PROPOSAL OF POLARIZED GAMMA-RAY SOURCE FOR ILC BASED ON CSR INVERSE COMPTON SCATTERING

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Abstract

The positron source of International Linear Collider (ILC)[1] requires a circular polarized gamma-ray with a flux more than 10^{16} phs./s. In this paper, we propose an alternative method, the inverse Compton scattering with a high-power mid-infrared optical pulse based on Coherent Synchrotron Radiation (CSR)[2, 3] instead of the baseline design of the helical undulator. To achieve the high flux gamma-ray, CSR with a few MHz is stacked in a high-finesse optical cavity made of a photonic crystal. In the proposed scheme, a stand-alone operation is feasible because the electron energy is less than 10 GeV.

INTRODUCTION

Inverse Compton scattering induced by an external laser is proposed as an intense polarized gamma-ray source around 30 MeV [4, 5, 6], which is used for a polarized positron source for ILC. A 1-4 GeV electron beam is enough in the alternative schemes while the basic scheme requires a 200 m long helical undulator and electron beam larger than 150 GeV. Therefore the relatively compact system makes it easy to operate the positron source independently of the electron beam of the main linac. This scheme has another advantage in high polarization.

We propose the inverse Compton scattering based on CSR emitted from the electron bunch itself[7], to be used for generation of the gamma-ray. CSR emitted in a bending magnet is stacked in an optical cavity, and collides with the following electron bunch. In this scheme, CSR is automatically synchronized with the electron bunch. The preferable accelerator is Energy Recovery Linac (ERL) [8] because the short electron bunch is necessary at a few mA. It is possible for the superconducting cavities to also accelerate the generated positron beam. The Fabry-Perot optical cavity is composed of four multi-layered mirror made of the photonic crystal[9]. The material and structure of the mirror determine the wavelength, bandwidth and polarization of CSR.

Consecutive CSR pulses are stacked coherently in an optical cavity. In other words electron bunches shorter than the wavelength of CSR interact with the electric fields in the optical cavity. We call it “coherent stacking”, in which the behavior is similar to a pulse stacker of a passive cavity. The inverse Compton scattering is optimized to avoid the nonlinear effect appearing in the case that the deflect parameter is larger than unit.

COHERENT STACKING OF CSR

CSR emitted in a bending magnet travels back and forth in an optical cavity, and then the following electron bunches experience the electric fields. Here, we assume the CSR propagates to the z-axis and the electron orbit lies on the xz plane as shown in Fig. 1. The energy exchange is written by using the velocity of the electron bunch v_x and the electric field E_x to the x-axis as follows [10],

$$\mathrm{m}_0 c^2 \frac{\mathrm{d}\gamma}{\mathrm{d}t} = q v_x E_x, \tag{1}$$

where q, c, γ and m_0 is the charge of the electron bunch, the velocity of light, the Lorentz factor and the electron rest mass. The electron energy continues to transfer to the electric field when the electron bunch is much shorter than the wavelength λ_R and the repetition rate of the electron bunch is synchronized with that of the optical cavity. The motion of the electron bunch is assumed to depend on only the magnetic field of the bending magnet, and the perturbation due to the energy exchange is negligible unlike FEL scheme[11, 12]. The positions of the reference particle of the electron bunch are,

$$x_B(t) = \int v_x(t)\mathrm{d}t = \frac{c}{\omega_B}(1-\cos\omega_B t) \tag{2}$$

$$y_B(t) = 0 \tag{3}$$

$$z_B(t) = \int v_z(t)\mathrm{d}t = \frac{c}{\omega_B}\sin\omega_B t. \tag{4}$$

where ω_B is the inverse of the bending radius, ρ_0, $\omega_B = c/\rho_0$.

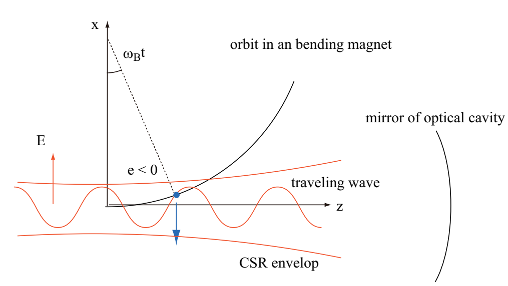

Figure 1: Schematic of the energy exchange between the electron and the electric field in the optical cavity.

The electric fields stacked in the optical cavity is assumed to be described as follows[13],

$$\mathbf{E}_r(r,z,t) = \pm iE_r(r,z,t)\exp[\pm i\Phi_r(r,z,t)]\,\mathbf{e}_r \tag{5}$$

$$\Phi_r(r,z) = k_R z - \omega_R t + \phi_r + \left(\eta(z) + r^2\frac{k_R}{2R(z)}\right),$$

where $r^2 = x^2 + y^2$, $\omega_R = k_R c = 2\pi c/\lambda_R$. The initial phase, ϕ_r is assumed to be zero in this paper and $\mathbf{e}$ indicates the unit vector. η and R are written by using the Rayleigh length z_0,

$$\eta(z) = -\tan^{-1}\left(\frac{z}{z_0}\right), \quad R(z) = z\left(1 + \frac{z_0^2}{z^2}\right).$$

The strength of the electric field, $E_r(r,z,t) = \hat{\mathcal{E}}_r(r,z,t)h_R(r,z,t)$, contains both the distribution function, h_R, and the temporal development due to the energy exchange, $\hat{\mathcal{E}}_r$. Equation (5) becomes the fundamental Gaussian beam when $\mathcal{E}_r$ is a constant. The distribution h_R is expressed by

$$h_R(r,z,t) = \sqrt{\frac{2}{\pi}}\frac{1}{w(z)}\exp\left[-\frac{r^2}{w^2(z)}\right]h_R^L(z-ct), \quad (6)$$

where $h_R^L(z-ct)$ is the longitudinal distribution, which is assumed to be the Fourier transform of the reflectance spectra of the mirrors. When the reflectance spectra is the rectangular shape with the bandwidth of $\Delta\omega_R$,

$$h_R^L(z-ct) = \sqrt{\frac{1}{\pi c\Delta\omega_R}}\frac{\sin(\Delta\omega_R(z-ct)/c)}{(z-ct)/c}. \quad (7)$$

The integral is normalized as $\int h_R^2 \mathrm{d}r\mathrm{d}z = 1$. The beam size, $w(z)$ is described by the waist size w_0 as follows,

$$w^2(z) = w_0^2\left(1 + \frac{z^2}{z_0^2}\right). \quad (8)$$

The differential equation of $E_x(r,z,t)$ is derived from the Maxwell equation.

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{A}_x(x,y,z,t) = -\mu_0\mathbf{J}_x(x,y,z,t) \quad (9)$$

where μ_0, $\mathbf{A}_x$, and $\mathbf{J}_x$ is the permeability of vacuum, the vector potential, and the electron current.

$$\mathbf{J}_x(x,y,z,t) = -iqc\rho_B(x,y,z,t)\exp[i\omega_B t]\,\mathbf{e}_x \quad (10)$$

where ρ_B is the distribution of the electron bunch. Here, we assumed that the rms bunch length is l_B while the transverse size is approximated to be much less than the waist size of CSR.

$$\begin{aligned}\rho_B(x,y,z,t) &\approx \frac{q}{\sqrt{2\pi}l_B}\delta(x-x_B(t))\delta(y-y_B(t)) \\ &\times \exp\left[-\frac{(z-z_B(t))^2}{2l_B^2}\right]\end{aligned} \quad (11)$$

The jitter in the longitudinal and transverse direction can be included in Eq. (11). Then we obtain the following expression.

$$\varepsilon_0\frac{\mathrm{d}E_x}{\mathrm{d}t} = qc\rho_B Re\left[\frac{\exp(-i\Psi_x^+) - \exp(i\Psi_x^-)}{4}\right] \quad (12)$$

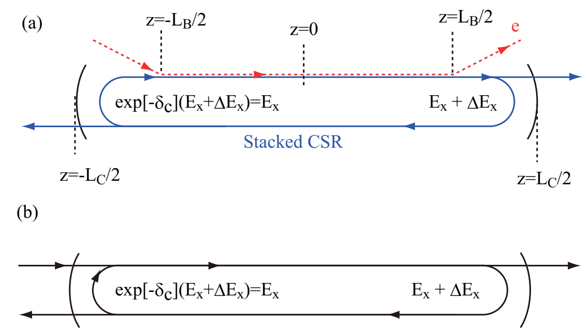

Figure 2: Comparison of coherent stacking scheme (a) with pulse stacker model (b).

where ε_0 is the permittivity of vacuum, and $\Psi_x^{\pm} = \Phi_x \mp \omega_B t$. You can see Eq. (12) is independent of the strength of the electric field, E_x. It suggests the behavior is similar to a pulse stacking in a passive cavity rather than FEL, in which the gain is constant.

According to Eq. (12), the distribution of E_x and $\hat{\mathcal{E}}_x$ depend on the trajectory and the distribution of the electron bunch, ρ_B. It is gradually smoothed into the shape of the Gaussian beam, h_R, after a number of turns. To simplify, however, it is assumed to be smoothed just after the energy exchange. Then the smoothed electric fields $\mathcal{E}_x$, which depends on only t, is related to E_x as following equation.

$$\frac{\mathrm{d}\mathcal{E}_x(t)}{\mathrm{d}t} = \int_V \mathrm{d}x\mathrm{d}y\mathrm{d}z h_R(x,y,z,t)\frac{\mathrm{d}E_x(x,y,z,t)}{\mathrm{d}t} \quad (13)$$

Then the total energy in the cavity U_R is simply expressed by the smoothed electron field, $\mathcal{E}_x$ as $U_R = \varepsilon_0\mathcal{E}_x^2$. The total energy exchange per turn ΔU_R is described as follows,

$$U_R + \Delta U_R = \varepsilon_0(\mathcal{E}_x + \Delta\mathcal{E}_x)^2 \quad (14)$$

where $\Delta\mathcal{E}_x$ is the integration over the cavity length L_B,

$$\Delta\mathcal{E}_x = \int_{-t_B/2}^{t_B/2}\frac{\mathrm{d}\mathcal{E}_x}{\mathrm{d}t}\mathrm{d}t, \qquad L_B = z_B(t_B). \quad (15)$$

The schematic of the optical cavity is shown in Fig. 2. In the case of a high-finesse cavity, in which the energy loss per turn is much less than unity, $\delta_c \ll 1$, the result is consistent with the energy loss of the electron bunch in Eq. (1).

$$\Delta U_R \approx 2\varepsilon_0\mathcal{E}_x\Delta\mathcal{E}_x = \mathrm{m}_0 c^2\Delta\gamma \quad (16)$$

where $\Delta\gamma$ is the integration of Eq. (1) in the range of $-t_B/2 < t < t_B/2$.

The total energy stacked in the optical cavity, U_R, is approximately obtained by following the pulse stacker model[14].

$$U_R = \left(\frac{2}{\delta_c}\right)^2 U_{inc}, \qquad U_{inc} = \Delta\varepsilon_0(\Delta\mathcal{E}_x)^2 \quad (17)$$

Then we can obtain the total energy of the stacked CSR.

$$U_R = \frac{4\chi_c}{\pi\varepsilon_0}\frac{q^2}{\delta_c^2}\frac{1}{\lambda_R}\left(\frac{\Delta\omega_R}{\omega_R}\right)\exp\left[-k_R^2 l_B^2\right] I^2 \quad (18)$$

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where

$$I = \int_{-n_B}^{n_B} f(\xi;\alpha_B)\mathrm{d}\xi \quad (19)$$

$$f(\xi;\alpha_B) = \frac{\alpha_B}{\sqrt{1+\xi^2}}\xi \exp\left[-\frac{\alpha_B^2}{4}\frac{\xi^4}{1+\xi^2}\right] \times \sin\left[-\frac{\alpha_B^2\xi^3}{3} - \tan^{-1}(\xi) + \frac{\alpha_B^2}{4}\frac{\xi^3}{1+\xi^{-2}}\right].$$

Some non-dimensional parameters are defined as $\xi = z/z_0$, $\alpha_B = k_B z_0^2/w_0$, and $n_B = L_B/2z_0$. The parameter $\chi_c = 1/2$ indicating the effect of the circular polarization is introduced because the the electric field growing to the x-axis is averaged to the y-axis. According to Eq. (18), U_R is proportional to q^2 as the same manner of CSR. It is also proportional to the square of the finesse F^2, where $F = 2/\delta_c$ while the energy of the stacked pulses is proportional to F in a conventional pulse stacker model. It is explained by the factor that the electron bunch does not transmit the high-reflectivity mirror. It also depends on the pulse length of CSR, which is controlled by the bandwidth of the mirrors, $\Delta\omega_R/\omega_R$.

GENERATION OF GAMMA-RAY BASED ON COMPTON SCATTERING

The schematic of the optical cavity is illustrated in Fig 3. The repetition rate is assumed to be 3∼4 MHz. The radius of the mirror and w at the mirror are 10 cm and 4 cm, respectively, to satisfy the high finesse of 1000 π[13]. The bending radius ρ_0 is less than 2000 m to let the electron bunch escape from the mirrors. In such a condition, the integration of I in Eq. (19) is close to 1.5.

As an example, we chose the following parameters. The CSR wavelength λ_R and the electron energy are 45 μm and 6 GeV for 10 MeV γ-ray. The normalized emittance is assumed to increase up to 1×10^{-4} mrad after bunch compression down to 24 fs. The longitudinal jitter should be comparable to the bunch length at least. The electron charge is 3 nC, which is operated under the quasi-CW to reduce the heat load of the superconducting cavity.

The total number of the scattered photons at the collision point (CP) is [15]

$$N_\gamma \sim \pi\alpha K^2 N_R \quad (20)$$

where α, K, and N_R is the fine structure constant, the deflection parameter, and the number of the cycles of λ_R, which is corresponding to the period of the undulator. The CSR pulse is lengthen by limiting $\Delta\omega_R$ to increase N_R because K should be less than $1/\sqrt{2}$ to avoid the nonlinear effects[4]. The Rayleigh length for the Compton scattering is the same with the pulse length, $N_R\lambda_R$.

The main parameters are listed in Table 1. The integral efficiency N_γ/N_e is close to unit, in which N_γ and N_e are the numbers of γ-rays and electrons. If the expected efficiency of converting the polarized γ-photons into polarized positrons is assumed to be 1% at 10 MeV, it is possible to generate 2×10^8 positrons per bunch. It requires almost 100 times stacking at the damping ring. In this scheme, almost 5 mA electron current is necessary for 2640 bunch train at 5 Hz.

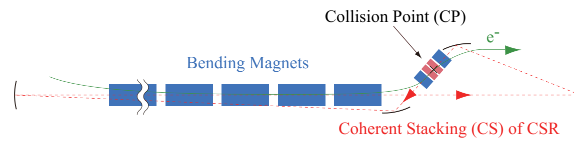

Figure 3: Schematic of the optical cavity.

Table 1: Main parameters for polarized positron source based on the CSR inverse Compton scattering.

Wavelength	λ_R	45 μm
Focus size at CP	w_0	250 μm
Number of periods	N_R	100
Pulse energy	U_R	8 J
Deflection parameter	K	0.6
Finesse	F	500 π
Number γ-photons at CP	N_γ	2×10^{10} phs./pulse
Number of positrons	N_{e+}	2×10^8 /pulse

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