POSITRON BEAMS PROPAGATION IN PLASMA WAKEFIELD ACCELERATORS

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Abstract

Preservation of beam emittance is a concern in all accelerators. The formation of a beam charge halo in a plasma wakefield accelerator (PWFA) driven by a single positron bunch is observed. This phenomenon is also observed in numerical simulations. These simulations indicate that it results in significant emittance growth of the positron bunch. We discuss theses results as well as possible means to preserve the positron emittance.

INTRODUCTION

In conventional accelerators using magnetic optics and rf waves in resonant cavities to focus and accelerate particles, positive and negative charge particles can be accommodated by merely a change of current sign in the magnets and phase in the rf.

In plasma-based accelerators (PBAs) the plasma itself sustains the focusing and the accelerating fields. Plasmas are composed of particles of opposite charge, electrons and protons or ions, but of very different mass. Therefore, the light electrons are the mobile species, while the heavier ions are usually considered as immobile on the time scale of an electron plasma period. In the linear theory of PBAs where the relative plasma density perturbations $\delta n/n_e$ (n_e the background plasma density) and wakefield amplitudes are small, the plasma wave is also symmetric for opposite sign charges, providing a simple 90° phase shift of the wave or wake.

However, the nonlinear or blowout regime of PBAs [1] offers some striking advantages over the linear regime for accelerating electrons. In this regime all the plasma electrons are blown out of a volume encompassing the drive and the witness beam. This regime is reached when the drive particle bunch density n_b is much larger than the plasma density: $n_b >> n_e$, or when the drive laser intensity exceeds a threshold value. In this regime the accelerated beam propagates in a pure ion column that acts as a long focusing element free of geometric aberrations. Also, the accelerating field ($\approx\delta n/n_e$) is larger than in the linear regime. In fact, all current PBA experiments operate in this regime. These experiments have shown emittance preservation of the incoming beam [2,3], matching of the beam to the plasma focusing [3], and energy doubling of 42 GeV incoming electrons in only 85 cm of plasma [4], all the above in beam driven PBAs or plasma wakefield accelerators (PWFAs). Acceleration of electron bunches to hundreds of MeVs with narrow energy spread was also demonstrated in this regime in PBAs driven by intense laser pulses or laser wakefield accelerators (LWFAs) [5,6,7]. In this case, access to the nonlinear regime is necessary since the source for the accelerated beam is the trapping of the plasma electron triggered by the breaking of the plasma wave. In recent all these experiments the accelerating gradient exceeded 50 GV/m.

POSITRON BEAMS IN PLASMAS

The situation is very different for the acceleration of positron beams in plasmas. No blowout regime exists because the mobile plasma species is still the electrons, and to focus the positron beam by partial charge neutralization the plasma electrons have to flow through the positron bunch. As a result, in uniform plasmas the electrons do not form a large region (of the order of the plasma wavelength cubed as in the case of an electron bunch) where the wakefield can be uniform enough to accelerate the positron bunch with low energy spread and to focus it while preserving its low incoming emittance. This is true whether the drive beam is a laser pulse or a particle bunch. For instance, simulations indicate that the accelerating field driven by single bunch positron beams is smaller [8] than that driven by an electron bunch with similar parameters. Also, emittance growth of the incoming bunch along the plasma is expected as a consequence of the non-linear focusing force exerted by the plasma onto the bunch. Acceleration and propagation of positron beams in plasmas have not been studied as extensively as they have been with electrons. This is of course due primarily to the fact that short, high current positron bunches are not readily available, except at the Stanford Linear Accelerator Center (SLAC).

The acceleration of positrons in the wakefield driven by a single positron bunch has been demonstrated [9]. The focusing of a positron beam by a short, high-density gas jet plasma was also demonstrated [10]. The effect of the propagation of the same positron beam along a L_p=1.4 m, low density ($<10^{12}$ cm^{-3}) plasma column was studied in detail with picosecond time resolution along the ≈10 ps long bunch [11]. However, in these experiments the product of plasma density and plasma length ($n_eL_p<3\text{x}10^{12}$ m^{-2}) was too small for the beam to significantly evolve in its transverse dimensions along the plasma.

In order to gain large amounts of energy (>10 GeV) the positron beam will have to propagate through a long (L_p>2 m), dense ($n_e>10^{16}$ cm^{-3}) plasma, since accelerating gradients of 5 to 10 GV/m are desirable. The effect of the non-ideal wakefield will therefore accumulate and emittance preservation is an open question.

We present here some experimental and simulation results demonstrating the formation of a beam halo around a single positron bunch propagating through a 1.4-

m-long plasma, as well as the corresponding emittance growth [12].

EXPERIMENTAL SETUP

Figure 1 shows a schematic of the experimental set up. The ultra-relativistic (E_0=28.5 GeV, γ≈56,000) beam available at the SLAC Final Focus Test Beam [13] facility with ≈1.8x10^{10} positrons is focused near the entrance of the plasma. The typical transverse beam size at the waist is σ_{r0}≈25 μm (round beam). The bunch length is σ_z≈700 μm (or 2.3 ps). Because of scattering in the entrance beryllium window, the upstream optical transition radiation (OTR) foil and the thin pellicle mirror that makes the ionizing laser pulse collinear with the positron beam, the normalized emittances at the plasma entrance are ε_{Nx}≈380 and ε_{Ny}≈80 mm-mrad. Here the x direction is in the horizontal plane, and y in the vertical plane. The beam propagates along z. The beam transverse size and shape are monitored ≈1 m upstream and downstream of the plasma using OTR. The visible OTR light is imaged onto CCD cameras to record images for each bunch.

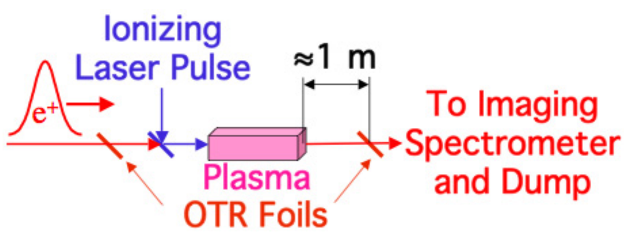

Figure 1: Schematic of the experimental setup. The beam transverse size and shape are monitored ≈1 m upstream and downstream of the plasma using optical transition radiation (OTR).

The plasma source consists of a hot lithium (Li) vapor contained in a heat-pipe oven [14,15]. A 20 ns uv laser pulse with a wavelength of 193 nm (6.4 eV/photon) ionizes the low ionization potential (5.4 eV) Li. The laser beam, and therefore the plasma, is made collinear with the positron beam by reflection off a 45°, 150 μm-thick glass pellicle coated for high reflectivity at 193 nm. The laser beam is also focused along the lithium vapor column to compensate for the uv photons absorption and thereby maintain a constant (±5%) plasma density over the column length. The plasma density is obtained from the measurements of the lithium neutral density and absorbed uv energy. The measurements of the positron characteristics with plasma (n_e>0) are acquired with the positron bunch traveling along the plasma 200 ns after the laser pulse. Every fourth event is recorded with the laser firing after the positron bunch (n_e=0) in order to continuously monitor the incoming beam characteristics. The plasma length is L_p=1.4 m, and n_e is varied between ≈10^{13} cm^{-3} and ≈5x10^{14} cm^{-3} by adjusting the laser pulse energy. The maximum ionization fraction is ≈13%.

HALO FORMATION, EXPERIMENT

Figure 2 show two images of the beam recorded at the downstream OTR foil location. With n_e=0 (Fig. (a)) the beam transverse shape is elliptical because of the round transverse size at the beam waist and the unequal emittances. The projections of the beam along the x and y directions are Gaussian to a good approximation. The corresponding transverse sizes are σ_x≈1430 μm (large) and σ_y≈310 μm (low emittance plane).

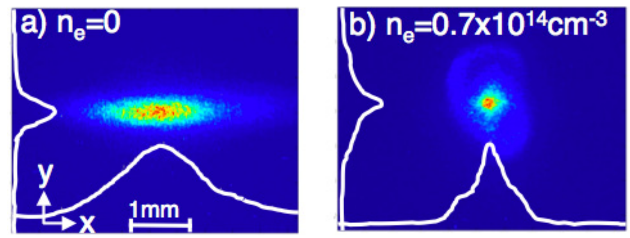

Figure 2: Experimental images of the beam recorded at the downstream OTR foil location. The white lines show the transverse beam profiles obtained by summing the images along the perpendicular direction. (a) With n_e=0, the beam profiles are Gaussian to a good approximation. The different x and y sizes are the result of the different emittances. (b) With n_e=0.7x10^{14} cm^{-3}, the image and the profiles exhibit a dense core surrounded by a charge halo (from [12]).

Figure 2 (b) shows an image of the beam after traveling through the n_e=0.7x10^{14} cm^{-3} plasma. This image shows that the beam has a tightly focused core, with a strong reduction of the beam transverse size in the x, large emittance plane. A halo of charge also appeared in the two planes, but is most noticeable in the y, low emittance plane. The transverse profiles are not Gaussian anymore, but instead reflect the core and halo structure. In order to describe these non-Gaussian profiles, a two-triangle fit [16]] is used to quantify the bunch core size as well as the relative amount of charge in the core and halo.

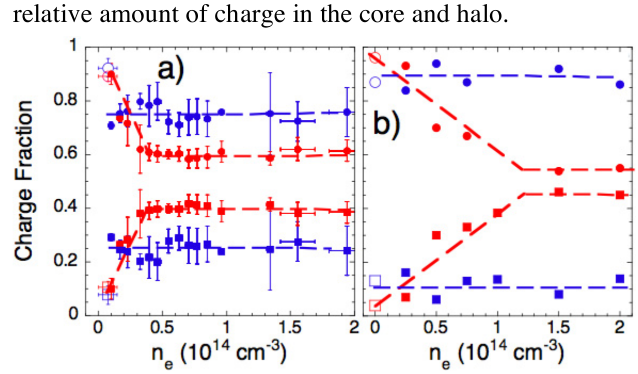

Figure 3: Charge fraction in the beam core (circles) and halo (squares) in the x (blue symbols) and y plane (red symbols) as a function of n_e obtained (a) from experimental OTR images (see Fig. 2) and (b) from simulations generated images. The beam parameters are those of the experiment. The lines are added to suggest trends.

Figure 3(a) shows the relative amount of charge in the focused core and in the halo as a function of n_e for densities up to $2\text{x}10^{14}$ cm^{-3}. These measurements are obtained from OTR images such as those on Fig. 2. In the y plane charge transfers from the core to the halo from n_e=0 to ≈$0.3\text{x}10^{14}$ cm^{-3}. Then the charge fractions remain approximately constant at 60% and 40% in the core and halo, respectively. In the x plane the charge fractions remain at 75% and 25% for all $0<n_e<2\text{x}10^{14}$ cm^{-3}.

HALO FORMATION, SIMULATION

The numerical code QuickPIC [17] is used to simulate the propagation of the positron bunch along the plasma. The positrons are then ballistically propagated a distance of one meter to generate images to be compared with those measured in the experiment at the location of the downstream OTR foil. Figure 4 show the evolution of the beam transverse size along the plasma obtained from one of these simulations. The beam parameters are those of the experiment, and the plasma density is n_e=10^{14} cm^{-3}. Over the first 10 cm the plasma focuses the beam. This effect is similar to the size reduction measured downstream from the plasma in ref. 11. The n_eL_p product is small, 10^{13} cm^{-2} in this case, and the plasma focusing force nonlinearities have not yet strongly spoiled the beam transverse phase space. The beam size is therefore reduced. Note that this focus occurs at a distance into the plasma that is shorter than the distance an electron beam with identical parameters would focus at. The betatron wavelength for electrons in a pure ion column with an ion density equal to n_e is $\lambda_\beta=2\pi(2\gamma)^{1/2}c/\omega_{pe}$, where $\omega_{pe}=(n_e e^2/\varepsilon_0 m)^{1/2}$ is the electron plasma angular frequency. The focus would appear at $\lambda_\beta/4$≈28 cm. This shorter focusing length reflects the fact that the plasma electron charge density can exceed the background density n_e and therefore the focusing force exceed that experienced by an electron beam in the same situation.

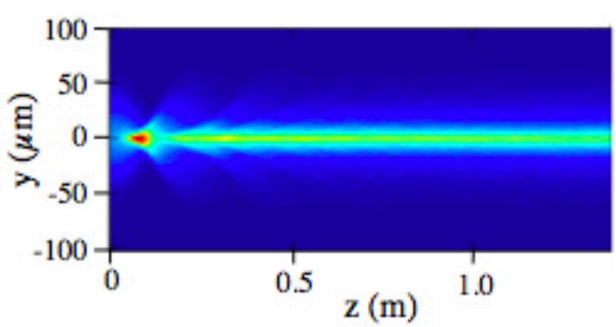

Figure 4: Beam transverse distribution (y, low emittance plane) along the L_p=140 cm, n_e=10^{14} cm^{-3} plasma obtained from numerical simulations. The beam parameters are those of the experiment.

After the first pinch the beam expands again, but does not come to a clear second pinch. Instead, the beam profile has a focused core on axis surrounded by charge in a beam halo, as seen on Fig. 2, and as seen on simulated images [12]. The beam profile then remains essentially constant over the length of the plasma from L=0.5 m to L_p=1.4 m, and n_eL_p=$1.4\text{x}10^{14}$ cm^{-2}.

Figure 3 (b) shows the charge fraction in the beam core and halo at the downstream OTR location as a function of n_e and can be compared to the experimental result of Fig. (a). Similarly to Fig. (a), Fig. (b) also shows a continuous transfer of charge from the core to the halo. However, this transfer process extends over a higher density range than observed in the experiment, up to ≈$1.2\text{x}10^{14}$ cm^{-3}. At higher n_e the fractions remain at 55% and 45% in the core and halo, respectively, values similar to those measured in the experiment. Beam transverse size measurements show excellent agreement with the sizes calculated from simulations images [12]. They also indicate that the beam exits the plasma with approximately equal transverse sizes.

The formation of the halo is the result of the nonlinear focusing force from the non uniform neutralization of the positron space charge by the plasma electrons rushing through it. The halo formation is therefore expected to lead to emittance growth. The bunch emittance is obtained from simulation results.

EMITTANCE GROWTH, SIMULATION

The normalized rms emittance of the beam in the x plane is calculated from the particles position x and momentum p_x as:

$$\varepsilon_{Nx} = \gamma\left(\left\langle x^2\right\rangle\left\langle x'^2\right\rangle - \left\langle xx'\right\rangle^2\right)^{1/2}$$

where $x'=p_x/<p_z>$, <.> stands for the quantity average, and $<p_z>$ is the beam average longitudinal momentum. A similar expression is used for the y plane normalized emittance.

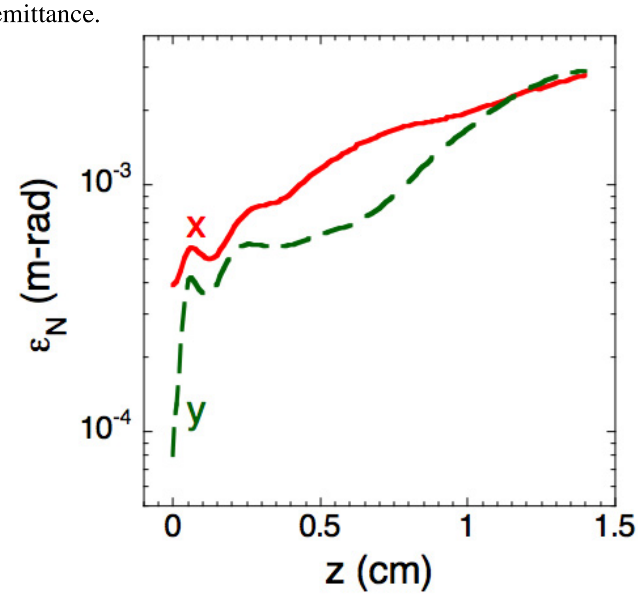

Figure 5: Evolution of the beam emittances (x plane, red continuous line, y plane green dashed line) along the plasma with n_e=$2\text{x}10^{14}$ cm^{-3} obtained from numerical simulations. Both final emittances are ≈$3\text{x}10^{-3}$ m-rad, corresponding to an emittance growth by a factor of ≈8 in the x-plane and 38 in the y-plane. The beam parameters are those of the experiment.

Figure 5 shows the evolution of the positron bunch normalized emittance in both transverse planes along the plasma. In the low emittance *y* plane the emittance quickly grows from the incoming 80 mm-mrad over the first few centimeter of plasma, to become approximately equal to the *x* emittance. After that the two emittances grow together and remain approximately equal. Both final emittances are ≈3x10^{-3} m-rad, corresponding to an emittance growth by a factor of ≈8 in the *x* plane and 38 in the *y* plane. As noted before, the beam transverses sizes are also about equal (as for example on Fig. 2 (b)).

EMITTANCE PRESERVATION

The results presented here above show charge halo formation and emittance growth when a single positron propagates in a uniform plasma suitable for acceleration of trailing particles [9]. However, future plasma-based linear collider will use a drive/witness bunch scheme. In that scheme, a first bunch (electron or positron) drives the wake and loses energy, while a witness bunch, following about a plasma wavelength behind the drive bunch, only gains energy. A similar scheme will be used in a laser-driven PBA, with the drive bunch replaces by a laser pulse. The emittance preservation of a positron witness bunch has not been studied in a two-bunch scheme and will be the subject of future simulation work. However, the use of a plasma with an on-axis hollow channel has been proposed to increase the accelerating gradient in the single positron bunch case [18]. Hollow plasma channels may also have an effect on the emittance of the bunch. Hollow plasma channels also have advantageous effects for laser-driven PBAs [19]. Preliminary results seem to indicate that a plasma hollow channel guides the positron beam and minimizes the beam distortion [20]. The challenge is to find a configuration that generates a region of the wake large enough to encompass a high charge positron bunch, a region in which the accelerating gradient is large and uniform, and the focusing force linearly increasing with radius. An alternative approach is to shape the witness bunch in its transverse and longitudinal dimensions in order to compensate for the non uniformities of the wake fields.

POSITRONS ON ELECTRON WAKE

Short, high-charge positron bunches are difficult to produce. It may therefore be advantageous to accelerate the positron witness bunch in the wake driven by an electron bunch [21,22]. This scheme would increase the efficiency of a future PBA e^-/e^+ collider by avoiding the generation of a positron drive bunch. It is also similar to that of a positron bunch in the wake driven by a laser pulse. The scheme is shown on Fig. 6. The positron bunch is placed right after the density spike created by the expelled plasma electrons returning on axis, the region where the wakefield is both accelerating and focusing for positrons. This region becomes narrower as the wake is made more nonlinear. A scheme was recently proposed [22] to create the positron beam inside the plasma, thereby avoiding all the issues associated with the generation, transport and timing of a positron bunch ≈100 μm behind an electron bunch. The positron bunch is generated by e^-/e^+ pair creation in a high-Z foil embedded into the plasma, The incoming electron beam is split in a drive/witness bunch train using for example a mask technique [23]. After the foils, two positron bunches overlap in space and time with the two incoming electron bunches. The plasma wakefields act to select and preserve only the drive electron bunch and the positron witness bunch or positron beam load. The positron beam load size must be adjusted to fit inside the favorable wake volume. Simulations show that ≈10^8 positrons with energies >5 MeV can be injected into, and trapped by the plasma wake. They can be accelerated to ≈5 GeV in one meter with a relative energy spread of ≈8%. The positron beam load normalized emittances are 20 and 25 mm-mrad in the *x* and *y* plane, respectively.

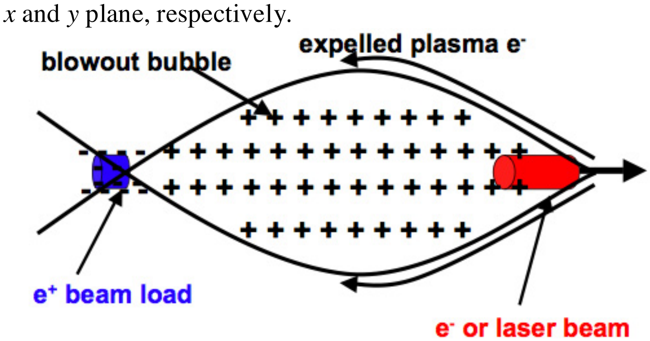

Figure 6: Schematic of the acceleration of a positron bunch (e^+ beam load) on the wake driven by an electron bunch or a laser pulse, from ref. 22.

SUMMARY

The acceleration of positron bunches in high-gradient PBAs while preserving the quality of the incoming bunch is key for a future plasma-based e^-/e^+ high-energy collider, whether driven by a laser pulse or a particle bunch. Experimental results obtained with a single positron PWFA show the appearance of a beam charge halo after the propagation through a 1.4 m-long plasma with a density in the 0.5-5x10^{14} cm^{-3} range. Simulations show that this halo formation is the indicator of emittance growth along the plasma. Halo formation and emittance growth are the result of the nonlinear force exerted by the plasmas onto the positron bunch. Unlike in the case of an electron bunch whose emittance can be preserved in the nonlinear blowout regime, the preservation of the emittance of a positron beam in a plasma is more challenging. This issue must be studied using full-scale numerical simulations and confirmed by experiments. Possible solutions include the use of a hollow plasma channel and the careful placing of the positron bunch in a lower plasma density, more linear-like wake.

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REFERENCES

[1] J.B. Rosenzweig, *et al.* , Phys. Rev. Lett. 58, 555 (1987).
[2] C. E Clayton et al., Phys. Rev. Lett. 88, 154801 (2002).
[3] P. Muggli *et al.*, Phys. Rev. Lett. 93, 014802 (2004).
[4] I. Blumenfeld *et al.*, Nature 445, 741 (2007).
[5] S. P. D. Mangles *et al.*, Nature 431, 535–538 (2004).
[6] C. G. R. Geddes *et al.*. Nature 431, 538–541 (2004).
[7] J. Faure *et al.*, Nature 431, 541–544 (2004).
[8] S. Lee, *et al.*, Phys. Rev. E 64, 045501 (2001).
[9] B.E. Blue *et al.*, Phys. Rev. Lett. 90, 214801 (2003).
[10] J. S. T. Ng, *et al.* , Phys. Rev. Lett. 87, 244801 (2001).
[11] M. J. Hogan *et al.*, Phys. Rev. Lett. 90, 205002 (2003).
[12] P. Muggli et al., Phys. Rev. Lett. 101, 055001 (2008).
[13] V. Balakin *et al.*, Phys. Rev. Lett. 74, 2479 (1995).
[14] C. R. Vidal and J. Cooper, J. Appl. Phys. 40, 3370 (1969).
[15] P. Muggli *et al.*, IEEE Trans. Plasma Sci. 27, 791 (1999).
[16] P. Muggli *et al.*, Proceedings of the 2003 Particle Accelerator Conference, Portland OR, p. 1915, www.jacow.org.
[17] C.H. Huang, *et al.*, J. Comp. Phys., 217(2), 658, (2006).
[18] S. Lee *et al.* , Phys. Rev. E 64, 045501 (2001).
[19] T. C. Chiou et al., Physics Of Plasmas, 2(1), 310 (1995).
[20] K.A. Marsh *et al.*, Proceedings of the 2003 Particle Accelerator Conference, p. 731, www.jacow.org.
[21] K. V. Lotov, Phys. Plasmas 14, 023101 (2007).
[22] X. Wang *et al.*, accepted for publication in Phys. Rev. Lett.
[23] P. Muggli et al., Phys. Rev. Lett. 101, 054801 (2008).