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Transverse and Longitudinal Dynamics of a 28.5 GeV Electron Beam in the Plasma Wakefield Accelerator

P. Muggli[*], M.J. Hogan[†], B.E. Blue[Δ], C.L. O'Connell[†], R. Siemann[†], K.A. Marsh[Δ], D. Walz[†], R. Iverson[†], F.-J. Decker[†], P. Raimondi[†], C.E. Clayton[Δ], S. Wang[Δ], S. Lee[*], E.S. Dodd[Δ], C. Joshi[Δ], T.C. Katsouleas[*], W.B. Mori[Δ], C. Huang[Δ]

[*]*University of Southern California, Los Angeles, CA 90089, USA*
[†]*Stanford Linear Accelerator Center, Stanford, CA 94309, USA*
[Δ]*University of California, Los Angeles, CA 90095, USA*

Short particle bunches can drive very large amplitude relativistic plasma waves. These waves can be used to accelerate particles to very high energies over short distances. In the plasma wakefield accelerator (PWFA), the energy is extracted from the particles in the front and core of a single bunch (or from a short driver bunch) and transferred to the particles in the back of the same bunch (or to a witness, trailing bunch). The PWFA is thus suitable to double the energy of a high-energy particle beam[1]. In the case of an electron bunch with a density n_b larger than the plasma electron density n_b, all the plasma electrons are expelled from the bunch volume, and the core and back of the bunch propagates in a pure ion column. The ion column partially neutralizes the relativistic bunch, which is thus focused by an ideal, aberration free, thick plasma lens. This non-linear regime (n_b>n_e) of the PWFA is known as the blow out regime. An experiment is performed at the Stanford Linear Accelerator Center to address the issues relevant to a meter long PWFA module. These include:

- The building meter-long sources of uniform plasma with n_e in the 10^{14} to 10^{16} cm^{-3}.
- The propagation of electron and positron bunches in such long, dense plasmas.
- The stability of the propagation, in particular against the two-stream, electron hose instability.
- The demonstration of the acceleration to high energy of electrons and positrons in meter long plasmas.

The additional issues that should be addressed to demonstrate the relevance of the PWFA to high-energy accelerators and particle physics also include:

- The preservation of the longitudinal and transverse emittances of the incoming beam.
- The increase in luminosity necessary to compensate for the loss of the driver bunch charge.

- The generation of backgrounds in the particle detector generated by the presence of the plasma.

In the present experiment, the σ_z≈0.7mm, 28.5 GeV Gaussian bunches with N=2×10^{10} particles are focused near the entrance of a ≈1.4 m long plasma. The plasma is obtained by single-photon, photo-ionization of a lithium vapor contained in a heat-pipe oven[2]. The ionizing laser beam is focused along the oven to compensate for the absorption of the ultra-violet photons by the lithium vapor. The plasma density is varied by changing the energy of the ionizing laser pulse at the plasma entrance. The spot size of the particle beam is monitored ≈1 m before and ≈1 m after the plasma by imaging onto CCD cameras the optical transition radiation (OTR) emitted by the bunch when traversing thin titanium foils (Fig. 1). After the plasma the beam travels through a combination of quadrupole and dipole magnets arranged in an imaging energy spectrometer configuration. The beam at the plasma exit is imaged onto a thin piece of aerogel located ≈25 m downstream from the plasma exit. The imaging properties of the spectrometer minimize the contribution from the eventual beam tilt and/or tail to the beam energy measurements. The Cherenkov light emitted by the beam in the aerogel is imaged onto a CCD and a streak camera to obtain time integrated and time dispersed energy spectra of the beam after it is dispersed in energy.

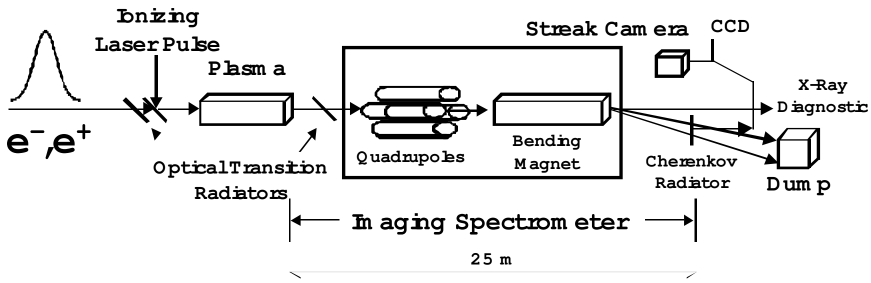

Figure 1: Schematic of the experimental set up[3].

Figure 2 shows the beam spot size σ_x measure at the ≈1 m downstream from the plasma exit as a function of n_e. At this location the beam is first focused by the plasma lens effect with $n_e \approx 4\times10^{12}$ cm^{-3}. As n_e is increased, the focusing strength of the plasma is so strong that the beam experiences multiple foci over the 1.4 m long plasma, for example three foci at $n_e \approx 1.8\times10^{13}$ cm^{-3}. The behavior of the beam spot size is well described by a simple beam envelope model[6] because the experience is performed in the blow out regime[4] ($n_b > n_b$). The good agreement between the measured spot size and the envelope model shows that the beam emittance is preserved as n_e is increased, and that the beam propagation is stable over the experimental parameter range. Subsequent experiments with smaller electron beam sizes have shown the guiding of the core of the electron beam by the plasma over more than 13 (limited only by the plasma length) beam equivalent Raleigh lengths, or β-functions. The dynamic formation of the ion channel has also been observed experimentally and will be reported elsewhere[5].

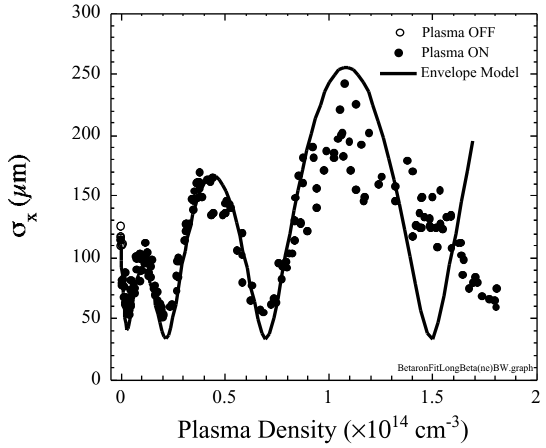

Figure 2: Beam spot size measured ≈1 m downstream from the plasma exit using OTR. The line corresponds to the beam spot size as calculated from a simple envelope model[6].

In the case of positrons, the plasma electrons are attracted toward the axis of propagation of the bunch, and there is no blow out situation. The focusing of positrons is thus not uniform, neither along the bunch nor along the bunch radius. This leads to the formation of a bunch halo that is observed experimentally (Fig. 3), in addition to the bunch focusing.[7] As the beam envelope is focused multiple times over the plasma length, the bunch particles execute betatron oscillations. The plasma acts on the beam as a plasma wiggler. The radiation emitted by the particles is in the x-ray range and is observed to have a high integrated intensity and peak spectral brightness[8].

In a homogeneous plasma, the ion channel produced by a short cylindrical electron bunch is also cylindrical with a radius $r_c \cong \alpha(N/(2\pi)^{3/2}\sigma_z n_e)^{1/2}$, where $\alpha \cong 1$ for a long bunch and $\alpha \cong 2$ for a short bunch of the order of one plasma wavelength long. The focusing is provided by the partial neutralization of the beam space charge, or equivalently by the focusing field of the ion column within the beam volume. In a plasma with a density gradient, the focusing force becomes asymmetric and the beam is steered by the plasma[9]. When the beam crosses the boundary between the plasma and the surrounding vacuum or neutral gas, the ion channel becomes asymmetric (positive charges missing on the vacuum side), and the beam is collectively deflected toward the plasma boundary. This collective deflection of the electron beam at the plasma/vacuum boundary can be seen as being analogous to the refraction of a photon beam at a dielectric interface. It can be described by a non-linear Snell's law[10]. This effect has been measured for the first time, and was found to follow the expected angular dependency[11].

In the PWFA the bunch particles displace the plasma electrons to create the large amplitude wake. The particles thus work on the plasma and loose energy. Energy loss by electrons and positrons has been observed. Energy gain by electron has also been observed, and the analysis of positron/ plasma interaction data is an ongoing activity. Results will be published in the near future.

The PWFA experiment at the Stanford Linear Accelerator center has already produced numerous original and important experimental results[4,5,7,8,11]. Future experiments are scheduled to use shorter electron bunches ($\sigma_z \approx 100$ µm and $n_e \approx 6\times10^{15}$ cm^{-3} $L\approx30$ cm), to reach an energy gain >1 GeV.

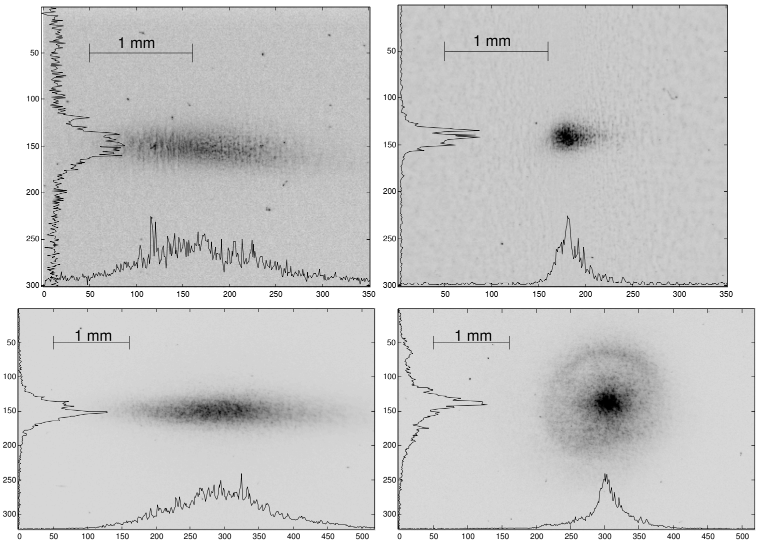

Figure 3: Images of the beam (top electrons, bottom positrons) with n_e=0 (left hand side) and $n_e \approx 10^{14}$ cm^{-3} (right hand side). The beam is asymmetric with n_e=0 because the beam is focused to a round spot size near the plasma entrance and the beam emittances are different in the vertical and horizontal planes.

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1 S. Lee *et al.*, PRST-AB 5, 011001 (2002).
2 P. Muggli *et al.*, IEEE Trans. Plasma Sci. **27**, 791 (1999).
3 M.J. Hogan *et al.*, Phys. Plasmas **7**, 2241 (2000).
4 C.E. Clayton *et al.*, Phys. Rev. Lett. **88**(15), 154801-1 (2002).
5 C.L. O'Connell *et al.*, to be submitted (2002).
6 K.G. Steffen, in *High Energy Beam Optics* (John Willey, NY, 1965), 173.
7 D. Walz *et al.*, to be submitted (2002).
8 S. Wang *et al.,* Phys. Rev. Lett. **88**(13), 135004-1 (2002).
9 W.B. Mori, *et al.*, Bull. Am. Phys. Soc. 46(8), 91 (2001).
10 T.C. Katsouleas *et al.*, Nucl.Instr. Meth. Phys. Res. A 455, 161 (2000).
11 P. Muggli *et al.*, Nature 411, 43 (2001), P. Muggli *et al.*, PRST-AB 4(9), 091301 (2001).