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COHERENT PAIR CREATION AS A POSITRON SOURCE FOR LINEAR COLLIDERS*

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ABSTRACT

We propose a positron source for future linear colliders which uses the mechanism of coherent pair creation process from the collision of a high energy electron beam and a monochromatic photon beam. We show that there is a sharp spike in the pair-produced positron energy spectrum at an energy much lower than the primary beam energy. The transverse emittance is "damped", yielding final positrons with lower normalized emittance than the initial electrons. Numerical examples invoking conventional lasers and Free Electron Lasers (FEL) for the photon beams are considered.

INTRODUCTION

A high energy linear collider is a complex system. In the conventional approach, the electron beam, once emitted from the electron gun, is to be pre-accelerated to a certain energy so as to be injected into a damping ring, before eventually be accelerated to the machine energy through the main linac. For the positron beam, there is an additional intermediate step of positron production. This is achieved by bombarding a metalic target by an electron beam at tens of GeV energy (see Fig. 1a), and e^+e^- pairs are produced by the (incoherent) Bethe-Heitler process. Since future linear colliders generally require high beam currents, one potential problem is the melting of the solid target. Furthermore, the damping rings limit the minimum emittance attainable, and are expensive. While there is a good prospect that the electron beam can be produced at very low emittance right from the gun,[1] thus eliminating the need for the electron damping ring, the problem still awaits to be solved for the positron beam.

Recently, it has been suggested[2] that the electron-laser interaction through the single-photon Compton scattering and the subsequent two-photon Breit-Wheeler process can be a potential positron source for linear colliders (see Fig. 1b). An experimental effort is currently underway to test this idea.[3] In this paper we point out that for the purpose of a positron source, it maybe desirable to invoke the multi-photon, or *coherent*, regime of the electrom-photon beam-beam interaction. We show that in this approach the positron yield is high, and the emittance low. When looking at the numerical examples, we find that the laser or FEL technology needed for the photon beam is not too far from reach.

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Figure 1 presents the general form of a feedback controller applied to a dynamic system. This model shows a summing node, from which an error signal is generated, a feedback amplifier with complex gain $A(\omega)$, a second summing node which adds an external driving term $F(\omega)$, and a beam dynamics block with complex transfer function $H(\omega)$. The beam response acts back on the input summing node, closing the feedback loop.

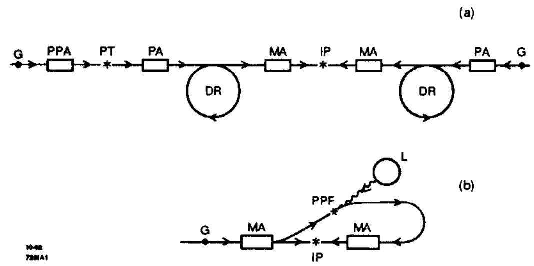

Fig. 1 Conceptual systems of linear colliders; (a) conventional approach, (b) that proposed here. G= gun, PPA= positron production accelereator, PA= pre-accelerator, DR= damping ring, MA= main accelerator, IP= interaction point, L= laser, PPF= Positron production focus.

2. Electron Interaction with Intense EM Waves For the sake of discussion, we will assume that the monochromatic photon beam is circularly polarized. It is well known that the interaction between a relativistic electron and a monochromatic EM wave can be described by a Lorentz invariant parameter η:[1]

$$\eta \equiv \frac{e\sqrt{-a^2}}{mc} \quad , \tag{2.1}$$

where a is the 4-amplitude of the classical 4-potential of the EM wave. Physically, this parameter measures the ratio of the outcoming angle of the radiated photon, $\theta_c \simeq 1/\gamma$, as a result of the interaction, and the pitch angle, θ_H, of the electron trajectory which is helical in this case:

$$\eta = \frac{\theta_H}{\theta_c} \simeq \gamma\theta_H = \frac{eE}{\omega mc} \quad . \tag{2.2}$$

where ω is the EM wave frequency in the Lab frame. The last expression is identical to eq.(2.1) when a^2 is made explicit. A factor 2 coming from the fact that both E field and B field contribute equally to the bending of the electron trajectory is cancelled by the doubling of the electron oscillation frequency due to the relative electron wave velocities. We see that when $\eta \gg 1$, the radiation cone angle is much smaller than the pitch angle, and the process can be well described by synchrotron radiation; when $\eta \ll 1$, on the other hand, the process is describable by the (single-photon) Compton scattering. In another word, when $\eta \gg 1$, the number of photons absorbed in one physical process becomes large, and therefore the interaction with the photons becomes *coherent*, the physics approaches that of the interaction between the relativistic electron and the calssical EM field in the photon beam. This can be easily appreciated by recalling the well-known Correspondence Principle in quantum mechanics.

Consider a numerical example where the electron beam is at 250 GeV, with normalized emittance $\epsilon_n = 1 \times 10^{-6}$mrad, and the bunch length $\sigma_z \ll 150\mu$m. Consider also a laser at wavelength $\lambda = 350$ nm, energy $J = 15$ Joules, and the pulse length $\sigma_t = 0.5$ psec(150 μm). If this laser is focused with $f/d = 10$, the focused beam will have a radius $r = 2\mu$m, with a depth of focus of 70 μm, and a converging angle 3^o. One can easily varify that maximum EM field in the laser beam is

$$\begin{aligned} E =& \Big[\frac{Z_0 J}{\sqrt{2\pi}\sigma_t c \cdot \pi r^2}\Big]^{1/2} = 2.43 \times 10^{13}\text{V/m} \quad , \\ B =& \frac{E}{c} = 0.81 \times 10^9\text{Gauss} \quad . \end{aligned} \tag{2.3}$$

Inserting into eq.(2.2), we find $\eta_{max} = 2.7$. So the interaction is coherent, and is in the multiphoton regime.

In this coherent regime, one may invoke the language which describes the electron interaction with a static EM field. In this case the number of photons emitted by the relativistic electron per unit length of traverse in the transverse static EM field can be described by another Lorentz invariant parameter Υ:[2]

$$\frac{dn_\gamma}{dz} = \frac{5}{2\sqrt{3}}\frac{\alpha\Upsilon}{\lambda_c\gamma}U_0(\Upsilon) \quad , \tag{2.4}$$

where

$$\Upsilon = \gamma\frac{2E}{B_c} \quad ; \quad U_0(\Upsilon) \approx \frac{1}{(1+\Upsilon^{2/3})^{1/2}} \quad . \tag{2.5}$$

Here $B_c = m^2c^3/e\hbar \approx 4.4 \times 10^{13}$ Gauss is the Schwinger critical field strength. Obviously, Υ does not have any frequency content. We see that Υ and η are related by

$$\Upsilon = \frac{2\gamma\hbar\omega}{mc^2}\eta \quad . \tag{2.6}$$

Thus in the regime of $\eta \gg 1$, a physical process can be either calssical ($\Upsilon \ll 1$) or quantum mechanical ($\Upsilon \gg 1$), depending on whether the photon is much less or more energetic than the electron in the electron rest frame. In the same numerical example discussed above, we find $\Upsilon_{max} = 19$. Thus at the peak of the photon beam field the interaction is deep in the quantum regime.

The photons that are emitted in this process will further interact with the same EM field, and have a finite probability of turning into e^+e^- pairs. This process has been called the *coherent pair creation* in the context of beamstrahlung.[3] In essense, this is the cross channel of the radiation process discussed above.

Let us define an equivalent Lorentz factor $\gamma' \equiv E_\gamma/mc^2$, and introduce an equivalent Lorentz invariant parameter $\Upsilon' = \gamma' 2E/B_c$ for the coherent pair creation process: $\gamma \to e^+e^-$. It can be shown that in the asymptotic limits, the energy spectrum of the pair-produced particle, with fractional energy $x = E_{e^+}/E_\gamma$, are given by[3,4]

$$\frac{d^2 n_{e^+}}{dx dz} = \frac{1}{\sqrt{3}\pi}\frac{\alpha}{\lambda_c \gamma'}\Big\{\Big[\frac{1-x}{x} + \frac{x}{1-x}\Big] K_{2/3}(\xi) + \int_\xi^\infty dz K_{1/3}(z)\Big\}$$

$$\approx \frac{\sqrt{3}}{8\pi}\frac{\alpha \Upsilon}{\lambda_c \gamma'} \cdot e^{-\xi} \begin{cases} \sqrt{\pi}(\xi/2)^{1/2}[3 + (1-2x)^2], & \Upsilon' \leq 50; \\ 2\Gamma(2/3)(\xi/2)^{1/3}[1 + (1-2x)^2], & \Upsilon' > 50; \end{cases} \qquad (2.7)$$

where

$$\xi \equiv \frac{2}{3\Upsilon'}\frac{1}{x(1-x)} \quad .$$

The approximate forms are obtained by taking series and asymptotic expansions of the Bessel functions for $\xi \ll 1$ and $\xi \gg 1$, respectively. Since ξ depends on a combination of Υ' and x, these approximations in principle are not proper in describing different regimes of Υ's. Emperically, however, we find that if we take the upper expression for $Y' \leq 50$ and switch to the lower expression for $\Upsilon' > 50$, then the approximation is very good (see Fig. 2). In fact the worst fit occurs only in a very small range around $\Upsilon' \approx 50$ where the error is less then 15%. For all other values of Υ', the error is less than 5%.

In Fig. 2, we see that there exists a *threshold* at $\Upsilon' \sim 1$ in the coherent pair creation process, below which the probability is exponentially suppressed. This fact is one of the major motivations in our proposal for a positron source: In the showering process of successive radiations and pair productions during the electron-laser beam-beam collision, the further branchings essentially ceased when Υ' cascades down to around one.

This helps to accumulate positrons at a certain threshold energy, which in turn helps the yield of positrons within a reasonable energy window (see Fig. 3).

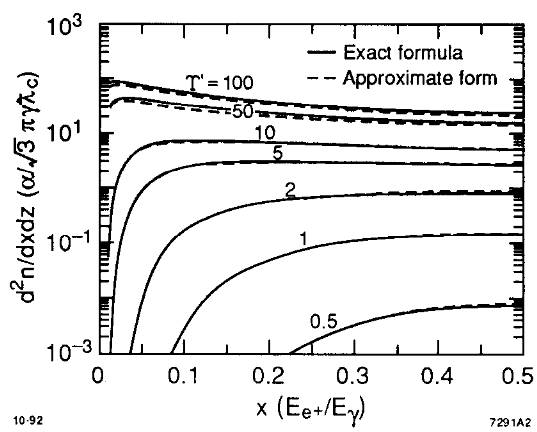

Fig. 2 A comparison of the exact and the approximate coherent pair creation spectrum in Eq.(2.7).

3. Damping of Positron Emittance

Another major advantage of this scheme is the damping of positron emittance. The *rms* angle of the initial electrons is

$$\theta_{in} = \sqrt{\frac{\epsilon_n}{\gamma_{in}\beta^*_{in}}} \quad . \tag{3.1}$$

In the successive radiation-pair creation process, the final state positron outcoming angle is widened.

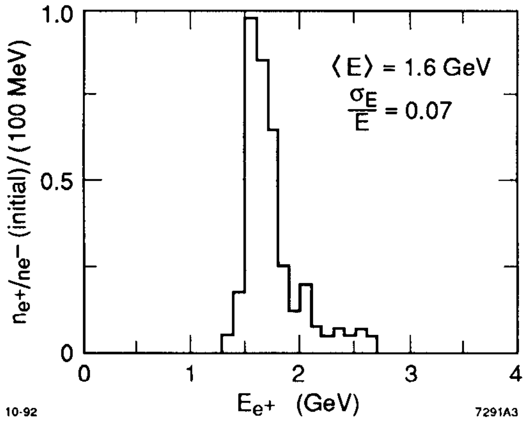

Fig. 3 The final energy spectrum of positrons. The parameters of example A in Table 1 are used in this calculation.

The typical angle of synchrotron radiation is an amount $1/\gamma$ tangential to the instantaneous trajectory of the electron. The pitch angle of the electron, as discussed earlier, is $\theta_H = \eta/\gamma$ at a given γ, where η is independent of the electron energy as long as it is relativistic (or $\gamma \gg 1$). Thus the typical outcoming angle of the photon is about an amount $1/\gamma$ departing from θ_H. For the electron, the difference between the initial state and final state pitch angles due to the energy loss is

$$\Delta\theta_H = \theta_{H1} - \theta_{H2} = \eta\left(\frac{1}{\gamma_2} - \frac{1}{\gamma_2}\right) \quad . \tag{3.2}$$

There is also a contribution to the angular increase from the conservation of momentum:

$$\Delta\theta_\gamma = \frac{1}{\gamma}\frac{E_\gamma}{E_{e_2}} \quad . \tag{3.3}$$

When the photon with energy γ' further turns into a e^+e^- pair, there is an additional transeverse momentum introduced which is of the order $p_\perp \sim mc$. This corresponds to an angle

$$\Delta\theta_{e^+e^-} \simeq 1/\gamma' \tag{3.4}$$

Then the final emittance of the positrons is

$$\epsilon_f = \gamma_{out}\beta^*_{out}\theta^2_{out} \quad , \tag{3.5}$$

where θ_{out} is all the above discussed angular contributions added in quadrature,

$$\theta_{out} = \left[\theta^2_{in} + \Delta\theta^2_H + \Delta\theta^2_\gamma + \Delta\theta^2_{\epsilon^+\epsilon^-}\right] \quad . \tag{3.6}$$

In the same numerical example that we discussed earlier, we find from a Monte Carlo simulation (see next section) that the *rms* angle increases from

$\theta_{in} = 6.3 \times 10^{-6}$ to $\theta_{out} = 120 \times 10^{-6}$. We see that although the angle is indeed degraded, it nevertheless is rather mild. On the other hand, to match with the input condition, the outcoming β^* remains to be 0.5 mm. The outcoming positron energy, however, is largely reduced due to the cascading process and the threshold effect that we discussed in the previous section. In this case, we find $\langle E \rangle \approx 2$ GeV, or $\langle \gamma \rangle \approx 3400$. This corresponds to an emittance of $\epsilon_{fn} = 3 \times 10^{-8}$ mrad $\ll \epsilon_n = 1 \times 10^{-6}$ mrad! Note that this emittance is comparable to the best one can achieve from the damping ring in one dimension, yet in this case it is in both.

4. Numerical Examples

To demonstrate the possibility of this idea of positron source, we perform Monte Carlo simulations of the electron-photon beam-beam collision process. The cascade of the initial electrons through the successive synchrotron radiation and coherent pair creation processes are tracked, using eq.(2.3) and eq.(2.4) for the radiation, and the approximate formulas in eq.(2.7) for the pair creation spectrum.

The first example studied (A in Table 1) used the parameters defined in earlier sections of this paper. Figure 4 shows the time structure of the parameter η inside the photon beam, which is assumed to be Gaussian, the mean energy of the initial electrons, and the yield of positrons per initial electron, n_{e^+}/n_{e^-}. We see that before the electrons encounter the maximum field strength in the photon beam, their energies have largely been lost to the synchrotron radiation. On the other hand, the positron yield becomes significant only after η starts to be larger than unity, as we expected. The yield in this example is $n_{e^+}/n_{e^-} \sim 4.5$, with an *rms* width equal to 7% of the peak (see Fig. 3). If positrons are accepted in a momentum window of $\Delta p/p = \pm 2.5\%$, then 1.6 positrons are obtained for each initial electron. The final normalized emittance is $\epsilon_{fn} \approx 3 \times 10^{-8}$ mrad.

In Table 1 parameters are given for a number of other examples. In all cases the initial normalized emittance is taken as 1×10^{-6} mrad, the initial and final β^*'s are 0.5 mm, and the apertures used were chosen to set the depth of focus equal to the interaction length. Different initial electron energies, laser pulse lengths and laser frequencies are chosen and in each case a laser power selected to give appoximately 1.5 positrons per initial electron.

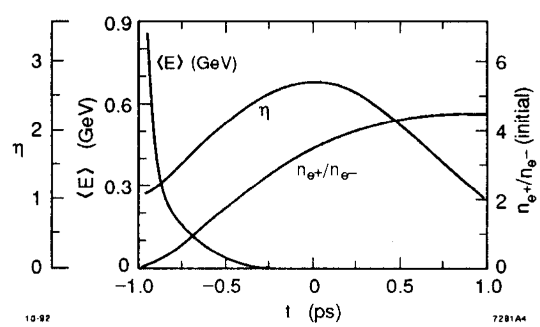

Fig. 4 The time structure of the parameter η inside the photon beam, the mean energy of the initial electrons, and the yield of positrons per initial electron, n_{e^+}/n_{e^-}.

It is seen that the required number of Joules is roughly inversely proportional to the electron energy, and almost proportional to the EM pulse length. The required EM energies falls even faster than linearly with the wavelength, giving a strong argument in favor of using very short wavelengths. The final emittance is seen to be strongly dependent of η, with values as low as possible favored.

Table 1. Parameters of Examples of Coherent Positron Sources

Electron Beam	A	B	C	D	E	F
E_e[GeV]	250	50	250	50	250	50
$\epsilon_n[10^{-6}$mrad]	1	1	1	1	1	1
β^*[mm]	0.5	0.5	0.5	0.5	0.5	0.5
σ_z max [μm]	150	150	37	37	19	19
Photon Beam						
λ[nm]	350	350	350	350	40	40
J[Joule]	15	75	5	25	0.2	1.5
σ_t[fsec]	500	500	125	125	60	60
f/d	10.4	10.4	5.2	5.2	10.6	10.6
Pair Creation						
η	2.7	6.0	6.2	14	0.9	2.4
Υ	19	9	44	20	54	30
n_{e^+}/n_{e^-}	4.5	2.5	6.5	3.5	5.6	4.6
$\langle E\rangle$[GeV]	1.6	0.5	0.95	0.28	1.0	0.22
σ_E/E	0.07	0.06	0.11	0.08	0.12	0.08
$n_{e^+}/n_{e^-}[\Delta p/p = \pm 2.5\%]$	1.6	1.2	1.6	1.3	1.3	1.5
$\epsilon_{fn}[10^{-6}$mrad]	0.03	0.06	0.28	0.69	0.04	0.10

5. Conclusion

The two key ingredients of our positron source are the existence of a thredshold in the coherent pair creation process, and the mild increase of the positron beam divergence at a much lower produced energy. The former helps for the selection of positrons within a narrow energy window, while the latter helps to damp the normalized eimttance of the produced positron beam. These features ensure that the positron beam thus produced has the right qualitative characteristic that meets the demand in future linear colliders.

In the actual Monte Carlo studies that we performed certain approximations have been made. First, at the early stage of the electron- photon beam-beam collision the laser intensity is generally low, and $\eta < 1$. This lies outside the coherent regime of interaction. Yet in the calculations, we apply the coherent formulas to the entire collision. Second, instead of using the general expression for coherent pair creation as in the first line in eq.(2.7), for the ease of computation we employed the approximate forms in eq.(2.7) instead. Furthermore, the transverse variations of the electron and photon beam intensities have been ignored in the calculation. However, since a photon beam would typically follow a Gaussian variation in time, which has a rather rapid rise in intensity, we do not expect the general features of our discussion to have been distorted too much in the calculation. In addition, the approximate coherent pair creation spectrum is actually quite accurate. Nevertheless, a more refined treatment should be persuit in our next effort.

In the numerical examples, it appears that at longer wavelength, e.g., $\lambda = 350$ nm, the energy requirements are not too far beyond the reach of convertional lasers. The problem is, such high power lasers tend to have low repetition rates. As a proof-of-princeple experiment, however, this type of lasers can still be very useful. When we turn to much lower wavelengths, it is only natural to consider a Free Electron Laser (FEL). It is believed that such FEL's with $\lambda \sim 40$ nm, energy of a fraction of a Joule, and pulse length around 60 femtosecond are feasible.[5] Certainly, laser and FEL experts will be more competent in assess the technical challenges in meeting the requirements in our scheme.

6. Acknowledgement

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