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

Final Report of the START Program

First Results of Calculation of Fluency for the Determination of Absorbed Dose of Irradiated Samples During of Run8.

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Abstract

A method for analysis of the intensity and profile data of the 3.8 GeV/nucleon $^{124}Xe^{54+}$ ion beam is used for precise determination of fluence on irradiated materials. The beam profile and intensity distributions together with overall intensity are analyzed for calculation of fluence for a set of samples of different geometries and chemical compositions. Raw data were collected in a long-term exposure mode. This is the only option which is currently available in the target station of ARIADNA in the NICA facility. The intensity measurement required further study that included the effect of passing thought each detector before the beam reached the target. The result of the fluence obtained will be used for further precise calculation of energy losses and absorbed dose in irradiated materials. This study is performed within the frames of the ARIADNA collaboration.

Content

1. Introduction

Nuclotron-based Ion Collider fAcility (NICA) is an accelerator complex which is under construction at the Joint Institute for Nuclear Research to study properties of dense baryonicmatter. Besides of basic fundamental research program at NICA have big part of applied research as well, which will be held at several dedicated stations. [1]

1.1 NICA Complex

The NICA complex's scheme of the is shown in Figure 1. It includes an injection complex, a new superconducting synchrotron Booster, a superconducting heavy ion synchrotron Nuclotron (which is currently being developed to meet the project specifications), a collider that has two new superconducting storage rings and new channels beam transfer. The beamline and Station Of Chip Irradiation (SOCHI) was completed in December 2021 and was running during of last data taking of Nuclotron. New station, which is the Station for Long-Term Exposure were assembled behand BM@N experiment. Other stations: SHINE, ISTRA, SIMBO are still under construction and will be developed near future.

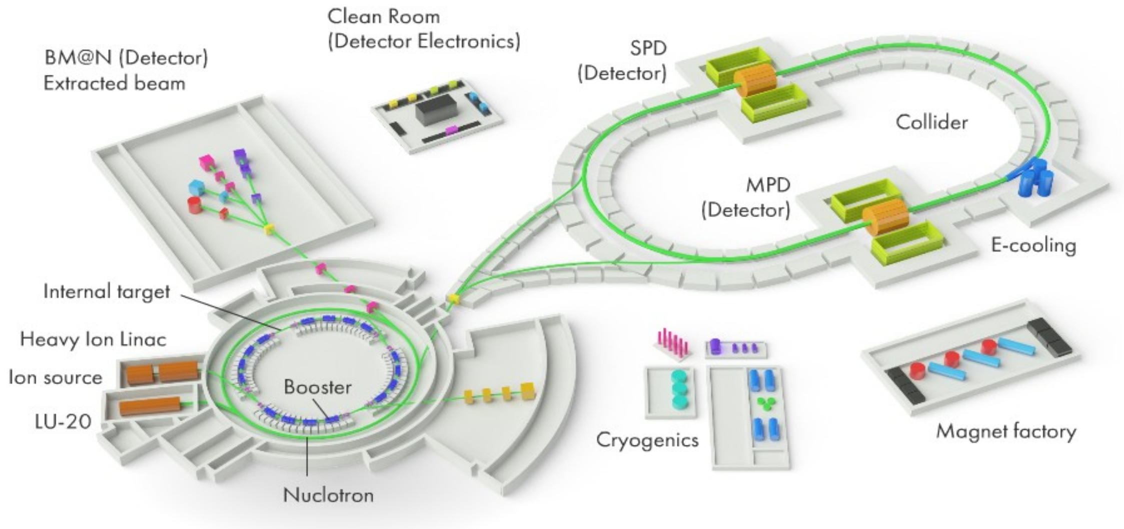


Figure 1: Scheme of the structure of the NICA Complex. [1]

1.1.1 BM@N Expriment and Target Station

BM@N (Baryonic Matter at Nuclotron) is the first experiment undertaken at the accelerator complex of NICA-Nuclotron. The aim fo the BM@N experiment is to study interactions of relativistic heavy ion beams with fixed targets [2].

The beam extracted from the Nuclotron is transported to the BM@N experimental area. Figure 2 shows a schematic view of the BM@N setup, used in the first physics run in 2023 with a Xe beam, with Station of LTE for applied research. The target station is located at the end of the second beam pipe section. It is designed to provide the possibility to insert a target in the beam line inside the vacuum volume and to interchange several targets without breaking the vacuum.

In 2023 Xe Run, three disk targets with a diameter of 3.2 cm were used: 1.75 mm thick CsI, 0.85 mm thick CsI, and 1.02 mm thick Ge. One frame of the target assembly was left empty and was used to evaluate the background level caused by the interaction of beam particles with the structural elements of the target station [3]. The target station of LTE has an advantage to use beams for applies research purposes in parallel with operation of the BM@N setup.

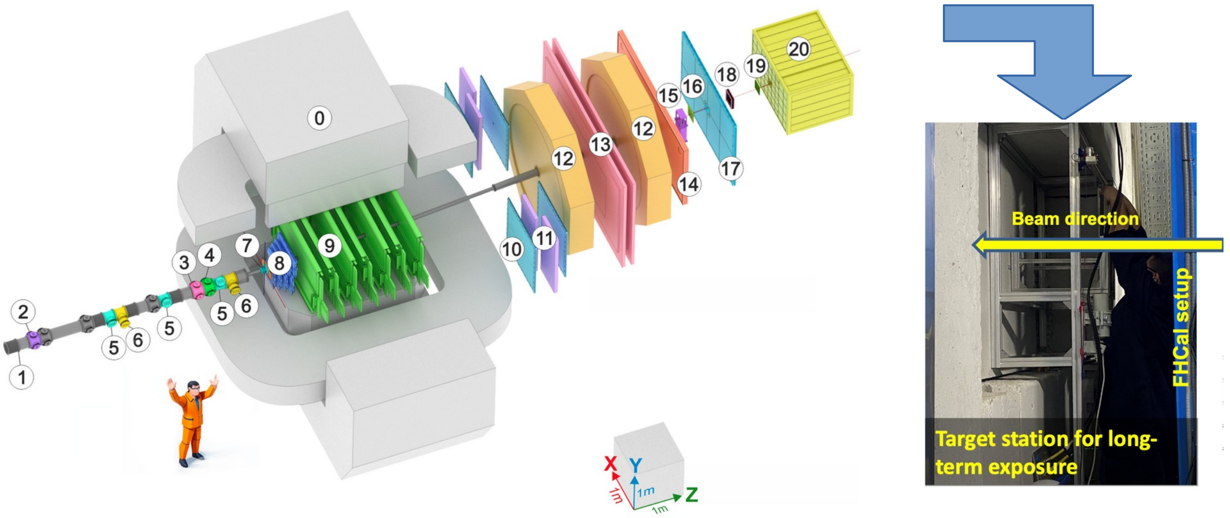


Figure 2: Schematic view of the BM@N setup in the 2023 Xe run with long-term station after FHCal. Main components: 0) SP-41 analyzing magnet, 1) vacuum beam pipe, 2) BC1 beam counter, 3) Veto counter (VC), 4) BC2 beam counter, 5) Silicon Beam Tracker (SiBT), 6) Silicon beam profilometers, 7) Barrel Detector (BD) and Target station, 8) Forward Silicon Detector (FSD), 9) Gaseous Electron Multiplier (GEM) detectors, 10) Small cathode strip chambers (Small CSC), 11) TOF400 system, 12) drift chambers (DCH), 13) TOF700 system, 14) Scintillation Wall (ScWall), 15) Fragment Detector (FD), 16) Small GEM detector, 17) Large cathode strip chamber (Large CSC), 18) gas ionization chamber as beam profilometer, 19) Forward Quartz Hodoscope (FQH), 20) Forward Hadron Calorimeter (FHCal). [2]

Previous analyzes were recently carried out to determine the radiation intensity and the profile of the irradiated samples, based on the information from each of the detectors of the BM@N experiment. A study about the configuration of the detectors was necessary, because the sample would be located after the entire detector array. With this information, and the measurement of the profile and intensity of the ion beam during each Run, the calculation of the intensity integral for each sample was carried out. [4]

The goal of the work is to calculate particle fluence from the analysis of beam data that were taken during physical data collection with 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.

2. Methodology

2.1 Experimental Data Collection.

A section of the experiment is shown schematically in Figure 3. To calculate fluence it is necessary to obtain the value of the intensity, and also, to determine the physical parameters of each detector positioned in the beam line. The parameters are shown in Table 1.

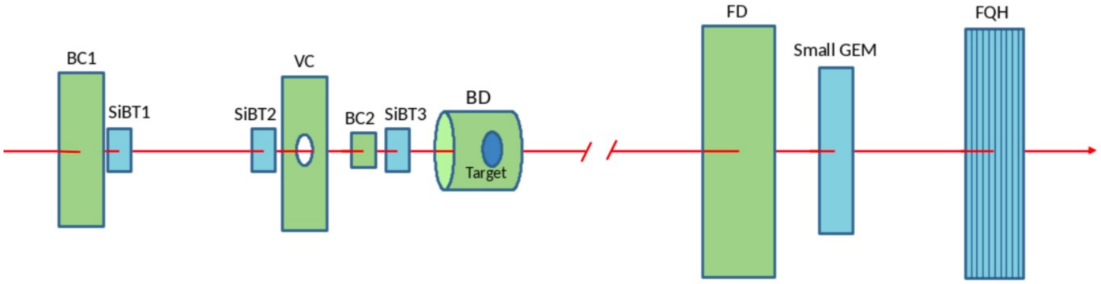


Figure 3: The beam, trigger, and fragment detector layout. [3]

Detector	Z position (cm)	Active area (mm×mm)	Material	Thickness (mm)
BC1	-422	100 × 100	Scint. BC400B	0.25
SiBT1	-283	61 × 61	Silicon	0.175
SiBT2	-183	61 × 61	Silicon	0.175
VC	-124	113 × 113 (hole ⊘ 25)	Plastic Scint.	4
BC2	-104	34 × 34	Scint. BC400B	0.15
SiBT3	-84	61 × 61	Silicon	0.175
FD	+784	150 × 150	Scint. BC408	0.5
Small GEM	+793	100 × 100		
FQH	+970	160 × 160	Quartz	4

Table 1: Physical characteristics of the detectors located in the beam line. [3]

In the 2023 Xe Run, an 80 % of the beam was accepted by the Veto Counter (VC). In order to minimize interactions upstream of the target, the scintillators and active parts of the silicon detectors were located in vacuum, while the pho-tomultiplier tubes (PMTs) of the scintillation counters and the front-end electronics of the silicon detectors are kept in the airwith their housings mounted to the flanges of the beam pipe. The beam aperture is limited by the 25 mm diameter hole in the scintillation (VC), which rejects the beam halo.[3]

The beam ions or spectator fragments can be detected by a 4 mm thick quartz hodoscope FQH located in front of the beam hole in the FHCal. Information from the hodoscope is used in the offline analysis for event selection and determination of event centrality. The small GEM detector is placed between the FD and FQH and used to monitor the position, shape and spot size of the beam downstream of the analyzing magnet. From hodoscopes we are getting distribution for beam intensity. Our samples are ~2 m from these FQH, beam are in air and passing through FHCal. The FHCal has a granular structure in the transverse and longitudinal planes. Beam ions that did not interact pass to a beam dump located behind the FHCal through the hole in the center of the calorimeter. [4]

2.2 Computer Analysis of Data

Several sources were analyzed to get all necessary information. All data are written at e-Log platform from were we can get number for run for corresponding data. In the beginning the data is written by Binary format, then digitize writing in Root format, and this is the file that we will analyze, file by file for the dates when samples where putted at beam. This DIGIT files keeps information for each detector, and we are analyzed for beam line detectors: FD, small GEM,FQH. Information of profile of beam written at DST_exp files, for each run for corresponding dates. By analyzing these files we are creating miniDST which keeps all necessary information.

To carry out this processing, BmnRoot software was used [5]. Figure 4 shows schematically how the files are processed for the physical analysis of the event data.

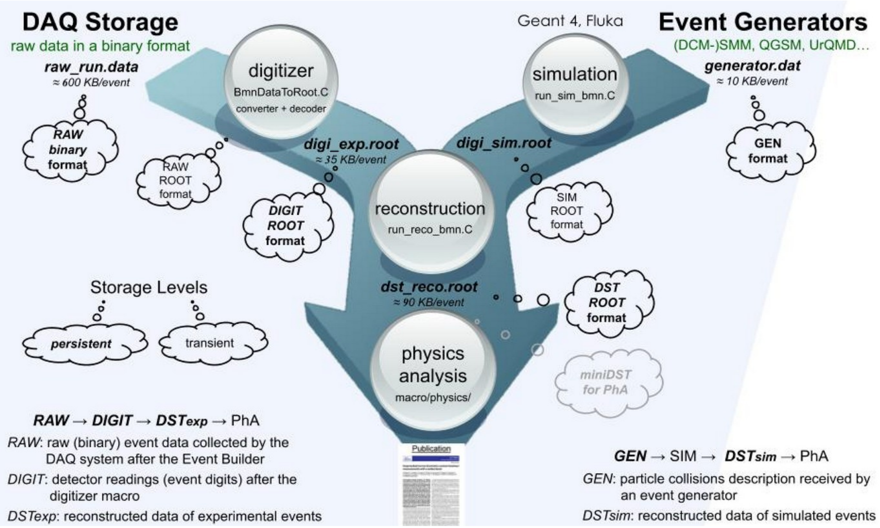


Figure 4: Event Data Processing in BmnRoot

2.3 Dosimetric analysis of the samples

2.3.1 Absorbed Dose

Absorbed dose is a measure of the effect caused by radiation on materials. It is relevant to all types of ionizing radiation fields, whether directly or indirectly ionizing, as well as to any ionizing radiation source distributed within the absorbing medium[6]. We can define the absorbed dose D at any point P in a volume V as

$$D=d\varepsilon/dm \quad (1)$$

Where ε is the expectation value of the energy imparted in the finite volume V during some time interval, and dm is the mass in dv. Thus the absorbed dose D is the expectation value of the energy imparted to match per unit mars at a point [6].

2.3.2 Definition and calculation of Fluence

Particle Fluence in dosimetry is a measure of the number of ionizing particles that pass through a given surface in a given time. It is an important parameter in dosimetry because it is used to calculate the absorbed dose, which is the amount of energy deposited by radiation in a material. It is defined as the number of particles incident per unit area. This physical magnitude is calculated as

$$\phi = d(N)/da \quad (2)$$

Where ϕ represents the fluence value, N is the number of particles (nucleons) that arriving on the area, A is the surface area (in cm^2). Therefore, the unit of measurement for fluence is particles per square centimeters.

In our work, the value of the number of particles was obtained by calculating the integral of the beam intensity, measured in all the Root files that were obtained in each run for the different samples [4]. Knowing the characteristics of the ion beam, as well as the geometry of each sample, it is possible to determine, from the total number of nucleons contained in the beam, how many of them impact the sample.

2.3.3 Physical Relationship between the Absorbed Dose and the Fluence

For heavy charged particles it is feasible to obtain the Absorbed Dose value from the fluence if the thickness of the sheet is only a few percent or less of the range. The energy lost in collision interactions by a fluence ϕ (charged particles/cm^2) of energy To passing perpendicularly through a foil of mass thickness ρt (g/cm^2) is:

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

Where $\left(\frac{dT}{\rho dx}\right)$ is the mass collision stopping power of the foil medium, and ρt is the particle path length through the foil. Under assumption c the energy thus lost by the particles remains in the foil as energy imparted. Hence the absorbed dose in the foil can be gotten as:

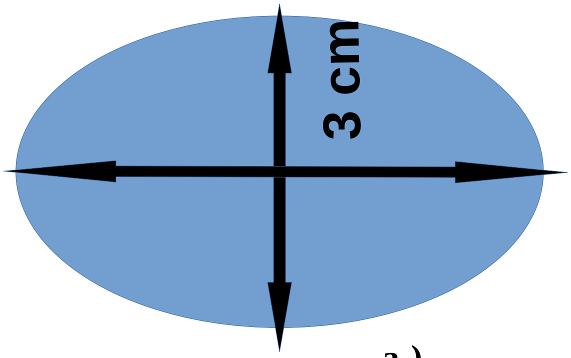
$$D=\phi\frac{\left(\frac{dT}{\rho dx}\right)\rho x}{\rho x}=\phi\left(\frac{dT}{\rho dx}\right) \quad (4)$$

Where the foil mass thickness ρt cancels, leaving the dose as simply the product of fluence and mass collision stopping power. This cancellation is very important, meaning that the dose in the foil is independent of its thickness as long as the particles travel straight through and do not lose enough energy to cause the stopping power to change significantly. [6].

3. Results and Discussion

3.1 Fluence calculating

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 it is located. For these first calculations, it is considered that the sample is located right in the center of the ion beam, and it is also considered that the nucleons in the beam are distributed homogeneously, that is, that there are the same number of nucleons throughout the area. that comprises the beam. A schematic representation of the geometry of the beam and the sample is shown in Figure 5.



a-) **b-)**

Figure 5: a-) Geometric representation of the ion beam, including the dimensions of the main axes. b-) Location of the sample with respect to the beam, its geometric representation and area value.

As can be seen, the shape of the beam has been approximated to an ellipse, whose main axes have a value of a=2 cm and b=1.5 cm. The area of the ellipse that represents the surface of the beam was calculated as:

$$A=\pi\times(a\times b) \quad (5)$$

Resulting in a value of 9.4248 cm^2, and the sample has a square shape with an area of $1cm^2$.

The value of the beam intensity was obtained by reading the results ejected by the FQH detector at the end of the beam line [4], this value represents the total number of nucleons that are transported by it.

To know the number of nucleons that affect the sample, the number of nucleons was divided by the area of the ellipse, this shows how many nucleons are found in a unit of area, and then this result must be multiplied by the area occupied by the sample.. This value represents the flow of particles over the area of interest, as expressed in Formula (2).

Table 2 shows the values of the total number of nuleons measured, and the fluence value calculated for each of the samples.

An approximate value of the deposited energy was also calculated, knowing that the $^{124}Xe^{54}$ beam has an energy of 3.8 GeV/nucleon, this value is multiplied by the number of nucleons incident on the sample area (ϕ), previously calculated. The results are shown in Table 3.

Samples	**Intensity (number of nucleons)**	**Fluence ϕ (nucleons/cm^2)**
Seed I	2.42622e+08	2.6e+07
Seed II	2.47850e+08	2.6e+07
Seed III	3.46815e+08	3.7e+07
Seed IV	2.24907e+08	2.4e+07
Sapphire + Films +Aluminum	5.79354e+09	6.1e+08
Add composite ROCC+VTSP(1)	4.86455e+09	5.2e+08
Add composite MCS+VTSP(2)	2.39928e+09	2.5e+08

Table 2: Measured intensity and calculated fluence for each of the samples.

Samples	**Fluence ϕ (nucleons/cm^2)**	**Energy distribution on the surface (GeV/cm^2)**
Seed I	2.6e+07	9.88e+07
Seed II	2.6e+07	9.88e+07
Seed III	3.7e+07	1.33e+08
Seed IV	2.4e+07	9.12E+07
Sapphire + Films +Aluminum	6.1e+08	2.32E+09
Add composite ROCC+VTSP(1)	5.2e+08	1.98E+09
Add composite MCS+VTSP(2)	2.5e+08	9.5E+08

Table 3: Calculation of the Energy that reaches each sample area.

3.2 Sources of Uncertainty

The first source of uncertainty comes from the fact that between the sample and the FHQ hoboscope there is a distance of two meters that contains air (see Figure 3). Therefore, when the ion beam crosses that distance traveling from one point to another, it is possible that there are interactions, deviations and energy loss that were not measured, this causes 100% of the real intensity of the radiation not to be recorded, but a percent was lost along the way.

The second source of uncertainty is that we have considered that the nucleons throughout the beam are distributed homogeneously, in an elliptical geometry. However, this is an approximation, since, in reality, the nucleons tend to concentrate in the center of the beam, as shown in the Figure 6, so stating that they are distributed throughout the surface in equal parts does not offer an precise value of intensity and fluence.

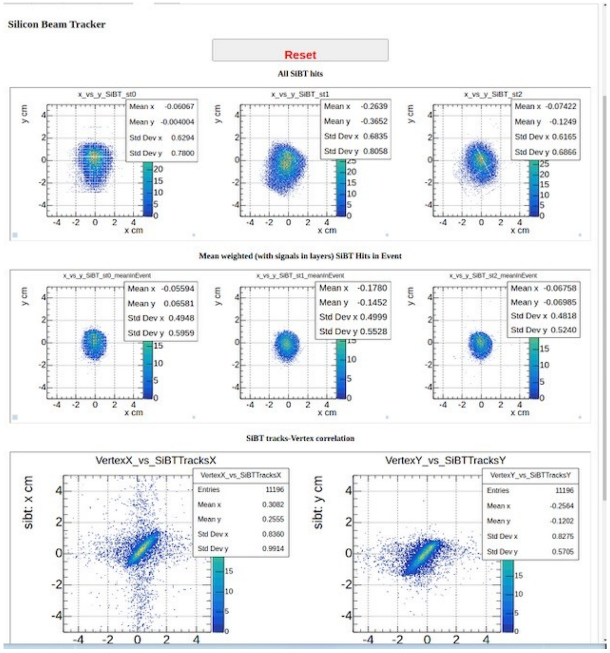


Figure 6: Intensity measured during the Xe Run 2023, for the sample VI "Add composite ROCC+VTSP(1)"[4]

It is also considered that the sample is located right in the center of the incident beam (making the center of coordinates of both coincide). This gives an imprecise result, since it is necessary to know he coordinates in which the sample is located with high precision , and to take into account the distribution of intensity and energy, in order to obtain more realistic results. This is strongly related to the intensity distribution, since, as it is not homogeneous, but concentrated in an area of the geometry, the value of the intensity that the sample receives would also be varying depending on the position in the coordinates in which it is located. Figure 7 shows the Gaussian distribution of intensity. The center of the curve (highlighted in red) shows the maximum values, the sample was located in the center of the beam, to receive as much radiation as possible.

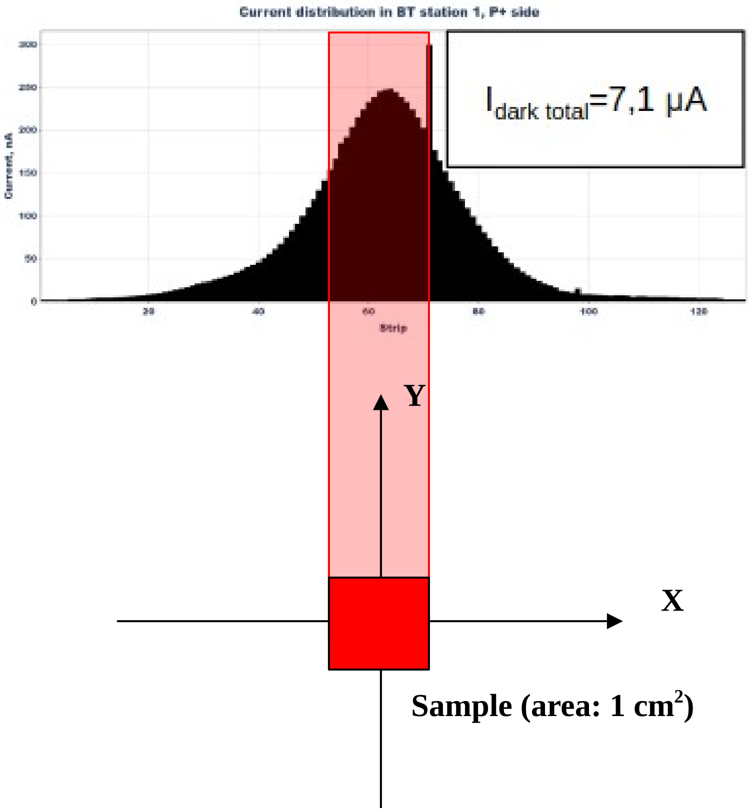


Figure 7: Gaussian intensity distribution and sample position [7]

4. Conclusions

Particle fluence from the analysis of beam data that were taken during physical data collection with 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 of applied research in Station for LTE with high energy ions. Results uncertainty were analyzed, in order to improve the precision of the calculations. More study is necessary for obtaining precise number of intensity and profile of beam. Further studies are in progress in order to compare the parameters obtained in our Monte Carlo simulations with models.

5. References

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6. Acknowledgments

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