FOCUSING OF 28.5 GEV ELECTRON AND POSITRON BEAMS IN METER-LONG PLASMAS

Patric Muggli*
University of Southern California, Los Angeles CA 90089, USA

Abstract

Plasmas can focus both electron and positron beams. However, while the incoming Gaussian transverse profile of an electron beam is preserved upon focusing, the focusing of a positron beam by a long, high-density plasma results in a tightly focused core with the formation of a charge halo. The plasma acts on the positron beam as focusing element with transverse and longitudinal aberrations. The analysis of the focused positron beam transverse profiles is presented here.

INTRODUCTION

Plasma-based accelerators are characterized by their large accelerating gradient, one or more order of magnitude larger than those in today's state of the art radio-frequency base accelerators. Laser-driven plasma accelerators have demonstrated extremely high gradients, in excess of 100 GV/m [1]. However energy gains have been limited to ≈200 MeV [2], because the TW laser beam needs to be focused to an extremely tight focal spot to achieve the large intensity (>10^{18} W/cm^2) necessary to drive the large amplitude plasma wave. As a result the acceleration distance is limited to a few Rayleigh length of the laser beam, i.e., less than one millimeter. In particle beam driven plasma accelerators [3] or Plasma Wakefield Accelerators (PWFAs), gradients in the 1-10 GV/m range are expected. However, particle beams are focused by he plasma and can be channeled over long distances, therefore allowing in principle for multi-GeV energy gains to be achieved in meters-long plasmas [4]. Present experiments are performed in the very nonlinear regime of the PWFA, reached when the beam density n_b is larger than the plasma density n_e. Focusing of both electron and positron beams is predicted and observed experimentally. However differences are expected since an electron bunch expels the plasma electrons from the bunch volume, while a positron beam, attracts them toward the bunch volume. Electron bunches can be focused by an ideal, aberration-free plasma focusing element. For a positron bunch the plasma acts as a focusing element with transverse (spherical) and longitudinal aberrations. Previous results showing the dynamics of the focusing of positrons by low-density (n_e<10^{12} cm^{-3}) plasmas have been published [5]. Focusing of a positron beam by a short, dense plasma has also been observed previously [6].

FOCUSING OF ELECTRONS

A dense (n_b>n_e) electron bunch is sent into an initially neutral plasma expels all the plasma electrons from the bunch volume (blow-out), a short distance behind the bunch front. The remaining pure ion column partially neutralizes the space charge field of the core of the bunch, and the bunch is therefore focused by its self-magnetic field. The density of a Gaussian cylindrical bunch with radius σ_r, length σ_z, and N particles, is given by $n_b=N/\sigma_r^2\sigma_z(2\pi)^{3/2}$. For a highly relativistic electron bunch the pure ion column focusing field can be calculated using Poisson's equation and is given by:

$$E_r=\frac{1}{2}\frac{n_e e}{\varepsilon_0}r \tag{1}$$

The plasma is initially neutral, and the ion column density n_i is equal to n_e. Alternatively, the focusing strength of the pure ion column is given by:

$$\frac{B_\theta}{r}=\frac{E_r}{rc}=\frac{1}{2}\frac{n_e e}{\varepsilon_0 c} \tag{2}$$

and amounts to 6 kT/m for n_e=2×10^{14} cm^{-3}. Previous works [7] have shown that the focusing of narrow ($k_{pe}\sigma_r$<<1) electron bunches in this blow-out regime (n_b>n_e) is well described by a beam envelope model [8] for the beam transverse size σ_r: $\sigma_r''+K\sigma_r=\varepsilon^{\square}/\sigma_r^3$. The plasma restoring term is given by: $K=(1/\gamma mc^2)(F_r/r)=(1/\gamma mc^2)(eE_r/r)=\omega_{pe}^2/2\gamma c^2$. Here $k_{pe}=\omega_{pe}/c$ is the relativistic plasma wave wavenumber, $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$ is the plasma pulsation, and ε is the beam emittance. The incoming Gaussian beam (in the transverse dimensions x and y) is focused to a nearly Gaussian spot, as seen on Fig. 1. In this blow-out regime, most of the bunch charge is focused by the pure ion column, which acts on the beam as an essentially aberration-free focusing element. The formation of the pure ion column, and access to the blow-out regime within a single bunch has also been studied [9].

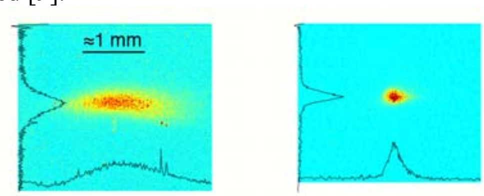

Figure 1: OTR images of the electron bunch without plasma (n_e=0 left), and with n_e≈10^{14} cm^{-3} (right) with the x (horizontal) and y (vertical) beam profiles. Without plasma the beam size is asymmetric because the beam emittances are different in the x and y planes.

FOCUSING OF POSITRONS

A positron bunch sent into an initially neutral plasma, attracts the plasma electrons toward, rather than expels them from the bunch volume, and they stream through it. As a result no blow-out condition exists. The neutralizing plasma electron density has a radial maximum on axis, and varies along the entire bunch length. The positron bunch is partially neutralized and is therefore focused by the plasma. However, the focusing field varies nonlinearly both along r and z, and the plasma acts on the positron bunch as a focusing element with strong spherical and longitudinal aberrations [10].

An experiment known as E-162 [11] has been performed at the Stanford Linear Accelerator Center (SLAC) to study the acceleration of 28.5 GeV electrons and positrons [12] in a 1.4 m-long plasma. The 1.4 m long plasma with n_e in the 0-2×10^{14} cm^{-3} range is obtained by photo-ionization of a lithium vapor by a ultra-violet laser pulse [13]. The particle beam is $\sigma_z\approx700$ µm long, has $N\approx2\times10^{10}$ particles, and is focused at the plasma entrance to a round spot with $\sigma_x\approx\sigma_y\approx25$ µm. In this experiment the focusing of the beam by the plasma is monitored by recording the beam size at a distance of ≈1 m downstream from the plasma. At that location the backward optical transition radiation (OTR) emitted by the particle beam when traversing a thin titanium foil is imaged onto a CCD camera to obtain time integrated transverse images of the beam on a shot-to-shot basis.

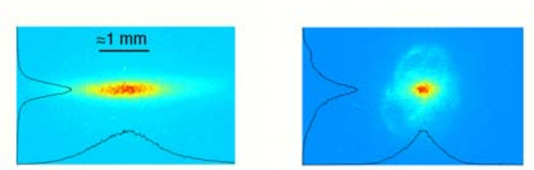

Figure 2: OTR images of the positron bunch without plasma (n_e=0, left), and with $n_e\approx10^{14}$ cm^{-3} (right) with the x (horizontal) and y (vertical) beam profiles. Without plasma the beam size is asymmetric because the beam emittances are different in the x and y planes.

Experimental results show that the incoming Gaussian positron beam acquires non-Gaussian transverse profiles after the high-density plasma ($n_e>10^{13}$ cm^{-3}), as seen on Figs 2. The focused beam shows a focused core surrounded by a charge halo, and the transverse profiles have a narrow triangular core profile sitting on a broader triangular pedestal (the halo). A simple bi-triangular profile fitting routine has been developed to describe the focused positron x and y beam profiles. The routine is initiated with linear fits to the experimental profiles in the 20% and 80% amplitude range for the triangular pedestal and core, respectively. The routine then minimizes the difference between the area under the experimental beam profile and the fit profile shape, assuming left-right symmetric profiles for each image. The beam size is obtained from the full width at half maximum (FWHM) of the core triangle fitted to the data, while the relative halo size is described by the ratio between the charge in the triangular core to the charge in the triangular halo, as shown on Fig. 3. Note that the profiles of the beam in absence of plasma are nearly Gaussian, with a root mean square width σ. Fig. 3 shows that in the case of a test Gaussian profile, the width of the profile obtained by using σ_{FWHM}=FWHM/$2(2\ln2)^{1/2}$=22.3 is in very good agreement with the input Gaussian width σ=24. Note that in this bi-triangular description, the best fit to a Gaussian profile has a halo that contains <4% of the Gaussian curve area.

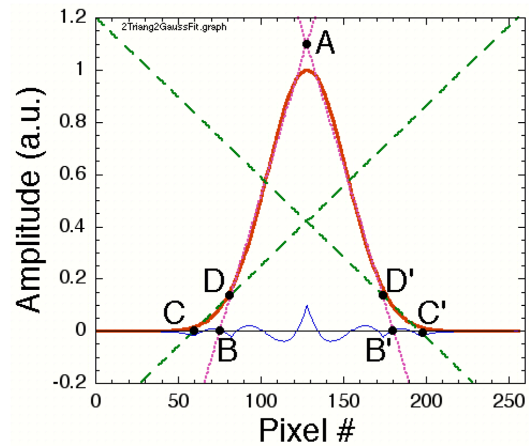

Figure 3: result of the bi-triangular fit to a test Gaussian profile. The fit to the core is represented by the dotted purple lines (area ABB'), while the fit to the halo is represented by the dashed green line (area BCD and B'C'D'). The thin blue line is the difference between the fit and the Gaussian curve.

This bi-triangular shape fitting is applied to the x- and y-profiles of the positron beam measured in the E-162 experiment. On Fig. 4 the result of the bi-triangular fit applied to the x-profile of the plasma off case of Fig. 2 is shown. The Gaussian fit result is also shown for comparison. From the bi-triangular fit results, the bunch core size σ_{FWHM} is ≈69 pixels or ≈622 µm. The "halo" contains ≈10% of the total charge. Figure 5 shows the same results for the plasma on case of Fig. 2. The core sizes σ_{FWHM} are ≈303 µm and ≈181 µm, and the halos contain ≈14% and ≈54% of the total charge in the x and y direction, respectively. These results show both focusing of the beam by a factor ≈2 In the x direction, and the formation of a significant halo in the y-direction. Complete results showing the focusing of the positron beam and the size of the beam halo as a function of the plasma density will be published later. Preliminary results indicate that, at the OTR screen location, a reduction in beam core size by a factor of three or more is observed. In the electron beam case, oscillation of the beam size as a function of n_e were observed [7], reflecting the betatron oscillation of the beam envelope along the plasma length. However, in the case of a positron beam no such size oscillation is observed. In the blow-out regime reached with electrons, the pure ion column focusing force is linear with radius (Eq. 1) and constant along the bunch, therefore allowing for the preservation of the emittance of the beam charge reaching the blow-out. This emittance preservation is very important for future PWFA, in which a driver bunch with $n_b>n_e$ will drive the wake, loose energy, and experience a significant emittance growth, while the witness bunch trailing the driver bunch will gain energy, and preserve its emittance. The study of emittance preservation for electron and positron beams in the PWFA will be the subject of a future publication.

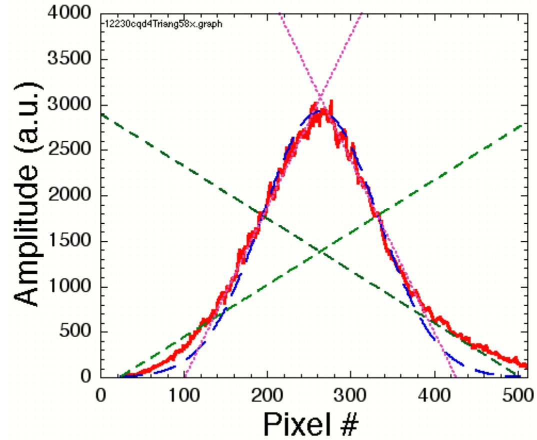

Figure 4: The x beam profiles (red line) from the beam on Fig. 2 with plasma off, and its fits: Gaussian (blue line), and bi-triangular core.(purple dotted lines) and halo (green dashed lines).

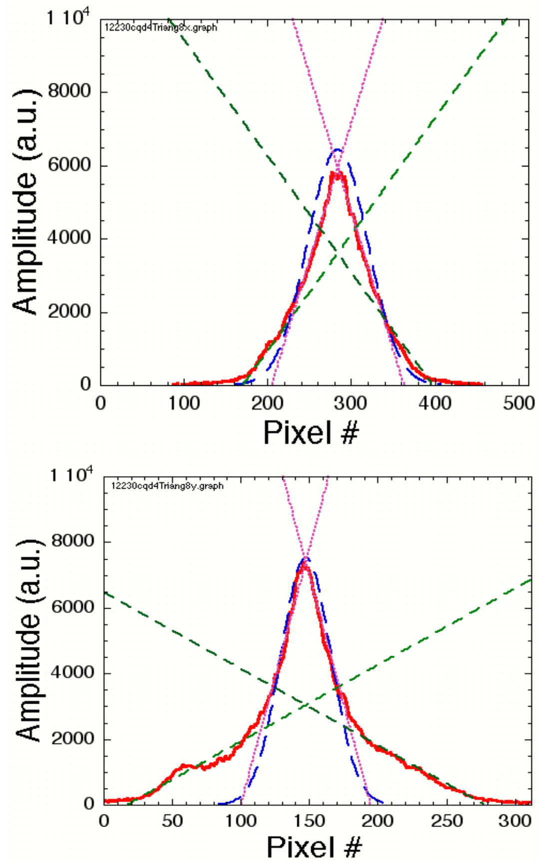

Figure 5: The x (top) and y (bottom) beam profiles (red lines) from the beam on Fig. 2, and their fits: Gaussian (blue line), and bi-triangular core.(purple dotted lines) and halo (green dashed lines). The halo is larger in the y-profile.

CONCLUSIONS

The focusing of electron and positron beams a distance of ≈1 m downstream from a 1.4 m-long plasma has bee observed experimentally. The incoming Gaussian bunch (in the transverse dimension) is focused to a Gaussian shape in the case of an electron bunch. In the case of a positrons beam, the bunch is focused to a tight core surrounded by a charge halo. The focused beam profiles are accurately described by a bi-triangular distribution for the bunch core and halo. The beam core size as well as the relative amount of charge contained in the halo are derived from the fitting parameters.

ACKNOWLEDGEMENTS

This work is supported by the US DoE and NSF grants.

REFERENCES

[1] D. Gordon *et al.*, Phys. Rev. Lett. **80**, 2133 (1998), C.I. Moore *et al.,* Phys. Rev. Lett. **79**, 3909 (1997); R. Wagner *et al.,* Phys. Rev. Lett. **78**, 3125 (1997); A. Modena, *et al.*, Nature **377**, 606 (1995).
[2] V. Malka *et al.*, Science **298**, 1596 (2002).
[3] P. Chen, *et al.* , Phys. Rev. Lett. **54**, 693 (1985).
[4] S. Lee *et al.*, Phys. Rev. STAB **5**, 011001 (2002).
[5] M.J. Hogan et al., Phys. Rev. Lett. **90**, 205002 (2003).
[6] J.S.T. Ng *et al.,* Phys. Rev. Lett. **87**, 244801-1 (2001).
[7] C.E. Clayton *et al.*, Phys. Rev. Lett. **88**, 154801 (2002).
[8] K.G. Steffen, in *High Energy Beam Optics* (John Wiley, New York, 1965), p. 173.
[9] C.L. O'Connell *et al.*, Phys. Rev. ST Accel. Beams 5, 121301 (2002)
[10] S. Lee *et al.*, Phys. Rev. E **64** , 045501(R) (2001).
[11] M. Hogan *et al.,* Phys. Plasmas **7**, 2241 (2000).
[12] B.E. Blue *et al.*, Phys. Rev. Lett. **90**, 214801 (2003).
[13] P. Muggli *et al.*, IEEE Trans. on Plasma Sci. **27** (3), 79 (1999).
*muggli@usc.edu