GENERATION OF BUNCH TRAINS FOR PLASMA WAKEFIELD ACCELERATOR APPLICATIONS

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Abstract

Experimental and simulation results on the propagation, acceleration, and production of positron (e^+) bunches are presented. The results show that e^+ bunches can be accelerated in plasma-based accelerators, but that preserving the incoming beam emittance is a challenge. Results also show that the betatron radiation emitted by e^- bunches in a beam-driven plasma wakefield accelerator (PWFA) produce bright betatron radiation that could be used in a e^+ source.

INTRODUCTION

With the recent progress in plasma-based accelerators, one can contemplate the possibility of a future plasma-based electron/positron (e^-/e^+) collider at the TeV energy frontier. In particular, it was demonstrated in a particle beam driven plasma wakefield accelerator (or PWFA) experiment, that the energy of 42 GeV incoming electrons can be doubled over a plasma length of only 85 cm [1]. This result shows that an accelerating gradient of 50 GeV/m can be sustained over meter-long plasmas. In that experiment the acceleration length was limited by the erosion of the beam head that propagates in the neutral gas and in the forming wakefields. However, this limitation can easily be overcome by using lower emittance beams, such as those envisaged for future linear colliders. The large energy gain obtained in the PWFA results from the combination of large accelerating gradient, strong plasma focusing force, and lack of dephasing by the ultra-relativistic particles. When the beam density n_b exceeds the plasma density n_e, the core of the e^- bunch propagates in a pure and uniform density ion column [2]. The ion column has an ideal focusing force, increasing linearly with radius and constant along the bunch direction of propagation. The longitudinal [3] and transverse [4] dynamics of e^- bunches propagating in plasmas is well understood. While current experiments are performed with single particle bunches, future collider applications will require a drive bunch that only loses energy to the wakefields, followed by a witness bunch that that only gains energy from the wakefields. Both bunches will be within a plasma wavelength λ_{pe} ($\lambda_{pe}=2\pi c/\omega_{pe}$, $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$) often referred to in conventional accelerators as the "rf bucket". The witness has to be short (compared to λ_{pe}), and with beam loading will gain energy, extract a significant fraction of the wakefield energy, and maintain a narrow energy spread. Also, because of the plasma focusing provided by the uniform plasma ions its incoming emittance can be preserved.

The case of positron bunches propagating in plasmas is equally important to a future plasma based e^-/e^+ collider. e^+ bunches suitable for high-gradient plasma-based acceleration experiments such as those just described are not readily available. However, ultra-relativistic picosecond, nano Coulomb charge e^+ bunches are available at the SLAC National Accelerator Laboratory.

TRANSVERSE DYNAMICS OF POSITRONS IN A PWFA

In the nonlinear regime of the PWFA ($n_b>n_e$), the interaction of a e^+ bunch with the plasma is rather different from that of an e^- bunch: the plasma e^- are attracted towards and flow through the bunch, rather than being expelled. This results in the propagation of the e^+ bunch in a non-uniform plasma e^- density, rather than in the uniform plasma density ion column as in the case of an e^- driver. The focusing force created by the neutralization of the e^+ bunch space charge field by the plasma e^- is non linear across the bunch radius and non-uniform along the beam propagation direction. In addition, the plasma e^- density within the e^+ bunch can exceed the bunch density even if initially $n_b>n_e$.

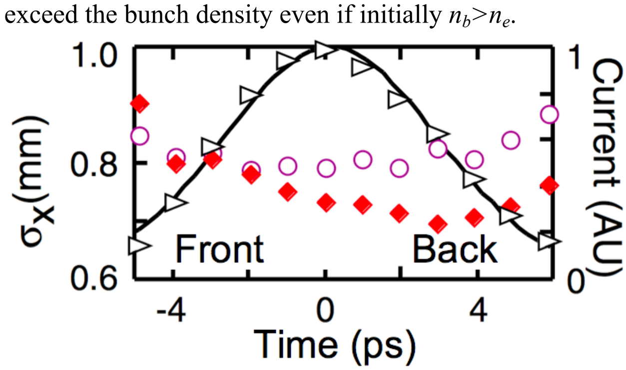


Figure 1: Transverse size along the e^+ bunch measured ≈1 m downstream of the plasma exit with a ≈1 ps resolution (from [5]). L_p=1.4 m and n_e=0 (purple circles) and 4x10^9 cm^{-3} (red diamonds). The black triangles show the bunch current profile.

The effect of the plasma focusing (transverse wakefield) on e^+ was studied experimentally in the case when the product of plasma density and length L_p ($n_e L_p$) is small enough so that the e^+ transverse size does not evolve significantly along the plasma. Figure 1 shows the time-resolved transverse size of the 28.5 GeV e^+ bunch as measured on screen one meter downstream for the plasma exit [6]. The plasma length is L_p=1.4 m and n_e=4x10^9 cm^{-3}. The figure shows that the focusing force increases from the front to the back of the bunch as more and more plasma e$^-$ are attracted toward the bunch.

The optimum density for the acceleration of the e$^+$ in the back of a single bunch is reached when the bunch length σ_z and the plasma wavelength λ_{pe} satisfy $\sigma_z \approx \lambda_{pe}/(\sqrt{2}\pi)$. For σ_z ≈700 µm this corresponds to $n_e \approx 10^{14}$ cm^{-3}, the $n_e L_p$ product is ≈2.5x10^4 times larger than in the case of Fig. 1, and evolution of the transverse beam size is expected over the plasma length. Figure 2 shows the beam transverse size along the plasma obtained from numerical simulations using the code QuickPIC [7] [2] for n_e=10^{14} cm^{-3}. As expected, at the beginning of the plasma (small $n_e L_p$ product) the beam is focused to a smaller size. However, since the plasma focusing force is non-linear along the bunch radius and varies along the bunch (Fig. 1), phase mixing of the e$^+$ trajectories prevents the beam from reaching a clear second focus, and the beam size only slowly increases along the plasma.

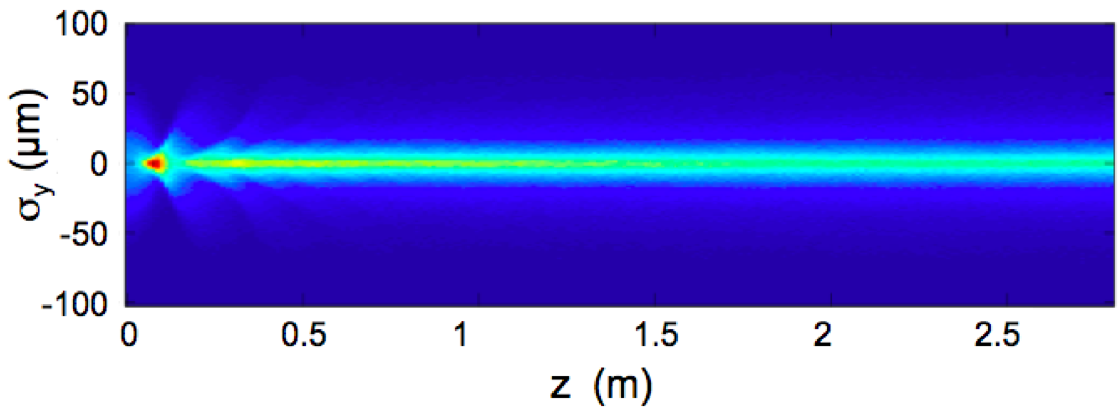


Figure 2: Transverse e$^+$ bunch size along the plasma obtained from numerical simulations for n_e=10^{14} cm^{-3} a beam size at the plasma entrance $\sigma_{x0}=\sigma_{y0}$=25µm, normalized emittances ε_{Nx}=390x10^{-6}, ε_{Ny}=80x10^{-6} m-rad, and N=1.9x10^{10} e$^+$ in the bunch.

Figure 3 shows the focusing field as a function of the position across and along the e$^+$ bunch. The focusing field varies nonlinearly across the bunch, and is not constant along the bunch. These fields create the mixing of the e$^+$ trajectories and the beam halo formation and emittance growth described below.

Figure 4 shows the beam size measured from experimental beam images and from simulation images of the beam 1 m downstream from the plasma exit as a function of n_e [8]. Unlike in the case of an e$^-$ bunch with similar parameters [4], no evidence of beam envelope betatron oscillation is observed. The beam size in the large emittance transverse x-plane is strongly reduced when the plasma is turned on, whereas in the low emittance plane the beam size does not change significantly. As n_e is increased, the beam size in the two planes increases slowly, and the two sizes are essentially equal. There is very good agreement between the experimental and simulation sizes. Note that since the focusing force is non linear and evolves both along the bunch and along the plasma, there is no simple envelope model to describe the evolution of the beam sizes along the plasma, unlike in the case of e$^-$ bunches, and numerical simulations are needed. In the simulations the particles are propagated ballistically from the plasma exit to the equivalent location of the screen in the experiment.

The beam images also reveal the presence of a beam charge halo that contains as much as 50% of the total beam charge at large values of n_e [8].

The beam emittance can be calculated from the particles phase space obtained in the numerical simulations and is shown on Fig. 5 as a function of the plasma length for a density n_e=2x10^{14} cm^{-3}. The emittances are calculated for five longitudinal beam slices containing 25% of the beam charge each, as well as for the whole bunch. The beam emittance in the initially low emittance y-plane quickly grows over the first 5 cm. After that the interplay between the force exerted by the bunch on the plasma e$^-$, the resulting neutralization of the bunch charge, and the coupling between the x- and y-plane results in a in a slow growth of the whole bunch emittance in both planes. The final emittance also increases with plasma density [9]. The two emittances become essentially equal at the end of the plasma.

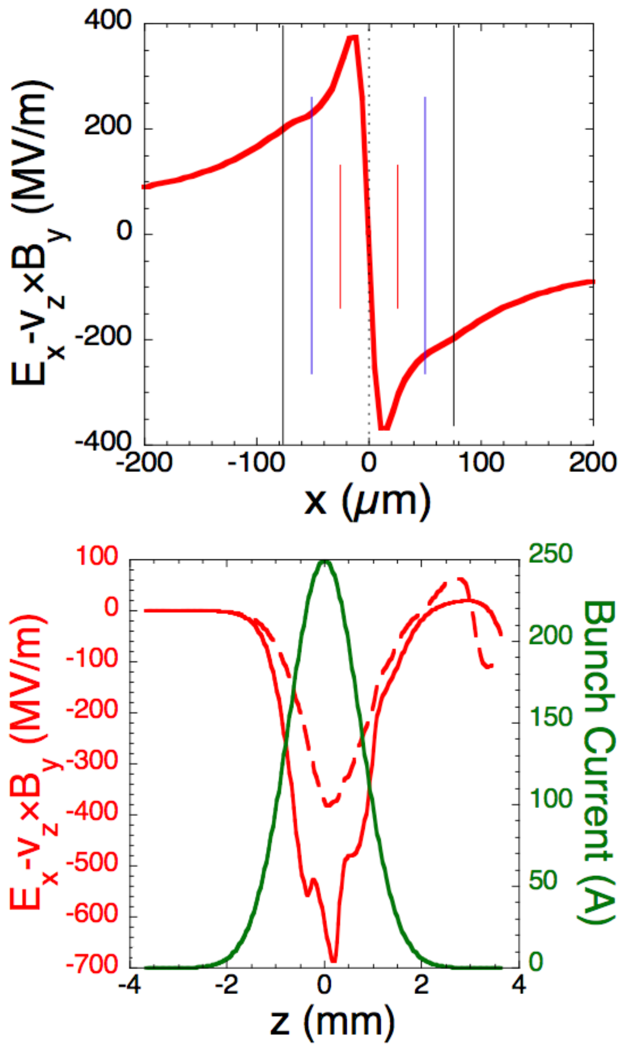
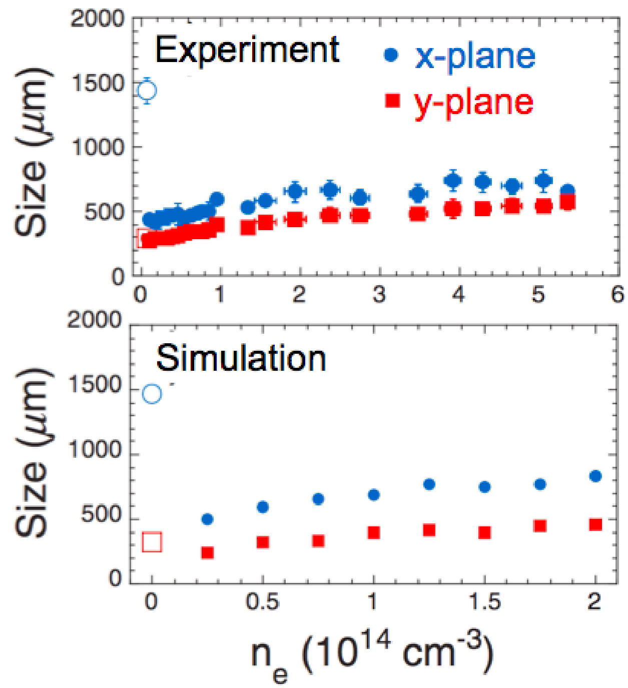


Figure 3: Focusing field obtained from simulations: top, across the bunch, along the x axis in the middle of the e^+, and bottom, along the bunch direction propagation at a radius of σ_r (solid line) and $3\sigma_r$ (dashed line). The σ_r, $2\sigma_r$, and $3\sigma_r$ widths are also indicated by vertical lines in the top graph. The plasma density is n_e=1.5x10^{-14} cm^{-3}.

Transverse e^+ bunch size as a function of the plasma density n_e obtained from beam images acquired in the experiment and from images generated from numerical simulations. In both cases the beam sizes at the plasma entrance are $\sigma_{x0}=\sigma_{y0}$=25µm, the normalized emittances are ε_{Nx}=390x10^{-6}, ε_{Ny}=80x10^{-6} m-rad, and there are N=1.9x10^{10} e^+ in the bunch (from [8]). Notice the different n_e scales. The empty symbols indicate sizes for n_e=0.

The previous results show that the beam exits the plasma with essentially equal size and emittances. This is the consequence of the coupling between the x- and y-planes and of the interplay between the focusing force and the beam size. Once the dephasing between the bunch particles trajectories under the influence of the plasma focusing force has "randomized" the beam phase space, the emittance and the beam size reach quasi-equilibrium values. Simulations show that even after longer propagation in the plasma, modest emittance growth occurs. Note that the focusing of the same e^+ bunch by a mm-long high-density plasma was also observed experimentally [10].



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POSITRONS ACCELERATION

The previous section shows that the transverse wakefields driven by a e^+ bunch in a plasma must create a nonlinear focusing force, which leads to emittance growth and halo formation. The longitudinal wakefields also have a decelerating and an accelerating component. We showed experimentally that, as in the case of a single e^- bunch [1,3], e^+ in the front and core of the bunch lose energy to the wakefields, while at the proper density, e^+ in the back of the bunch can gain energy from the wakefields [11]. The PWFA concept first demonstrated for e^- bunches can also be used to accelerate positrons in a plasma-based accelerator (particle or laser beam driven). For collider application, a drive bunch witness bunch train will be necessary. The drive bunch could be either a e^- or a e^+ bunch. One way to produce a train of e- or e^+ is to split a single incoming bunch using a recently demonstrated masking technique [12]. However, it may be advantageous to accelerate a e^+ bunch on the wake driven by a e^- bunch [13]. A hybrid train with a few tens of microns of separation between the bunches does not exist at present. A method to create such a hybrid train by embedding a conversion target directly into the plasma and using a e^-/e^- trains [14] was recently proposed to test this acceleration scheme before a proper train becomes available at SLAC [15]. In this method, the strong transverse plasma wakefields naturally select the proper drive and witness bunches. Acceleration of e^+ in a plasma with high-gradient (multi-GeV) while preserving the beam emittance is one of the challenges of plasma-based particle acceleration.

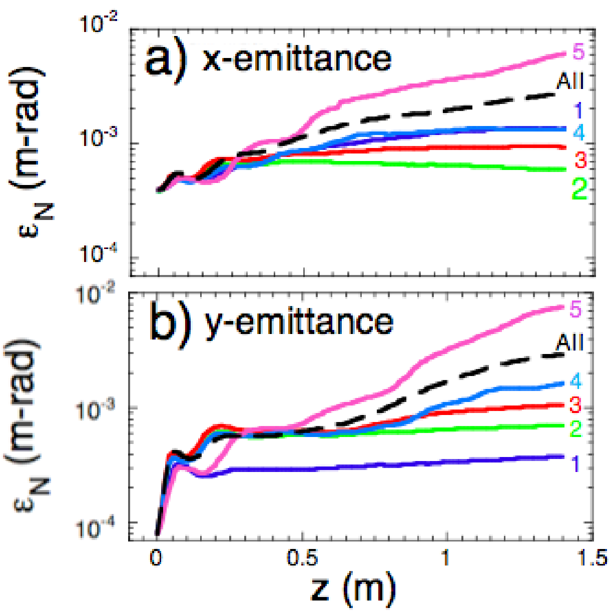

Figure 5: Beam emittances along the 1.4 m long plasma with n_e=2x10^{14} cm^{-3} calculated for five longitudinal beam slices (labeled from 1 at the beam front to 5 at the beam back) containing 20% of the beam charge each, as well as for the whole beam (labeled All). For the simulation the beam sizes at the plasma entrance are $\sigma_{x0}=\sigma_{y0}$=25µm, the normalized emittances are ε_{Nx}=390x10^{-6}, ε_{Ny}=80x10^{-6} m-rad, and there are N=1.9x10^{10} e^+ in the bunch (from [8]).

POSITRONS PRODUCTION

Positrons are produced by pair creation in a high Z target. At SLAC, the 28 GeV electron beam hits a Ta-W target. The e^+ yield is about four e^+ per e^- (after acceleration to 200 MeV), and one once the e^+ beam enters the linac [16]. However, for a future collider with large e^+ flux it may be advantageous to separate the gamma ray production from the pair creation itself to minimize the thermal stress in the conversion target. Polarized e^+ beams are also desirable for particle physics applications. Producing polarized gamma rays in a separate radiation device would open that possibility.

As mentioned earlier, e^- experience betatron oscillations in the strong focusing force of the plasma ion column. As they oscillate, they emit synchrotron radiation often referred to as betatron radiation. Bright betatron radiation in the keV range was observed in the SLAC PWFA experiments with long (≈700 µm) bunches in plasmas with densities around 10^{14} cm^{-3} [17]. A photon with energy >$2m_ec^2$≈1.022 MeV is necessary for pair production. Copious amount of gamma rays were produced at SLAC with e^- bunches 20 to 50 µm long in a meter long plasma with a density in the 10^{16} to 10^{17} cm^{-3} range. These un-polarized gamma rays were converted into e^-/e^+ pairs in a high Z target. [18]. Figure 6 shows the spectrum of the e^+ obtained from the betatron radiation emitted by the e^- beam propagating through a meter-long plasma with three different values of plasma density. The absolute numbers of e^+ are limited by the large distance between the plasma and the conversion target, and the collimation of the gamma ray that was used to limit their scattering between the plasma and the target. However, they are in good agreement with the numbers obtained from the calculation of the beam radiation spectra and conversion process in the target.

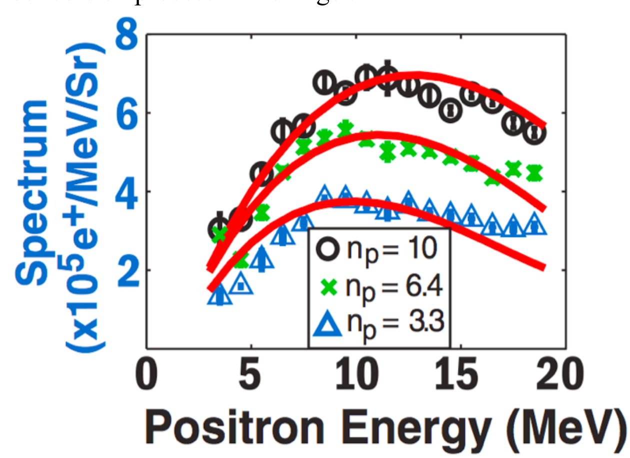

Figure 6: Measured (symbols) and calculated (lines) e^+ spectra for three plasma densities. The densities are labeled in units of 10^{16} cm^{-3}, from [18].

Polarized gamma rays could be produced by a e^- beam entering the plasma with a transverse angular momentum. The beam would spiral in the plasma focusing field and produce the desired polarized gamma rays subsequently converted into polarized e^+ in a high Z target.

SUMMARY

While the propagation and acceleration of e^- in plasma-based accelerators have been extensively studied and are well understood, the case is different for e^+. Positron beams are not readily available. In addition the fact that the plasma $e^-$are attracted toward and flow through a e^+ bunch, instead of flowing around a e^- bunch has drastic consequences on e^+ propagation and wake excitation in plasmas. Unlike in the case of the e^- bunch where the uniform ion column acts as an ideal focusing element, the plasma e^- density is non uniform along an across the e^+ bunch and can even exceed the bunch density. This leads no a nonlinear focusing force that is responsible for beam halo formation and emittance growth, as observed in experiments and simulations. Positrons can also be accelerated in plasma-based accelerators, albeit at lower gradient than e^- bunches with similar parameters. A possible means to avoid emittance growth and preserve the incoming beam emittance while increasing the accelerating gradient is to use a hollow plasma channel. However, this option needs to be studied with numerical simulations. Experiments are also planned at the SLAC FACET facility. The acceleration of e^+ bunches in high-gradient plasma-based accelerators while preserving the incoming emittance is the next challenge.

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REFERENCES

[1] I. Blumenfeld et al., Nature 445, 741-744 (15 February 2007).
[2] J.B. Rosenzweig et al., Phys. Fluids B2, 1376(1990).
[3] P. Muggli et al., Phys. Rev. Lett. 93, 014802 (2004), M.J. Hogan et al., Phys. Rev. Lett. 95, 054802 (2005).
[4] C. E Clayton et al., Phys. Rev. Lett. 88, 154801 (2002), C. O'Connell et al., Phys. Rev. ST Accel. Beams 5, 121301 (2002).
[5] M. J. Hogan et al., Phys. Rev. Lett. 90, 205002 (2003).
[6] M. J. Hogan et al., Phys. Rev. Lett. 90, 205002 (2003).
[7] C.H. Huang, et al., J. Comp. Phys., 217(2), 658, (2006).
[8] P. Muggli et al., Phys. Rev. Lett. 101, 055001 (2008).
[9] X. Li, these Proceedings.
[10] J. Ng et al., Phys. Rev. Lett. 87, 244801 (2001).
[11] B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003).
[12] P. Muggli et al., Phys. Rev. Lett. 101, 054801 (2008).
[13] K. V. Lotov, Phys. Plasmas 14, 023101 (2007).
[14] X. Wang et al., Phys. Rev. Lett. 101, 124801 (2008).
[15] M.J. Hogan, A. Seryi, private communication.
[16] S. Ecklund, 1997 Proceedings of the Workshop on New Kinds of Positron Sources for Linear Colliders, available at http://www.slac.stanford.edu/pubs/confproc/nkpslc97/nkpslc97-004.html
[17] S. Wang et al., Phys. Rev. Lett. 88, 135004 (2002).
[18] D.K. Johnson et al., Phys. Rev. Lett. 97, 175003 (2006).