 1a.

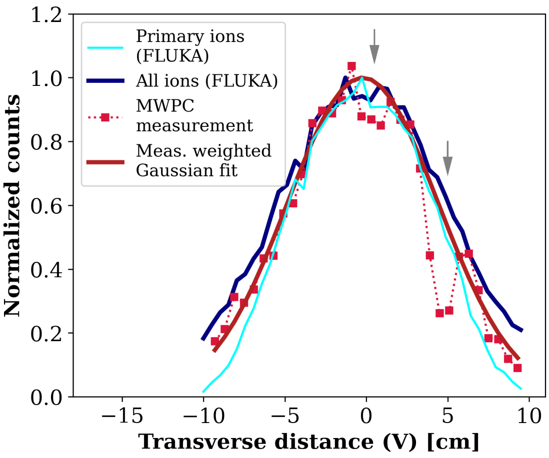

Figure 2: Comparison between the FLUKA simulated beam sizes for primary ions only (cyan), all ions (navy), and measurement data from the MWPC (red squares). A weighted Gaussian fit of the data takes into account instruments and support frames in the ”view” of the MWPC (arrows).

Simulation and Physics Settings

The user-defined settings in FLUKA were chosen as a compromise between accuracy and simulation time: full transport of heavy ions (no biasing) and hadronic secondaries down to 1 keV was requested, electromagnetic particles were dumped on the spot to save computational resources. As particle source, either a pencil beam (point source and fixed momentum) or a realistic distribution based on measurements was used (in this study only for beam size calculations). Simulation data was extracted using 1) ”lossmaps”, longitudinal profiles of locations where the particles either fall below the transport threshold, hit the aperture restriction or escape the geometry, 2) by tracking particles when they cross from one geometrical region to the next or 3) specifically requesting a certain type of interaction, e.g. inelastic collisions. In all cases, information such as particle type, position, direction and total energy is recorded.

SIMULATION RESULTS

Longitudinal loss profiles along the beam line are shown in Fig. 1b, including for reference the 24 GeV/c protons map. The profile for Pb ions at 1 GeV/u is representative for other (lower) energies of interest for testing. The inelastic interaction map reveals that locations of high losses are associated to non-vacuum regions, i.e. the air sections delimited by vacuum windows and beam instrumentation devices. Selecting out only the locations of particles hitting the aperture reveals the impact of particle (Coulomb) scattering, primarily happening in non-vacuum regions and in regions of higher dispersion directly downstream of the bending dipoles (e.g. between -100 and -80 m). As function of particle type and energy, we can define the transmission probability as the simulated amount of particles reaching the DUT position per primary particle simulated (expressed as a percentage). This quantity is 93% for 24 GeV/c protons but is only 12% for 1 GeV/u Pb ions and decreasing for lower energies. The horizontal (H) and vertical (V) transverse beam profiles are shown in Fig. 1c for three representative extracted ion energies: 1 GeV/u, 750 MeV/u and 650 MeV/u. In both planes, the resulting Gaussian beam size at the DUT position is very similar for all three energies between 7 and 10 cm FWHM, starting from a Gaussian distribution sourced in the PS. The bottom profile Fig. 1d shows the energy straggling along the beam line. Electronic stopping power (dE/dx) in non-vacuum sections causes the primary beam energy to significantly diminish before reaching the CHARM. E.g. a Pb beam extracted at 1 GeV/u kinetic energy arrives at the DUT position with 750 MeV/u left. This also puts a lower limit on the extracted beam energy that can be transported to the test location.

COMPARISON TO EXPERIMENTAL DATA

In 2022, a series of experimental campaigns was carried out in the form of one-day machine development sessions and a 5-day dedicated heavy ion run. Gathered data from the present beam instrumentation devices allowed to cross-check measurements with simulation findings. As an example for a 750 MeV/u Pb ion beam, Fig. 2 shows the comparison between the calculated beam size in the vertical plane from FLUKA and measurements made using the MultiWire Proportional Chamber (MWPC), located directly downstream of the test location. The measurement data, which cannot distinguish between primary beam particles or secondaries, correspond very well to the simulated profiles, both when considering only primary ions as when taking into account all generated ion fragments along the beam path. This conclusion could be made throughout the experimental campaign, it was also verified using data taken over the course of the experimental run that the beam size remains very similar, independent of the extracted beam energy.

CONCLUSION AND OUTLOOK

This study shows the merit of using Monte Carlo simulations as a decisive tool in beam line development. Direct comparison of simulation results with experimental data showed a good agreement. The created geometrical model and simulation workflow can be readily adapted to future needs when further optimizations are required. This can include changes of the optics settings to manipulate the beam size, addition of magnetic elements or beam-intercepting devices (beam degraders and masks) and possible additions of vacuum systems to reduce the amount of air the beam travels through. As shown, the beam energy is degraded significantly at the DUT position and this quantification is indispensible when making an estimate of the LET at the testing location. The transfer line calculations will also prove useful to further characterize the radiation field by taking into account secondary particles and fragments which might affect the testing conditions or harm ancillary electronics. Simulation activities will continue within a dedicated Monte Carlo simulation work package of the HEARTS project.

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