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Computer simulation of electron-positron pair production by channeling radiation in amorphous converter

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Abstract. We consider the radiator-converter approach at 200 MeV channeled electrons (the SPARC_LAB LNF facility energies) for the case of using W crystalline radiator and W amorphous converter. A comparison of the positron production by the axial channeling radiation and the bremsstrahlung is performed. The positron stopping in the convertor is studied by means of computer simulations. It is shown that for the maximum yield of positrons the thickness of the W amorphous converter should be taken 0.35 cm in the case of using the axial channeling radiation resulting to total yield of positrons 5 10^{-3} e^+/e^- and 0.71 cm in the case of using the bremsstrahlung resulting to total yield of positrons 3.3 10^{-3} e^+/e^-.

1. Introduction

The problem of the positron beam generation remains of interest during last decade, in connection with the physics of slow positrons [1], relativistic positronium atom beams [2–4], modern research of electron-positron plasma [5] and with the search for the effective positron source for the electron–positron colliders [6–9]. The positrons are usually produced via conversion of photons with an energy greater than 1 MeV into e^--e^+ pair in the field of a nucleus. Several schemes are suggested for the intense positron beam generation. Basically, the initial high energy electron beam is used for the photon beam generation in several different ways: bremsstrahlung (BS) [10], channeling radiation (CR) [11–12] or coherent bremsstrahlung (CB) [10, 13–14], the Compton scattering [15], and even undulator radiation [16]. A new technique involving the high-energy laser to irradiate solid gold and platinum targets [17] seems to be very promising for the neutral electron-positron plasma production but poorly applicable as a positron source for colliders. A comparison of these schemes is given in details in [18]. Most of all of these schemes are used as the source of the photons a multi-GeV electron beam: 1.2 GeV at the Institute for Nuclear Study, Tokyo, Japan [11, 13]; 3 and 8 GeV at KEK, Tsukuba, Japan [14] and electron beams on the SPS CERN transfer lines, Geneva, Switzerland [10, 15]; 46.6 GeV at the SLAC, USA [16].

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However, the features of the positron production by sub-GeV electron beam remain not described in detail. One of the important advantage of sub-GeV electron beam for the positron production is the avoiding the thermal degradation of the crystal wherein the CR photons are generated. The comparison of the $1 \div 3$ MeV positron yield from a thin amorphous W converter of 0.1 mm thickness produced by BS, by <100> axial and (110) planar CR in a 10 μm W crystal for the positron energy range of was carried out recently in [18]. Obviously, the positron energy spectrum after the W converter depends not only on incident photon spectrum, but also on positron energy loss in a radiator on the way to leave it. Therefore, in continuation of [18], here we perform a computer simulation of the positrons stopping in an amorphous W converter for the cases when one uses the <100> axial CR and BS from 200 MeV electrons. The principal scheme of hybrid positron source is shown in figure 1.

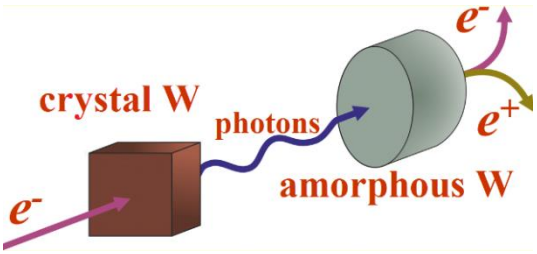


Figure 1. The scheme of hybrid positron source using CR from primary electron beam.

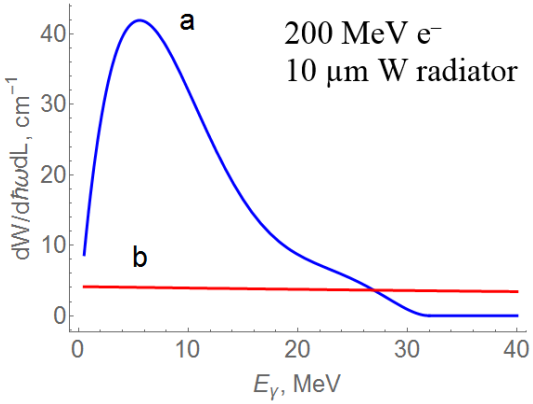


Figure 2. (a) CR intensity spectrum from 200 MeV electrons <100> axial channeling in W; (b) BS intensity spectrum from 200 MeV electrons in amorphous W.

2. Bremsstrahlung and channeling radiation spectra

In our simulations, the thickness of a W crystal (radiator) was10 μm, that is less than the dechanneling length for 200 MeV electrons [19]. The general properties of CR are well described in [20–21]. The realistic simulations of CR spectra can be performed using different models. For example, it can be done in the frame of binary collision model [22]. The faster way to simulate the CR intensity spectra (energy radiated during penetration through a crystal per unit crystal length) in the case of axial CR (figure 2a) from 200 MeV electrons in W is to apply the BCM-1.0 code [23]. This code was recently applied to simulate the orientation dependence of the CR total yield [18, 24]. The BS spectrum in an amorphous W (figure 2b) was calculated according to the Schiff formulae [25].

For the SPARC_LAB primary 200 MeV electron beam the brilliant peak of axial CR is located near 6 MeV, thus allowing creation of positrons with maximal kinetic energy up to 5 MeV. The total yield of BS is twice greater than that of axial CR [24], but the axial CR spectrum is almost 20 times narrower than the BS one and the maximum value of it is almost 10 times greater than the maximum for BS spectrum (figure 2).

3. Electron-positron pair production in a thick converter

For calculation of the e^--e^+ pair production by a photon in an atomic field we shall use the Bethe-Heitler formula [26–28].

The spectrum of positrons generated by CR from electrons in thin converter can be determined in the following way:

$$\frac{dN_P}{dE_P} = n \cdot L_C \int \frac{1}{E_\gamma} \frac{dW}{dE_\gamma dL} \cdot L \cdot \frac{d\sigma(Z, E_P, E_\gamma)}{dE_P} dE_\gamma , \quad (1)$$

where n is the number of atoms per volume unit of W convertor, L_C is the convertor thickness, Z is the atomic number of the converter material, E_P is the total energy of positron, E_γ is the energy of the photon, $dW/dE_\gamma dL$ is the photon intensity spectra, L = 10 μm – the thickness of the radiator and $d\sigma(Z, E_P, E_\gamma)/dE_P$ – the Bethe-Heitler e^--e^+ pair production cross-section by a photon [29].

The yield of positrons from conversion of CR or BS into e^--e^+ pair in thin convertor of thickness L_C is determined by the expression:

$$N_P = n \cdot L_C \iint \frac{1}{E_\gamma} \frac{dW}{dE_\gamma dL} \cdot L \cdot \frac{d\sigma(Z, E_P, E_\gamma)}{dE_P} dE_\gamma dE_P = \int \frac{dN_P}{dE_P} dE_P . \quad (2)$$

Computer simulations shows that the total yield of positrons (2) produced in a thin 0.1 mm W convertor by axial CR from 200 MeV electrons in a 10 μm W crystal is about 3.5 10^{-4} e^+/e^- and 1.6 10^{-4} e^+/e^- in the case of BS. The more detail on results of simulation of photoproduction of positrons in a thin W amorphous converter by CR and BS are presented in in [18].

Let divide a thick W converter into N thin layers of thickness 0.1 mm. The e^--e^+ pair production by the radiation in the thin layer of the converter numbered i is calculated according to (1) neglecting to the radiation attenuation and positron energy losses in the one layer under consideration. The attenuation of the radiation passed through converter from the first layer to the layer i-1 is described in terms of linear attenuation coefficient. The main contributions to radiation attenuation are coherent and incoherent scattering, pair production and photoelectric absorption and defined using XCOM: Photon Cross Sections Database [30]. The positrons energy losses in the converter from the i+1 layer to the N^{th} layer are described in terms of continuous slowing down approximation (CSDA). For the positron energies under consideration, CSDA ranges of the positrons in a matter practically coincide with one for the electrons [31]. CSDA ranges for the electrons are calculated using the CASINO code [32].

Our computer simulation carried out for the N=100 W layers shows (figure 3) that the total yield of positrons reaches a maximum value about 5.0 10^{-3} e^+/e^- at the thickness of converter equal to 0.35 cm in the case of photoproduction by axial CR from 200 MeV electrons in W crystal, and 3.3 10^{-3} e^+/e^- at 0.71 cm in the case of using BS.

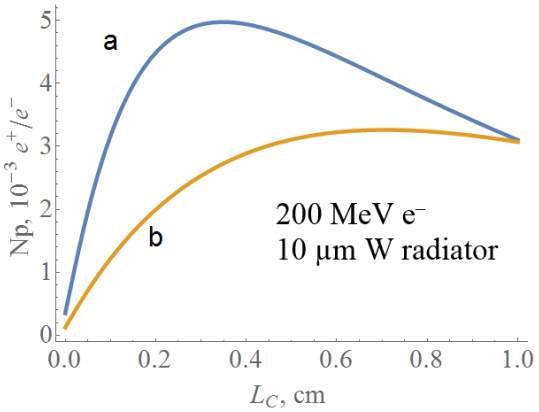


Figure 3. Total yield of positrons produced by the radiation from 200 MeV electrons in W as the function of the converter thickness: (a) axial CR; (b) BS

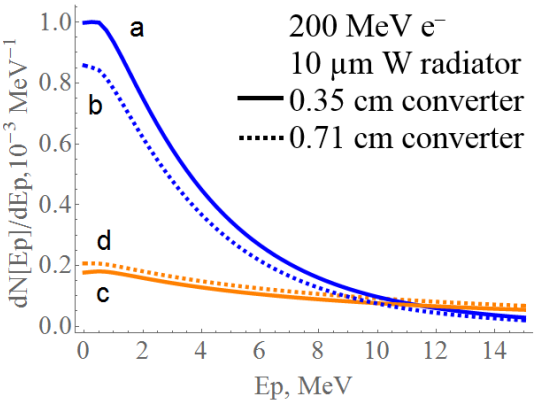


Figure 4. The energy spectra of positrons, produced by the radiation from 200 MeV electrons in W: (a, b) axial CR; (c, d) BS. Solid lines correspond to converter thickness 0.35 cm; dashed – 0.71 cm.

The energy spectrum of positrons produced by the axial CR from 200 MeV electrons in W is narrower than that produced by the BS (figure 4) for all thicknesses of converter. Moreover, in the case of axial CR it is possible to produce up to 5 time greater amount of low energy positrons than using the BS (figure 4a and 4d). These characteristics determine the benefits of the axial CR compared to BS.

4. Conclusions

Our previous studies [18] on hybrid positron source using channeling radiation and a thin W amorphous convertor are extended here to the case of more thick radiators. Two stages of simulations have been used: the first one is to calculate CR spectrum from initial 200 MeV electron beam in a 10 μm W radiator. The second stage is to take into account the created positrons energy loss in a downstream amorphous W convertor, in order to determine the final energy spectrum of positrons leaving a convertor.

The main new result is, that suggested hybrid scheme in the case of 0.35 cm amorphous W converter lead to the maximum total yield of positrons produced by axial CR from 200 MeV electrons in W crystal about 5.0 10^{-3} e^+/e^-, and 2.8 10^{-3} e^+/e^- in the case of using BS. The converter of greater thickness equals 0.71 cm allows to maximum total yield of positrons 3.3 10^{-3} e^+/e^- in the case BS and 4.1 10^{-3} e^+/e^- in the case of CR.

That means, for the SPARC_LAB electron beam parameters [33] and suggested hybrid scheme, in the case of 200 MeV electrons one can expect the maximum positron yield of about 2.3 $10^6 \div 10^7$ e^+/s in the case of BS (0.71 cm W converter) and about 3.5 $10^6 \div 10^7$ e^+/s in the case of <100> CR (0.35 cm W converter).

These numbers characterizing the total yield of positrons at SPARC_LAB electron beam can be increased using CR in a thicker radiator. In this case the influence of dechanneling on CR should be taken into account [34] as well as the contribution of coherent and incoherent bremsstrahlung [35] at channeling conditions.

Acknowledgements

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