EXPERIMENTAL OBSERVATION OF ELECTRON BEAM FOCUSING THROUGH PLASMA LENSES*

R. Govil, S. J. Wheeler, W. P. Leemans, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA.

Abstract

A comprehensive experimental study of focusing of relativistic electron beams with overdense and underdense plasma lenses is being conducted at the Beam Test Facility at LBNL [1]. Short (15ps rms) electron bunches, from the 50 MeV LBNL Advanced Light Source injector are transported through laser produced plasmas. The electron beam spot size and divergence at the plasma lens is adjusted using quadrupoles. The plasmas are 1-5 cm long with densities of 10^{13} -10^{14} cm^{-3}. By changing the laser intensity and shape, the plasma density and profile can be controlled. This allows for exploration of both the charge and current compensation regimes, by changing the ratio of the plasma wavenumber, k_p, to the electron beam size, σ_r. Experimental results on the production of plasma through two-photon UV ionization and electron beam diagnostics have been presented earlier [2]. Here we present results from experimentally observed plasma focusing for overdense lenses in charge and current compensation regimes. Detailed interferometric results from the production of highly overdense plasmas are also discussed.

1 INTRODUCTION

The next generation of colliders require tightly focused beams with high luminosity. To focus charged particle beams for such applications, a plasma focusing scheme has been proposed [3]. Plasma lenses can be overdense (plasma density, n_p, much greater than electron beam density, n_b) or underdense ($n_p < 2n_b$). In overdense lenses the space-charge force of the electron beam is canceled by the plasma and the self magnetic force causes the electron beam to pinch. The focusing gradient is non-linear, resulting in spherical aberrations. In underdense lenses, the self-forces of the electron beam cancel, allowing the plasma ions to focus the beam. Although for a given beam density, a uniform underdense lens produces smaller focusing gradients than an overdense lens, it produces better beam quality. The underdense lens focusing strength can be increased by tapering the density of the plasma for optimal focusing [4]. The underdense lens performance can be enhanced further by producing adiabatic plasma lenses to avoid the Oide limit on spot size due to synchrotron radiation by the electron beam [5].

The plasma lens experiment at the Beam Test Facility (BTF) is designed to study the properties of plasma lenses in both overdense and underdense regimes. In particular, important issues such as electron beam matching, time response of the lens, lens aberrations and shot-to-shot reproducibility are being investigated.

2 EXPERIMENTAL SETUP

The Beam Test Facility (BTF) uses the ALS injector which provides 50 MeV electron beam with a charge of 1-2 nC in 15 ps long bunches. The unnormalized emittance is 0.2 - 0.5 mm-mrad. The BTF line is equipped with a wide range of diagnostics including integrating current transformers for charge

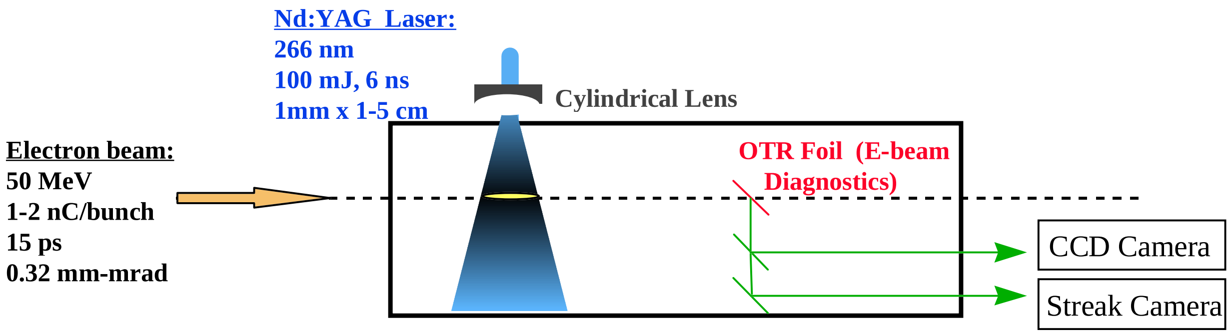

Figure 1. Layout for the plasma lens experiment. The laser is brought to a line focus at the position of the e-beam. Backward OTR is collected for electron beam diagnostics and imaged on to CCD and Streak cameras.

* Work supported by the Director, Office of Energy Research, Office of High Energy Physics and Nuclear Research, High Energy Physics Division, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

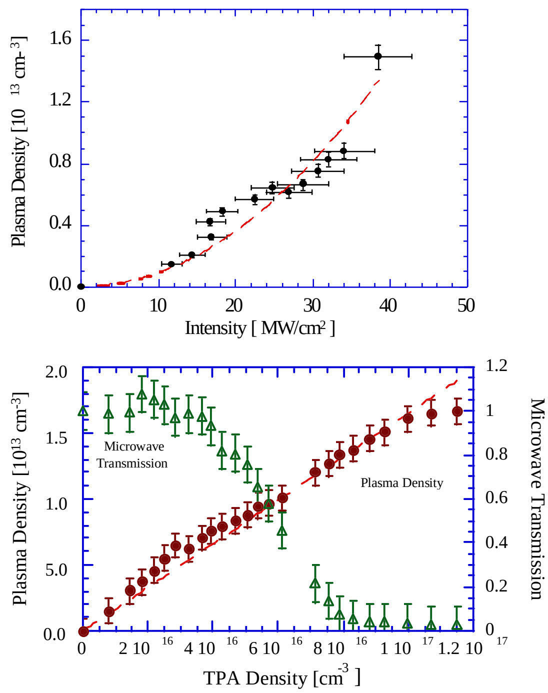

Figure 2. Plasma density (solid dots) scales quadratically with laser intensity and linearly with TPA density. The hollow triangles represent the transmitted microwave signal strength.

measurement, high bandwidth BPMs, fluorescent screens, and optical transition radiation (OTR) diagnostics [6].

The electron beam is focused into a plasma chamber that is separated from the ultra-high vacuum beam line by an 8 µm thick Kapton window. Plasma is produced in tripropylamine (TPA) vapor through two-photon ionization using a 266 nm laser beam. The ionizing laser beam enters the plasma chamber at right angles to the electron beam. The laser is brought to a line focus at the position of the electron beam. The plasma length is adjusted by changing the laser focusing and the density is controlled through the TPA fill pressure and laser intensity.

3 PLASMA PRODUCTION

For ionizing the vapor, 1064 µm radiation from a Nd:YAG laser is frequency quadrupled to provide 6 ns long 266 nm pulses. The two-photon ionization process can be expressed as,

$$n_p = \alpha \frac{n_0 I^2 \Delta t}{h\nu}, \qquad [1]$$

where n_p is the plasma density [cm^{-3}], n_0 is the neutral gas density [cm^{-3}], I is the laser pulse intensity [W/cm^2], Δt is the laser pulse length [s], and $(h\nu)$ the photon energy [Jsec]. Here all the other constants have been absorbed in α, the two-photon ionization coefficient [cm^4/W].

To achieve plasma lengths on the order of a few centimeters, the laser beam is defocused horizontally using a cylindrical defocusing lens (Figure 1). To maintain the laser intensity (and therefore, the plasma density), the beam is focused in the vertical direction.

The plasma density is measured through microwave interferometry at 94.3 GHz described previously [2]. The microwave signal is launched transversely to the plasma sheet. The plasma density is calculated by measuring the relative microwave phase shift introduced by the plasma. Since the plasma densities are close to critical density for microwave beam absorption, a two-channel in-quadrature measurement technique [7] is used to compensate for absorption effects. For plasmas with thickness comparable to collisionless skin-depth, this technique allows super-critical plasma densities to be measured. The plasma density was measured as a function of neutral gas fill pressure and laser intensity as shown in Figure 2. The two-photon ionization coefficient, α, was measured to be 2.5 x 10^{-29} W/cm^4. Plasma densities up to 2 x 10^{14} cm^{-3} were measured using this technique. At this density the transmitted microwave amplitude was only 3% of the initial amplitude, in agreement with calculations.

3 ELECTRON BEAM DIAGNOSTICS

The electron beam is diagnosed using optical transition radiation that is produced by a charged particle at it passes through a boundary between two media with different dielectric constants. The radiation contains information about the size, divergence and energy of the source charged particle beam.

A five micron thin nitrocellulose foil coated with

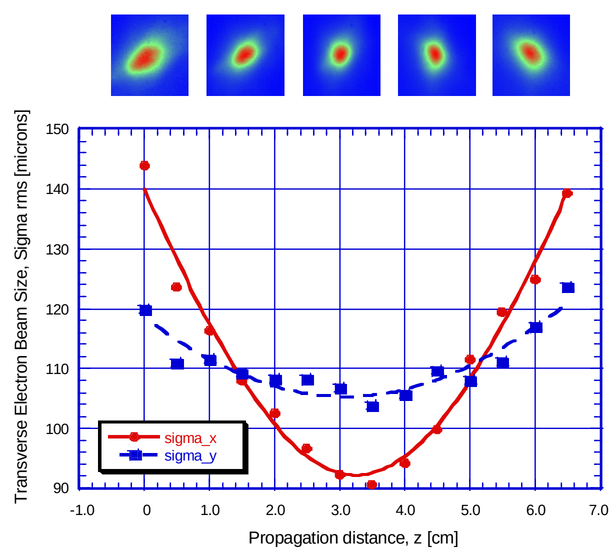

Figure 3. Measurement of beam size through OTR at various positions along the direction of propagation. The solid and dashed lines represent the best fit through the transverse beam size, σ_{rms}, along the x-axis and y-axis, respectively.

high reflectivity aluminum is inserted in the electron beam path. When the beam passes through the foil, it emits transition radiation, which is imaged onto a CCD camera. The OTR foil is mounted on a motorized stage. As the stage is moved along the trajectory of the electron beam, a direct measurement of the beam size as a function of propagation distance is obtained (Figure 3). To study the temporal dynamics of the plasma lens, OTR is imaged to a streak camera with 2ps resolution [2].

4 ELECTRON BEAM FOCUSING BY BEAM-INDUCED PLASMAS

A relativistic electron beam passing through a gas can collisionally ionize the gas. The density of the plasma, n_p, produced by the e-beam is given by,

$$n_p = \left|\frac{dE}{dx}\right| \frac{N_b \sigma_z \rho_m}{E_{th}}, \qquad [2]$$

where dE/dx is the stopping power of electron beam [eVcm^2/g], N_b is the electron beam density [cm^{-3}], σ_z is the electron bunch length [cm], ρ_{gas} is the mass density of background gas [cm^{-3}], and E_{thresh} is the ionization threshold of the gas [eV]. For BTF parameters, this corresponds to a plasma density of approximately 10^{11} - 10^{12} cm^{-3}. Since the plasma is produced by the electron beam, the spatial profile of the plasma follows the evolution of the electron beam and is calculated to be: $n_p(z) = n_{p\max}\beta_0 \big/ \sqrt{\beta_0^2 + s^2}$, where $s=z-ct$ and β_0 is the minimum value of the electron beam beta function in the plasma. The plasmas produced through electron beam ionization are underdense. The focusing strength of an underdense plasma lens is given by $K = 2\pi r_e n_p / \gamma$, where r_e is the classical electron radius, γ the electron beam energy and n_p the plasma density.

Figure 4 shows the measured electron beam size as a function of propagation distance inside the plasma chamber. In vacuum, the beam size at the waist is measured to be 130 µm. As the neutral gas pressure is increased, the beam ionizes the vapor, and is focused by the resulting plasma to 100 µm.

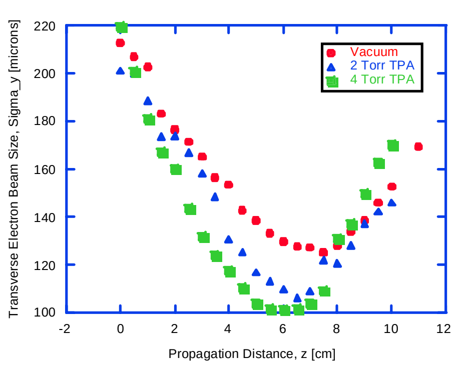

Figure 4. Measured electron beam focusing by beam-ionized plasma for various neutral gas densities.

5 ELECTRON BEAM FOCUSING BY OVERDENSE LASER PRODUCED PLASMAS

The laser beam is temporally and spatially aligned with the electron beam. The electron beam size as a function of propagation distance is measured with and without the laser beam (Figure 5). When the laser beam is turned on to produce plasma, the electron beam is focused to a smaller spot size. A corresponding increase in electron beam peak intensity is measured using OTR. The strength of focusing is found to depend strongly on electron beam beta function matching into the plasma.

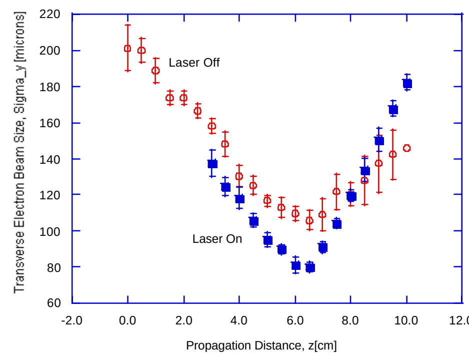

Figure 5. Measured electron beam focusing by laser-produced plasma. When the laser is turned on, the laser produced plasma focuses the electron bunch to a smaller spot size.

6 CONCLUSION

The 50 MeV electron beam from the ALS injector has been focused through plasma lenses at BTF. Electron beam focusing by beam induced plasmas has been studied using optical transition radiation diagnostics. Laser produced overdense plasmas have been observed to focus the electron beam. Both types of lenses show strong dependence on e-beam beta function matching. Currently, highly overdense plasmas are being studied to observe return current cancellation. Detailed simulations are being conducted for comparison with theoretical predictions and temporal dynamics of plasma lenses is being experimentally investigated.

REFERENCES

[1] W. Leemans et al., Proc. 1993 Part. Accel. Conf., 83 (1993).
[2] R. Govil et al., Proc. 1995 Part. Accel. conf., 776 (1995).
[3] P. Chen, Part. Accel. 20, 171 (1987).
[4] T. Katsouleas, et al., Proc. 1992 Adv. Accel. Workshop (1992).
[5] P. Chen, et al., Phys. Rev. Lett. 64, 1231 (1990).
[6] M. de Loos et al., Proc. European Part.Accel. Conf. (1994).
[7] W. Barry, private communication.