

Joint Institute for Nuclear Research (JINR)
Veksler and Baldin Laboratory of High Energy Physics
NICA Accelerator Complex
BM@N Experiment



Fluence estimation during xenon beam irradiation of a glass sample (target)

Scientific Report

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Abstract

This report presents an experimental study performed in the BM@N experimental area at the NICA accelerator complex, with the aim of monitoring ion beam parameters and determining particle fluence during irradiation.

The experimental setup includes ionization chambers, a strip chamber detector, a lumiphor screen with a camera system, and a data acquisition system connected to a central server within the ARIADNA data grid. These components are used to measure beam intensity, monitor beam position, and visualize the beam profile during irradiation of the material sample (target).

The irradiation procedure is carried out under controlled beam conditions, where detector systems operate simultaneously and provide continuous monitoring of the beam. The particle fluence is determined from the measured beam intensity and the estimated beam geometry.

The obtained results include beam intensity measurements, beam profile observations, and calculated fluence values. These results confirm that the beam conditions are stable and suitable for irradiation studies. The presented approach provides a consistent method for fluence estimation in experiments using heavy ion beams at the BM@N facility.

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Introduction

The interaction of energetic ion beams with matter is an important subject in nuclear and applied physics. When ions with high kinetic energy pass through materials, they deposit energy and can produce different physical effects such as ionization, structural modification, and radiation damage. In order to study these effects, it is necessary to know the irradiation conditions and determine how much radiation reaches the material being exposed to the beam.

One of the most commonly used quantities for describing irradiation conditions is **particle fluence**. Fluence represents the number of particles that pass through a unit surface area. This parameter is widely used in radiation studies because it provides a direct measure of the particle exposure of a material. By determining the fluence during an experiment, it becomes possible to relate the observed changes in a material to the amount of radiation it received.

The experiment described in this report is related to studies performed at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. At this institute, a large accelerator complex known as the NICA (Nuclotron-based Ion Collider fAcility) has been developed. The structure of the NICA accelerator complex is shown in *Figure 1*. The purpose of the NICA complex is to investigate strongly interacting matter under extreme conditions of temperature and baryon density. Such conditions can be produced in collisions of heavy ions accelerated to relativistic energies.

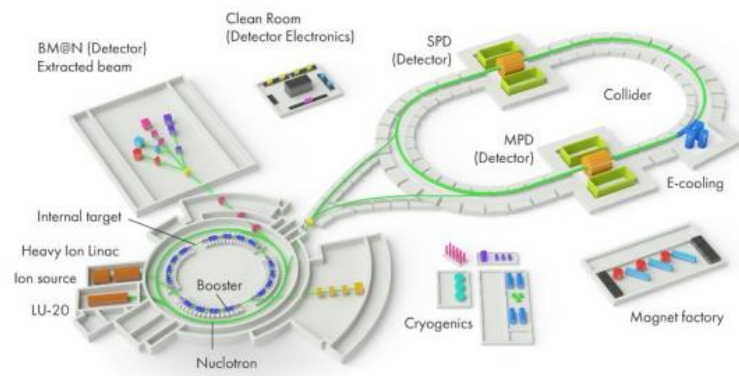


Figure 1. Scheme of the NICA accelerator complex. Adapted from NICA project documentation.

One of the first experiments operating at this facility is BM@N (Baryonic Matter at Nuclotron). BM@N is a fixed-target experiment designed to study interactions of relativistic heavy-ion beams with stationary nuclear targets. A schematic view of the BM@N experimental setup is shown in *Figure 2*. In this type of experiment, the ion beam is accelerated in the synchrotron and then extracted toward the experimental area where it interacts with a solid **target**. The collision produces a large number of secondary particles that can be measured with different detector systems.

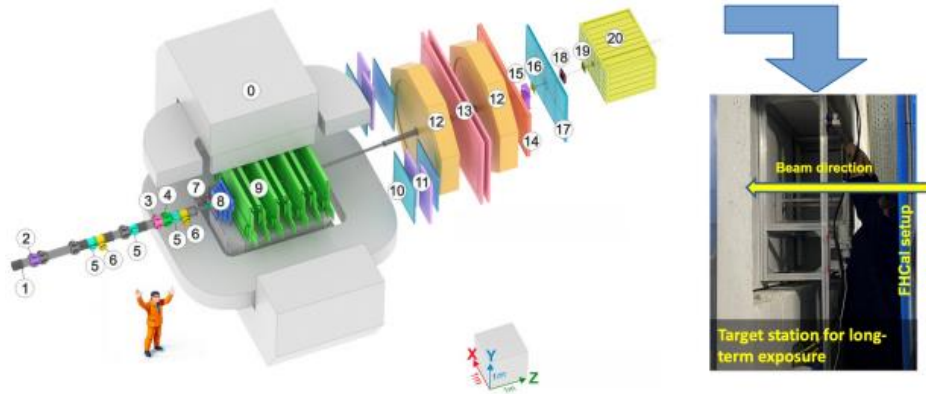


Figure 2. Schematic layout of the BM@N experimental setup during the Xe run. The position of the main detector systems along the beam line is shown.

In fixed-target experiments only a small fraction of the beam interacts with the target. In such experiments, only about 2% of the beam interacts with the target, while the remaining beam continues along the beam line. Since the acceleration of heavy ion beams requires significant resources, the unused part of the beam is utilized for applied research.

The irradiation setup is designed for this purpose, allowing controlled exposure of different materials to the ion beam. This enables systematic studies of radiation effects under well-defined beam conditions. The remaining part of the beam continues along the beam line and can be used for additional measurements. This allows the beam to be used for irradiation studies of materials. Such studies are important for understanding radiation effects and for testing the resistance of materials to ionizing radiation.

Different types of materials can be studied in this setup, including glass, graphene and microchannel plates (MCP). Microchannel plates consist of a structure of microscopic channels arranged in a hexagonal pattern, similar to a honeycomb. This structure allows efficient detection of particles and is commonly used in experimental physics setups. Their performance depends on irradiation conditions, and parameters of MCP detectors must be well understood. Irradiation studies therefore provide important information for detector development and applications. In the present work, the focus is on irradiation of glass samples, while other materials are planned for future studies, including MCP.



Figure 3. MCP sample to be used soon.

The goal of the experiment presented in this report is to estimate the particle fluence during irradiation with a xenon ion beam. The material being irradiated is referred to as **sample**. In this case, the sample is a glass plate and its diameter is 3cm. The experimental setup contains several detectors used to monitor the beam conditions and record the irradiation process.



Figure 4. Glass plate sample used in the experiment.

All detector signals are collected and processed through the **Ariadna Data Grid** system, which allows multiple devices to operate simultaneously and store the experimental data. The collected information is then used to determine the number of particles reaching the sample and to calculate the particle fluence.

The goal of this work is to determine the particle fluence for irradiation of the TARGET and to provide information about beam conditions during the experiment.

1 Experimental setup

The irradiation measurements are performed in the experimental area connected with the BM@N experiment at the NICA accelerator complex. The setup is designed to monitor the ion beam parameters and to allow irradiation of material samples using high-energy heavy ion beams.

The station is located downstream of the BM@N detector system and operates in parallel with the physics program. In this configuration the beam passes through the detector chain of the experiment before reaching the irradiation station where the samples are placed.

The experimental setup used for the irradiation measurements consists of several detector elements used for beam monitoring and control. These include ionization chambers, a strip chamber detector, a luminophor screen with a camera system, as well as a data acquisition system connected to a central server.



Figure 5. Experimental setup used in the irradiation measurements.

1.1 BM@N detector environment

The BM@N experiment (Baryonic Matter at Nuclotron) is designed to study interactions of relativistic heavy ion beams with fixed targets. The detector system includes several subsystems used for particle tracking, identification and timing measurements.

Among these subsystems are the time-of-flight detectors, known as TOF400 and TOF700. These detectors measure the time that particles need to travel from the interaction point to the detector plane. From the measured flight time and the known distance, the velocity of the particles can be determined.

Combined with momentum measurements from tracking detectors, the time-of-flight information allows identification of different particle species produced in heavy-ion collisions. The TOF400 detector is located closer to the central region of the detector setup, while the TOF700 system is positioned further downstream along the beam line.

Although these detectors are primarily used for physics measurements in the BM@N experiment, they are part of the beamline environment through which the ion beam travels before reaching the irradiation station.

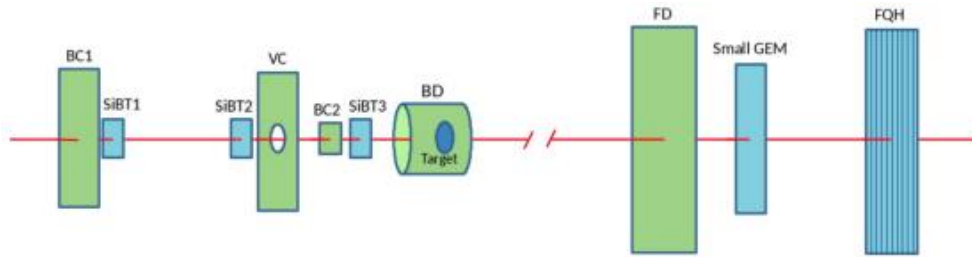


Figure 6. Schematic layout of the BM@N experimental setup showing the position of detector systems along the beam line.

1.2 Time-of-Flight Detectors (TOF400 and TOF700)

In addition to tracking detectors, the BM@N experimental setup includes time-of-flight detector systems, denoted as TOF400 and TOF700. As shown in *Figure 6*, the TOF detectors are positioned along the beam line at different distances from the interaction point. These detectors are used for particle identification by measuring the time required for particles to travel a known distance from the interaction point to the detector.

The principle of operation is based on the measurement of the particle flight time. When a particle is produced in a collision, it travels through the detector system and reaches the TOF detector after a certain time interval. By measuring this time and knowing the distance between the interaction point and the detector, the velocity of the particle can be determined.

The particle velocity is an important parameter for identification. When combined with momentum information obtained from tracking detectors, it allows determination of the particle mass and therefore identification of different particle species produced in heavy-ion collisions.

The TOF400 detector is positioned closer to the central region of the experimental setup and covers the main acceptance region of the experiment. It is used for measurements of particles with a wide range of momenta. The TOF700 detector is located further downstream along the beam line and extends the range of measurements to particles that travel longer distances.

The presence of two TOF systems allows improved coverage and contributes to more reliable particle identification across different regions of the detector. This is particularly important in heavy-ion experiments, where a large number of particles is produced in each event.

Although the TOF detectors are not directly used for fluence determination in this work, they are part of the beamline environment through which the beam propagates before reaching the irradiation station. Their presence defines part of the experimental geometry and contributes to the overall understanding of beam conditions.

1.3 Ionization chambers

Monitoring of the beam intensity during irradiation is performed using ionization chambers. These detectors measure the electric charge produced by ionization of the gas inside the chamber when charged particles pass through it.

Ionization chambers are widely used in irradiation experiments due to their ability to provide stable and continuous measurements of beam intensity. In applied research, where

materials are exposed to radiation over extended periods, it is necessary to monitor the beam in a reliable and reproducible way.

The chambers operate in a regime where the collected charge is proportional to the number of ionizing particles passing through the detector. They provide reliable operation over a wide range of beam intensities, which is important for experiments with varying beam conditions. This allows direct measurement of beam intensity and makes ionization chambers suitable for quantitative analysis of irradiation conditions.

Two ionization chambers, denoted IK-1 and IK-2, were developed for applied research at the NICA facility and for use at the long-term irradiation station located in the BM@N experimental area. These chambers are designed to operate with high-energy heavy ion beams used in irradiation experiments in order to monitor the beam intensity.

The IK-1 chamber has an active area of 160×160 mm and uses electrodes made of foil-clad fiberglass. The IK-2 chamber has a smaller active area of 100×100 mm and uses electrodes made of foil-clad polyimide. In both chambers the electrodes form a sensitive region where ionization occurs when the beam passes through the detector volume.

An electric field is applied between the electrodes of the chamber. When ionizing particles cross the gas volume, they produce pairs of electrons and ions. These charges are collected by the electrodes, producing an electric signal that is proportional to the intensity of the incident beam. Therefore, the signal from the chamber is collected under an applied electric field, which ensures efficient transport of charge carriers and stable detector response during operation.

This type of detector is particularly suitable for beam diagnostics in irradiation setups, where precise knowledge of beam intensity is required for determination of particle fluence. Stable and reliable monitoring of particle flux makes it useful for continuous operation during long irradiation periods.

1.4 Strip chamber detector

A strip chamber detector is also included in the experimental setup for monitoring variations of the beam position and spatial distribution.

This detector consists of multiple readout strips that allow the determination of the beam profile across the detector surface. By analyzing the signals from the individual strips it is possible to determine the position of the beam and observe possible variations in the beam shape during irradiation.

Such monitoring is important for ensuring that the beam is properly aligned with the position of the irradiated sample. This detector is also used for determination of beam coordinates during irradiation.

1.5 Luminophor detector and camera system

Visualization of the beam profile is performed using a luminophor detector. A luminophor screen emits visible light when it is excited by the incoming ion beam.

When the beam interacts with the screen, light is produced as a result of the excitation of the luminophor material. This light signal is recorded by a camera placed in front of the

detector. The camera system allows direct observation of the beam spot and its position during the irradiation process.

The images recorded by the camera are used for qualitative monitoring of the beam and for verification that the beam is correctly aligned with the irradiated sample.

According to the developed setup for irradiation experiments, the luminophor detector works together with the ionization chambers and strip chamber to provide information about the beam conditions during operation. A mirror system can be used to direct the emitted light towards the camera, allowing flexible positioning of the detector system.

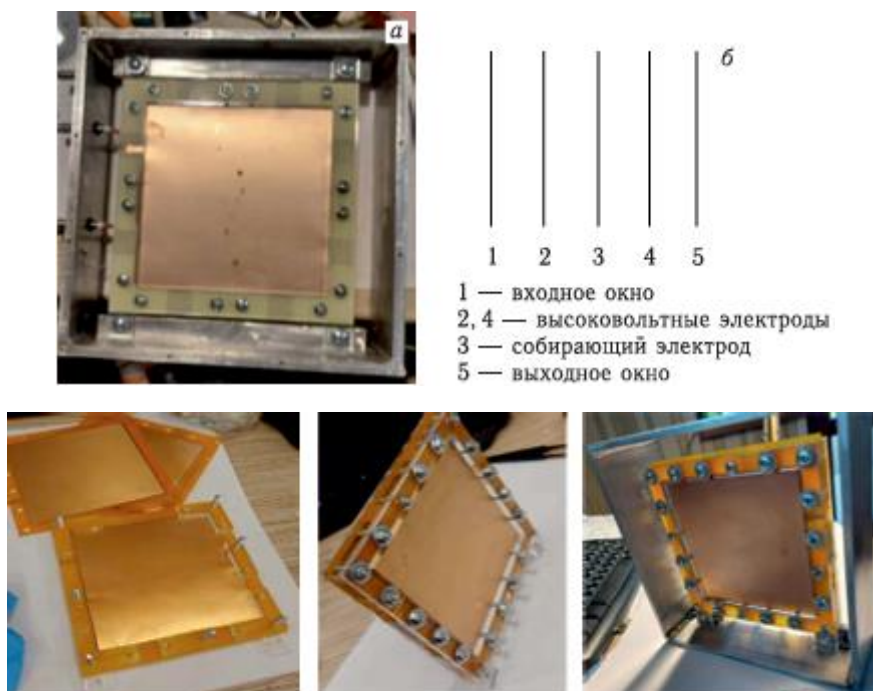


Figure 7. Cameras used for collecting data (Up: IK-1; Down: IK-2).



Figure 8. Mirror system used to direct the emitted light towards the camera.

1.6 Sample holder and irradiation geometry

The irradiated material sample (target) is placed on a sample holder located in the beam path. The holder allows positioning of the sample inside the irradiation region.

In the current setup two sample holders are available, although in this experiment one of them is used for repeated irradiation measurements of the same sample. The exact composition of the irradiated material will be specified after the experimental conditions are finalized.

The position of the sample relative to the beam is an important parameter for the calculation of particle fluence and absorbed dose.

1.7 Data acquisition system

The experimental setup is connected to a data acquisition system that allows simultaneous operation of the detectors and monitoring devices.

Dedicated software is used for collecting data from the detectors and camera systems. The signals from the ionization chambers, strip chamber and luminophor detector are recorded and stored in a database for further analysis.

The data acquisition system is connected to a central server that operates within the ARIADNA data grid infrastructure. This system ensures that data from different detectors are collected in parallel and can be processed for further analysis of beam parameters and irradiation conditions.

2 Experimental procedure

2.1 Irradiation procedure

The experiment is performed using a high-energy heavy ion beam provided by the NICA accelerator complex in the BM@N experimental area. During operation, the ion beam is extracted and transported through the detector system before reaching the irradiation station.

At the irradiation station, the beam passes through the monitoring detectors and then reaches the position where the material sample is placed. The irradiation is performed in a controlled regime, where the beam conditions are monitored continuously during the exposure.

The experimental setup allows repeated irradiation of the same target. For this reason, one sample holder is used multiple times in order to study the accumulated effects of radiation under similar beam conditions.

During the irradiation, several detector systems operate simultaneously. Ionization chambers are used to monitor the beam intensity, while the strip chamber and luminophor detector provide information about the beam position and spatial distribution. The camera system records the light emitted from the luminophor screen, allowing visual control of the beam spot.

Before irradiation, the initial state of the target is recorded. After irradiation, the material can be analyzed in order to observe changes caused by interaction with heavy ions. Such changes are important for understanding radiation effects in materials.

All detector signals are collected through the data acquisition system and stored for further analysis.

Among these systems, time-of-flight detectors are of particular importance and are described in the following section.

2.2 Beam monitoring

Accurate determination of the beam parameters is necessary for further calculation of fluence. For this purpose, multiple detector systems are used in parallel. In addition to ionization chambers, silicon detectors can be used for precise counting of heavy ions in the beam. These detectors provide direct measurement of the number of particles passing through the system, which is important for accurate determination of fluence.

The ionization chambers provide a measurement of the beam intensity by collecting the charge produced in the detector gas due to ionization. The measured signal is proportional to the number of charged particles passing through the detector.

The strip chamber detector provides information about the spatial distribution of the beam. By analyzing the signals from different strips, it is possible to determine the position of the beam and observe possible variations during irradiation.

In addition, the luminophor detector together with the camera system allows direct visualization of the beam profile. This provides a qualitative confirmation of the beam position and alignment with respect to the target.

The combination of these measurements ensures that both the intensity and the geometry of the beam are known during the irradiation process.

2.3 Samples

The experiment is focused on irradiation of material samples under controlled beam conditions. In the present study, the investigated material (target) is glass, while other materials such as graphene and microchannel plates (MCP) are considered for future measurements.

The samples are mounted on a sample holder and positioned in the beam path during irradiation. In the current setup, one sample holder is used repeatedly for multiple irradiation cycles.

The aim of the irradiation is to study changes in the material caused by interaction with heavy ion beams. These changes can be analyzed by comparing the state of the sample before and after irradiation.

The determined fluence corresponds to the total number of particles incident on the target and represents the key parameter for analysis of radiation effects in the material.

2.4 Data processing

The data recorded during the experiment are processed using the data acquisition system connected to the experimental setup.

Signals from the ionization chambers, strip chamber and camera system are collected and stored in a database for further analysis. The processing includes extraction of beam intensity values, verification of beam stability and evaluation of the irradiation conditions.

Dedicated software is used to handle the recorded data and to ensure that all detector systems operate simultaneously during the measurement.

The processed data are then used for the calculation of fluence and for further analysis of the irradiation effects on the target.

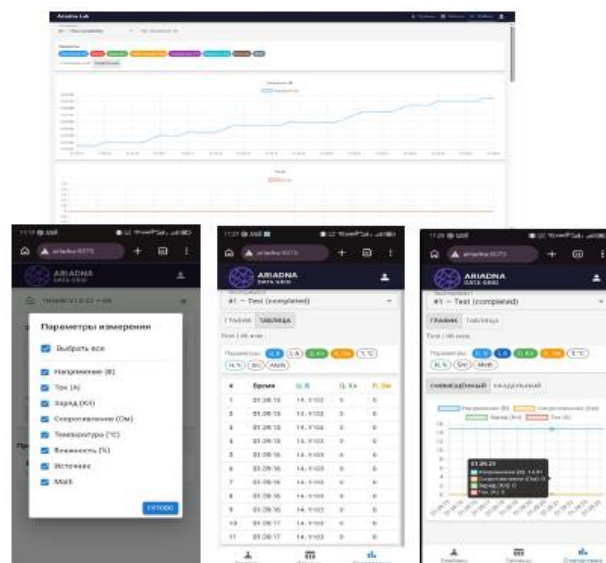


Figure 9. Data from cameras and detectors is stored in the database.

2.5 Sources of uncertainty

Several factors can influence the accuracy of the fluence determination.

One source of uncertainty is related to the approximation of the beam profile. In the calculation, the beam is assumed to have a uniform distribution over a simple geometrical shape. In reality, the beam intensity is not perfectly uniform and is typically higher in the central region.

Another source of uncertainty is related to the alignment of the target with respect to the beam. Small deviations in position can lead to variations in the number of particles incident on the sample.

Additional uncertainties may arise from the detector response and measurement precision of the ionization chambers and other monitoring devices.

These effects should be taken into account when interpreting the calculated values of fluence.

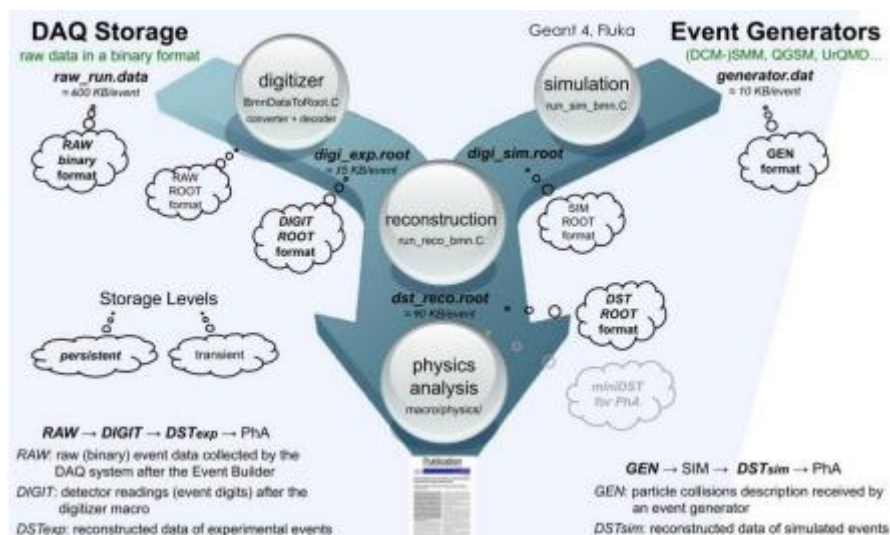


Figure 10. Schematic representation of event data processing in the BM@N software framework.

The irradiation measurements are performed two times, which allows comparison between the measurement periods and verification of the stability of the collected data.

3 Fluence Determination

3.1 Definition of fluence

In radiation measurements, particle fluence is defined as the number of particles incident on a given surface per unit area. It represents a fundamental quantity used for the characterization of radiation fields.

The fluence is defined as:

$$\phi = \frac{dN}{dA},$$

where ϕ is the fluence, N is the number of incident particles, and A is the area through which the particles pass. The unit of fluence is particles per unit area, typically expressed in particles/cm². In the present experiment, the value of N is obtained from the measurements of the beam intensity, while the area A corresponds to the effective area of the beam or the irradiated target.

3.2 Fluence calculation

The determination of fluence requires knowledge of both the total number of particles in the beam and the geometrical characteristics of the beam profile. The beam intensity can be interpreted as the particle flow through the system. From the measured intensity, the total number of particles can be determined, which is then used for fluence calculation.

For the purpose of calculation, the beam cross-section is approximated by a simple geometrical shape. In many cases, the beam profile can be represented by an elliptical distribution. The area of the beam cross-section is then calculated using the expression for an ellipse:

$$A = \pi \cdot a \cdot b,$$

where a and b represent the semi-axes of the ellipse.

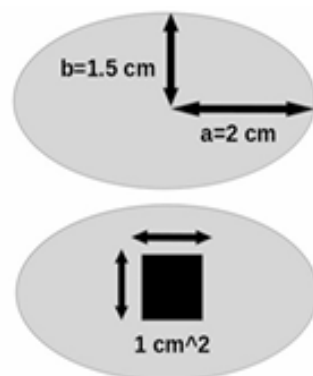


Figure 11. Beam-sample geometry (Up: Geometric representation of the ion beam; Down: Location of the sample, in respect to the beam, its geometric representation and area)

Assuming that the particles are distributed uniformly over the beam area, the number of particles per unit area can be determined by dividing the total number of particles by the beam area. The number of particles incident on the target is then obtained by multiplying this value by the area of the target.

Finally, the fluence is calculated as the number of particles per unit area of the target, according to the definition given above. The determined fluence is the key parameter for analysis of radiation effects.

4 Results

4.1 Beam monitoring results

During the irradiation, beam parameters are continuously monitored using the detector systems described in the previous sections. The ionization chambers provide time-dependent measurements of beam intensity, while the strip chamber and luminophor detector give information about the spatial distribution of the beam. Initial tests of the setup were performed using electron and proton beams. The present results confirm that the setup operates correctly under heavy ion beam conditions.

The recorded signals allow verification that the beam remains stable during the irradiation process. In particular, the measurements from the ionization chambers can be used to observe variations of beam intensity over time.

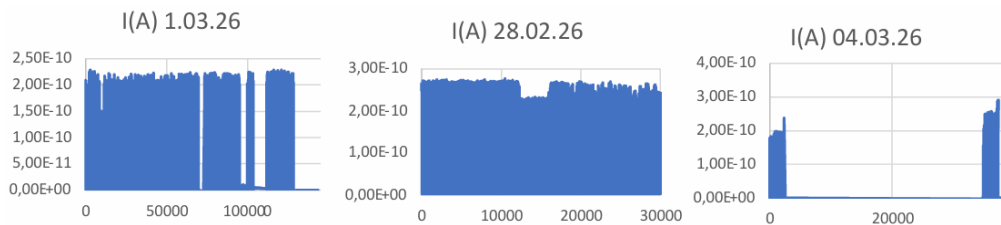


Figure 12. Example of beam intensity as a function of time obtained from ionization chamber measurements on 3 separate occasions.

The strip chamber data provide information about the position of the beam. These measurements can be used to verify that the beam remains aligned with the target during the entire irradiation period.

The luminophor detector, together with the camera system, provides visual confirmation of the beam spot. The recorded images show the shape and position of the beam and allow identification of possible deviations or instabilities.

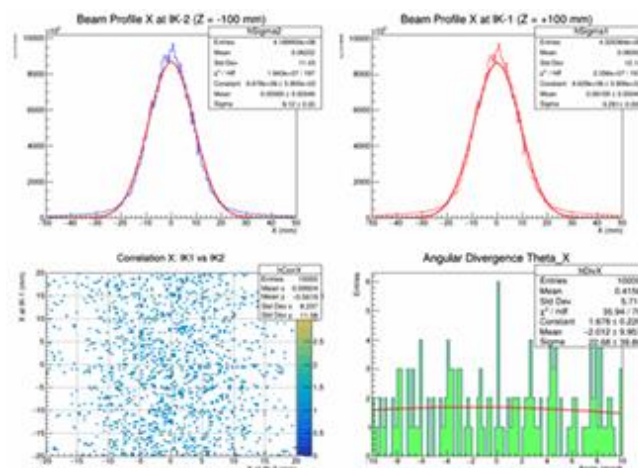


Figure 13. Beam profile recorded using the luminophor detector and camera system.

4.2 Simulation (GEANT)

GEANT-based simulations are used to model the interaction of the ion beam with detector components and materials. These simulations provide information about particle transport and energy deposition and support interpretation of experimental results.

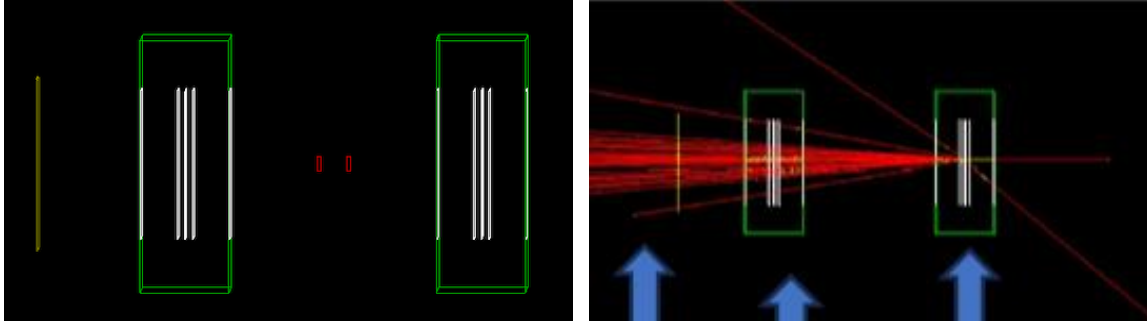


Figure 14. GEANT simulation of the experiment. (Left: representation of the experimental setup which includes Luminofor; ionization chamber and in between them is the target (glass); Right: Representation of the Xe beam during the experiment).

4.3 TOF400 signal analysis

In addition to beam intensity measurements, signals from the TOF400 detector can be analyzed. The recorded time-of-flight information provides insight into the types of particles present in the beam.

The detector signal corresponds to the measured time-of-flight for particles reaching the TOF400 system. From this information, and using known detector geometry, it is possible to distinguish between different particle species.

The obtained signal shows the presence of particle components that can be associated with specific types of heavy ions. The identification is based on the characteristic time-of-flight values corresponding to different particle velocities.

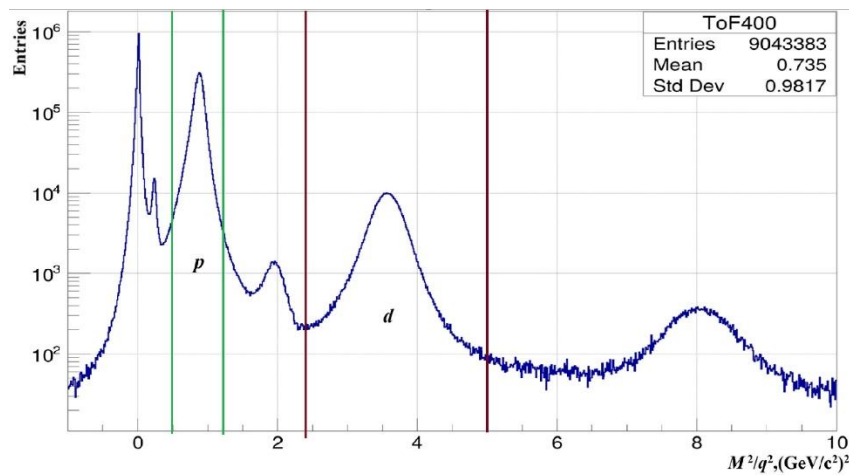


Figure 15. TOF400 signal distribution.

The recorded time-of-flight distribution is further processed using ROOT-based analysis tools. ROOT framework is commonly used in high-energy physics data processing. The data are analyzed using dedicated code in order to obtain more detailed diagnostic representations of the signal.

These processed results allow clearer separation of different particle contributions and provide additional insight into the structure of the measured signal. In particular, characteristic features of the distribution can be identified and associated with specific particle types.

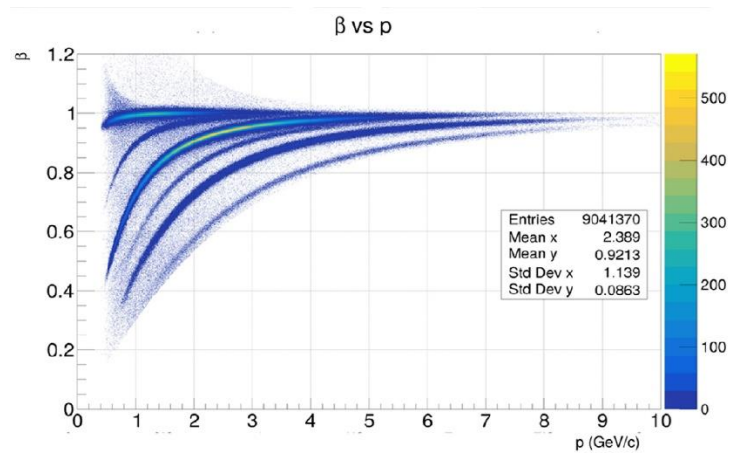


Figure 16. Processed TOF400 data obtained using ROOT analysis.

Although the TOF400 data are not directly used in the calculation of fluence, they provide useful information about the beam content and confirm that the irradiation is performed under expected beam conditions.

4.3 Fluence estimation

Based on the measured beam intensity and the geometrical parameters of the beam, the particle fluence is calculated according to the previously described procedure.

The total number of particles incident on the target is obtained from the ionization chamber measurements, while the effective beam area is determined from the beam profile. The resulting fluence values represent the total particle exposure of the target during irradiation. These values are essential for further analysis of radiation effects on the material.

At this stage, the results are presented in a general form. The obtained results provide a consistent description of the beam conditions during irradiation. The agreement between different monitoring systems confirms that the beam parameters are well controlled. The ionization chambers provide quantitative information about the beam intensity, while the strip chamber and luminophor detector confirm the spatial stability of the beam.

The calculated fluence values depend on both the measured intensity and the assumed beam geometry. Therefore, uncertainties in these parameters directly affect the results.

Conclusion

In this work, an experimental study of ion beam irradiation was performed in the BM@N experimental area at the NICA accelerator complex. The main goal of the experiment was to monitor xenon beam parameters and determine particle fluence during irradiation of a material target, in our case glass.

The experimental setup included several detector systems used for beam monitoring. Ionization chambers were used for measurement of beam intensity, while the strip chamber and luminophor detector provided information about the spatial distribution and position of the beam. The camera system allowed direct visualization of the beam profile during irradiation.

The data acquisition system enabled simultaneous operation of all detectors and recording of measurement data. The collected data were used for analysis of beam conditions and for calculation of particle fluence.

The results show that the beam parameters remained stable during irradiation, which is important for reliable determination of fluence. The calculated fluence values provide the basis for further analysis of radiation effects on the irradiated material.

This work demonstrates that the described experimental setup can be effectively used for beam monitoring and fluence estimation in irradiation experiments at the BM@N facility. The setup is designed for applied research, where different materials can be irradiated and their response to heavy ion beams can be studied under controlled conditions. In the near future, experiments including MCP and graphene as targets are planned.

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