# Monte Carlo simulation of a collimation system for low-energy beamline of ELI-NP Gamma Beam System

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**Abstract**

ELI-Nuclear Physics (NP) Gamma Beam System (GBS) is an intense and monochromatic gamma beam source based on inverse Compton interaction, currently being built in Bucharest, Romania. The gamma beam produced, with energy ranging from 0.2 to 20 MeV, energy bandwidth 0.5% and flux of about $10^8$ photons/s, will be devoted to investigate a broad range of applications such as nuclear physics, astrophysics, material science and life sciences. The radiation produced by an inverse Compton interaction is not intrinsically monochromatic. In fact, the energy of the photons produced is related to the emission angle, therefore the energy bandwidth can be modified adjusting the collimation of the gamma beam. In order to define the optimal layout and evaluate the performance of a collimation system for the ELI-NP-GBS low-energy beamline (0.2-3.5 MeV), a detailed Monte Carlo simulation activity has been carried out. The simulation, using Geant4 and MCNPX codes, included the transport of the gamma beam from the interaction point to the experimental area passing through vacuum pipes, vacuum chambers, collimation system and relative shielding. The effectiveness of the collimation system, in obtaining the required energy distribution and avoiding the contamination due to secondary radiation production, was evaluated. Also, the background radiation generated by collimation and the shielding layout have been studied.

*Keywords:* Inverse Compton, monochromatic radiation, x-ray and gamma sources

## 1. Introduction

ELI-Nuclear Physics (NP), currently being built in Bucharest, Romania, is one of the three pillars of ELI (Extreme Light Infrastructures) European Project [1, 2]. This facility will host the Gamma Beam System (GBS), an intense and monochromatic gamma source based on inverse Compton interaction between a high-power laser and an accelerated electron beam produced by a warm linac. In 2014, EuroGammaS association, composed by many European research institutes and companies, guided by INFN, won a tender to provide the design, manufacturing, installation and commissioning of ELI-NP-GBS, to be completed in 2018 [3, 4, 5]. The gamma beam produced, with energy ranging from 0.2 to 20 MeV, an energy bandwidth 0.5% and a flux of about $10^8$ photons/s, will be devoted to the investigation of a broad range of applications, from nuclear physics and astrophysics, to material science and life sciences.

As a result of the inverse Compton interaction, the maximum energy of the gamma beam is tunable by adjusting the electron energy ($E_\gamma \propto \gamma^2$), while the bandwidth depends on the collimation aperture. In fact, the radiation emitted is not intrinsically monochromatic, but the energy is related to the emission angle: it is maximum along the laser backscattering direction and decreases as the emission angle increase. Therefore, the required energy bandwidth can be obtained only by developing specific methods of collimation of the gamma beam, *i.e.* filtering out the radiation emitted at larger an-

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gles.

In particular, in the case of ELI-NP-GBS collimation system the main characteristics required are:

1. continuously adjustable circular aperture, adaptable to the required maximum energy and bandwidth: from a few hundreds of $\mu$rad, down to about 40 $\mu$rad, in order to operate in the entire energy range with nominal specifications;
2. effective attenuation of the gamma radiation: considering the energy range, the collimator must be made of materials with high atomic number and high density;
3. minimum contamination of the downstream experimental area with scattered radiation produced in the interaction of the primary beam with the collimation system.

In order to cover the whole energy interval the GBS will consist of two parallel beamlines, with two separated interaction points (IPs) and collimation systems. The low energy beamline, for gamma energies ranging from 0.2 to 3.5 MeV, and the high energy line, which after a further acceleration of the electron beam, will allow to reach energies from 3.5 to 20 MeV. In the following, the optimal solution identified for the low energy collimation system and a summary of its expected performance are described.

## 2. Materials and Methods

In order to evaluate the optimal layout and the performance of the collimation system, a series of Monte Carlo simulations using MCNPX [6] and Geant4 [7, 8] has been performed. The transport of the gamma beam has been simulated from the IP to the experimental area downstream the collimation system, including vacuum pipes and chambers, walls, floor, ceiling and additional shielding. The gamma beam we used in our simulations is obtained by accelerating and transporting a realistic electron beam to the IP where its interaction with the laser beam occurs. The electron transport is simulated by using the codes TSTEP, an updated version of PARMELA code [9], (from photocatode to photoinjector exit) and Elegant (from photoinjector to IP) [10]. A detailed description of this procedure can be found in Bacci et al. (2013) [11]. The simulation of the interaction between the electron beam and the laser pulse at the interaction point

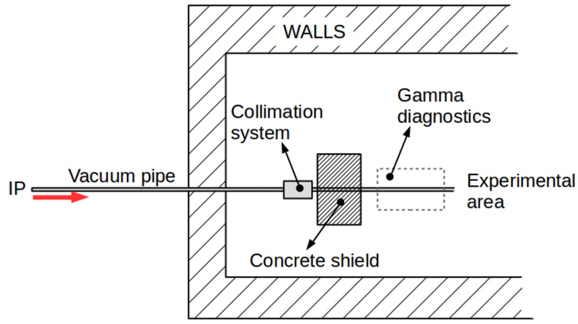


Fig. 1: Sketch of the low energy beamline of ELI-NP-GBS.

is performed by means of the Monte Carlo code CAIN [12]. This code generates a complete phase space of the gamma emission that is finally used as the source file for the simulation of the beamline and collimation system described in this work.

A representation of the beamline layout is shown in Fig. 1. In this sketch the gamma beam, that moves from left to right, emerges from IP and travels in vacuum in a stainless steel pipe across a concrete wall, reaching the vacuum chamber that contains the collimation system. After the collimation, the primary beam can reach the experimental area traveling in a further vacuum pipe, passing through a concrete block to shield the experimental area from the radiation scattered in the collimation process. The same geometry and composition of materials was implemented in both Monte Carlo codes: MCNPX and Geant4.

In particular the simulation activities have been mainly focused on:

1. the evaluation of the optimal size, layout and composition of collimation system;
2. the evaluation of the energy bandwidth in relation to the collimation aperture;
3. the analysis of the secondary radiation produced in the collimation process, with particular attention to the possible contamination of the experimental area downstream the collimator.

The simulations have been carried out for various gamma beam energies in the range from 1 to 5 MeV, in the following, we report the results for two selected values: 2.5 and 5 MeV. Even if the maximum nominal energy for the low energy beamline is 3.5 MeV, we extended our analysis to 5 MeV because that is the maximum gamma energy achiev-

Fig. 2: Sketch of the collimation system layout. (This image was obtained directly from MCNPX input file, using MCAM by FDS team, China [13]).

able with the maximum electron acceleration reachable at the low-energy line IP. Considering that at higher energies collimation aperture is smaller and background production increases, we selected 5 MeV as a worst-case scenario to test collimation system performance in the most demanding conditions.

### 3. Results and Discussion

The first part of the simulation process was devoted to find the optimal combination of materials and layout to produce an effective collimation device that would fulfill all requirements previously stated. The analysis of the results suggests that an optimal solution, for this energy range, is that shown in Fig. 2. In this configuration the collimation system is composed by a stack of 12 linear tungsten slits. Each slit is composed by an aluminum frame holding two tungsten edges 20 mm-thick that can translate, in order to continuously adjust the collimation aperture. These slits are stacked along the beam direction, each one with a rotation around the beam axis of 30° with respect to the previous one. This layout allows to obtain, with a good approximation, a circular shaped hole as a result of the overlap of the 12 slits.

Given the above solution for the slit assembly, the effect of the collimation on the final gamma beam energy distribution was evaluated, by studying the variation of the energy $RMS$ value as a function of the aperture size. A set of simulations with the same geometry and sources was performed using both Geant4 and MCNPX. Taking statistical fluctuations into account, the results obtained with the two codes were in perfect agreement. Results for the energy distributions, obtained at the exit of the collimation system, are reported in Fig. 3 for two values of the gamma beam energy, *i.e.* 2.5 and 5 MeV. In the case of 5 MeV, the relative energy bandwidth, resulting from an aperture of 258 $\mu$rad, is 0.44%, while in the case of 2.5 MeV the bandwidth is 0.48% with an aperture corresponding to 397 $\mu$rad. Considering the distance between IP and collimator entrance, these values correspond to aperture diameters of 4.0 mm for 2.5 MeV and 2.6 mm for 5 MeV. The energy bandwidths obtained are perfectly compatible with the nominal values required for ELI-NP-GBS, that is 0.5%. However, both the average energy and the bandwidth will be continuously adjustable, allowing a fine tuning of the beam parameters required for specific applications.

The last analysis carried out concerns the background radiation in the proximity of the collimator. In fact, downstream the collimation system and before the experimental area, a set of detectors for gamma diagnostic will be placed, to characterise and monitor the radiation produced. In order to avoid the contamination of this area with secondary radiation and allow the operation of these devices, a block of concrete, provided with a hole to allow the crossing of the primary beam, was considered. To have a negligible background radiation, the size of this block was evaluated to have a cross-section of 200 x 200 $cm^2$ and a thickness of 100 cm. The block will be located right after the collimation system before the gamma diagnostic area. The energy and spatial distribution plots of the gamma radiation background are shown in Fig. 4 for a 5 MeV gamma beam. These results were obtained using Geant4 simulation code. The main plot represents the energy distribution of the gamma radiation, reported counts are the hits on the whole surface per pulse (rep.rate 3200 Hz). The embedded surface plot shows the spatial distribution of the background radiation; the color coding indicates the number of photons per pulse (rep. rate 3200 Hz) over an area of 10 x 10 $cm^2$. In both plots the primary beam, which passes through the collimation aperture not scattered, is not shown in order to permit a clearer display of the background with an appropriate scaling. The amount of background for lower energies is always less than that in the above case. No particles such as electrons, positrons or neutrons reach the area behind the concrete wall. This background was evaluated to be compatible with the intended operation of the gamma diagnostic detectors.

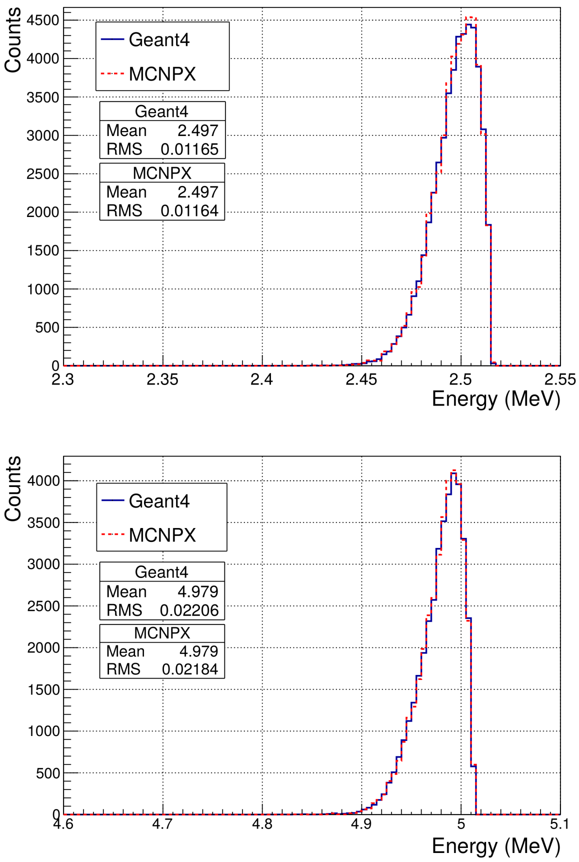


Fig. 3: Plots of the energy distribution obtained in the vacuum pipe after collimation. Each plot shows the results of the simulations obtained with Geant4 (solid blue line) and MCNPX (dashed red line), the values of counts are per pulse (repetition rate 3200 Hz). (*Top*) energy distribution for 2.5 MeV gamma beam; (*bottom*) energy distribution for 5 MeV gamma beam.

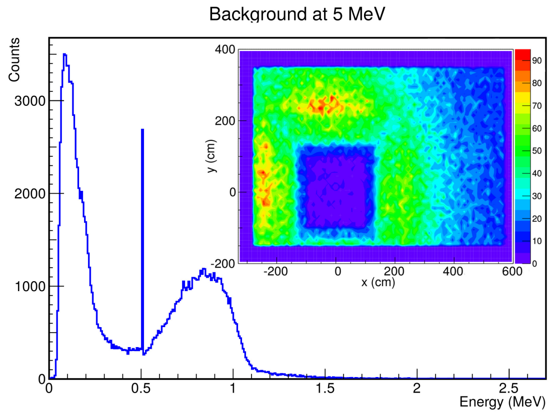


Fig. 4: Background radiation. The scoring surface area correspond to the entire room cross-section on the $xy$ plane downstream the concrete-block shielding (850x500 $cm^2$); reference frame is centered on the beam axis.

## 4. Conclusions

A detailed Monte Carlo simulations was carried out to define the layout and composition of a collimation system for the low energy line of ELI-NP-GBS. The evaluation of the performance of a stack of 12 tungsten linear slits was carried out. Results have shown that the required energy bandwidth (0.5%) can be attained using this system. Therefore it is compliant with the parameter requirements of the source. The collimation aperture, and consequently the energy bandwidth, can be continuously adjusted to obtain the required value compatible with different applications. The secondary radiation along the vacuum pipe reaching the experimental area is negligible, when not absent. The background radiation in the area next to the collimation system, where a set of detectors for gamma diagnostic will be placed, was verified to be compatible with the operation of those devices.

The simulation activities to design and evaluate performance of the collimation system for the high energy line are currently ongoing.


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