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Positron Production at Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

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Abstract. Applied and material physics studies with positron beams of Fermi–surfaces, defects, interfaces etc. offer excellent diagnostics tools. At ELI-NP, an intense γ beam of about 10^{11} photons/s with energies up to 3.5 MeV will be used to generate a positron beam via pair production in a tungsten converter target. To obtain a high intensity beam of moderated positrons the design of the positron source is of high importance. The design of a dedicated positron source at ELI–NP is being investigated based on extensive GEANT4 simulations. The goal of the simulations is to optimize the geometry of the target and the gamma beam collimation. We present here the characteristics of the positron beam obtained for different geometries of the converter target.

INTRODUCTION

At ELI–NP we propose to obtain an intense moderated positron beam of approximately 10^7 e^+/s via the (γ, e^+e^-) reaction, using an intense γ beam of about 10^{11} photons/s with energies up to 3.5 MeV [1]. The small diameter and the low emittance of the γ beam should lead in the case of the ELI–NP positron source to a brilliance of 10^7 e^+/s(mm mrad)^2 [at 0.1% BW] that is about four orders of magnitude higher than in the case of the NEPOMUC source [2].

The interest in the use of the positrons is due to the following properties [3]:

- Positrons are the anti–particle of electrons. This makes a beam of positrons very well suited for the analysis of the electronic structure of materials; when a positron collides with an electron, annihilation occurs, resulting in the production of two gamma–ray photons.
- Positrons are positively charged. They present a high sensitivity in detecting and identifying defects at the atomic scale in matter.
- Positrons are non–destructive. It allows for in–situ analysis on a variety of materials.

Positron–electron pairs can be obtained in an appropriate target via pair production by using a brilliant gamma beam. To obtain a beam of moderated positrons with a gamma beam, one can use two different approaches: (1) the converter is used also as a positron moderator and therefore the moderated positrons are obtained directly from the convertor surface (self–moderation), (2) the simple converter γ–to–positron configuration, for which the electron and the positron moderator are separate components. The conversion process γ–to–'positron and electron pairs' occurs more likely in materials with high nuclear charge Z such as tungsten (W) or platinum (Pt); W and Pt can also be used as moderator materials. To create free positrons one can use a thin W or Pt converter sheet that is irradiated with a γ beam, as shown in Fig. 1.

To obtain a high intensity beam of moderated positrons, the geometry of the positron source is very important. The design of the positron source at ELI–NP is based on GEANT4 simulations. The Monte Carlo simulation code GEANT4 [4] is a free software toolkit package that can be used to accurately simulate the interaction of the radiation and particles with matter. In particular, GEANT4 can be used to simulate γ–to–slow e^+ conversion in different complex converter geometries.

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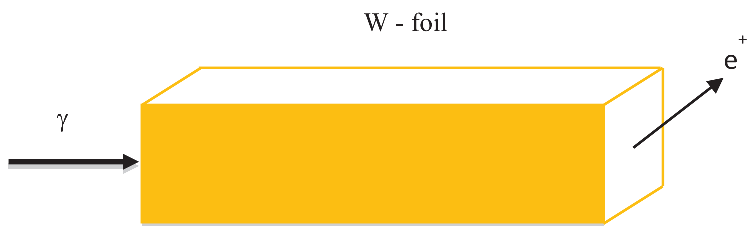


FIGURE 1. Sketch of a simple W converter foil irradiated with a γ beam for positron–electron pair production.

POSITRON PRODUCTION AT ELI–NP SIMULATED WITH GEANT4

The number of positrons and electrons emitted upon the interaction of a gamma–ray beam (with an uniform energy distribution from 1.022 MeV to 3.5 MeV) incident on a tungsten multifoil target [5] is calculated by using the GEANT4 Monte Carlo simulation code.

We considered a stack of N single crystalline tungsten (W) foils ($1 \le N \le 3000$) with the width b = 200 µm, spacing between foils s = 67 µm and the thickness d_w = 10 µm. The tungsten density is 19.25 g/cm^3. The stack was placed in the center of a sphere (with radius 150 cm) filled with air at normal pressure and temperature. A GEANT4 application was used to calculate the number of positrons and photons (that passed through the surface of the sphere) divided by the number of the incident gamma rays, their average energy and the angle θ between the directions of positrons and gamma rays that enter in the sphere along the x axis. The calculations were done for a uniform distribution of gamma rays in the energy interval 1.022 ÷ 3.5 MeV and for 10^{11} gamma rays incident on the target stack. The ratio of the secondary particles (electrons, positrons and photons) divided by the number of primary gamma rays was multiplied with 10^{11} (the gamma beam intensity) to calculate the number of positrons and photons emitted from the stack per second. The geometry for the stack of tungsten foils used in the GEANT4 simulations for positron production is shown in Fig. 2.

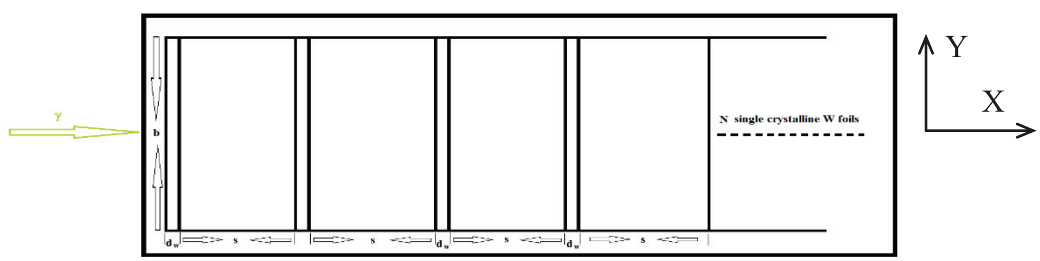
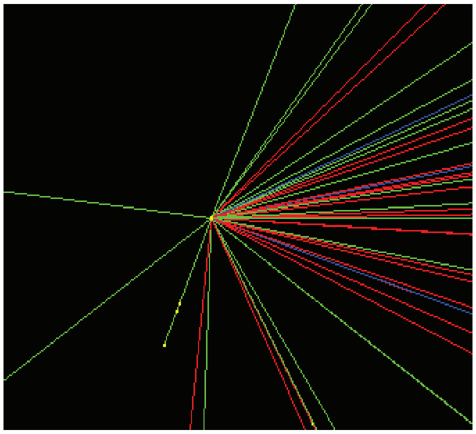
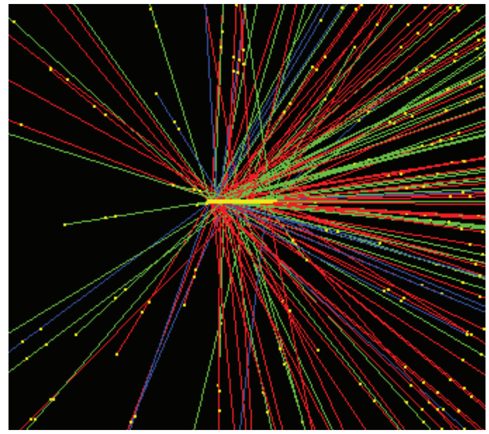


FIGURE 2. Scheme of a stack of N tungsten thin foils irradiated by a gamma beam

The trajectories of the electrons, positrons and gamma photons produced by the gamma beam on a tungsten target with 1 and 3000 foils, are presented in Fig. 3. The gamma beam, with a diameter of 200 µm, enters in the target from the left. All gamma rays in the beam, incident on the target, are parallel with the axis of the target. The distribution of the gamma rays over the transversal area of the beam is considered uniform.



(a)



(b)

FIGURE 3. The trajectories of the electrons, positrons and gamma rays generated when the gamma beam is incident on a target with 1 foil (a) and 3000 foils (b) are calculated in GEANT4.

In this article we present the optimum geometry of the tungsten target for which the flux of positrons calculated in GEANT4 was maximum.

THE RESULTS

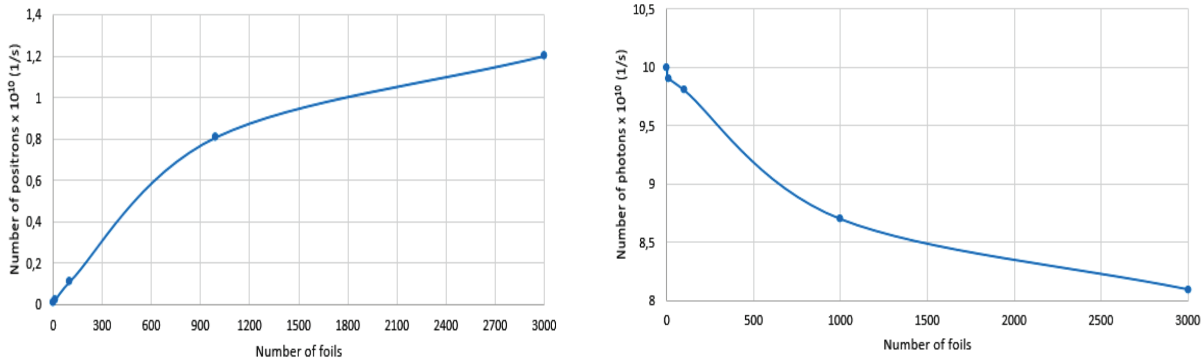
Table 1 presents the number of positrons and gamma–ray photons produced in the target for 10^{11} primary gamma rays incident on the target. For each of the two particles the mean energy is the sum of the energy for all particles exiting from the target divided with their number. The mean angle θ between the positron momentum when it exits from the sphere and the direction of the X axis (Fig. 2) is also calculated.

TABLE 1. The number of positrons and photons produced in the target for 10^{11} primary gamma rays incident on the target, their mean energy, and mean angle θ.

			positrons			gamma photons	
Number of foils	**E_{gamma} (MeV**	**I_{gamma} (1/s)**	**Number of positrons (1/s)**	**Mean energy positrons (keV)**	**Mean θ (deg)**	**Number of photons**	**Mean energy photons (MeV)**
1			2×10^7	870.38	76.7	9.9×10^{10}	2.251
10			2×10^8	861.3	63.48	9.9×10^{10}	2.25
100	[1.022÷3.5]	10^{11}	1.1×10^9	850.7	65.7	9.8×10^{10}	2.16
1000			8.1×10^9	847.2	66.4	8.7×10^{10}	1.59
3000			1.2×10^{10}	846	74.2	8.1×10^{10}	1.09

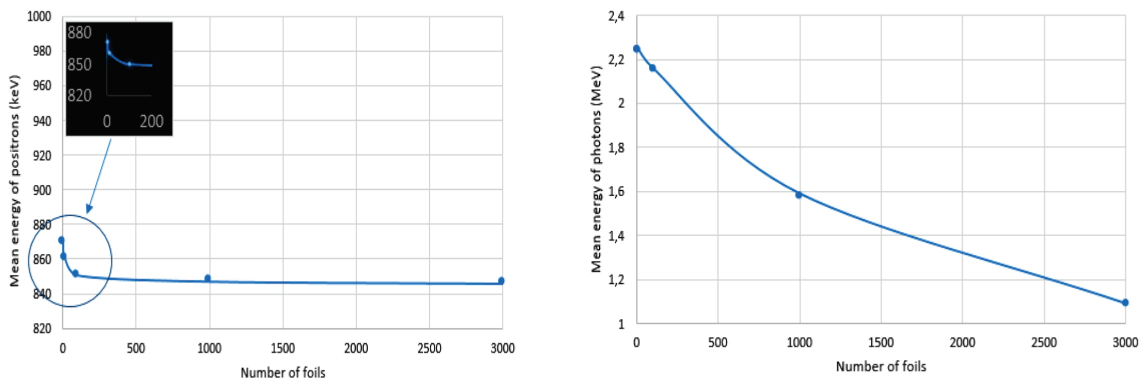
As the number of tungsten foils increases the flux of positrons emitted from the target is more intense, while the flux of gamma rays decreases. The dependence of the flux of positrons and gamma–ray photons emitted in all directions from the tungsten target on the number of foils is shown in Fig. 4 in the case of a gamma ray flux of 10^{11} photons/s.

The mean energy of the positrons and gamma–ray photons also depends on the number of foils. For the positrons it decreases very slowly with the number of foils, if the target has more than 150 foils. For the photons the mean energy decreases more rapid as the number of foils increase (Fig. 5).



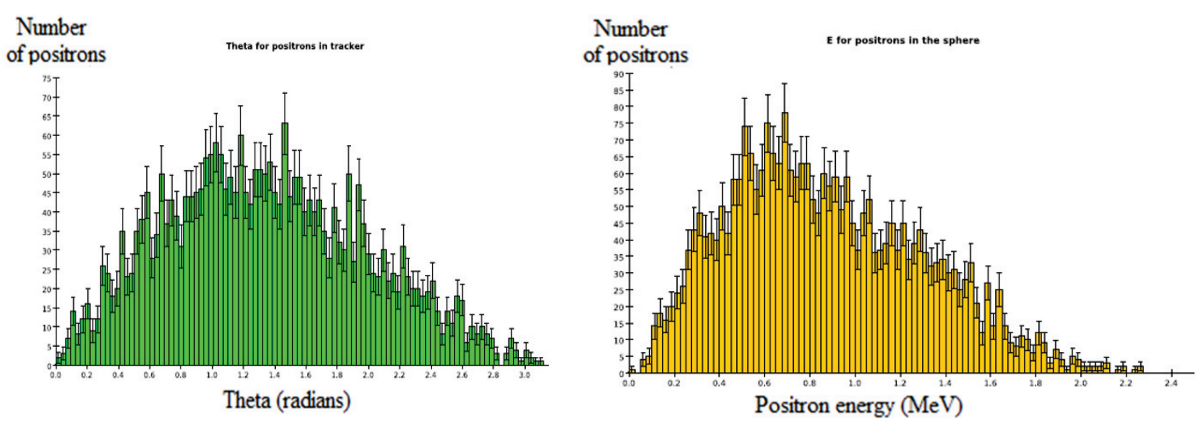
(a) (b)

FIGURE 4. The number of positrons and photons per second, emitted from the stack of tungsten foils, is calculated for different number of foils.



(a) (b)

FIGURE 5. The dependence of the mean energy (a) of the positrons and (b) of the gamma–ray photons on the number of foils composing the converter.



(a) (b)

FIGURE 6. The histogram of the angle θ (left figure) and energy (right figure) of the positrons that exit the target.

Fig. 6 presents the dependence of the number of positrons on (a) the θ angle and (b) on the positrons energy for the case of one single foil. In both figures it can be observed that the number of positrons has a maximum for a certain angle and a certain energy.

CONCLUSIONS

The present work was dedicated to the optimization of the positron production at ELI–NP by using GEANT4 simulations. The case of a multifoil tungsten converter was considered. The results of the simulations indicate that the flux of positrons depends on the thickness of the tungsten foils and on the number of the foils. The mean angle of the positron direction relative to the direction of gamma beam axis, is almost independent on the number of foils. The maximum number of 1.2 x 10^{10} (fast) positrons/s that we can obtained at ELI–NP was calculated for ~ 3000 tungsten foils and a gamma beam intensity of 10^{11} photons/s . This means that the flux of moderated positrons will be ~ 10^{7} (1/s). The fast positrons have to be moderated and transported to the experiment for e.g. solid-state studies.

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