European Organization for Nuclear Research
SY-STI-BMI section

FINAL REPORT ON THE CERN 2021 SUMMER STUDENT PROGRAMME

Study of Heavy Ion Fragmentation with the FLUKA Monte Carlo code

Supervisors:
Giuseppe LERNER
Andreas WAETS

Summer Student:
Alexandra - Gabriela ȘERBAN

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1. Introduction

Heavy ion testing is critical for the study of Single Event Effects (SEEs) in electronic devices [1], [2]. In particular, high-Z ions generate SEEs via direct ionisation, due to their high LET (Linear Energy Transfer). These kind of tests for electronic components and systems are done at CHARM (CERN High Energy Accelerator Mixed-field) facility, in the context of the Radiation to Electronics (R2E) project. The baseline operation mode of CHARM is a 24 proton GeV beam from the Proton Synchrotron (PS) on a target, yielding a mixed and distributed radiation field that resembles the accelerator environment. Heavy ion beams are also used at CHARM, the top energy available for the ^{208}Pb ions being around 5.5 - 6 GeV/n. In this case of heavy ion testing, the target is removed and the test devices are exposed directly to the beam. The CHIMERA (Charm High-energy Ions for Micro Electronics Reliability Assurance) project, which includes a collaboration contract between CERN and ESA (European Space Agency), aims at expanding the ion test capabilities at CHARM with the goal of lowering the beam energy in order to reach higher LET values.

2. Project goals

- Study of heavy ion fragmentation as a function of depth in a Silicon target, relevant for heavy ion tests of electronic equipment at the CHARM facility at CERN;
- Investigation of the distribution of atomic number (Z) and Linear Energy Transfer (LET) of heavy ion fragments in Si with the help of Monte Carlo simulations (FLUKA) [3, 4, 5].

3. Monte Carlo simulations: FLUKA

FLUKA is a Monte Carlo (MC) code for particle - matter interaction. It is a simulation tool that samples stochastically the transport and interaction of particles in matter in arbitrary geometries.

The geometry I designed is a cylindrical Silicon target, as shown in figure 1, representing characteristic material of the active region of electronic devices. It has a total depth of 15 cm in order to allow the study of fragmentation effects up to a large thickness. There are also many regions divided by planes in order to study the fragments at different depths.

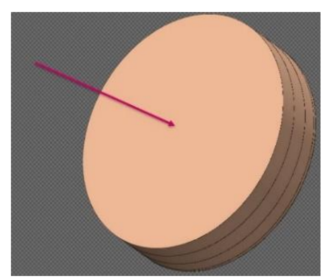


Figure 1: Cylindrical Silicon target.

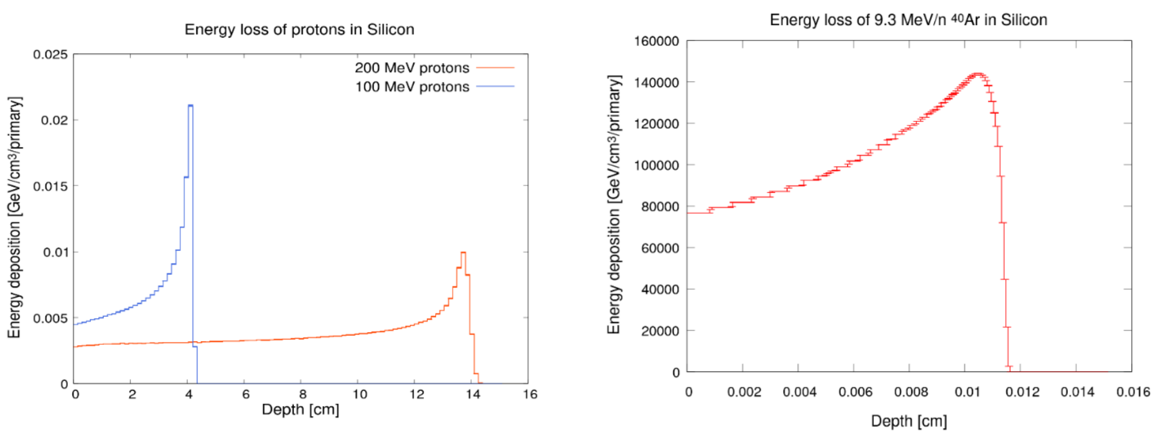
We considerd pencil-like beams of protons, ^{40}Ar and ^{208}Pb, starting at the origin and impacting the target on the z direction.

4. FLUKA simulations results

The preliminary step of the study was to analyze the ionization losses in Silicon, namely the Bragg peak which is obtained at a variable depth depending on the energy and the particle type. When analyzing fragmentation, it is important to keep in mind that ionisation losses are also taking place and the position of the Bragg peak of the projectiles which gives the range of the particles is a key parameter.

Figure 2.a shows the energy loss in the case of two beams of protons having different energies and what we observe is that the higher the energy, the higher the range of protons inside the Silicon target. Figure 2.b shows a different species of particles, namely an Argon ion beam having the energy of 9.3 MeV/n. If in the case of protons the range inside the Silicon target was of the order of cm, in the case of Argon it is of the order of µm, the Bragg peak being situated close to 100 µm.

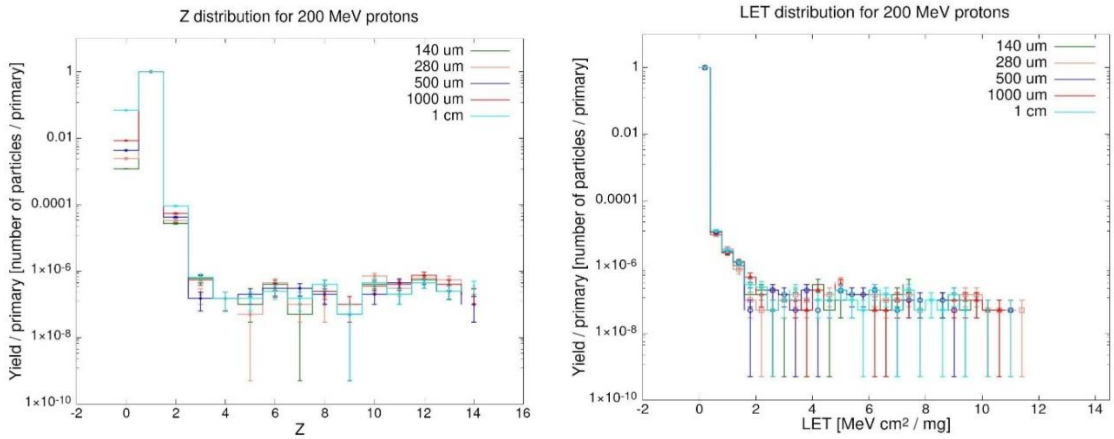
This kind of analysis is very important when studying heavy ion fragmentation since it gives the range of the particles in the considered material and it allows us to look at the precise scale of interest.



(a) (b)

Figure 2: Energy loss in Silicon for (a) protons and (b) 9.3 MeV/n ^{40}Ar

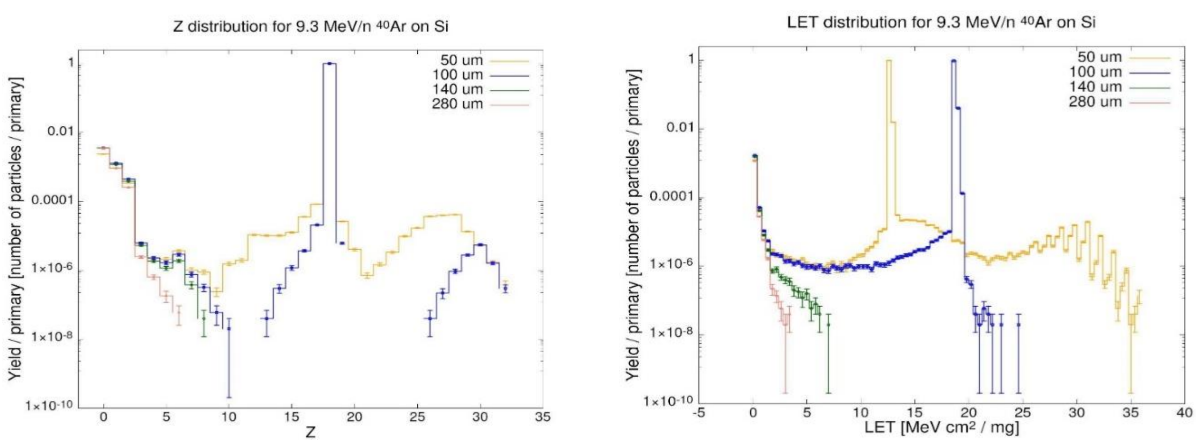
The first simple check for the distributions of Z and LET was done in the case of a 200 MeV proton beam. In the Z distribution, shown in figure 3.a, we observe a large peak for Z = 1 which corresponds to protons and it shows that they are dominant regardless of the depth in the target. The fragments with different Z emerge as a result of nuclear reactions in the target and they have similar distributions at all depths, with a significant build-up effect at Z = 0 (neutrons) and a milder build-up effect for Z = 2 (alpha particles). Moreover, we note that the maximum value of Z is 14, corresponding to Si recoil nuclei. We examine the LET distribution, from figure 3.b, at different depths, similarly to what we have done in the case of the Z distribution. High-LET corresponds to ions with $4 < Z < 14$ having very low energies and thus, very low range. Hence, these ions stop almost immediately, preventing any build-up from happening. However, the vast majority of particles have low LET.



(a) (b)

Figure 3: (a) Z and (b) LET distributions of 200 MeV protons on Silicon.

The case of the 9.3 MeV/n ^{40}Ar beam represents the first check with heavy ions. Contrarily to the case of the proton beam, in the case of Argon, some planes in the depth of the target are before and others are after the Bragg peak. From the Z distribution in figure 4.a, we see that there is a large number of fragments with high Z at 50 µm and a bit less at 100 µm. At these two depths we observe a large peak corresponding to the Z of ^{40}Ar, while beyond the Bragg peak there are only low-Z fragments left. For the LET distribution, shown in figure 4.b, before the Bragg peak at 50 µm there is a high peak for the LET of ^{40}Ar together with a high-LET tail that consists of ionizing high Z fragments. Almost on the Bragg peak, at 100 µm, we see a shifted ^{40}Ar LET peak and a much smaller high-LET tail, while after the Bragg peak, at 140 µm and 280 µm, we observe that there are only low-LET fragments.



(a) (b)

Figure 4: (a) Z and (b) LET distributions for 9.3 MeV/n ^{40}Ar on Silicon.

The next step was to analyze different energies of ^{208}Pb ions that are specifically relevant for Radiation to Electronics (R2E) tests at the CHARM facility, particularly in the context of the CHIMERA upgrade.

From the plots of the energy loss in the Silicon target covering a wide range of energies for the ^{208}Pb beam, shown in figures 5, we observe that higher ^{208}Pb energies correspond to relatively lower LETs and higher ranges in the target. Moreover, we note that for the highest energy considered in our study, 5.5 GeV/n, the energy loss vs. depth does not show any more the characteristic Bragg peak, as the majority of the primary ^{208}Pb ions undergo nuclear reactions before stopping. Only for this case we extended the length of the target up to 50 cm.

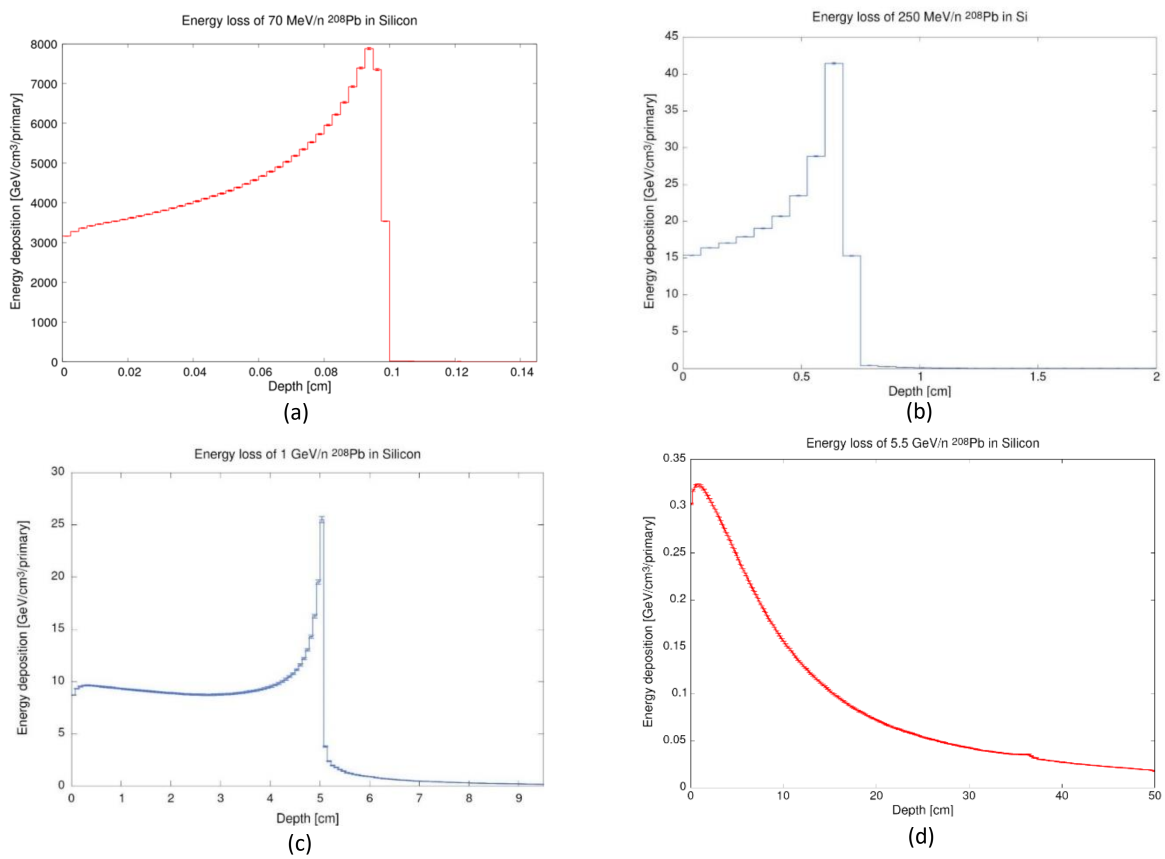
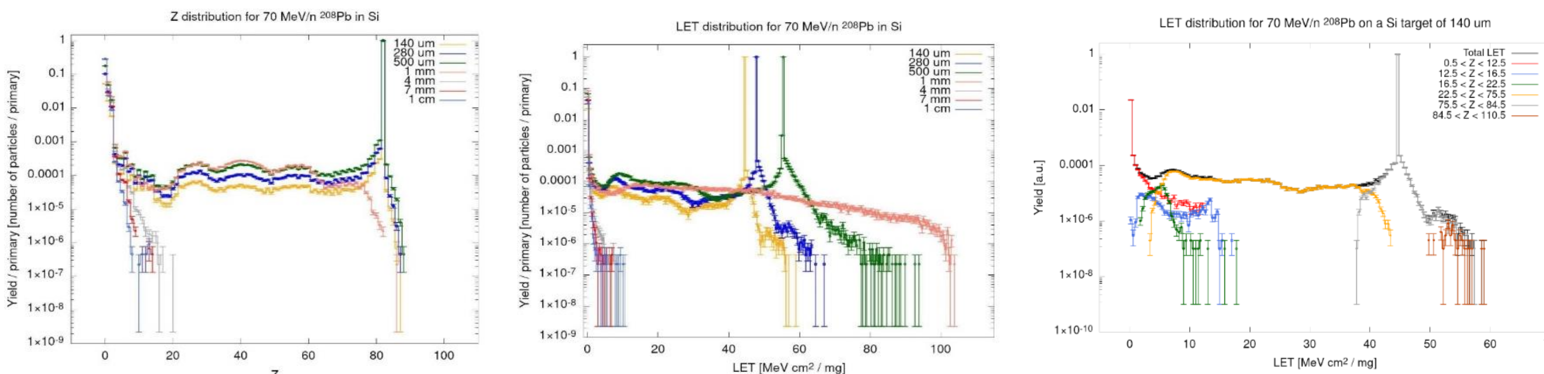


Figure 5: Energy loss of (a) 70 MeV/n, (b) 250 MeV/n, (c) 1 GeV/n and (d) 5.5 GeV/n ^{208}Pb in Silicon.

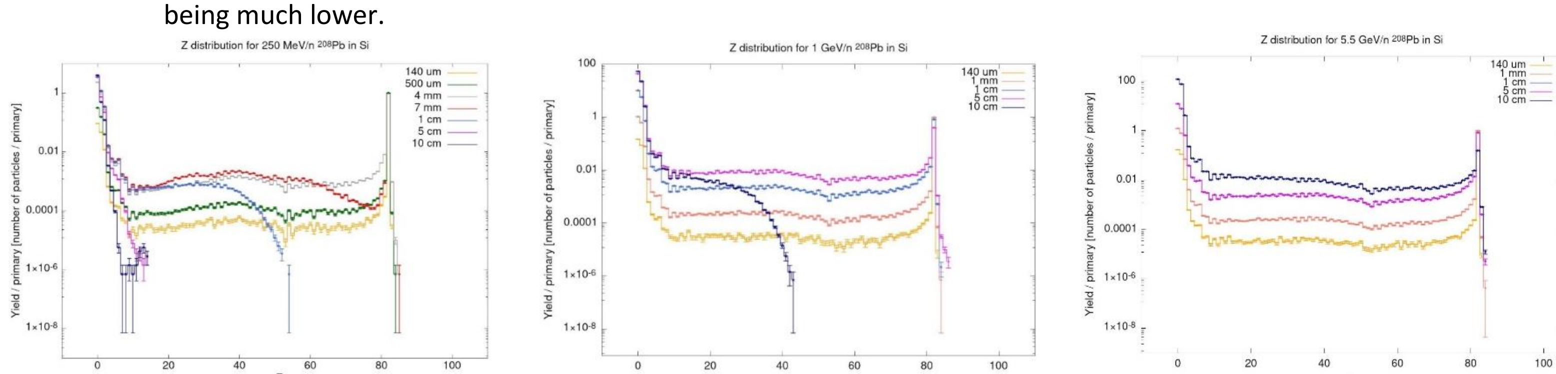
The first energy considered for the ^{208}Pb beam is 70 MeV/n. The Z distribution from figure 6.a covers planes before as well as after the Bragg peak. We observe that the distributions before the Bragg peak are very similar to each other. The plot shows a high peak corresponding to Z = 82 which is that of ^{208}Pb and only low-Z fragments after the Bragg peak. Similar distributions before the Bragg peak with a large peak corresponding to ^{208}Pb shifted for each depth are also visible for the LET distribution, in figure 6.b. At 1 mm we clearly see there is no ^{208}Pb peak, but there are many fragments with very high LET (slow high-Z ions). At 4 mm, 7 mm and 1 cm there are only low-LET fragments left. For the specific case of 70 MeV/n ^{208}Pb ions, and for a depth of 140 µm, we studied the breakdown of the LET distribution for fragments with different Z ranges (see figure 6.c). We were able to identify the target-like products for Z between 12.5 and 16.5 and for Z between 75.5 and 84.5 the projectile-like fragments. We were also able to confirm that high Z particles typically have high LET.



(a) (b) (c)

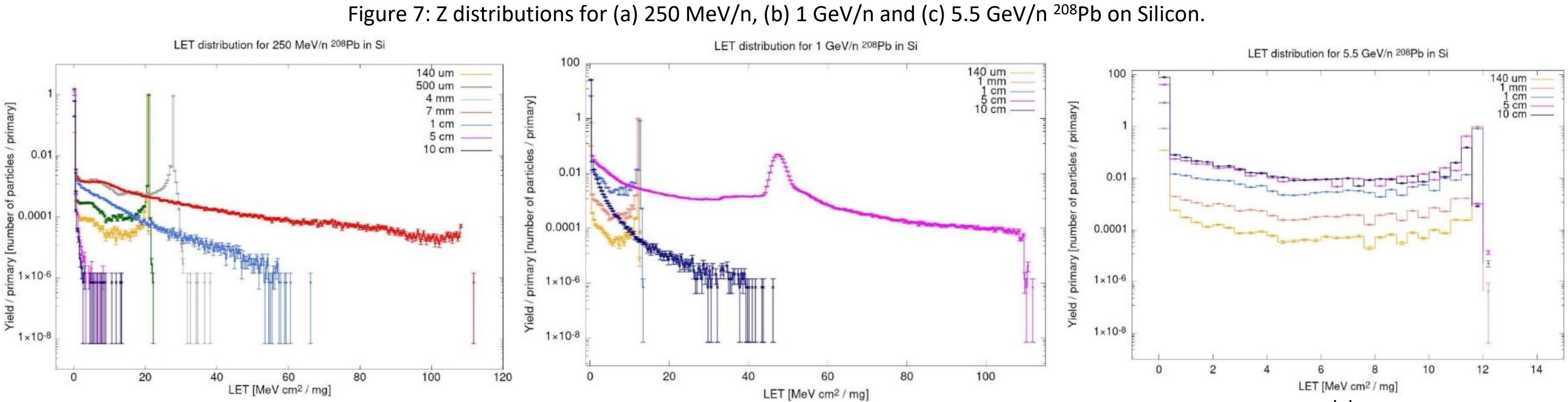
Figure 6: (a) Z, (b) LET distribution and (c) LET distribution for fragments with different Z ranges for 70 MeV/n ^{208}Pb on Silicon.

In the case of the 250 MeV/n and 1 GeV/n ^{208}Pb beams, we observe fragments with very large LETs (up to more than 100 MeV·cm^2/mg) at specific depths, that are absent at other depths. This is very relevant for R2E tests because if test devices are placed exactly at one of these depths, the observed LET distribution would be very different compared to the LET of the primary ion beam. The effect seen in the distributions for these two energies is absent in the case of the 5.5 GeV/n ^{208}Pb beam, the maximum LET being much lower.



(a) (b) (c)

Figure 7: Z distributions for (a) 250 MeV/n, (b) 1 GeV/n and (c) 5.5 GeV/n ^{208}Pb on Silicon.



(a) (b) (c)

Figure 8: LET distributions for (a) 250 MeV/n, (b) 1 GeV/n and (c) 5.5 GeV/n ^{208}Pb on Silicon.

5. Conclusions

In the first part of my internship I set up FLUKA simulations to study the fragmentation products resulting from the interaction of protons (of 100 MeV and 200 MeV) and ^{40}Ar ions (of 9.3 MeV/n) with a Silicon target, focusing on the distributions of Z and LET at different depths.

The study was repeated in the case of a ^{208}Pb beam covering a wide range of energies, relevant for Radiation to Electronics (R2E) tests at the CHARM facility, particularly in the context of the CHIMERA upgrade.

From the ionization losses studies, we observed that the higher the energy, the deeper the projectile particles go inside the target. We also noted that at very high energies the energy loss pattern is different since the ionisation range increases, therefore a large number of nuclear reactions take place inside the target, with fragmentation processes becoming the dominant loss mechanism.

From the disentanglement of the contributions of different Z fragments we were able to confirm that high Z fragments have high LET and also we identified the target-like and projectile-like products.

6. References

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