A Method of Polarized Positron Beam Production

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A method of the polarized positron beam production is suggested. In this method a beam of longitudinally polarized relativistic electrons produce a hard circularly polarized photon beam in matter and then this circularly polarized photon beam produce a longitudinally polarized positron beam in the conversion process. This method allows to produce a beam with high degree of longitudinal polarization at the upper limit of the positron's energy in the produced positron beam, when the degree of initial electron beam polarization is high.

1. Introduction

From the very beginning of the Linear Collider activity, the importance of simultaneous polarization of e^- and e^+ beams was recognized. The suitable method for generation polarized positrons (and electrons) have been proposed many years ago [1]. This method based exclusively on the technology, used for linear collider itself. In this method the longitudinally polarized positrons and electrons can be produced by the conversion of circularly polarized photons in a thin target. For production of hard (energy > 10 *MeV*) circularly polarized photons here proposed to use the undulator radiation sources based on high energy ($\geq$ 100 *GeV*) electron beams and long (~ 100 *m*) undulators. The other possible source of high energy gamma radiation is a backward Compton scattered photons, based on intermediate energy (~ 1 *GeV*) storage rings and powerful lasers. In this paper we considered the method of longitudinally polarized positron beam production, when the source of the circularly polarized photons is based on the bremsstrahlung of the longitudinally polarized relativistic *electrons* in the target itself. Of cause, one can consider the separate target for photon production and the second one for positron production. The space between these targets can be used for bending the electrons. The electron gun(s), producing the electron beams with high degree of longitudinal polarization (available at the present times) and low energy (~ 0.1-1 *GeV*) linear accelerator(s), are used in this method.

2. The properties of the bremsstrahlung radiation emitted by longitudinally polarized electrons

An electron, passing through the matter, lose it's energy by collisions. In the case of ultrarelativistic particles the bremsstrahlung radiation is the dominant mode of energy loss. The properties of polarization of this bremsstrahlung radiation are strongly depend on the polarization of a primary electron beam.

The number of the photons, emitted by one electron of energy $mc^2\gamma$ in the matter within an energy interval $\Delta\varepsilon_\gamma$ at the energy ε_γ and in a solid angle *do* in the first approximation is

$$\frac{dN_\gamma}{d\varepsilon_\gamma do} = f(\vartheta)\frac{dN_\gamma}{d\varepsilon_\gamma} \qquad (1)$$

where $f(\vartheta) = \frac{3\gamma^2}{2\pi}\frac{1+\vartheta^4}{(1+\vartheta^2)^4}$, $\frac{dN_\gamma}{d\varepsilon_\gamma} \cong \frac{d_t}{\varepsilon_\gamma}$

$\int_0^\pi f(\vartheta)d\vartheta = 1$, $\vartheta = \gamma\theta$, θ -- is the angle between the initial electron velocity and the direction of photon propagation, $d_r = d / X_0 << 1$, d is the thickness of the target (g/cm^2), $X_0^{-1} \cong 4r_e^2\alpha Z(Z+1)NA^{-1}\ln(183Z^{-1/3})$ is the radiation length [2], Z is the atomic number of the nuclear of the media, $r_e = e^2/mc^2$ is the classical radius of the electron. $N \cong 6\cdot 10^{23}$ is the Avohadro number, A is the mass number. The degree of circular polarization of the emitted photon when $\xi_\gamma = \varepsilon_\gamma / mc^2\gamma > 0.3$ is

$$\xi_2 = \zeta_{e^-}\left[1 - 1.48(1-\xi_\gamma)^2\right] \qquad (2)$$

where ζ_{e^-} is the degree of longitudinal polarization of the electron beam [3,4].

2.1 The conversion

The degree of longitudinal polarization of the positrons, produced in a process of pair production by photons in media, is determined by the expression

$$\zeta_{e^+} = \xi_2 f(\varepsilon_{e^+0}, \varepsilon_{e^+m}), \qquad (3)$$

where $f(\varepsilon_{e^+0}, \varepsilon_{e^+m})$ is the universal function of the initial energy of the produced positrons ε_{e^+0} to the maximal energy of the positrons $\varepsilon_{e^+m} = \varepsilon_\gamma - 2mc^2$ [3,4]. To an approximation of 10%, $f(\varepsilon_{e^+0}, \varepsilon_{e^+m}) \cong 1 - 2(1-\xi_{e^+})^2$, where $\xi_{e^+} = \varepsilon_{e^+0} / \varepsilon_{e^+m}$.

The differential cross-section of the pair production

$$\frac{d\sigma}{d\varepsilon_{e^+0}} = \frac{4\alpha Z(Z+1)r_e^2}{\varepsilon_{e^+m}} G(\varepsilon_{e^+0}, \varepsilon_{e^+m}), \quad (4)$$

where, $G(\varepsilon_{e^+0}, \varepsilon_{e^+m})$ is the universal function of ε_{e^+0}, ε_{e^+m}, *Z*. The function $G(\varepsilon_{e^+0}, \varepsilon_{e^+m})$ has rather complicate analytical form in the region of energy $\varepsilon_{e^+0} / \varepsilon_{e^+m} > 0.8$, when the energy ε_{e^+m} is ~ 10-30 *MeV*. That is why we are forced to use the corresponding figures and tables for that function [5], or to choose an approximate expressions. For heavy elements like $_{82}Pb$ and the energy $\varepsilon_\gamma \cong 50mc^2$ it can be presented in the form

$$G \cong \begin{cases} 4.75\sqrt{\xi_{e^+}}, & 0 \le \xi_{e^+} < 0.11 \\ 1.55, & 0.11 \le \xi_{e^+} \le 0.89 \\ 4.75\sqrt{1-\xi_{e^+}}, & 0.89 < \xi_{e^+} \le 1 \end{cases} \quad (5)$$

The probability of the positron with the initial energy ε_{e^+0} produced by photon at depth of $t = y / X_0$, where *y* marked from the beginning of the converter of the thickness *d* to have the energy from ε_{e^+} to $\varepsilon_{e^+} + d\varepsilon_{e^+}$ at the exit of the converter is $wd\varepsilon_{e^+}$, where

$$w(\varepsilon_{e^+0}, \varepsilon_{e^+}, t) = \frac{\left(ln\,\dfrac{\varepsilon_{e^+0}}{\varepsilon_{e^+}} \right)^{\frac{d-t}{ln\,2} - 1}}{\Gamma\left(\dfrac{d-t}{ln\,2}\right)\varepsilon_{e^+0}} \quad (6)$$

$\Gamma(p) = \int_0^\infty x^{p-1} e^{-x} dx$ [6,7]. The value $w\big|_{d\to 0} \to \delta(\varepsilon_{e^+} - \varepsilon_{e^+0})$.

The number of positrons produced in the converter at the depth t_γ by one photon of the energy ε_γ at the initial energy $\varepsilon_{e^+0} < \varepsilon_\gamma$ per the energy interval $d\varepsilon_{e^+}$ and coming out of the converter at the energy ε_{e^+} per the energy interval $d\varepsilon_{e^+}$ (and per one initial electron) is determined by the expression [8,9,10]

$$\frac{\partial^2 N_{e^+}}{\partial\varepsilon_{e^+}\partial\varepsilon_{e^+0}} = \int_0^d dt_\gamma \int_{d-t_\gamma}^d w \frac{\partial^2 N_{e^+}}{\partial\varepsilon_{e^+0}\partial t} dt = \\ = \frac{4\alpha Z(Z+1)r_e^2 X_0 N A^{-1}}{\varepsilon_{e^+}} = \frac{GI}{\varepsilon_{e^+m}\ln(183Z^{-1/3})}$$

where

$$\partial^2 N_{e^+} \big/ \partial\varepsilon_{e^+0}\partial t = X_0 (N/A) \exp(-7t/9) d\sigma / d\varepsilon_{e^+0},$$

$$I(\varepsilon_{e^+0}, \varepsilon_{e^+}) = \int_0^d dt_\gamma \int_{d-t_\gamma}^d exp(-7t/9) w dt.$$

The factor *exp(-7t/9)* takes into account the absorption of the γ -quanta. The value $I\big|_{d\to 0} \to d \cdot \delta(\varepsilon_{e^+} - \varepsilon_{e^+0})/2$.

The number of positrons that will come out of the converter with the energy ε_{e^+} in the interval $d\varepsilon_{e^+}$ when photons emitted by one high energy electron in matter is used in the conversion system is determined by the convolution of the expressions (1), (7) :

$$\frac{dN_{e^+}}{d\varepsilon_{e^+}} = \int \frac{\partial^2 N_{e^+}}{\partial\varepsilon_{e^+0}\varepsilon_{e^+}} \frac{\partial N_\gamma}{\partial\varepsilon_\gamma} d\varepsilon_{e^+0} d\varepsilon_\gamma = \\ = \frac{d}{\varepsilon_\gamma\, ln(183Z^{-1/3})} \int GId\varepsilon_\gamma d\varepsilon_{e^+} \quad (8)$$

Crossing the converter, the particle beam according to (6) acquires a marked spread in the losses of the energy on bremsstrahlung [6]. That is why the target must be thin (*d<<1*). In this case we can get

$$e^{-7t/9} \cong 1, \quad \Gamma^{-1}\left(\frac{d-t}{\ln 2}\right) \cong \frac{d-t}{\ln 2}.$$

Correspondingly the value *I* in (6) can be presented in the form

$$I = \frac{\Delta_\varepsilon^{d/\ln 2} \cdot \ln(\Delta_\varepsilon^d / 2)}{(\varepsilon_{e0} - \varepsilon_e)\ln^2 \Delta_e}, \quad (9)$$

where $\Delta_\varepsilon = \ln(\varepsilon_{e^+0} / \varepsilon_{e^+})$.

The number of positrons that will come out of the converter with the energy laying at the interval ($\varepsilon_{e^+}, \varepsilon_{e^+m}$), can be represented in the form

$$\Delta N_{e^+} \cong \int \frac{dN_{e^+}}{d\varepsilon_{e^+}} d\varepsilon_{e^+}. \quad (10)$$

For the thin target, when *d<<1* and $\xi_{e^+} > 0.9$ $(I \cong d \cdot \delta(\varepsilon_{e^+} - \varepsilon_{e^+0})/2)$, the number of emitted positrons is

$$\Delta N_{e^+} \cong \frac{d^2}{2ln(183Z^{-1/2})} \begin{cases} 19/15 \cdot (1-\xi_{e^+})^{5/2}, & 0.89 < \xi_{e^+} \le 1 \\ 0.015 + \dfrac{31}{40} \cdot (0.89 - \xi_{e^+})^2, & 0.11 \le \xi_{e^+} \le 0.89 \end{cases} \quad (11)$$

The root-mean square angle produced by the photon in the converter [6] is

$$\sqrt{<\theta^2>} = 0.47 \frac{mc^2}{\varepsilon_{e^+0}} \ln\frac{\varepsilon_y}{mc^2} \quad (12)$$

The mean-square scattering angle of the positron beam produced by photons in the converter and the increasing of the square transverse dimensions of the positron beams are

$$<\theta^2> = \frac{1}{2}\left(\frac{E_s}{\varepsilon_{e^+0}}\right)^2 d, \quad <y^2> = \frac{\theta_s^2}{24} X_0^2 d^3 \quad (13), (14)$$

where $E_s = mc^2\sqrt{4\pi/\alpha} \approx 21 MeV$, $\theta_s^2 = E_s / \varepsilon_{e^+m}$.
We introduced the coefficients 1/2 and 1/4 in (13), (14) to take into account the production of the positrons all over the thickness of the converter.
Complete conversion coefficient $\eta = \Delta N_{e^+} \times \eta_\theta$, where η_θ is the angular efficiency of the capture of the positrons in the accelerator. According to (11) the value $<\theta^2> \cong 21\sqrt{2}d/\gamma_{e^-}$. That is why we must use accelerators with $\gamma_{e^-} \geq 10^2$ and special elements to reach $\eta_\theta \approx 1$. On practice, the capture efficiency for narrow energy interval can be made around 10%.
Example. Let us consider the CLIC linear collider [11]. The CLIC drive beam has the beam of four trains of 22 bunches in each train. Each of these bunches in a train has a charge of 30 *nC*, so the number of the particles in each bunch is about $1.9 \cdot 10^{11}$. If the photocathod is now rearranged for polarized electron production, then efficiency will drop to the level, say 10% of initial. If we suppose that $\xi_{e^+ min} \approx 0.25$, i.e. collection arranged for the positrons in 25% energy interval around the maximal energy, $d \cong 0.3$, then, according to (11) $\Delta N_{e^+} \approx 1.5 \cdot 10^{-2}$, i.e. 1.5%. and the total number of positrons created will be

$$N_{e^+} \cong 1.5 \cdot 10^{-2} \times 22 \times 4 \times 1.9 \cdot 10^{10} \cdot \eta_\theta = 2.5 \cdot 10^9 .$$

The degree of polarization will be

$$\zeta_{e^+} \cong \zeta_{e^-} \cdot 0.91 \cdot 0.87 \cong 0.79 \zeta_{e^-} ,$$

i.e. about 80% of initial electron polarization. These numbers give an idea of efficiency of this method.
Of cause, this method can be applied not only for linear collider activity. The efficiency around 0.15% of polarized positron production may be interesting for some laboratories also.

3. Conclusion

The polarized positron sources are rather large and expensive facilities. The more attractive sources are based on the high energy linear accelerators (~100-200 *GeV*, 1-2 *km* long), undulators and damping rings on the energy 1-2 *GeV* [7-9]. More cheaper sources are based on backward scattered circularly polarized laser beams on electrons of storage rings on the energy of some *GeV* and sources are under consideration in this paper. However the assumed average intensity of such sources is essentially less now.

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