# PARTICLE FLUENCE ESTIMATION FOR SAMPLES IRRADIATED AT A LONG-TERM EXPOSURE STATION (NICA COMPLEX, DUBNA)

## ESTIMACIÓN DE LA FLUENCIA DE PARTÍCULAS PARA MUESTRAS IRRADIADAS EN UNA ESTACIÓN DE EXPOSICIÓN PROLONGADA (COMPLEJO NICA, DUBNA)

M. Pérez-Tápanez[a†], N. Pukhaeva[b,c], N.Zamiatin[b], O. Díaz [a†], D. Chemezov[b]

a) Higher Institute for Applied Sciences and Technology at Havana University, Havana, Cuba.marcela.perez@instec.cu; odrizo@instec.cu[†]
b) Joint Institute for Nuclear Research, Dubna, Russia.
c) North-Ositian State University, Vladikavkaz, Russia.
† corresponding author

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The prototype of the Target Station for Long-Term Exposure was assembled after all detectors of BM@N Experiment. During collection of the physical data with the $^{124}Xe_{54}$ beam of 3.8 GeV kinetic energy at BM@N, different samples were irradiated. Data was analyzed for precise determination of the intensity, the fluence and the absorbed dose for irradiated materials. The beam intensity and profile distributions were determined for each sample. From the obtained intensity, the fluence was calculated for each irradiated sample. Then, the absorbed dose of irradiated materials was be calculated. The study was performed within the ARIADNA Collaboration.

El prototipo de la Estación de Objetivos para Exposición a Largo Plazo fue desplegado al final de la línea de detectores del experimento BM@N. Fueron irradiadas diferentes muestras en el BM@N durante la recopilación física de datos con el haz de iones de $^{124}Xe_{54}$,de energía cinética de 3.8 GeV. Los datos fueron analizados para la determinación precisa de la intensidad, para la estimación de la fluencia y la dosis absorbida de los materiales irradiados. Para cada muestra fueron determinados la intensidad y el perfil del haz. La fluencia fue calculada a partir de la intensidad obtenida para cada muestra. Luego, se calcula la dosis absorbida por los materiales irradiados. Este estudio es llevado a cabo como parte de la Colaboración ARIADNA.

Keywords: fluence (fluencia), absorbed dose (dosis absorbida), high energy ion beam (haz de iones de alta energía ), irradiated samples (muestras irradiadas).

## I. INTRODUCTION

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) is an accelerator complex that is under construction at the Joint Institute for Nuclear Research in Dubna, Russian Federation. The main purpose of NICA is to study the properties of dense baryonic matter [1]. BM@N (Baryonic Matter at Nuclotron) is the first experiment undertaken at the NICA-Nuclotron accelerator complex. Its goal is the study of heavy-ion beams interactions with fixed targets. The beam, extracted from the Nuclotron, is transported to the BM@N experimental installation. Only a 2 % of the beam interacts with the target, and it was decided to use it for applied research. Recently, after the Forward Hadron Calorimeter [2], a new Station for Long-Term Exposure (SLTE) was assembled, which is after all detectors of the BM@N experiment. This station is devoted to the irradiation of samples for applied research. The rest of the beam at the LTE station, in parallel with the operation of the BM@N set-up [3], is used for applied studies of samples of different geometry and chemical composition. Previously, some analyzes were carried out in order to determine the radiation intensity and the profile of the irradiated samples, based on the information from each of the detectors associated with the BM@N experiment [3]. This study was necessary because the samples would be set after the BM@N detector array. Finally, the integral intensity or the total number of ions passing through the samples was estimated [3].

## II. MATERIALS AND METHODS.

### *II.1. Experimental Data Collection.*

In order to estimate the fluence, it is necessary to measure the beam intensity and to determine the physical parameters of each detector located in the beam line. During the Xe beam run [3], Veto Counter (VC) registered a 80 % of the beam. In order to minimize the interactions upstream of the target, the scintillators and active parts of the Si detectors were located in vacuum, while the photomultiplier tubes (PMTs) of the scintillation counters and the front-end electronics of the silicon detectors were kept in air, with their housings mounted on the flanges of the beam pipe. In order to reject the beam halo, the beam aperture was limited by the 25 mm diameter hole in the scintillation counter (VC). Independently, the beam ions or expected fragments can be detected by a 4 mm thick quartz hodoscope (FQH), located in front of the beam hole. Information from the hodoscope is used in outline analysis for event selection and determination of event centrality.

### *II.2. Computer Analysis.*

All data were written on an e-Log platform from the number of runs for each corresponding data. Initially, data are written in binary format, and then digitized to Root format. Information about the bean profile is written as DST.exp files for each run. By analyzing these files, a miniDST file is created to keep all necessary information [4]. BmnRoot software [3] was used for the information processing.

### *II.3. Dosimetrical Analysis.*

The *absorbed dose* (D) is a measure of the effect caused by radiation on materials. It is relevant to all types of ionizing radiation fields (directly or indirectly), as well as to any ionizing radiation source distributed within the absorbing medium. It is defined as:

$$D = \frac{d\varepsilon}{dm} \tag{1}$$

where, $d\varepsilon$ is the expected energy value of a particle impacted by finite volume V, and $dm$ is the mass differential [5].

The fluence of particles ($\phi$), in dosimetric studies, is a measure of the number of ionizing particles that arrive at the detector surface in a given time. It is defined as:

$$\phi = \frac{dN}{dA} \tag{2}$$

where, $N$ is the number of particles (nucleons) that arrive at the area, and $A$ is the surface area (cm$^2$). It is an important parameter, because it is used to estimate the *absorbed dose*. Therefore, the unit of measurement for fluence is the particles per square centimeter [5].

For charged particles, it is possible to obtain the *absorbed dose* value from the fluence, if the target thickness is a few percent or less of the range. Then, the energy lost in collision interactions for a fluence $\phi$ (charged particles$\cdot$cm$^{-2}$) of energy will be:

$$E = \phi\left(\frac{dT}{\rho dx}\right)\rho x \tag{3}$$

where, $dT/\rho dx$ is the collision stopping power of the foil mass, and the density thickness ($\rho t$), is the length of the particle path through the foil. Hence, the absorbed dose in the foil can be estimated as

$$D = \phi\frac{\left(\frac{dT}{\rho dx}\right)\rho x}{\rho x} = \phi\left(\frac{dT}{\rho dx}\right) \tag{4}$$

where, the foil thickness $\rho x$ must be canceled, leaving the dose as a product of fluence and mass collision stopping power. This cancellation is very important, taking into account that the dose in the foil, does not depend at the thickness [5].

### *II.4. Irradiated samples.*

Before the experiment, scientific and methodological tasks were selected to establish the main parameters of the beam and irradiation schemes for each type of sample [6].

Different tasks were related to the study of protective properties, radiation resistance, and radio modification of composite materials for the space industry, developed and produced at V. G. Shukhov Belgorod State Technological University (BSTU) [6]. It is also of interest in some research related to support, for spacecraft crews, in the study of the effect induced by heavy ions on seed germination and plant development features. In that sense, the structural modification and state of matter as a result of the action of accelerated ion beams on artificial sapphires ($Al_2O_3$) is studied.

Furthermore, radiation damage of thin polymer films (up to 100 μm thick) films, based in polytetrafluoroethylene (PTFE) and thermo-radiationally modified PTFE, polyethylene terephthalate, polyimides, and the irradiation of high-temperature superconducting tapes (1st and 2nd generation), produced by JSC "S-Innovations" (Moscow) [6], was also studied during the experiment.

The program also includes the study of the effects induced by the irradiation of targets of some metals, and measurement of the induced activity. In particular, the isotopes $^{7}$Be, $^{22}$Na and $^{24}$Na, in the spectra of the aluminum-irradiated targets [6].

## III. RESULTS AND DISCUSSION

### *III.1. Fluence estimation.*

To determine the *fluence*, it is necessary to know the dimensions of the incident beam and the irradiated sample, as well as the coordinates where the sample is located. To achieve it, it was assumed that the sample was located just in the center of the ion beam and also that nucleons, in the beam, are distributed homogeneously. The geometry of the beam sample is presented in Figure 1.

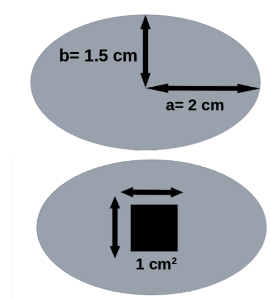


Figure 1. Bean-sample geometry. Top panel: geometric representation of the ion beam, including the dimensions of the surface radius a and b. Bottom panel: location of the sample, respect to the beam, its geometric representation and area [7]).

The shape of the beam has been approximated as an ellipse, whose radii a and b have values of 2 cm and 1.5 cm, respectively. The ellipse area represents the surface of the beam. It was calculated as follows:

$$A = \pi \cdot a \cdot b \tag{5}$$

resulting in a value of 9.4248 cm$^2$, and the sample has a squared shape with an area of 1 cm$^2$. The beam intensity was obtained by reading the results ejected by the FQH detector at the end of the beam line [6]. This value represents the total number of nucleons transported by it [6].

To determine the number of nucleons affected in the sample, we divided the total number of nucleons by the area of the ellipse. That shows how many nucleons are found in a unit of area, and then this result must be multiplied by the area defined by the sample. This value represents the fluence of the particles in the area of interest (da), introduced in the equation (2). The approximate value of the deposited energy was also estimated, knowing that the $^{124}Xe_{54}$ beam has an energy of 3.8 GeV $\cdot$ nucleon$^{-1}$. This energy is multiplied by the number of incident nucleons on the sample area ($\phi$). Finally, the total number of measured nucleons and the fluence calculated for each sample are shown in Table 1.

Table 1. Measured intensity, fluence (nucleons$\cdot$cm$^{-2}$), and energy distribution (GeV $\cdot$ cm$^{-2}$) for each of the samples. [7]

| **Samples** | **Intensity** | **Fluence** | **Energy distribution** |
|---|---|---|---|
| Seed I | 2.42622e+08 | 6.4e+06 | 2.43e+07 |
| Seed II | 2.47850e+08 | 6.6e+06 | 2.51e+07 |
| Seed III | 3.46815e+08 | 9.2e+06 | 3.50e+07 |
| Seed IV | 2.24907e+08 | 6.6e+06 | 6.6e+06 |
| Sapphire + Films + Al | 5.79354e+09 | 1.5e+08 | 5.7e+08 |
| Add composite ROCC + VTSP(1) | 4.86455e+09 | 1.3e+08 | 4.94e+08 |
| Add composite MCS + VTSP(2) | 2.39928e+09 | 6.4e+07 | 2.43e+08 |

### *III.2. Uncertainty sources.*

The first source of uncertainty comes from the fact that, between the sample and the FHQ hodoscope, there is a distance of 2 meters in air [3]. Therefore, when the ion beam crosses that distance, traveling from one point to another, it is possible that there are interactions, deviations, and/or energy loss that were not measured. The last causes the 100 % of the real intensity of the radiation to not be recorded. The second source of uncertainty is that we have considered that the nucleons throughout the beam are distributed homogeneously [8], in an elliptical geometry. This is an approximation, since, in reality, the nucleons tend to concentrate at the center of the beam, as shown in Figure 2.

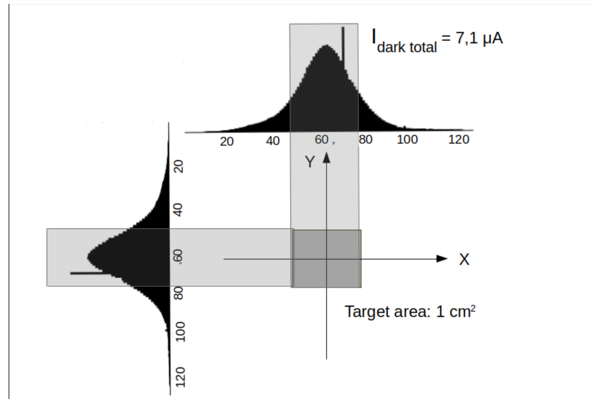


Figure 2. Gaussian intensity distribution and sample position [7]

## IV. CONCLUSION

The particle fluence of the analysis of beam data that was taken during physical data collection with the $^{124}$Xe beam of the 3.8 A GeV kinetic energy at the BM@N installation in the 8th Commissioning Run of the NICA Complex was calculated. This is the first experiment of irradiation of different samples for applied research in the LTE Station with high energy ions. The uncertainties of the results were analyzed to improve the precision of the calculations. Further studies are in progress to compare the parameters obtained by Monte Carlo simulations.

## V. ACKNOWLEDGMENTS


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