POSITRON SOURCE FROM X-RAYS EMITTED BY PLASMA BETATRON MOTION

D.K. Johnson, C.E. Clayton, C. Huang, C.Joshi, W. Lu, K.A. Marsh,
W.B. Mori,M. Zhou, UCLA, Los Angeles, CA 90025
I. Blumenfeld, C.D. Barnes, F.J. Decker, P. Emma, M.J. Hogan, R. Ischebeck, R. Iverson, N. Kirby,
P. Krejcik, R.H. Siemann, C.L. O'Connell, D. Walz, SLAC, Menlo Park, CA 94025
S. Deng, T.C. Katsouleas, P. Muggli, E. Oz, USC, Los Angeles, CA 90089

Abstract

A new method for generating positrons has been proposed that uses betatron X-rays emitted by an electron beam in a high-K plasma wiggler. The plasma wiggler is an ion column produced by the head of the beam when the peak beam density exceeds the plasma density. The radial electric field of the beam blows out the plasma electrons transversely, creating an ion column. The focusing electric field of the ion column causes the beam electrons to execute betatron oscillations about the ion column axis. At the proper plasma density, this leads to synchrotron radiation in the 1-50 MeV range. These photons strike a thin (.5Xo), high-Z target and create electron-positron pairs. Experimental results from work conducted at the Stanford Linear Accelerator Center (SLAC), where a 28.5 GeV electron beam was used in a proof-of-principle demonstration of this scheme, were matched with a simulation model. This model was expanded to design a potential positron source, giving positron yields of 0.44 positrons/electron, a number that is close to the target goal of 1-2 positrons/electron for future positron sources.

INTRODUCTION

Positron beam requirements for future linear colliders suggest that traditional "thick", Bremsstrahlung e^+ sources are not feasible. This source will likely fail from thermal stress within the target. There have been several alternate designs for next generation positron sources [1, 2]. All of the methods considered produce positrons after colliding MeV X-rays with a "thin", high-Z target. Any source must also have a high conversion efficiency of drive beam energy to MeV X-ray photons since an average photon energy of 10-30 MeV is desired for efficient positron production [3].

Photo-production of positrons is seen as the solution for future linear colliders, but the methods for efficiently producing the X-rays are being studied. Our proposed method utilizes a plasma wiggler to wiggle beam electrons via betatron oscillations. If the electron beam density n_b is greater than the plasma density n_{pe}, all plasma electrons are expelled. The resulting ion column exerts a focusing force on the beam leading to electron betatron oscillations [4].

The details of the dynamics, radiation spectrum and total electron energy loss from a plasma wiggler can be found in Refs. [5, 6, 7]. As an example, with a standard plasma density utilized at SLAC of $n_{pe} = 3 \times 10^{17} cm^{-3}$ and SLAC beam conditions, a 28.5 GeV, $r_o = 10\mu m$ electron experiences a wiggler strength K of 173 with an on-axis critical photon energy of roughly 50 MeV, ideal for positron production. This electron radiates ~4.3 GeV/m. Thus, such a high-K plasma wiggler is well-suited for efficiently converting the electron beam energy into a large number of multi-MeV photons, a necessary condition for a practical positron source.

EXPERIMENTAL SETUP

An experiment was carried out at the Final Focus Test Beam Facility (FFTB) at the Stanford Linear Accelerator Center (SLAC) as a proof-of-principle of this source [8]. A 28.5 GeV beam containing $N_{bo} = 1.7 \times 10^{10}$ electrons was focused into a lithium (Li) vapor of variable length of $10 - 30cm$ and variable neutral density of $n_o = 1 - 30 \times 10^{16} cm^{-3}$, field ionizing the vapor to form a Li plasma.

The radiated betatron X-rays propagated in vacuum $40m$ downstream to the positron experiment. To minimize background noise, the maximum photon angular divergence of 9 mrad was collimated down to 0.1 mrad using two tungsten (W) collimators. These created an $8mm$ photon beam at the $1.7mm$ ($\approx .5$ radiation lengths) thick W positron convertor target. The resulting positrons exiting the target were imaged up to an energy of 20 MeV in a magnetic spectrometer with an aperture of roughly $12mm$ (vertical) by $32mm$ (horizontal) and detected using $1mm$ thick silicon surface barrier detectors (SBDs).

The electron beam exiting the plasma was steered out of the beamline by a dipole magnet. It was subsequently imaged on a Cherenkov radiator to record the spectrum of the beam electrons. These images were used to estimate the actual number of electrons that interact with the ion column N_{bi}, and the average electron energy loss from the plasma.

Coherent transition radiation (CTR) in the THz range was detected after the bunch propagated through a $1\mu m$ thick Ti foil upstream of the plasma. For a fixed N_{bo}, CTR energy is correlated to the inverse pulse length ($1/\sigma_z$) of the electron beam [8].

SIMULATION VS. EXPERIMENT

The radiation spectrum from the oscillating electrons in a plasma wiggler was computed using the saddle-point formalism described in Ref. [9], which is well-suited for a high-K wiggler. The X-ray spectrum as a function of position is input into the Electron-Gamma Shower 4 code (EGS4) [10]. Within EGS4, the photons collide with the W target generating the positrons. The positrons emanating from the target are propagated through the appropriate magnetic transport matrices to the location of the SBDs.

It was determined that the three critical parameters which determine the positron yield are the number of electrons N_{bi} that participate in betatron oscillations, the effective energy those electrons γ_{bi} and the spot-size of the beam $\sigma_{x,y:i}$ in the plasma [7]. We experimentally estimated N_{bi} and γ_{bi} using the Cherenkov energy diagnostic mentioned above [7], and calculated $\sigma_{x,y:i}$ based on the excellent agreement between the experimentally observed spot size and that predicted by an envelope model [7, 11].

Figure 1(a) shows a comparison between the experimentally measured positron spectrum and the calculated spectrum for three different plasma densities. The values of N_{bi}, γ_{bi} and $\sigma_{i:x,y}$ used in the calculation are obtained for each density as described above. The absolute agreement between the two is excellent, giving confidence to our ability to calculate yields for other parameters. Figure 1(b) shows how the total yield in the energy range 4-20 MeV varies as a function of the CTR energy for $n_p = 1 \times 10^{17} cm^{-3}$ and an 11 cm plasma. At a given density, as the CTR energy increases, the mean energy loss also increases reaching nearly 2.6 GeV at a CTR energy of 500. Since the betatron photon emission scales as γ_b^2 one might expect the total positron yield to go down as the CTR energy increases. Experimentally, the total yield first increases mainly because the number of particles that radiate in the ion column increases up to a CTR energy of 300. However, beyond this point, the energy loss of the beam to the wakefield continues to increase, while the number of electrons in the ion column saturates, and the total positron yield decreases. When these two effects are quantitatively taken into account, the agreement between the measured and the calculated yield is good.

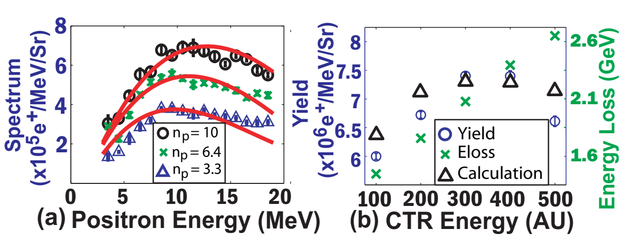


Figure 1: (a) Measured and calculated positron spectra for three n_{pe} values ($\times 10^{16} cm^{-3}$). (b) The integrated measured and computed positron yield between 4-20 MeV versus CTR signal. Also plotted is the wakefield loss as a function of CTR signal.

POSITRON SOURCE SIMULATION

The agreement between the experiment and the model provides confidence that this model can be extended to design a positron source with more optimum parameters. A schematic of such a source is shown in figure 2. The source uses a 1-m Cs plasma with a $0.5X_o$ W target that resides 2-m downstream from the exit of the plasma. This distance provides space for a dipole magnet to be installed that would deflect the electrons away from the target, eliminating critical thermal stress issues.

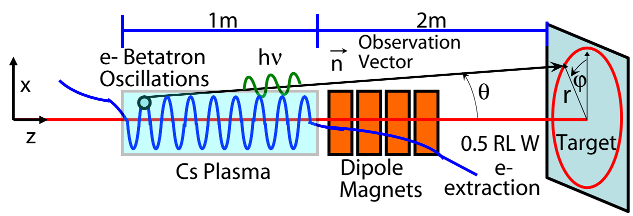


Figure 2: Schematic of the proposed positron source experiment.

The simulation input parameters are determined using QuickPIC [12]. QuickPIC is a fully nonlinear, three-dimensional particle-in-cell code that utilizes the quasi-static approximation. Table 1 defines the scaling laws for this regime using QuickPIC simulations [7].

Table 1: The plasma scaling laws in this regime from using a 3-D Gaussian electron beam in QuickPIC.

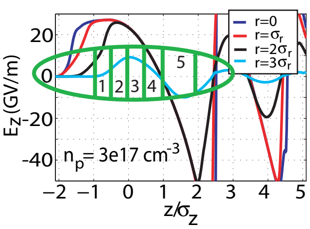
$Parameter$	$Scaling$
Radiated Energy (dW/dz)	$(\gamma^2 , n_{pe}^2 , r_\beta^2)$
Critical Energy (E_c)	$(\gamma^2 , n_{pe} , r_\beta)$
Photon Number $[dW/dz]/E_c$	(n_{pe} , r_β)
Max Ion Col. Rad. $(r_{i,max})$	$(\sqrt{N_b} , n_{pe}^{-1/2} , \sigma_z^{-1/2})$
Peak Energy Loss $(E_{z,peak})$	$(\sqrt{N_b} , \sqrt{n_{pe}} , \sigma_z^{-1/2})$

Parameters were chosen that had already been used experimentally at SLAC. Using QuickPIC, we conclude that an "ideal" case would have a 3-D Gaussian beam with $N_b = 4 \times 10^{10}$ with $\sigma_r = 9\mu m$, $\sigma_z = 35\mu m$, and $n_{pe} = 3 \times 10^{17} cm^{-3}$. A $\sigma_r = 9\mu m$ electron beam could be transversely supported in the ion column driven in a plasma of this density with $\sigma_z = 35\mu m$. The longitudinal wakefield driven with these beam and plasma parameters is shown in Fig. 3. This wakefield assumes a beam with $\sigma_r = 12\mu m$ as it enters the plasma. However, the electron beam focusing due to the ramped-density plasma profile [7, 11] would reduce the beam to $\sigma_r = 9\mu m$ with little effect on the wakefield.

An important scaling law to consider is n_{pe}. The energy loss to synchrotron radiation scales as n_{pe}^2, γ^2 and r_β^2. However, at a lower n_{pe}, the ion column is larger and $E_{z,peak}$ decreases. Using the parameters above, with $E_{beam} = 50GeV$, the wakefield was computed for $n_{pe} =$ 2, 3 and $4 \times 10^{17} cm^{-3}$. The $3 \times 10^{17} cm^{-3}$ case produced the largest positron yield. This is expected for the following reasons. When $n_{pe} = 2 \times 10^{17} cm^{-3}$, the ion column increase scales as $1/\sqrt{n_{pe}}$ and $E_{z,peak} \propto 1/\sqrt[4]{n_{pe}}$. However, those scaling laws are far smaller than the n_{pe}^2

scaling of radiated energy from betatron motion. With $n_{pe} = 4\times10^{17}cm^{-3}$, it was found that λ_p became so small that many of the longitudinal bins no longer resided in the ion column, reducing N_{bi} and thus the positron yield.

Three cases were investigated at $n_{pe} = 3 \times 10^{17}cm^{-3}$ with the parameters listed above. The initial γ_b has little effect on the longitudinal and transverse dynamics in the plasma. Thus, we can use Fig. 3 for the cases with $E_{beam} = 30$, 40 and 50 GeV. Figure 3 plots the wakeloss in each longitudinal portion of the electron beam. The Gaussian beam was split into 5 longitudinal bins of width $dz = .5\sigma_z$ with the number of electrons in each bin $N_{bi,x}$ being computed from a 3-D Gaussian shape. These bins will begin at $z = -\sigma_z$ since few electrons reside in an ion column upstream of this position. The wakeloss was given by the average between the two edges of the bin. The table in Fig. 3 gives the values for the 5 bins. The bin with $z > 2\sigma_z$ is excluded because these electrons no longer reside in the ion column.



Bin	σ_z Range	$N_{bi,x}$	Wakeloss (GeV/m)	$r_{i,max}/\sigma_r$
1		$5.99\text{x}10^9$	27	2.1
2		$7.66\text{x}10^9$	25	2.6
3		$7.66\text{x}10^9$	18	3.0
4		$5.99\text{x}10^9$	7	3.0
5		$5.40\text{x}10^9$	-12.5	3.0

Figure 3: (a) The longitudinal fields in a field ionized plasma with a $N_b = 4 \times 10^{10}$ electron beam with $\sigma_r = 12\mu m$, $\sigma_z = 35\mu m$ and $n_{pe} = 1 \times 10^{17}cm^{-3}$. (b) his table gives the values for the 5 bins in our positron source calculation. Negative wakeloss is an accelerating field.

The results of the three source simulations are shown in Table 2. The typical positron collection system will collect positrons up to 30 MeV. Thus, many of the 30-50 MeV positrons will be lost in a source with the current collection optics. The $E_{beam} = 50$ GeV case gives the best yield at all energies. Table 2 gives the output values from the simulation. It is logical to assume that a small average photon energy of ~ 20 MeV would be desired since these positrons can be easily collected. However, this is not the case because the high E_{beam} case gives the largest yield at all energies due to the e^+/e^- energy cross-section for pair production. Table 2 also plots the average number of e^+/beam e^- for each case. The $E_{beam} = 30$ GeV and $E_{beam} = 40$ GeV cases have yields that are too low for a realistic linear collider application. However, the $E_{beam} = 50$ GeV case has promise, as it collects 0.23 e^+/beam e^- from 1-30 MeV and 0.44 e^+/beam e^- from 1-50 MeV. These approach the initial goal of 1-2 e^+/beam e^-. Note that this result does not include the flux concentrator used in positron systems to enhance collection efficiency [2].

In this system, many positrons are created above the 50 MeV limit. If a system could be devised to collect these high energy positrons ($>$ 30 MeV) more efficiently, the yield would be increased substantially. However, a higher collection energy limit would not aid a low-K magnetic undulator, since few photons above 20 MeV are radiated [3].

Table 2: This table gives the output from the simulation considering three different beam energies of $E_{beam} = 30$ GeV, $E_{beam} = 40$ GeV and $E_{beam} = 50$ GeV. All cases assume a 3-D Gaussian beam with $N_b = 4\times10^{10}$ electrons with $\sigma_r = 9\mu m$, $\sigma_z = 35\mu m$ and $n_{pe} = 3 \times 10^{17}cm^{-3}$.

Beam Energy (GeV)	30	40	50
Average e^- Energy Loss (MeV)	935.4	2023	3343
Average Photon Energy (MeV)	14.2	22.9	34.9
Photons/Beam e^-	65.8	88.2	95.9
e^+/Beam e^- (1-30 MeV)	.09	.17	**.23**
e^+/Beam e^- (1-50 MeV)	.15	.30	**.44**

The radiated energy loss due to the $\theta = K/\gamma$ divergence of the photon beam is also important. The SLAC collection system will only accept a 2mm X-ray radius. However, with these parameters, the actual photon beam is about 7-10mm in radius. Thus, the total radiated power is $\sim 2-3$ times larger than that accepted with current designs, providing room for further source optimization.

CONCLUSION

Using parameters and densities that have been experimentally demonstrated and with the current SLAC collection optics (w/o the flux concentrator), about 0.44 e^+/ beam e^- could be collected with a 1-m long Cs plasma with $n_{pe} = 3 \times 10^{17}cm^{-3}$, $N_b = 4 \times 10^{10}$, $E_{beam} = 50$ GeV, $\sigma_r = 9\mu m$ and $\sigma_z = 35\mu m$. This is a respectable number and gives incentive to further explore this source design. All of the above parameters have assumed a constrained collection system. Thus, with a larger radial system capable of collecting higher energy positrons, the full benefit of the high-K wiggler could be realized.

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