Observation of Plasma Focusing of a 28.5 GeV Positron Beam

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(Received 21 September 2001; published 19 November 2001)

The observation of plasma focusing of a 28.5 GeV positron beam is reported. The plasma was formed by ionizing a nitrogen jet only 3 mm thick. Simultaneous focusing in both transverse dimensions was observed with effective focusing strengths of order tesla per micron. The minimum area of the beam spot was reduced by a factor of 2.0 ± 0.3 by the plasma. The longitudinal beam envelope was measured and compared with numerical calculations.

DOI: 10.1103/PhysRevLett.87.244801 PACS numbers: 41.85.Lc, 29.27.–a, 52.40.Mj

The plasma lens has been proposed as a final focusing element to improve the luminosity of future high energy electron-positron colliders [1]. In this Letter we report the observation, at the FFTB facility [2] at SLAC, of the focusing of a 28.5 GeV positron beam by a nitrogen plasma lens.

The focusing mechanism for bunched relativistic beams, of either charge, is the collective reaction of the plasma electrons to the relativistically foreshortened electromagnetic field of the bunch. Even in the time scale of a few picoseconds, plasma electrons are able to migrate towards a balance between the superimposed beam field and the collective field caused by separating the charges of the plasma. The primary effect is a partial neutralization of the electric field of the bunch. Whereas, in free space, the radial electric and toroidal magnetic fields of the bunch apply equal but opposite forces on the beam particles—so that there is no net focusing or defocusing—this balance is lost in plasma and self-focusing occurs [1,3].

The collective motion of plasma electrons is characterized by the plasma wavelength, $\lambda_p = \sqrt{\pi / r_e n_p}$, with r_e being the classical electron radius and n_p the plasma density. Although this plasma current tends to cancel the beam's toroidal magnetic field, its characteristic dimensions do not necessarily allow that to happen efficiently. For interesting cases, the beam spot is smaller than the plasma wavelength so that the beam toroidal field is spatially more concentrated than the plasma current and self-pinches the beam. As plasma density rises farther and its wavelength shortens, the fields overlap more completely and the pinch is again suppressed.

Focusing by plasma has been verified in previous experiments [4] for low energy (3.8–50 MeV) electron beams several mm in transverse size, and with relatively low density plasmas ($\leq 10^{14}$ ions per cm^3). Plasma focusing of positrons had not previously been demonstrated, and this was the primary goal of the work reported in this paper. We also sought to extend the beam energy into the multi-GeV range, using plasma densities 3 orders of magnitude higher than before, and beam spot cross-sectional areas 6 orders of magnitude smaller than before. (The experiment was limited, in principle, by the carbon fibers of the measuring system, which would be destroyed by spots of area less than 15 μm^2 for beam pulses of 1.5×10^{10} positrons [5].)

The plasma lens was created by the ionization of molecules in a pulsed gas jet. An 800 μs jet of nitrogen gas was released at 2 Hz into the vacuum chamber by a fast acting solenoid valve, timed so that the gas flow had stabilized when the positron beam passed through. The nozzle diameter was 3 mm, the inlet pressure was 1000 psi for this experiment, and the gas jet opening angle was 3°. The local beam line pressure bump was minimized by differentially pumping short sections between sets of 2 mm aperture thin-foil irises. A gas density value of $(6.5 \pm 2.5) \times 10^{18}$ cm^{-3} was obtained as an average of measurements made by Michelson interferometry and from bremsstrahlung observed during data taking.

As the positron beam passed through, ionization of the jet occurred by the normal energy loss process [6], enhanced by avalanche collisions during acceleration by the beam field. We found that an improved focusing effect could be obtained by irradiating the gas with focused, pulsed laser light. A commercially available Q-switched Nd:YAG laser delivered 10 Hz of 10 ns pulses at wavelength 1064 nm and pulse energies near 1.2 J. For comparison, the positron pulse width was 4 ps FWHM. The light, incident on the gas jet at right angles to the positron beam direction, was line focused astigmatically to a spot of 50 μm vertically by 330 μm horizontally FWHM. It is estimated that about 0.1% of the laser energy was absorbed through collisional ionization seeded by multiphoton absorption. The superheated gas expanded in a shock-wave shell, and thus a wide range of available plasma densities evolved over time. The time between the laser pulse and the beam was optimized (at about 400 ns) by observing the strength of the synchrotron radiation from the focusing. At this time the ionization caused by the positron beam was much stronger than that remaining from the laser, which had largely recombined and been spatially diluted. However, this process requires further investigation and will not be discussed here.

The layout of the experiment around the plasma lens is shown in Fig. 1. The direction of the positron beam defines the z axis of the right-handed coordinate system, and y is vertical. The beam energy was set to 28.5 GeV, with 0.6-mm-long bunches, normalized emittances of 5×10^{-5} m · rad (x) and 5×10^{-6} m · rad (y), and 1.5×10^{10} particles per bunch.

Conventional magnets were set to focus the positrons near the plasma lens, where the beam size was measured using a wire scanner system. A carbon fiber of 7 μm diameter was moved to a known position between 8 and 32 mm downstream of the entrance to the gas jet. In an automated procedure, the positron beam was steered orthogonally across the fiber in 1 μm steps (whose scale was calibrated to better than $\pm 5\%$). Bremsstrahlung from the carbon traveled 33 m downstream, escaped the vacuum pipe, showered in a 4 radiation length stack of polyethylene plates, and was detected by an air Cherenkov counter [5]. The correlation between steering and the bremsstrahlung signal gave the beam profile. We found that the elliptical beam spot size at the lens was typically 11.5 by 2.5 μm. The beam density within the 2σ contour was 2×10^{16} cm^{-3}.

Interleaved among the plates were planar ion chambers used to monitor the several-MeV critical energy of the synchrotron radiation emitted from the plasma lens (the synchrotron radiation monitor, or SRM). The ion chambers also detected the bremsstrahlung and were used as a check on the spot size measurement.

As a way of reducing the effects of drifts, measurements of plasma-on and plasma-off beam spot profiles were interleaved within the scan. At each scan step of the beam, signals from four pulses were recorded with the gas jet off, and averaged, and one was taken with the jet firing. These were plotted, as in Fig. 2, against the scan position.

There are several other systematic effects in the beam size measurement process. The carbon fiber diameter contributes 1.7 μm in quadrature to the rms beam size; this is corrected for. Since it takes many beam pulses to make a profile measurement, shot-to-shot fluctuations in the beam centroid position also contribute to the measured beam size. By measuring the rms fluctuation at a fixed fiber location and fixed beam steering, this contribution by itself is estimated to be 25% of the measured width, and, when subtracted in quadrature, it reduces the apparent beam width by 3%. For the data being reported here, the elliptical positron beam spot also had a roll angle of 13° with respect to the x direction, and this was accounted for.

An important correction was necessary because the strong focusing of the plasma increased the beam divergence at the wire scanner. As the focused beam was scanned, a portion of the bremsstrahlung photon cone was occluded by a downstream fixed aperture. The total photon flux, as given by the area under the scan profile curve, was reduced by 30%. The systematic effect was to make the scan profile asymmetric because of the correlation between the positron angle and position at the fiber. A check of the beam toroids confirmed that there was no loss in the charged beam flux as it passed through the lens to the dump.

To account for this effect, the measured beam profiles were fitted to a Gaussian function with different widths allowed on either side of the peak. The larger width parameter was taken as the estimate of the unoccluded

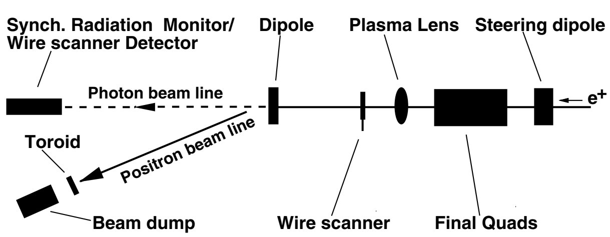

FIG. 1. Schematic layout of the SLAC Plasma Lens experiment at the FFTB. "Final Quads" are conventional focusing quadrupole magnets. The positron beam is deflected towards the dump by the magnetic dipole.

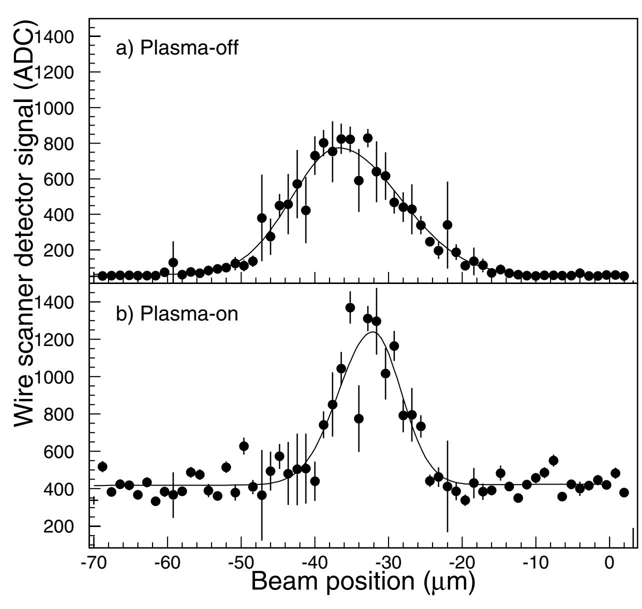

FIG. 2. Wire scan beam profile measurements, showing data taken (a) with no nitrogen present and (b) with focusing by the nitrogen plasma. The superimposed curves represent Gaussian function fits.

width. A first order polynomial took account of the background accompanying the beam, the synchrotron radiation, and beam-gas bremsstrahlung from the jet.

The accuracy of this procedure for determining the beam width was estimated by using a ray-tracing simulation of the experiment. The incoming beam envelope was parametrized with the help of upstream wire scanners, as well as jet-off local measurements at a range of z locations. These parameters were reproduced in the linear optics in the simulation. A model for the beam-plasma collective focusing field was then constructed [7]. This accounted for the spatial variation of the plasma focusing strength within the bunch. The focused positrons were followed to the carbon fiber, and the bremsstrahlung photons were traced from there to occluding apertures downstream. The geometric parameters were adjusted to reproduce the observed loss in the photon transmission. Using the same asymmetric Gaussian fit procedure as for the real data, the simulation showed some variations over the z range that led us to assign an uncertainty of $\pm 5\%$ for data without the plasma, and $\pm 15\%$ for the heavily occluded cases with plasma. These are taken as systematic uncertainties in the beam size measurements.

The plasma focusing was studied by making multiple measurements of the x and y profiles of the beam envelope at several values of z within the accessible range. Data at the same settings were averaged. The plasma-on data are compared with the simultaneous plasma-off envelope in Fig. 3. The pinch is quite striking, as seen in the y direction. From the y divergence angles, the lens quadrupole strength may be estimated to be 4 T/μm, and from the fitted waist positions the effective focal length is 1.6 mm. The values in the x direction are 0.7 T/μm and 34 mm.

Numerical integration over the expected transverse field profile of an ideal plasma lens shows that these values of quadrupole strength would yield synchrotron radiation with effective critical energies E_c [8] of 4.6 and 3.4 MeV. As a test of this, for a few representative scans we have examined the signals from the SRM chambers as a function of depth in the polyethylene. A simple simulation, based on the electromagnetic shower code EGS4 [9], was made of the response of the detectors to synchrotron radiation. The depth profile led to a value $E_c = 4.4 \pm 0.3$ MeV, in satisfactory agreement with the range of expected values.

Luminosity depends on the inverse of the minimum cross-sectional area of the beam, and this was reduced by a factor of 2.0 ± 0.3 by the plasma lens. However, the beam time available was inadequate for tuning the x- and y-focal spots to the same z location, either for the plasma on or off, and so we cannot report directly the reduction of spots as they would be optimized for luminosity. Also, aberrations are expected in plasma lenses from imperfect charge distributions [10], and tuning the beam optics to minimize their effects was not practical in this run.

A three-dimensional particle-in-cell (PIC) electromagnetic simulation code is being developed to describe the focusing process in this experiment for both positrons and electrons. In particular it will allow for the $\sigma_x/\sigma_y = 4.8$ aspect ratio and the beam-induced ionization. At present, results are available from a simplified two-dimensional PIC simulation. Plasma focusing in the x and y planes was simulated separately using a round beam configuration, where the size was selected to be σ_x or σ_y as appropriate. In order to maintain the same focusing strength, the number of beam particles was scaled by the aspect ratio between the two cases. A uniform plasma was used, 3 mm thick with a density of 5×10^{17} cm^{-3}. Since this density was greater than that of the beam, the focusing effect was in the self-limiting range and insensitive to the exact density assumed. Considering the simplifications that have been made, the results, shown as lines in Fig. 3, agree reasonably with the data, indicating that more complete simulations will have predictive power.

In summary, we have reported the observation of focusing of high energy positron beams by a thin lens of dense plasma. Simultaneous reduction of the beam spot in both

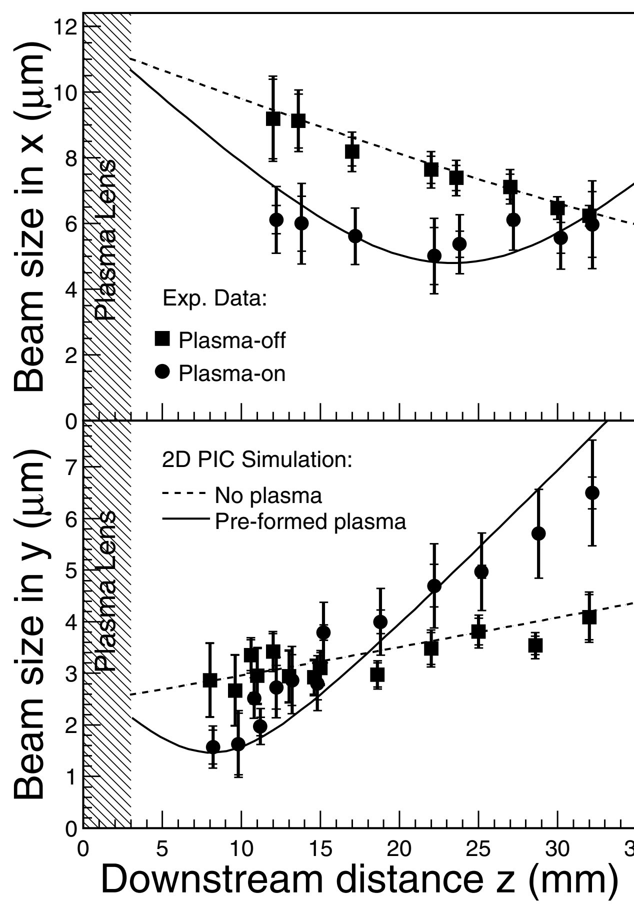

FIG. 3. Measured beam envelope Gaussian widths in the x and y dimensions, with and without plasma focusing. Inner error bars indicate the statistical uncertainty, and outer error bars indicate the quadrature sum of statistical and systematic uncertainties. The curves represent the particle-in-cell simulations.

dimensions was observed. Future work toward applying the technique to linear colliders will, however, require improvements to the available simulation codes and to the understanding of plasma production processes.

We thank the support staff at the various institutions for their hard work in the design and construction of the apparatus, in particular G. Collet, K. Krauter, G. Mazaheri, R. Rogers, Y. Sung, and W. Kaminskas (deceased) and his staff. The experiment would not have been possible without the dedicated efforts of the SLAC accelerator operations staff. This work is supported in part by the Department of Energy under Contracts No. DE-AC02-76CH03000, No. DE-AC03-76SF00515, No. DE-FG03-92ER40695, and No. DE-FG05-91ER40627, and the Lawrence Livermore National Laboratory through the Institute for Laser Science and Applications, under Contract No. W-7405-Eng-48, and by the U.S.-Japan Program for Cooperation in High Energy Physics.

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[1] P. Chen, Part. Accel. **20**, 171 (1987).
[2] V. Balakin *et al.,* Phys. Rev. Lett. **74**, 2479 (1995).
[3] The first calculation of self-focusing in countermoving streams of opposite charge was by Bennett [W. H. Bennett, Phys. Rev. **98**, 1584 (1955)].
[4] J. B. Rosenzweig *et al.,* Phys. Fluids B **2**, 1376 (1990); H. Nakanishi *et al.,* Phys. Rev. Lett. **66**, 1870 (1991); G. Hairapetian *et al.,* Phys. Rev. Lett. **72**, 2403 (1994); R. Govil *et al.,* Phys. Rev. Lett. **83**, 3202 (1999).
[5] C. Field, Nucl. Instrum. Methods Phys. Res., Sect. A **360**, 467 (1995).
[6] A. V. Zarubin, Nucl. Instrum. Methods Phys. Res., Sect. A **283**, 409 (1989).
[7] M. Bassetti *et al.,* IEEE Trans. Nucl. Sci. **30**, 2182 (1983).
[8] M. Sands, Report No. SLAC-121, 1970 (unpublished).
[9] W. R. Nelson *et al.,* Report No. SLAC-265, 1985 (unpublished).
[10] J. B. Rosenzweig and P. Chen, Phys. Rev. D **39**, 2039 (1989); J. J. Su, T. Katsouleas, J. M. Dawson, and R. Fedele, Phys. Rev. A **41**, 3321 (1990).