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FINAL REPORT ON THE START PROGRAMME

*Determination of energy deposition
and fluence in a single layer graphene
sample.*

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Abstract

This report details a simulation study conducted to determine the energy deposition and particle fluence on a single-layer graphene sample within the Long-Term Exposure (LTE) station at the NICA accelerator complex. Using the FLUKA Monte Carlo toolkit, the experiment simulated a beam of 3.8 GeV/nucleon ^{131}Xe ions, replicating the conditions of the LTE station located behind the BM@N detector. The geometry included two ionization chambers filled with air and a one-atom-thick graphene sample. The simulation tracked 50,000 primary particles to calculate fluence and absorbed dose.

Results indicate that the ionization chambers each intercepted over 99.6% of the beam fluence, absorbing a dose of approximately 97 GeV. In contrast, the graphene sample, due to its minimal size, intercepted 32.1% of the beam fluence. Despite its nanoscale thickness, the sample absorbed a significant 27 GeV of energy, corresponding to 0.545 MeV per primary particle. Particle track analysis confirmed interactions not only from primary xenon ions but also from secondary particles including protons, electrons, and neutrons. This study successfully characterizes the radiation environment for materials testing at the LTE station, providing crucial baseline data for future experiments on the radiation hardness of novel materials like graphene.

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Introduction

1. The NICA (Nuclotron Ion Collider fAcility), in construction at the Joint Institute of Nuclear Research (JINR) in Dubna, Russian Federation; is an accelerator complex designed to study dense baryonic matter. BM@N is the only detection setup currently working in NICA[1]. Back in 2023 a Long-Term Exposure Station was installed after the BM@N facility for applied research studies and in March, 25th of 2025 the first run of the NICA Accelerator Complex was initiated at Laboratory of High Energy Physics[2].

Literature Review

NICA Complex

NICA complex (figure 1.) the mega-science project , begin its construction in 2013 with the main target of studying the properties of dense baryonic materials. With its upgraded nuclotron (working from 1993) can produce beams up to 4.5GeV for heavy ions and 12.6GeV for protons[3].

The complex will have two main collision points, for heavy ions there is the Multi-Purpose Detector (MPD) and for the polarized beams is the Spin Physics Detector (SPD). MPD and SPD detectors are located at the collider in the complex.

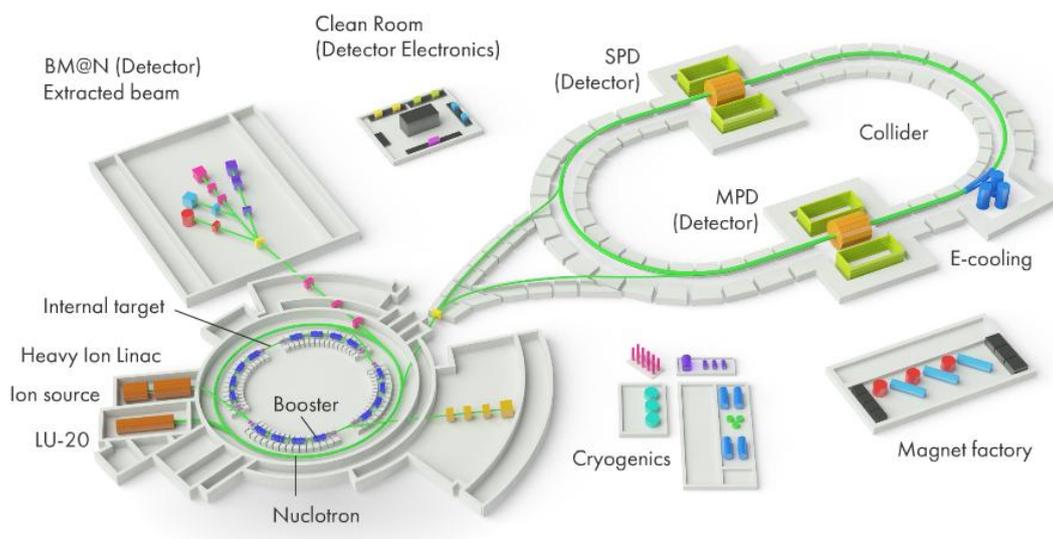


Figure 1. NICA complex scheme[1]

ARIADNA Collaboration

In addition to the fundamental physics research, the complex also dedicates an important part of its effort into development of a group of specialised channels for transporting charged particles beams for applied work. This infrastructure was named ARIADNA (Applied Research Infrastructure for Advanced Developments at NICA fAcility) and starts its construction at 2021[4].

Around the constructed infrastructure, located in the fixed-target hall in NICA, where build multiple collaborations; ARIADNA-LS for applied research of life sciences, ARIADNA-MSTE for radiation materials science and testing of

electronics and ARIADNA-NPT for development of new nuclear energetic technologies[4].

Different experiments are located in the extracted beam building (figure 2). The stations placed, have different objectives; mostly they are used for nuclear and particle physics (ALPOM-2, BM@N, FASA, HyperNIS, Marusya). The MPD, SPD tests and MPT stations are used for measure MPD and SPD detectors parameters. Finally the IS CRA, SIMBO and E&T&RM are used for material, life sciences and production of superconducting magnets[5].

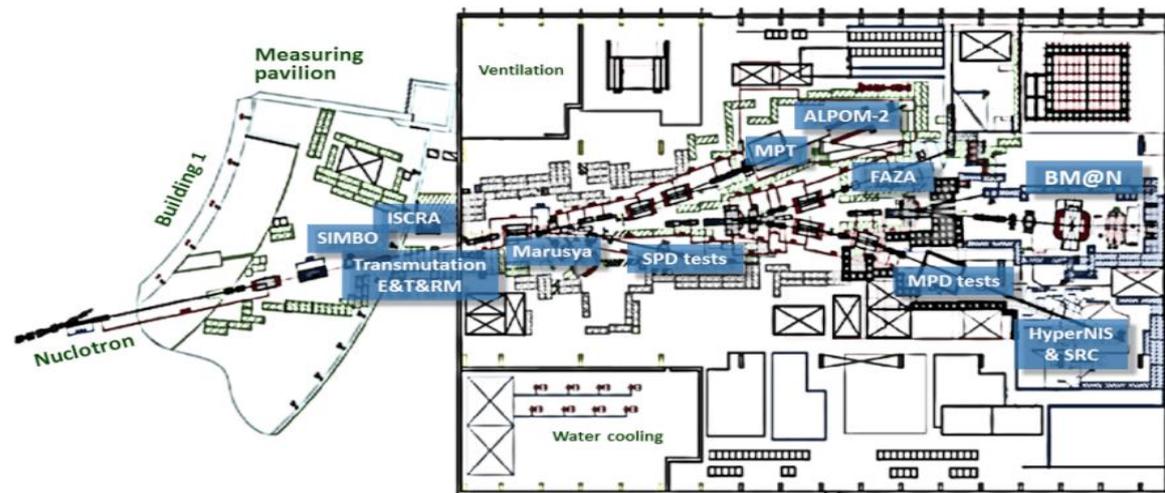


Figure 2. Extracted beam building scheme[5].

BM@N detector and Long-Term Exposure station

BM@N experiment is one of the central stations working at the NICA complex, installed at the fixed-target hall of the Nuclotron. Its goal is to perform research focused on the production of strange matter in heavy-ion collisions.

In order to get to the detector the heavy ion linear accelerator sends the ions to the booster, and then they are injected into the Nuclotron for further acceleration; finally they are extracted to the BM@N area. Just behind the BM@N detector (figure 3 a)) is located the Long Term Exposure station (LTE) which enables continuous exposure for the sample up to several months. Other advantages of the LTE station is that it is capable of parallel working with BM@N and can be used to study the problem of inducing and recovery from radiation of biological samples.

In low intensity beams permits to get as close as possible to the radiation conditions of deep-space missions, that imply prolonged exposure of biological objects to radiation. For high energy beams enable study microelectronics reliability for spacecraft[6].

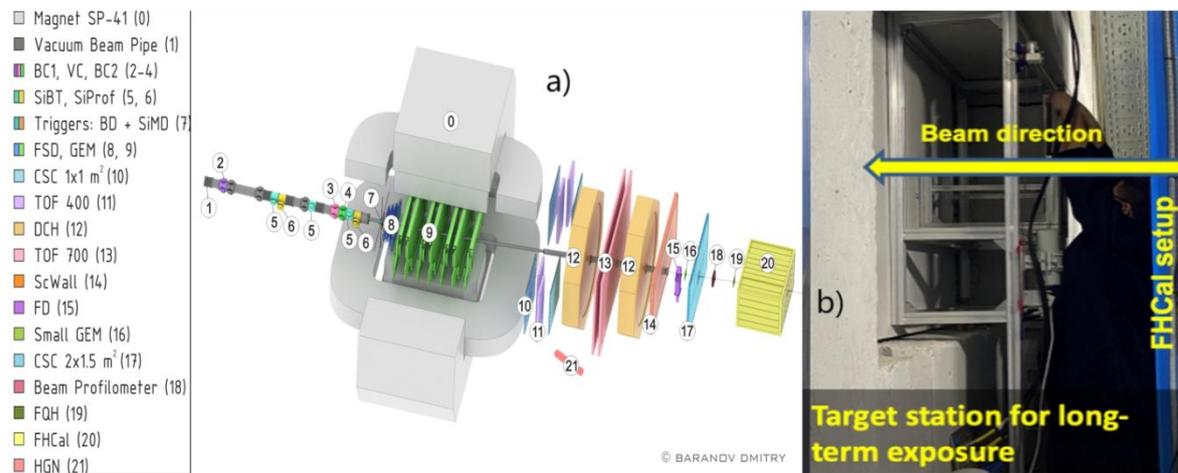


Figure 3. a) BM@N detector[5], b) Long-Term Exposure station.

In the figure 3b) is shown the Long-Term Exposure station (LTE) located after the FHCAL for applied research.

Interactions of charged particles with matter

The charged particle such as heavy ions, can interact with matter in the four different ways listed next[7]:

- 1- In Coulomb Interactions
- 2- Bremsstrahlung
- 3- Nuclear Interactions
- 4- Cherenkov Radiation
- 5-

The coulomb interactions can be divided in two groups, one for the electrons and the other is for the nuclei. The result of the interaction with electrons have to results ionization(when the electron is expelled from the atom) and excitation (the electron transfer to a higher orbit).

Some of the effects of the nuclear interactions are inelastic and elastic scattering, fusion and disintegration.

When a charged particle accelerate or decelerate loses some of his kinetic energy to electromagnetic radiation, this phenomenon is called bremsstrahlung, and the radiation can be emitted with every value up to the kinetic energy of the particle.

Finally the Cherenkov radiation is an special effect when a particle travel faster than the speed of light in the medium, emit visible electromagnetic radiation[7].

Are two important magnitudes that are worth mentioning when you are talking about the interaction of particles with matter; this are:

- Stopping Power (SP): every particle that travels through a material loses energy in coulomb interactions with all the electrons and nuclei in its path, reducing its kinetic energy; results impossible make all the individual calculations of energy loss, then SP is determined as the average energy loss per unit of distance travelled [7].
- Range: After a certain thickness of every material the particles traveling in the material lose most of its kinetic energy and stop (are absorbed in the material). The distance when the half of the particles stop is called range and when almost every stop is called extrapolated range.

Ionization Chambers

There are multiple types of detectors mostly used, for the charged particles like the ionization chambers. This detector belongs to the category of gas-filled detectors and uses the ionization produced by radiation in its path through the gas.

The ionization chamber consists of two electrodes with an electrical potential applied; and the chamber filled with a determined gas. In the pass of the ionizing radiation through the chamber, it loses a part or all of its energy ionizing the gas, producing multiple ion-electron pairs. Under the influence of the electrical field of the electrodes the charge of the pairs is collected and then it can be measured directly as a current or transformed into a pulse with the proper electronics [7].

Dosimetric Analysis

Fluence

Fluence (ϕ) is one of the fundamental magnitudes that are used for dosimetric analysis; and describes how many particles pass through a certain surface. The fluence is calculated with the next expression:

$$\phi = \frac{d(N)}{d(A)} \quad (1)$$

Where N is the number of particles (nucleons) and A the surface area (cm^2), this is called particle(ions/photons) fluence with dimensions of nucleons $\cdot\text{cm}^{-2}$; also there is the energy fluence that is calculated with $d(E)$ instead of $d(N)$, where E is the energy.

Related to the fluence is a magnitude called fluence rate ($\dot{\phi}$) which is simply determined by:

$$\dot{\phi} = \frac{d(\phi)}{d(t)} = \frac{d(N)}{d(A)d(t)} \quad (2)$$

Where t is the time (most of times in seconds); then $\dot{\phi}$ is the number of particles that pass through a unit of area per unit of time, and the unit is nucleons/cm²s [7].

Dose

The dose can represent the effect of radiation in the materials; and is the magnitude that represents the radiation received by the materials. Considering that not all the radiation is absorbed in the materials [7], there is the absorbed dose (D) that represent the damage of radiation in materials. D is a related to the energy imparted ($\bar{\epsilon}$), the mass (m) of the volume and it is calculated with the expression:

$$D = \frac{d\bar{\epsilon}}{dm} \quad (3)$$

Where $\bar{\epsilon}$ is determined as the difference between all the energy that enters the volume and the energy that leave's it, taking in count all the possible effects of mass-energy conversion, like pair-production, annihilation, etc. The unit of absorbed dose is joule/kilograms, but is named Gray(Gy) per convention[7].

Relation between Dose and Fluence

According to what is presented before, is possible to establish an relation between the absorbed dose and the fluence, taking into an account the mass collision stopping power ($\frac{dT}{pdx}$). Then, with the product of fluence and stopping power is possible to obtain the energy deposited in the material. That happen, because one represents the number of particles that enter the material and the stopping power the amount of energy loss by these particles. Is it necessary to remember that the particles have other means of losing energy, but for a thickness (x) of a few percent of the range or less the next expression can be used for calculations of the dose:

$$D = \phi * \frac{dT}{pdx} \quad (4)$$

FLUKA CODE

FLUKA is multi-purpose MONTE CARLO toolkit that allows the transport of all the elementary particles and heavy ions in complex geometries and materials[9]. The software is capable of simulate beams of most particles from 10^3eV to 10^{21}eV , with the exception of neutrons and photons that can go down to 10^{-5} and 10^2eV respectively and have different mechanisms for calculating the dose and fluence of the beam in a specific region such as USRBDX card[8].

Methodology

FLUKA simulation

A schematic representation of the simulated geometry is shown in figure 4, and in table 2 the exact geometrical parameters are shown. The primary particles are heavy ions of ^{131}Xe with an ecliptic form, all the beam parameters are shown in table 1.

Table 1. Beam parameter

Beam	Energy	Position	Distribution	FWHM(x)	FWHM(y)
^{131}Xe	3.8MeV	0x0x-10	Gauss	1.0	1.5

Table 2. Geometrical Parameters

	Size(cm)	Z position(cm)	Thickness(cm)	Material
target	10x10	-0.05	0.1	Xenon
FD	15x15	+784	0.5	Scint. BC408
fqh	16x16	+790	0.4	SiO ₂
Chamber1	25x25	+1190	6	Air
Sample	18x18	+1200	$3.34 \cdot 10^{-8}$	Graphene
Chamber2	17x17	+1206	6	Air

The graphene material was built as a graphite with the thickness of only one layer per graphene and an ideal density for this material of 2.267g/cm³ and the simulated air a density of 0.001205g/cm³. For Xenon, Air and BC408 material, the version already created in the FLUKA database are used. In the simulation where used 50 000 primary particles.

Experiment setup

In the figure 5 left the experimental setup, ready for deployment in the LTE station is shown. The setup has two ionization chamber filled with air, named Chamber1 and Chamber2, two sample holders 1 and 2; after that will be located a mirror and an alumina fold. The figure 5 right shows the the sample holders.



Figure5. left)Experiment setup, right) Sample holder

The table 3 shows all the geometric parameters of the detectors.

Table3 Geometric parameters of experiment setup

	Size(cm)	Z position	Thickness
A)Chamber1	25x25	+1190	6
B)Sample holder1	18x18	+1196	4
C)Sample holder2	18x18	+1200	4
D)Chamber2	17x17	+1206	6
E)Mirror	10x5	+1212	0.3
F)Lumina fold	10x10	~+1220	0.3

Results and discussion

The experiment was simulated in the FLUKA software through the flair interface. The number of primary particles of the beam was $5 \cdot 10^4$ and it took 24 hours to complete all the calculations.

In order to better compare between the fluence of the beam, the first thing measured was this value next to the origin of the beam. In figure 6 is shown the energy deposition with a color scale in a box of 16 (-8 to 8) for x and y direction and in z from -9.1 to -9.

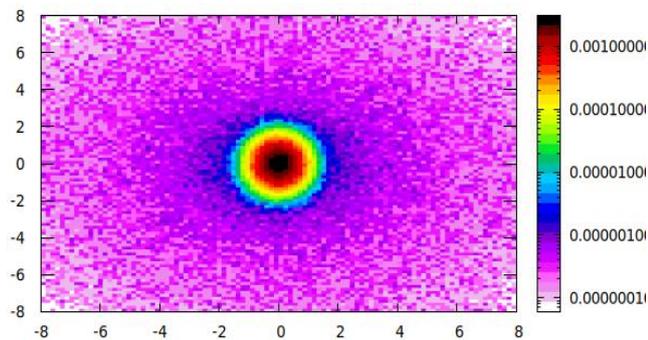


Figure 6. Beam energy in $z = -9.1$

In the figure 6 is appreciated the Gaussian distribution of the primary beam, and its elliptic shape. This proves the correct simulation of the primary particles beam.

Ionization Chambers

In order to learn about how the particles behave in the chambers we measure to magnitudes, first the fluence of beam particles entering to the chamber, and the amount of energy deposit inside the chambers.

The fluence of primary particles getting inside the a ionization chambers is nearly the same for the two; approximately 1,08054 In the figure 7 it can be seen how the beam is traveling through the two ionization chamber. This is concentrating in the center with a little dispersion, up to 2 centimeters.

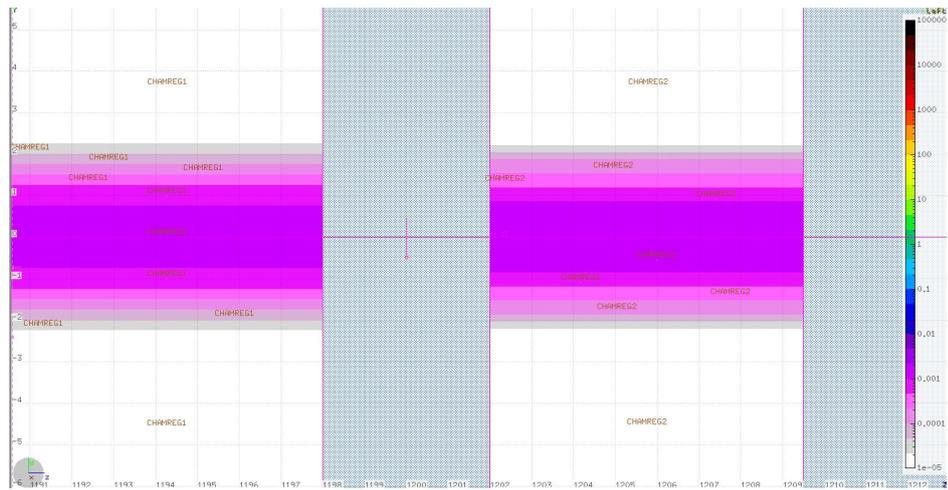


Figure 7. Beam traveling through the ionization chambers

For the chamber1 we see in the figure 8, how the energy deposition is distributed. Most of the energy is concentrated in the beam path (less than 2 cm).

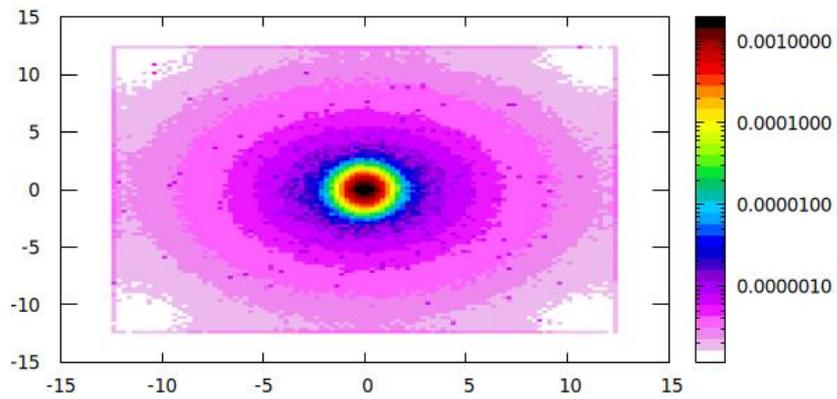


Figure 8. Energy deposition in the chamber1

For the chamber 2 in the figure 9, the results are similar to the ones of the chamber1; this is because both ionization chambers are filled with the same gas(air).

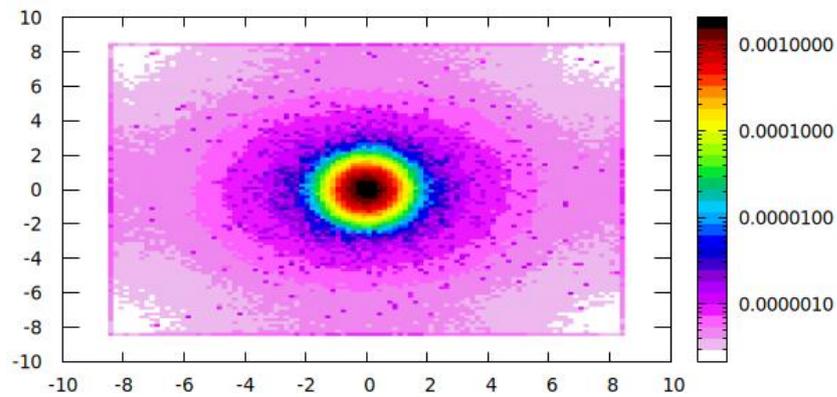


Figure 9. Energy deposition in the chamber1

Graphene Sample

Now, for the graphene sample in the simulation, in the figure 9 we see the energy deposition in the one layer (less than a nanometre thickness). In the figure the sample can be perceived with naked eyes, the sample absorbs a good amount of energy taking in count its thickness.

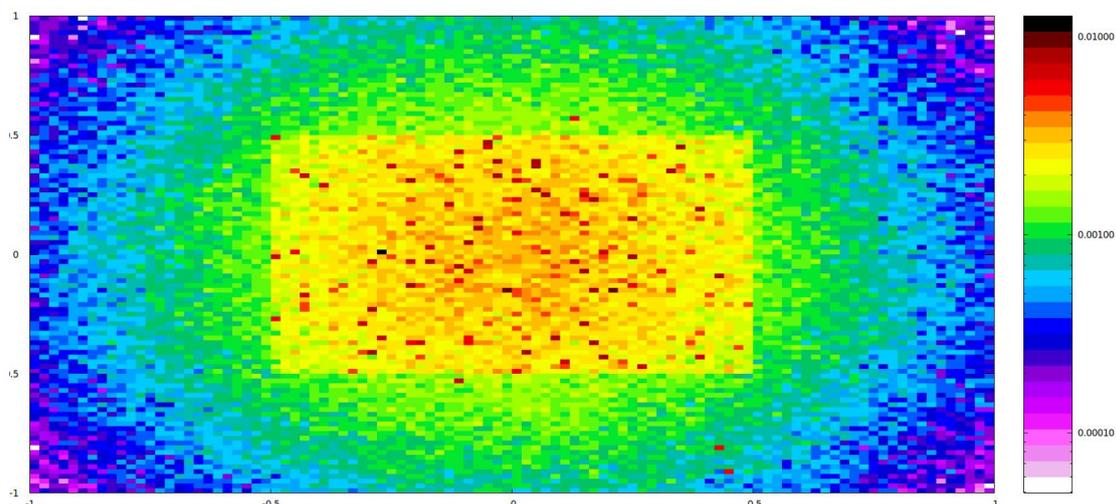


Figure 9. Energy deposition in the sample.

Fluence and Dose calculations

The fluence values of the sample were measured for both of the chambers and the graphene sample; these results are shown in table 4 that is presented next.

Table 4. Fluence and dose calculations per primary particle

	Fluence (part)	Dose Received (MeV*part)	Dose Absorbed (MeV)
Graphene Sample	0.321	1219.846	0.5457
Chamber1	0.9963	3,786.0498	1.9428
Chamber2	0.9962	3,785.6094	1.9426

Both of the chambers can receive more than 99% of the particles from the beam, and receive the same percentage of energy from the beam. Because they are built with traveling through the air, they will absorb the same amount of energy from the particles in its volume. The Fluence and Dose for the chambers has a small difference between them of 0.01%, this should be due to the different size of the both chambers and their geometrical positions.

The graphene sample takes 32.1% of the beam, due to its small size, and absorbs 0.54 MeV per heavy ion; that represents 0.004% of all the dose received (approximately 1219.8MeV).

Then in the table 5 the total amount of fluence(all the particles in beam), dose received and absorbed is presented.

Table 5. Fluence and dose calculations for the beam

	Fluence (part)	Dose Received (GeV)	Dose Absorbed (GeV)
Graphene Sample	16050	60'992.300	27.285
Chamber1	49815	189'302.490	97.140
Chamber2	49810	189'280.470	97.130

Particle tracks

Finally, the tracks of all particle that travels trough the sample is shown in the figure 10. In the right part of the graph are the primary particles, in the left part is seen all the electrons, and in the middle all the other particles passing through the sample like proton, alpha, deuterons, neutron etc.

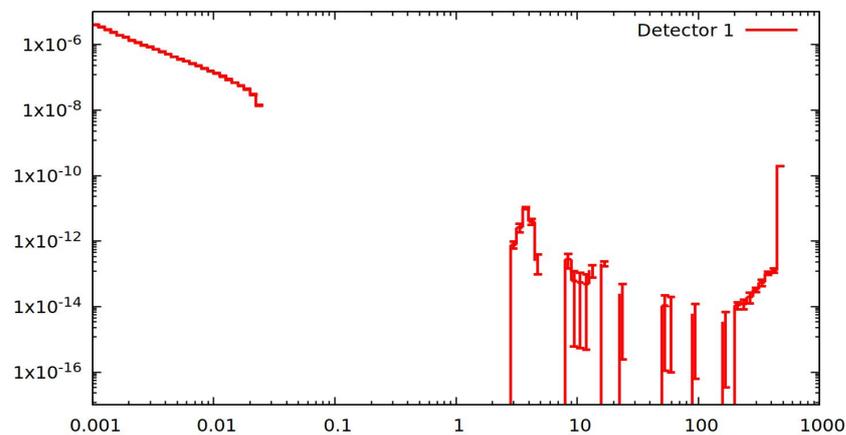


Figure 10. All particles recorded in the sample

Conclusions

The simulation of the Long-Term exposure station was completed with great results. The fluence and the dose received from the beam per primary particle in the ionization chambers was calculated; for the first one was 0.9963 of fluence (99.63% of the beam), 3.786 GeV of dose and for the second chamber 0.9962 and 3.785 GeV respectively. In the sample, only the 32.1% of the beam was received and it was absorbed 0.54MeV per primary particle, ascending to 27GeV approximately $4.4 \cdot 10^{-4}\%$ of the total dose received of 60'992.3GeV.

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