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Total yield and spectra of positrons produced by channeling radiation from 0.1 ÷ 1.6 GeV electrons

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The hybrid scheme of positron source involving channeling radiation from 0.1 ÷ 1.6 GeV ⟨1 0 0⟩ channeled electrons in a crystalline W target (radiator) and subsequent electron-positron pair production in a downstream thick amorphous W target (converter) is investigated by means of computer simulation using the BCM-1 code. Computer simulation is carried out taking into account positron energy loss in a thick converter. Total yield of positrons as a function of the thickness of the converter as well as the energy spectrum of positrons for the chosen converter thickness are obtained. According to the calculations, the total yield of positrons produced by channeling radiation from 0.1 ÷ 1.6 GeV electrons in a 10 μm W crystal equals 0.5 ÷ 160 positrons per 10^3 incident electrons, respectively, with the maximum of positron energy spectrum in the energy range 1 ÷ 3 MeV. Calculations are performed within the framework of the planned experimental program at SPARC_LAB LNF.

1. Introduction

Fundamental and applied problems such as physics of positronium atoms [1–4], properties of slow positrons [5], investigation of gravitation behavior of antimatter [6], research of astrophysical leptonic jets [7] and search for the effective positron source for the new electron–positron colliders [8–10] maintain high interest during last decades for the study on positron beam generation. For the low energy (below 1 MeV) positron production one can use interesting technique involving ultra-intense laser beam irradiating solid target [11] or impact of low energy (10 MeV) electron beam upon a thin solid target for the electron-positron pair production [12]. For the production of the intense positron beam of higher energy (above 1 MeV) the initial beam of ultra-relativistic electrons is used as a source of several MeV photons (in the first target – radiator) with subsequent conversion into electron-positron pair in the field of a nucleus (in the same target or in the second target – converter). Brief comparison of one- and two-component schemes of positron beam generation based on coherent and incoherent bremsstrahlung (B), channeling radiation (CR), Compton scattering and undulator radiation is given in [13]. The two-component so-called "hybrid" scheme of positron production (see, in Fig. 1) based on channeling radiation or coherent bremsstrahlung [14] from initial electron beam possesses the advantages of a higher total yield of positrons, the possibility to choose different materials and thicknesses of the radiator and converter and the lower thermal damage during proceeding experiment. Commonly, for the hybrid scheme a multi-GeV electron beam is used as the source of photons: 8 GeV at KEK, Tsukuba, Japan [15]; 6 and 10 GeV electron beams on the SPS CERN transfer lines, Geneva, Switzerland [16].

Here, we study in detail the features of positron production by CR from a sub-GeV electron beam in the hybrid scheme aiming at the determination of the total yields and energy spectra of emitted positrons. The initial electrons of energies from 0.1 to 1.6 GeV under ⟨1 0 0⟩ axial channeling condition in a 10 μm W crystalline radiator serves as a photon source. The choice of the electron beam energy corresponds to the recent proposals for possible upgrade of the SPARC_LAB facility [17]. According to [18] dechanneling length of 50÷400 MeV electrons at planar channeling in Si exceeds 20÷40 μm, that is of the order of the value obtained in the frame proposed by Baier et al. [19]. According to his approach the dechanneling length is proportional to the depth of potential U_0 and radiation length X_0 of crystal under consideration, thus the dechanneling length for the axial case is greatly exceeds dechan-

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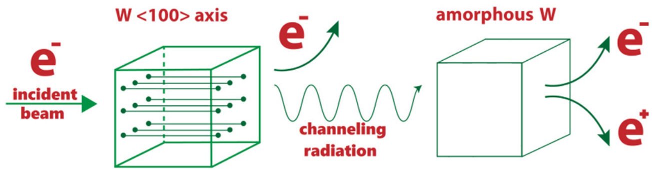

Fig. 1. The scheme of hybrid positron source using CR from primary electron beam.

neling length for the same crystal at the planar orientation. For the W crystal at ⟨1 0 0⟩ orientation the dechanneling lengths calculated in the frame of Baier approach are 2.5 μm and 10 μm for the electrons of energies 100 and 400 MeV respectively, that allow us to use 10 μm W crystalline radiator without taking into account dechanneling processes. In addition, for 0.8 GeV and 1.6 GeV electrons the thickness of the W radiator can be increased more than 40 μm.

For the calculation of positron energy spectrum we use method proposed in [20]. Brief description of the method is provided in Section 2. Earlier the method was applied in [13] for comparison of total yields and energy spectra of positron produced in a thin W converter by planar CR, axial CR and B from 200 MeV electrons in 10 μm W radiator. The calculations are carried out taking into account the energy loss of positrons and radiation attenuation in a thick W converter involving the method used in [21].

2. Electron-positron pair production by CR in a thin W amorphous converter

The BCM-1 code [22] enables calculating the realistic trajectories as well as the radiation spectra of both planar and axial channeled electrons in crystals. As the electron beam energies under consideration exceeds 100 MeV, we use classical approach, which involves calculations of classical trajectories. Trajectories are calculated using the model of continuum potential [23]. Calculations of CR spectra are carried out in the frame of classical model of Baier-Katkov [19]. Recently the BCM-1 code was used to calculate the orientation dependence of the CR total yield [24]. Alternatively, calculations of CR spectra can be carried out in the frame of binary collision [25]. In addition, the general properties of CR are well described in [26].

The radiation energy spectra (radiated energy during penetration through a W crystal of 10 μm thickness) of ⟨1 0 0⟩ axially channeled electrons of energies 0.1 ÷ 1.6 GeV (see, in Fig. 2) are calculated in the frame of classical approach using the code BCM-1 without taking into account the electron dechanneling [27]. For the primary electron beams of energies 0.1, 0.2, 0.4, 0.8

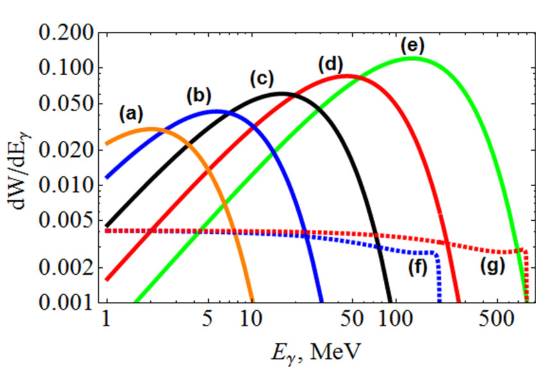

Fig. 2. ⟨1 0 0⟩ axial channeling radiation energy spectra (dW/dE_γ) from (a) 0.1 GeV, (b) 0.2 GeV, (c) 0.4 GeV, (d) 0.8 GeV and (e) 1.6 GeV electrons and energy spectra of bremsstrahlung from (f) 0.2 GeV and (g) 0.8 GeV electrons in L = 10 μm W.

and 1.6 GeV the maxima of axial CR energy spectrum, dW/dE_γ, are located near 2.0, 5.7, 16.1, 45.6, 128.9 MeV and have the values 0.030, 0.043, 0.060, 0.086, 0.121, respectively (see, in Table 1). The areas under the curves (see, in Fig. 2) correspond to the total yield of CR and quantitatively coincide with the ones obtained in [24].

The probability of photon emission by the channeled electron in the radiator of thickness L can be determined in the following way

$$\frac{dN(E_\gamma)}{dE_\gamma} = \frac{1}{E_\gamma}\frac{dW}{dE_\gamma}(\mathrm{MeV}^{-1}), \tag{1}$$

where E_γ is the energy of the photon, and dW/dE_γ is the CR energy spectrum.

Following [20], the energy spectrum of positrons generated by CR from electrons is determined by the integral

$$\frac{d\sigma(Z,E_P)}{dE_P} = \int \frac{1}{E_\gamma}\frac{dW}{dE_\gamma}\frac{d\sigma(Z,E_P,E_\gamma)}{dE_P}dE_\gamma(\mathrm{barn/MeV}), \tag{2}$$

where E_p is the total energy of positron, Z is the atomic number of the converter material, $d\sigma(Z,E_P,E_\gamma)/dE_P$ is the cross-section of e$^-$-e$^+$ pair production by a photon in the atomic field. In our calculations, the Bethe-Heitler formula of e$^-$-e$^+$ pair production by photon in the fields of atomic nuclei and electron cloud using empirical Coulomb correction has been used [28–30].

Thus, the yield of positrons due to conversion of CR into e$^-$-e$^+$ pair in a converter of the thickness L_C is determined by the same expression as in [31]

$$Y_P = n\cdot L_C\cdot\int\int\frac{1}{E_\gamma}\frac{dW}{dE_\gamma}\frac{d\sigma(Z,E_P,E_\gamma)}{dE_P}dE_\gamma dE_p, \tag{3}$$

where n is the number of atoms per volume unit of W converter. Here, L_C should be chosen small enough to neglect radiation attenuation and positron energy loss (0.1 mm in our calculations). The total yield of positrons produced in 0.1 mm W converter by CR from 0.1, 0.2, 0.4, 0.8 and 1.6 GeV electrons equals $5.61\cdot10^{-5}$, $3.49\cdot10^{-4}$, $1.10\cdot10^{-3}$, $2.49\cdot10^{-3}$ and $4.65\cdot10^{-3}$ positrons per one initial electron, respectively (see, in the Table 1 3rd column). The total yield of positrons produced in 0.1 mm W converter by bremsstrahlung form 0.2 GeV and 0.8 GeV electrons equals $1.61\cdot10^{-4}$ and $2.68\cdot10^{-4}$ e$^+$ per e$^-$, respectively.

3. CR attenuation, positron energy losses and electron-positron pair production by CR in thick W amorphous converter

The converter thickness selection is determined by two competing conditions. On the one hand, the converter thickness growth leads to the increase of the electron-positron pair photoproduction probability. But on the other hand, the thicker converter is the larger pass of positrons being produced in the converter bulk results in greater energy loss. If the converter is thick enough, the positrons lose energy down to zero, and successfully annihilate.

Let consider a thick W converter as a stack of N thin layers of thickness L_c = 0.1 mm. The total yield and energy spectrum of positrons produced by CR in a single thin layer are calculated according to Eqs. (2) and (3) respectively neglecting the radiation attenuation and positron energy loss.

The main contributions to radiation attenuation are due to coherent and incoherent scattering, pair production and photoelectric absorption and can be defined using XCOM: Photon Cross Sections Database [32]. The CR attenuation in the bulk of converter of thickness L_c is described in terms of linear attenuation coefficient [29,30]:

$$\frac{dW_{i+1}}{dE_\gamma} = \frac{dW_i}{dE_\gamma}\exp(-\mu(E_\gamma)\rho L_C), \tag{4}$$

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Table 1
Total yield of positrons produced by ⟨1 0 0⟩ CR from 0.1 ÷ 1.6 GeV electrons in 10 μm W radiator.

e^- energy, GeV	Photon energy of maximum intensity, MeV	Total yield of e^+/e^- in 0.1 mm W converter, 10^{-3}	The thickness L_{max} of W converter correspond to the maximum of the e^+ total yield, cm	Total yield of e^+/e^- in W converter of thickness L_{max}, 10^{-3}	The maximum of the energy spectra of positrons, 1/MeV
0.1 CR	2.0	0.056	0.19	0.46	$0.19{\cdot}10^{-3}$
0.2 CR	5.7	0.35	0.35	4.88	$1.01{\cdot}10^{-3}$
0.2 B	4.1	0.16	0.71	3.28	$0.72{\cdot}10^{-3}$
0.4 CR	16.1	1.10	0.56	25.14	$2.32{\cdot}10^{-3}$
0.8 CR	45.6	2.49	0.82	79.78	$3.15{\cdot}10^{-3}$
0.8 B	4.1	0.27	0.85	6.74	$0.53{\cdot}10^{-3}$
1.6 CR	128.9	4.65	1.00*	156.29	$2.88{\cdot}10^{-3}$

where $\mu(E_\gamma)$ is the mass attenuation coefficient for the photons of energy E_γ, ρ is the W density, dW_i/dE_γ is the CR intensity spectrum incident on the ith layer, while dW_{i+1}/dE_γ is the CR intensity spectrum passed through the ith layer. An attenuation of CR in the ith layer leads to the decrease of positrons number produced in the i + 1st layer.

Positrons produced in the i^{th} layer lose part of its energy during transition through the i + 1st layer. The positron energy loss in the i + 1st layer of converter is described in terms of continuous slowing down approximation (CSDA) [33]. For the positron energies under consideration, CSDA ranges of the positrons in a high-Z material practically coincide with one for the electrons [34]. CSDA ranges for the electrons are calculated using the ESTAR code [35]. According to [36] attenuation length for the 2 MeV photons in W is equal to 0.86 cm. According to [35] CSDA range for the 3 MeV electrons is equal to 0.12 cm. Radiation length for W is 0.35 cm. We assume that 0.1 mm W converter is thin enough to neglect attenuation of photons and energy loss of positrons of energies under consideration.

The computer simulations of total positron yield as a function of the converter thickness are carried out for the N = 100 W layers (see, in Fig. 3) and show that to obtain the maximal total positron yield the thickness of W converter should be chosen 0.19 cm for the initial electron beam of energy 0.1 GeV, 0.35 cm for 0.2 GeV, 0.56 cm for 0.4 GeV and 0.82 cm for 0.8 GeV, respectively. The values of total yield of positrons for these cases are $0.46{\cdot}10^{-3}$, $4.88{\cdot}10^{-3}$, $25.14{\cdot}10^{-3}$ and $79.78{\cdot}10^{-3}$ positron per incident electron, respectively. CR of 1.6 GeV electrons in W is characterized by a brilliant maximum at photon energy around 128 MeV (see Fig. 2(e)). For this quite high photon energy, the photon attenuation length is large enough to permit the increasing of layers number N to achieve a greater yield of positrons. Indeed, the maximum of the plot in Fig. 3(e) is at the end of the chosen scale, i.e. for N = 100 or L = 1.0 cm, at which the maximum value of total yield equals 0.16 positron per incident electron (see Table 1 4th and 5th columns). Bremsstrahlung from 0.2 GeV and 0.8 GeV electrons in 10 μm reaches maximal total yield of positrons $3.28{\cdot}10^{-3}$ and $6.74{\cdot}10^{-3}$ positron per incident electron at the converter lengths 0.71 cm and 0.85 cm, respectively.

For the initial electron beam energies 0.1 ÷ 1.6 GeV the positrons spectra calculated for the W amorphous converters of thicknesses L_{max} corresponding to the maximal positron total yield are shown in Fig. 4. For the all energies of initial electron beam under consideration the maximum of the energy spectra of positrons for this conditions are within the relatively low energy range 0 ÷ 3 MeV (see Table 1 6th column).

4. Conclusions

The hybrid scheme of the positron source using ⟨1 0 0⟩ CR from 0.1 ÷ 1.6 GeV electrons in W crystal and thick (up to 1.0 cm) amorphous W converter is investigated by means of computer simulations. The positron stopping in a bulk of the thick W converter is taken into account. The main results are summarized in the Table 1.

With increase of initial electron beam energy the total yield of CR increases as γ^2 (γ is the Lorentz factor). The total yield of positrons produced by CR using the hybrid scheme demonstrates more complicated dependence. Doubling of the electron beam energy from 0.1 to 0.2 GeV leads to increase of the total yield of the positrons 6.2 times for 0.1 mm converter and 10.6 times for converter of thickness L_{max}, with 1.8 times rising of L_{max} (see Table 1 3rd and 5th columns). With increase of initial electron beam energy an amount of photons in CR (the height of lines shown in Fig.2) increases as $\gamma^{1/2}$ [19], what can explain a 1.4 times increasing of positron total yield. The increasing of the converter

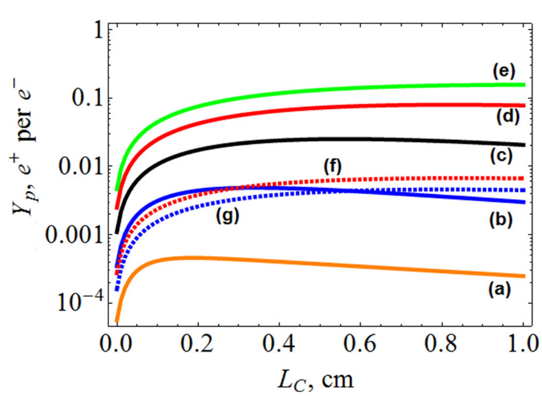

Fig. 3. Total yield of positrons Y_p (e^+ per e^-) produced by the ⟨1 0 0⟩ CR from (a) 0.1 GeV, (b) 0.2 GeV, (c) 0.4 GeV, (d) 0.8 GeV and (e) 1.6 GeV electrons and bremsstrahlung from (f) 0.2 GeV and (g) 0.8 GeV electrons in L = 10 μm W as the function of L_c – the W converter thickness (cm).

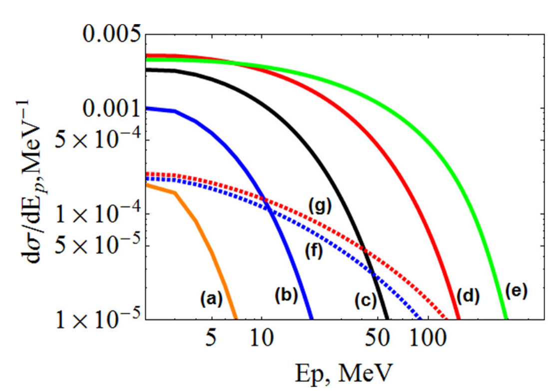

Fig. 4. The energy spectra of positrons $d\sigma/dE_p$ (1/MeV) produced by the ⟨1 0 0⟩ CR from (a) 0.1 GeV, (b) 0.2 GeV, (c) 0.4 GeV, (d) 0.8 GeV and (e) 1.6 GeV electrons and bremsstrahlung from (f) 0.2 GeV and (g) 0.8 GeV electrons in L = 10 μm W. Thickness of W converter is chosen at total yields maximum L_{max} (see Table 1).

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thickness in 1.8 times contributes the increasing of total positron yield less than 1.8 times, due to positron energy losses in addition layers of converter. With increase of initial electron beam energy the photon energy of maximum intensity in CR (Table 1 2nd column) increases as $\gamma^{3/2}$ [19]. With rising of photon energy in the range from 1 MeV to, say, 50 MeV the probability e^{-}-e^{+} pair production increases rapidly, what can explain the rest 2.4 times increasing of total yield of positrons. Further doubling of electron energy to 0.4 GeV leads to just 3.1 and 5.2 times increase of the positron total yield (0.1 mm and L_{max} converter respectively). Next doubling – to 2.3 and 3.2 times increase. Final doubling of the electron beam energy from 0.8 GeV up to 1.6 GeV leads to increase of the total yield of positrons in 1.9 and 2.0 times, respectively. Also the total yield of positrons can be increased using the radiator and converter of larger thicknesses. These calculations are planned to be done taking into account the dechanneling [27] and rechanneling [37,38] effects.

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