JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

FLUKA/FLAIR Simulation-Based Assessment of Absorbed Dose from ^{131}Xe Heavy-Ion Irradiation Using Water Phantoms as a Preliminary Model for Biological Samples

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1. LITERATURE REVIEW

1.1 Applications of Heavy Ions in Biological Research

Mutation breeding, a widely used technology in biotechnology, plays a key role in improving microbial strains for industrial applications. Among various mutagenic agents, heavy ion beams, such as carbon (^{12}C) and iron (^{56}Fe), have proven to be highly effective tools for inducing genetic variations in microorganisms. The unique properties of heavy ions, including high linear energy transfer (LET) and deep penetration ability, allow for precise and efficient induction of beneficial mutations. These mutations have broad applications in biotechnology and the food industry, particularly in enhancing microbial strains used for biofuel production, pharmaceutical synthesis, food fermentation, and food additive manufacturing.

Heavy ion irradiation differs from traditional mutagenesis methods, such as UV exposure or chemical mutagens, due to its ability to induce complex DNA damage, including double-strand breaks, large deletions, and chromosomal rearrangements [1]. These mutations, caused by high-LET radiation, often lead to the emergence of new phenotypes with improved industrial traits. Furthermore, heavy ion mutagenesis facilitates strain improvement without introducing foreign genetic material, making it a preferred method in the food and pharmaceutical industries, where non-genetically modified organism approaches are favored [2].

a) Application to Bacterial Strains

Heavy ion beams have been successfully used to enhance bacterial strains for industrial production. For example, carbon ion irradiation of *Clostridium* strains has led to increased butanol and butyric acid production—key components in biofuel manufacturing [1][2]. Mutant strains of *Lactobacillus thermophilus* obtained through heavy ion mutagenesis have demonstrated higher lactic acid production, improving efficiency in the dairy industry and probiotic manufacturing [3].

b) Application to Fungi

Fungi have also benefited significantly from heavy ion mutagenesis, particularly in the pharmaceutical and biofuel sectors. For instance, *Aspergillus* *terreus* mutants generated after carbon ion irradiation exhibited significantly enhanced lovastatin synthesis—an important compound used to lower cholesterol levels [4]. Similarly, *Trichoderma viride* strains with improved cellulase activity were optimized for the biofuel and paper industries, demonstrating increased enzymatic activity after exposure to heavy ion beams [5].

c) Application to Yeasts

Yeasts, particularly oleaginous species, are promising targets for heavy ion mutagenesis due to their ability to accumulate lipids. Mutant strains of *Rhodotorula glutinis* and *Pseudozyma* sp. obtained through ion beam irradiation showed increased lipid and squalene synthesis, making them valuable for biodiesel production and the cosmetics industry [6][7]. These advancements support the development of sustainable and efficient biotechnological applications.

d) Application to Microalgae

Microalgae are essential sources of biofuels and dietary supplements. Heavy ion mutagenesis has been applied to enhance lipid and docosahexaenoic acid (DHA) production in *Nannochloropsis oceanica* and *Aurantiochytrium* sp. [8][9]. The modified strains exhibit improved efficiency in biofuel production and functional food manufacturing, meeting the growing demand for renewable energy sources and bioactive compounds.

Advantages and Challenges of Heavy Ion Mutagenesis

Heavy ion mutagenesis offers several advantages, including high mutation efficiency, precise targeting, and the ability to generate diverse phenotypic variations. Unlike traditional genetic modification methods, this approach does not introduce foreign DNA, making it more acceptable for applications in the food and pharmaceutical industries. However, there are challenges, such as the high cost of irradiation facilities and the need for specialized equipment. Further research is required to optimize irradiation parameters and improve strain screening methods for large-scale industrial applications.

1.2. Review on ARIADNA, NICA, and BM@N Projects in the Context of Irradiated Radiobiological Samples by heavy ion

The Joint Institute for Nuclear Research (JINR) in Dubna, Russia, has established advanced research infrastructure for investigating the effects of ionizing radiation on biological systems. Key projects, including ARIADNA, NICA, and BM@N, provide unique platforms for irradiating biological samples using high-energy ion beams. The ARIADNA (Applied Research Infrastructure for Advanced Developments at NICA Facility) project focuses on applied research utilizing the NICA (Nuclotron-based Ion Collider fAcility) accelerator complex, with particular emphasis on life sciences and biomedicine. In December 2022, experts from five research institutions conducted a series of biological sample irradiations at a specially equipped stand within the BM@N (Baryonic Matter at Nuclotron) experimental zone. This setup enables controlled irradiation of biological samples, supporting studies on radiobiological damage and radiation protection strategies [10].

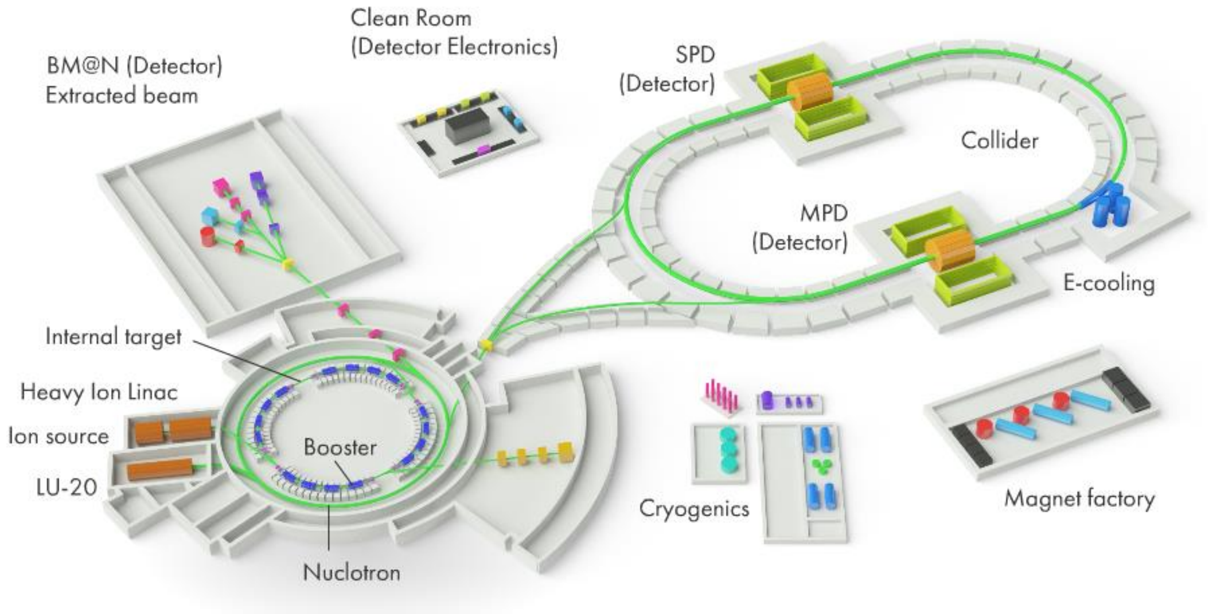


Figure 1: Scheme of the structure of the NICA Complex. [10]

The NICA project investigates dense baryonic matter properties using relativistic heavy-ion collisions. A core experiment within this facility is BM@N, which employs high-energy beams to study nuclear interactions with fixed targets, simulating extreme conditions found in space radiation environments and high-dose medical applications. The BM@N experiment has conducted multiple experimental runs using heavy-ion beams such as gold and uranium, with ongoing data analysis to assess radiation effects on biological structures [11,12].

The ARIADNA, NICA, and BM@N projects at JINR serve as vital research platforms for radiobiological investigations. By utilizing high-energy ion beams, these initiatives enhance our understanding of radiation effects on biological systems and contribute to the advancement of radiation protection technologies. Future research will further integrate radiobiological experiments with accelerator-based studies to refine therapeutic and protective strategies against ionizing radiation.

1.3 FLUKA and FLAIR in Absorbed Dose Simulation

The simulation of heavy ion interactions with biological samples plays a crucial role in radiation biology, medical physics, and radiation protection. One of the most reliable and widely used tools for such calculations is the FLUKA software package, which is supported by the FLAIR graphical interface. These programs enable accurate particle transport modeling, absorbed dose calculations, and energy distribution analysis.

a) **FLUKA: Monte Carlo Simulation of Particle Interactions with Matter**

FLUKA (FLUctuating KAscade) is a powerful Monte Carlo-based software for simulating the interaction of charged and neutral particles with matter. It is developed by the European Organization for Nuclear Research (CERN) and the Italian National Institute for Nuclear Physics (INFN) [13].

FLUKA is used in various fields, including:

- Radiation protection modeling [14];
- Dosimetry in medical physics, including proton and ion therapy [15];
- Space radiation and nuclear interaction simulations [16];
- Calculations in hadronic and nuclear physics [17].

The main advantages of FLUKA include:

- High accuracy in modeling charged particle interactions, including heavy ions;
- Support for a wide range of energies, from thermal neutrons to relativistic ions;
- Capability to model complex geometries.

b) ***FLAIR: Graphical Interface for FLUKA***

FLAIR (FLUKA Advanced Interface) is a graphical interface designed to simplify the use of FLUKA [18]. It provides tools for:

- Creating and editing input files;
- Running simulations and monitoring their progress;

- Analyzing output data, including dose distribution and particle spectra visualization.

c) **Applications of FLUKA and FLAIR in Absorbed Dose Calculations**

FLUKA and FLAIR are widely used in radiation biology research to assess radiation effects on living tissues. Specifically, they are applied for:

- Calculating dose distributions for ion beam irradiation [19];
- Analyzing particle trajectories and energy loss in biological materials [20];
- Optimizing irradiation parameters in medical and scientific experiments [21].

FLUKA and FLAIR are reliable tools for radiation effect modeling. Their application in this study enables accurate absorbed dose calculations and energy distribution analysis in irradiated biological samples. The use of these programs enhances the precision of radiation effect assessments and opens new possibilities for research in radiation biology and medical physics.

In this study, FLUKA and FLAIR are used to model the absorbed dose in biological samples. Since actual biological samples are not yet available, the initial experiment was conducted using water phantoms, which were irradiated with heavy-ion ^{131}Xe at the NICA complex under the ARIADNA project.

2. MATERIAL AND METHODOLOGY

2.1 Experimental Data Collection

A schematic representation of the experimental setup is presented in Figure 2. To accurately determine the absorbed dose in the sample, it is essential to precisely measure the beam intensity and thoroughly characterize the physical parameters of the detectors, target, and sample. These parameters are critical for providing accurate input data into FLUKA and FLAIR simulations, which, in turn, ensures reliable dosimetric calculations and accurate modeling of radiation transport. The key parameters used in these calculations are summarized in Table 1.

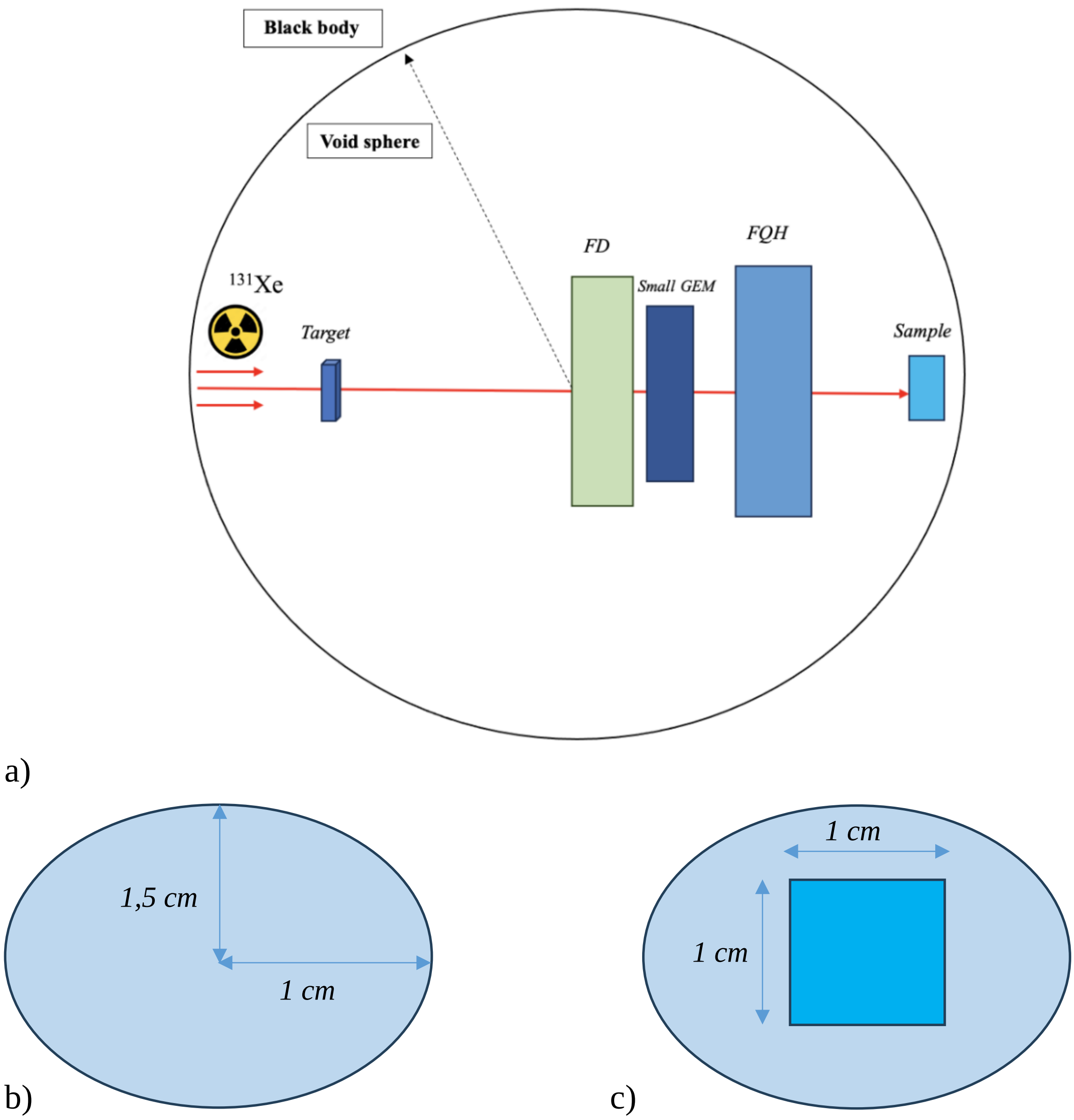


Figure 2:

a) Schematic of the experimental setup.

b) Geometric representation of the ion beam, highlighting the dimensions of the surface radius.

c) Position of the sample relative to the beam, including the geometric representation and the corresponding area value.

Table 1: Physical characteristics of the target, detectors and sample

Object		**Z position (cm)**	**Active area (mm×mm)**	**Material**	**Thickness (mm)**
Target		0	10 × 10	Xenon	1
Detectors	FD	+784	150 × 150	Scint. BC408	0.5
	Small GEM	+793	100 × 100		~0
	FQH	+970	160 × 160	Quartz	4
Sample		+1200	10 × 10	Water	5

In this heavy-ion collision experiment, several detectors are used to monitor and analyze the beam's behavior. A 4 mm thick quartz hodoscope (FQH) is placed before the FHCal to detect unscattered beam ions and spectator fragments, which remain unaffected by collisions. The hodoscope provides data for offline analysis, aiding in event selection and determining event centrality, which measures how direct a nuclear collision is. Between the Focusing Detector (FD) and FQH, a Gas Electron Multiplier (GEM) detector is placed to monitor the beam's position, shape, and size after passing through an analyzing magnet, ensuring proper alignment. The hodoscope records beam intensity distribution, ensuring uniformity and stability before reaching the target. In this setup, biological samples are positioned approximately 2 meters from the FQH, while the beam travels through the air before entering the FHCal. The FHCal features a granular structure in both transverse and longitudinal directions, enhancing energy measurement accuracy. Beam ions that do not interact continue through a hole in the center of the FHCal and are directed toward a beam dump, which absorbs the remaining particles, preventing unwanted radiation and interference. This arrangement ensures precise event selection, effective beam monitoring, and accurate measurement of collision outcomes, enabling detailed analysis of the beam's interaction with the target environment.

To isolate radiation interactions and ensure computational accuracy, two distinct environments were utilized. The Black Body environment, located outside the region with coordinates (x, y, z) = (0; 0; 750) cm and a radius starting from R = 801 cm, is a theoretical setup where no radiation interactions are recorded. It is used to model areas outside the experimental zone (e.g., beam dump or non-sensitive regions), eliminating boundary effects and simplifying particle tracking. The VoidSphere environment, with coordinates (x, y, z) = (0; 0; 750) cm and a radius of R = 800 cm, is a radiation-sensitive zone where all particle interactions (e.g., scattering, energy deposition) are recorded and analyzed. This environment encompasses the detectors, target, and biological sample.

2.2 Computer Analysis of Data Using FLUKA and FLAIR

The analysis of experimental data collected from the heavy-ion collision experiments is crucial for understanding radiation transport and ensuring accurate dosimetric calculations. The use of computational tools like FLUKA and FLAIR facilitates detailed simulations that complement experimental findings.

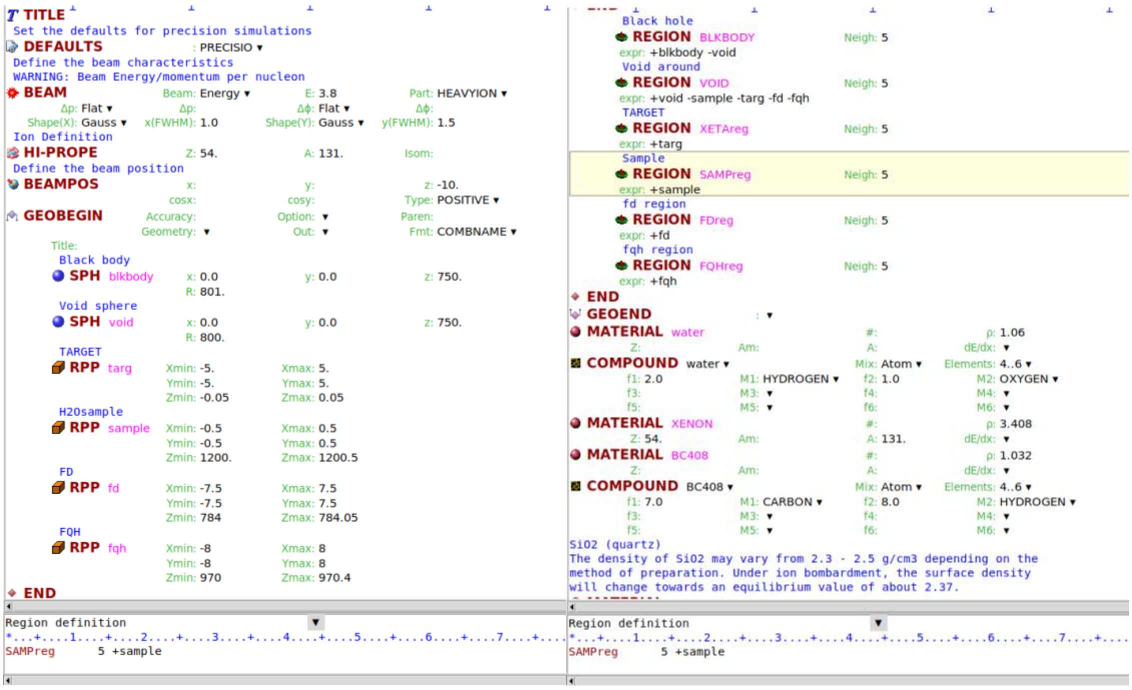
Simulation Setup:

Beam parameters, including energy, size, material composition, position, and geometric configuration, were configured in FLAIR. The simulation incorporated the following key elements:

- **Beam properties:** ^{131}Xe ions with an initial energy of 3.8 GeV.
- **Geometry:** A detailed 3D model of the experimental setup (Figure 2) was reconstructed, including detectors, target, and sample positions.

- **Materials:** Material properties of air, detectors (e.g., BC408 scintillator, quartz), target (xenon), and the biological sample (water) were defined based on experimental measurements.
- **Boundary conditions:** Two distinct environments were modeled:
    - **Black Body:** A non-interactive zone (radius > 801 cm) to eliminate boundary effects.
    - **VoidSphere:** A radiation-sensitive zone (radius = 800 cm) encompassing detectors and the sample.

After configuring these parameters, the simulation was executed in FLAIR. Particle transport, energy deposition, and dose distribution were tracked using FLUKA's Monte Carlo algorithms. Output data, including energy spectra and spatial dose profiles, were extracted for further analysis.



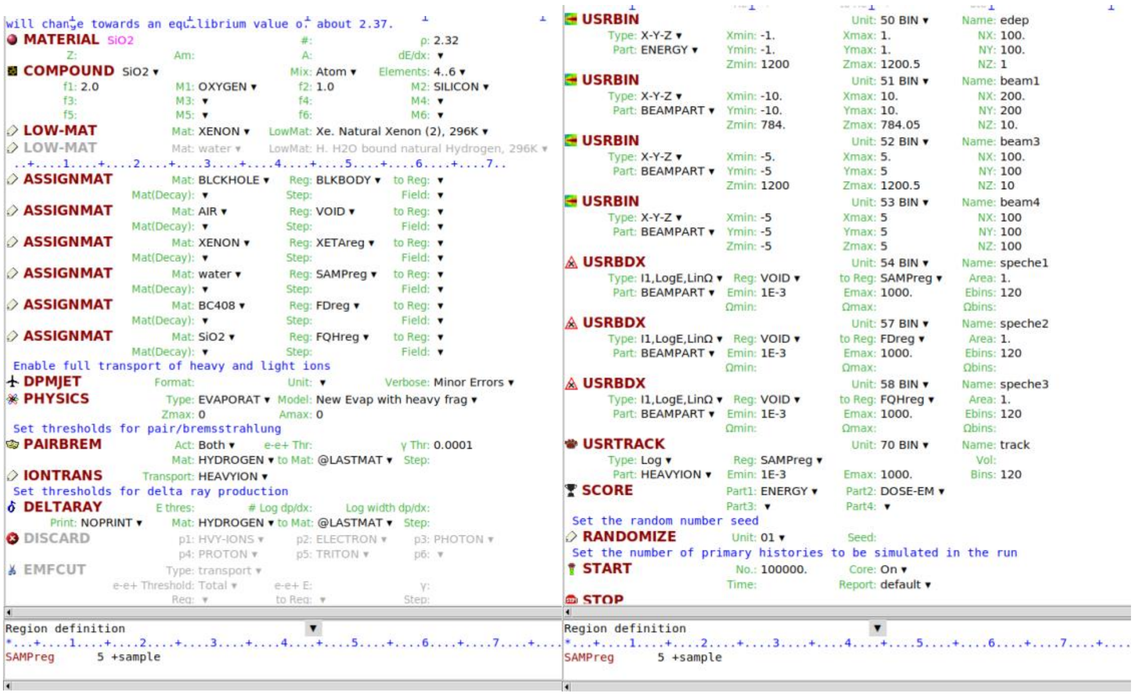


Figure 3. Simulation setup for radiation transport modeling

2.3 Dosimetric analysis of the samples

2.3.1 Definition and Significance

Absorbed dose is a fundamental concept in radiation dosimetry, representing the amount of energy deposited per unit mass of a material when exposed to ionizing radiation. It is expressed in Gray (Gy), where 1 Gy = 1 Joule per kilogram (1 Gy=1 J/kg) [22]. This measure is crucial in various fields, including medical radiation therapy, radiation protection, and nuclear research, as it quantifies the biological and physical effects of radiation exposure [23].

2.3.2 Mathematical Expression

The absorbed dose D at a specific point in a given volume is defined as:

$$D=\frac{d\varepsilon}{dm} \quad (1)$$

where:

- $d\varepsilon$ is the mean energy imparted to matter in a volume element dv,
- dm is the mass of that volume element (ICRP, 2007).

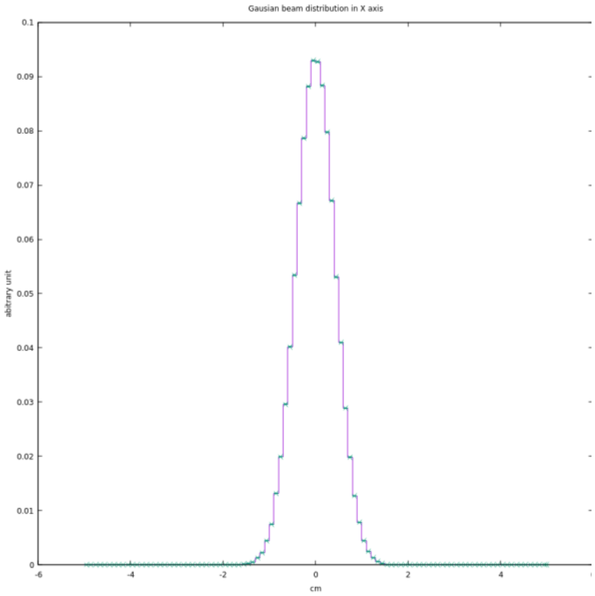
3. RESULTS

Using FLUKA and FLAIR, the energy deposition on the sample was calculated based on complete input parameters, including beam energy, material composition of the beamline, air, target, detectors, and sample. The simulation was performed in a Black Body and VoidSphere environment to ensure accurate radiation transport modeling.

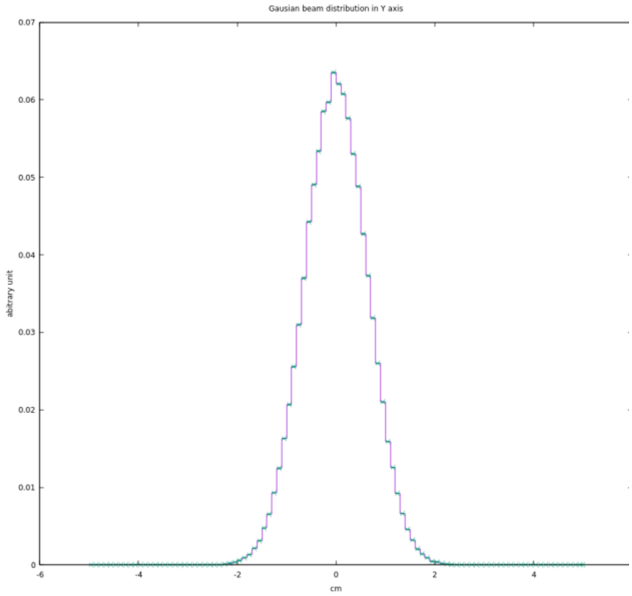
3.1 Beam Profile Characterization

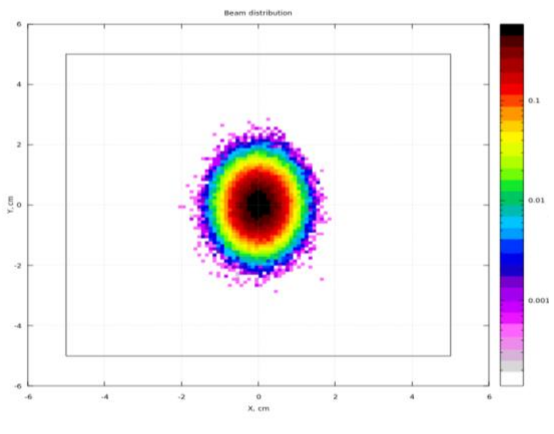
The beam exhibited an asymmetric Gaussian spatial distribution, with Full Width at Half Maximum (FWHM) measurements of 1.0 cm along the X-axis (Figure 3a) and 1.5 cm along the Y-axis (Figure 3b). This profile asymmetry reflects divergence and scattering effects during beam propagation (Figure 3c).

a)



b)





c)

Figure 4. Gaussian distribution of The Xenon beam

3.2 Beam Transmission Efficiency

Only 32.1% of the incident beam reached the water phantom, with 67.9% attenuation due to scattering and energy loss in air and detector materials. The total energy deposited in the sample was 926 MeV.

3.3 Absorbed Dose Calculation

Energy deposition in the sample: 926 MeV.

Energy conversion to Joules:

$$926\ \text{MeV} = 926 \times 1.602 \times 10^{-13}\ \text{J} \approx 1.483452 \times 10^{-10}\ \text{J}$$

Sample mass correction:

The biological sample mass was 0.52 g (0.00052 kg), as measured experimentally.

Absorbed dose calculation:

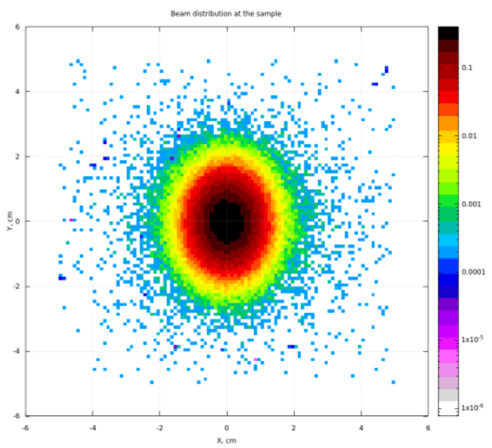
To determine the absorbed dose, Equation (1) was applied, considering the sample's 0,00052kg mass. The energy deposition distribution within the sample (Figure 5) demonstrated a peak concentration at the beam center, consistent with the Gaussian profile. Detailed results are summarized in Table 2.

$$D = \frac{\text{Energy (J)}}{\text{Mass (kg)}} = \frac{1.483452 \times 10^{-10}\text{J}}{0.00052\text{kg}} \approx 2.85\times10^{-7}\ \text{Gy}$$

Table 2: Summary of experimental results

Incident Beam Energy (Beam Line ^{131}Xe)	**Energy Deposited in Sample**	**Absorbed Dose**
3.8 GeV	926 MeV	2.85×10^{-7} Gy

a)



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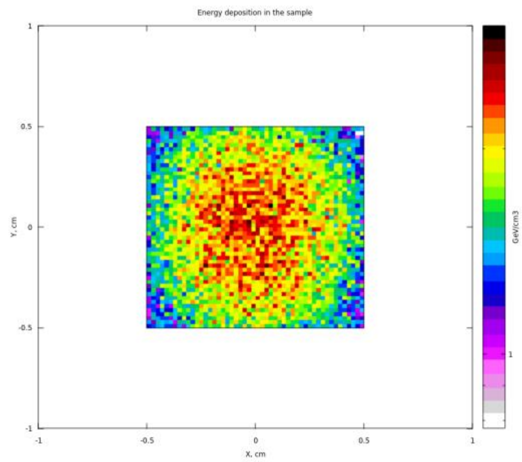
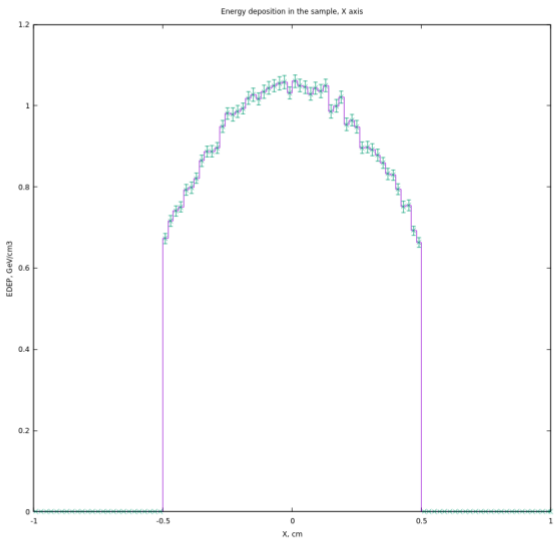


c)



d)

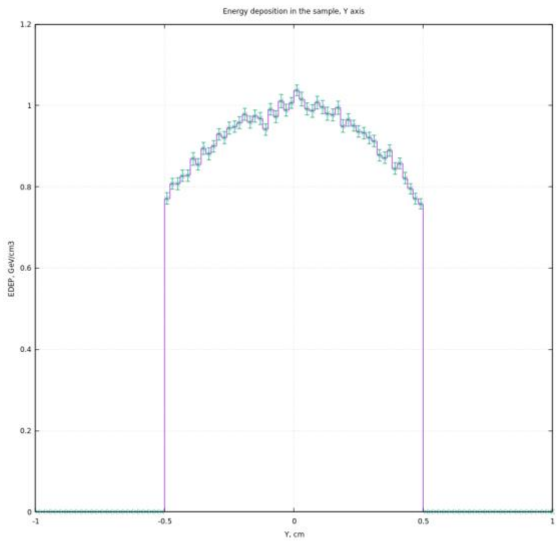


Figure 5. Energy deposition profile in the biological sample. The beam showed an asymmetric Gaussian distribution, with Full Width at Half Maximum (FWHM) values of [X-axis value] cm (Figure 5b) and [Y-axis value] cm (Figure 5c). This asymmetry results from beam divergence and scattering effects during propagation, as illustrated in Figure 5a and 5b.

4. CONCLUSION

This study successfully utilized FLUKA/FLAIR simulations to estimate the absorbed dose in water phantoms irradiated with ^{131}Xe heavy ions, yielding a value of **2.85×10^{-7} Gy**. These findings demonstrate the applicability of Monte Carlo methods for radiation transport modeling; however, further experimental validation is necessary for precise dose quantification. One critical observation is the **67.9% beam attenuation** before reaching the sample, primarily due to scattering in air and interactions with detector materials. This highlights inefficiencies in the current beamline setup that may impact dose delivery accuracy.

To improve future experiments, the following recommendations are proposed:

1. **Optimizing vacuum conditions** in the beamline to reduce air-induced energy loss and enhance transmission efficiency.
2. **Implementing collimators** to minimize beam divergence and improve dose localization.
3. **Refining detector calibration protocols** to enhance energy resolution and improve event selection accuracy.

These modifications will contribute to more reliable radiobiological dose assessments and support the advancement of heavy-ion applications in biotechnology and medical research.

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I look forward to future opportunities for collaboration in advancing research at JINR.

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