SLAC-PUB-10139

The Plasma Lens as an e-e- Luminosity Enhancer: SLAC Experimental Results

Paul R. Bolton (for the E150 Collaboration),
Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, California 94309 USA.

(Presented at the Fourth International Workshop on Electron-Electron Interactions at TeV Energies held at the University of California at Santa Cruz during December 07-09, 2001)

Motivation and Principle

It is important to demonstrate the use of plasmas for focusing positron and electron beams at high energy. By reducing the transverse area of colliding beams the plasma optical element affords a potential simplicity for enhancing the luminosity in the interaction region of linear colliders. Focusing of both transverse dimensions as well as both charge states has generated interest in this technology as a final focusing element. Furthermore, the focusing strength of a plasma lens can exceed that of conventional magnets by orders of magnitude.

The balance (in vacuum) between the radial electric and toroidal magnetic fields accompanying the single bunch of an electron or positron beam is lost in the plasma environment. Within time scales determined by the plasma frequency, plasma electrons can rapidly migrate to achieve a balance between the beam-induced field and collective plasma field. Canceling the radial bunch field alone will result in a self ‘pinching’ of the single beam bunch by the unchecked toroidal field. The dynamics of this focusing action are determined by the beam bunch and plasma densities. For plasma densities in excess of 10^{18} cm^{-3} the plasma oscillation period (which characterizes its response time) is less than 100 femtoseconds.

In addition to addressing the feasibility of the plasma lens as a high energy linear collider final focus element, this work is also motivated by the need to better understand the interaction of particle beams with plasmas. Testing the feasibility as a linear collider final focusing element requires use of appropriate plasma and beam bunch parameters such as density. Examining the beam-plasma interaction facilitates the design of simple, compact, and economical plasma lenses for high energy applications.

Experimental Configuration and Methodology

In establishing relevance it was important to obtain operating beam parameters similar to those anticipated in future linear colliders. The FFTB (final focus test beam) beamline was set to focus high energy (28.5 GeV) positrons and electrons near a gas interaction region (using conventional final quadrupole magnets upstream). This region was the site of the gaseous plasmas used for the focusing study. Incident beam sizes were

Work supported in part by Department of Energy Contract DE-AC03-76SF00515

5-8 microns and 3-5 microns in the x and y directions respectively (i.e. a ‘flat’ beam). Also, incident beam emittances were typically 50 and 5 micrometer radians for the x and y directions respectively. The bunch charge levels were about 2.5 nC corresponding to densities near 7×10^{16} cm^{-3}.

Incident electron and positron beam bunches traversed the plasma focusing section along the beamline (z direction). Bunches (4 psec FWHM) arrived at this interaction region at a 10 Hz repetition rate. Downstream of the plasma (distances from 8 to 32 mm) a carbon wire scanning assembly (wire diameter was 7 microns) was used to determine beam sizes . The wire scan signals are beam-induced bremsstrahlung from the wires. A sketch of this experimental arrangement is shown in figure 1. Beam sizes were therefore determined based on data from a multiple bunches. Rather than traverse a wire, it was preferable to raster the beam position about the wire in 1 micron steps (keeping the wire location fixed).

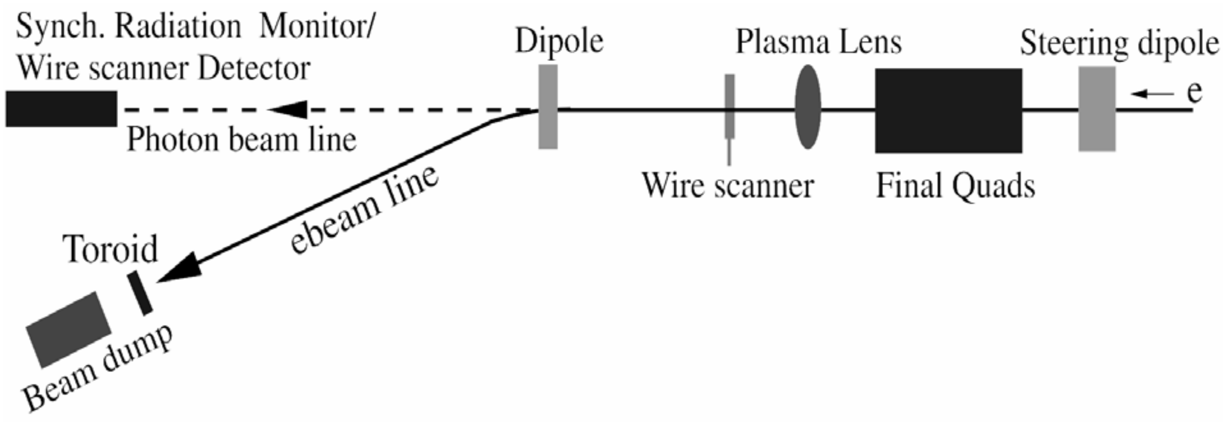

Figure 1. Layout of the plasma lens experiment in the FFTB tunnel at SLAC.

Beyond the wire scanner a dipole magnet steered particles down towards a beam dump. Photons proceeded straight to a segmented detector located 33 m downstream which was used to monitor both synchrotron and bremsstrahlung radiation. Bremmstrahlung from the scanning wires was detected by an air Cerenkov counter located behind a four radiation length stack of polyethylene plates. Ten planar ion chambers located between these plates were used to detect synchrotron radiation (the synchrotron radiation monitors or SRM’s) that was generated by the plasma focusing action in the interaction region. Some bremsstrahlung was also detectable with the SRM’s but it was best isolated using those further downstream.

Nitrogen or hydrogen gas was injected vertically (y direction) into the beamline prior to the beam bunch arrival through a pulsed solenoid valve at a 2 Hz repetition rate where the open time was set to 800 microseconds. Differential pumping through four thin titanium foil iris pairs minimized the pressure bump along the beamline and limited this repetition rate for a given opening time and inlet pressure. Therefore the 10 Hz observations of multiple bunches would include those with and without a focusing plasma. The local gas density could be controlled by varying the inlet pressure. For an inlet pressure of 1000 psi Michelson interferometry and bremsstrahlung observations determine the local density in the beamline to be (6.5+-2.5) x 10^{18} cm^{-3} for nitrogen and 8 x $10^{18}cm^{-3}$ for hydrogen (hydrogen densities were determined from interferometry alone). The gas column exiting the nozzle orifice was well directed (opening angle of 3 degrees) and as a result was 3 mm wide along the beam propagation direction.

Preformed plasma was generated by laser-induced collisional ionization of molecular nitrogen in advance of the beam bunch arrival. A commercial ‘Q’ switched Nd:YAG laser delivered pulse energies at the 1 Joule level (1064 nm wavelength) within a 10 nsec duration at 10 Hz which was set to arrive at specified advance times relative to the beam bunch. Laser pulses were directed horizontally across the beamline (x direction) where it intersected with the vertical gas column. For 80% of the beam bunches only a laser pulse and beam bunch arrived and no plasma was present.. The depth of the preformed plasma section within the gas column was determined by the dimensions of the line focused laser irradiation. Along the beamline the laser line focus extended to 330 microns for the positron runs (120 microns for the electron run). The vertical height of only 50 microns for positrons (30 microns for electrons) was still much larger than the transverse dimensions of the beam bunch.

Whether the gaseous plasma interaction region could be considered in three sections or as a single section was determined by the presence of a laser pulse. When the laser was used the beam bunch encountered a short central component of preformed plasma. On the upstream and downstream sides the majority of the gas was not preionized and instead was ionized on impact with the beam bunch. For cases where the laser was not fired the full 3 mm gas column would be impact ionized by the beam and therefore considered as a single section.

Experimental Results

(i)Observations of Beam Focusing from Wire Scans

Figure 2 illustrates a typical beam raster scan for which nitrogen plasma and no plasma data are interleaved. For this data no laser was used. Solid curves are Gaussian fits used to extract the beam size. A clear reduction in beam diameter is observed. The carbon wire size contributes 1.7 microns to the beam diameters seen in the figure. Details of other systematic corrections used in the data analysis are discussed in reference [1]. Plasma focusing is verified by performing such scans in several z planes downstream of the interaction region.

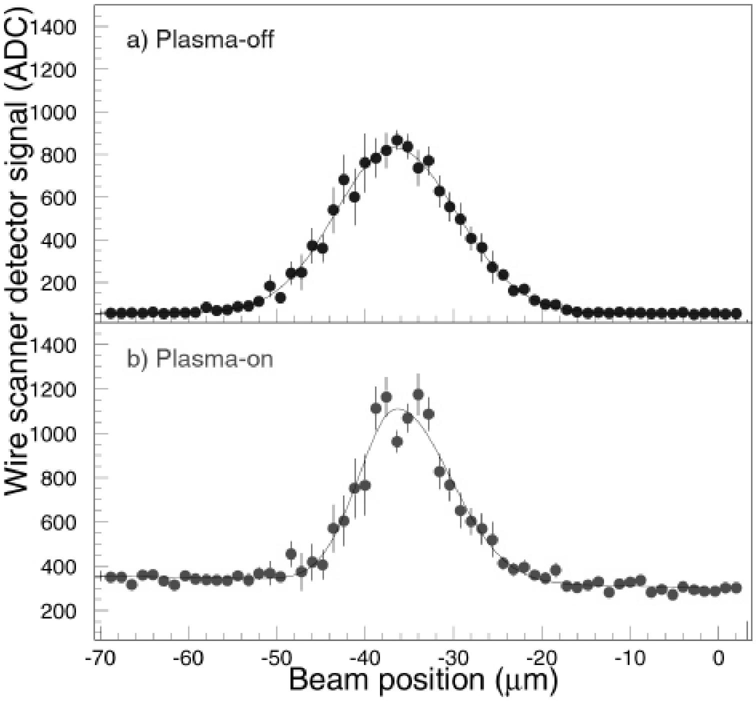

Figure 2. Beam profile wire scan measurements with (a) and without (b)nitrogen plasma. No laser pulse was used so data is for impact ionization.

Figure 3 illustrates the z dependence of the positron beam sizes with and without a focusing plasma for z values downstream of the plasma (i.e. beam envelope). For this data the laser was used to preform the central portion of the plasma region. Similar results are shown in figure 4 for electrons. Note that the plasma is turned on and off by turning the gas jet on and off. Focusing action is evidenced by enhanced divergences and by upstream shifts in beam waist locations (i.e. closer to the plasma region). Focusing is observed in both x and y directions. For a given z plane the largest reduction of positron beam area is by a factor of 2 (+- 0.3) because the x and y beam waists were not ‘tuned’ to be in the same z plane. We anticipate a larger reduction in beam area for the case where the beam waists co-exist in the same plane. With all other parameters unchanged, the area reduction factor is the luminosity enhancement factor.

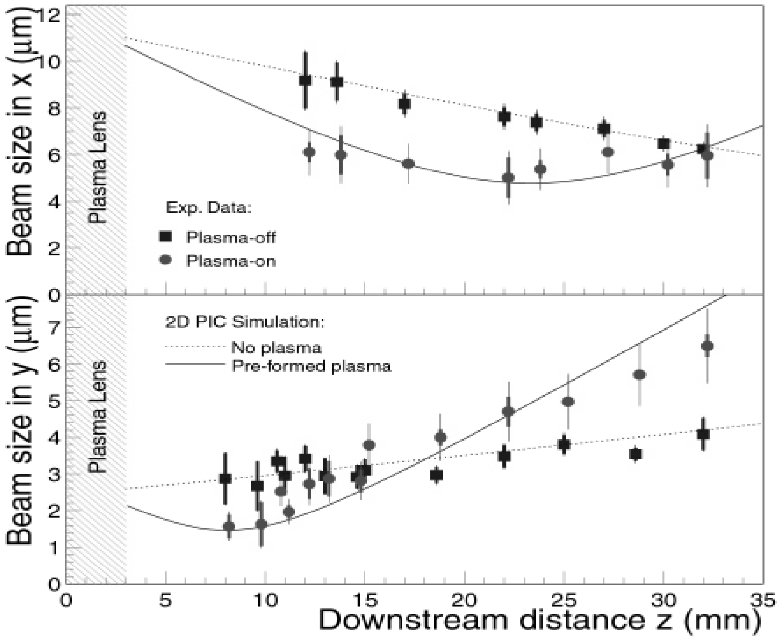

Figure 3. Positron beam envelope data in x and y directions with and without plasma. Laser pulses were used to preform the central

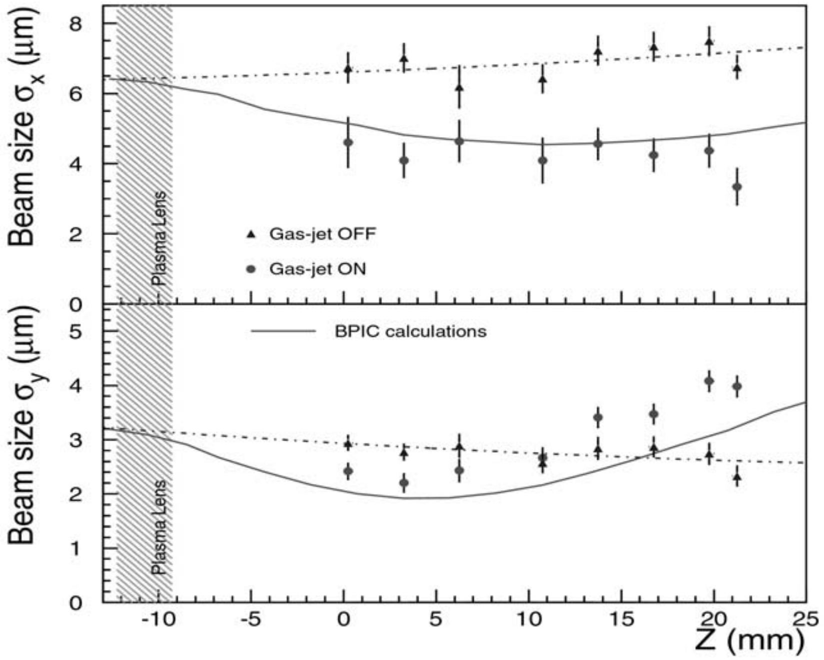

Figure 4. Electron beam envelope data in x and y directions with and without plasma. Laser pulses were used to preform the central portion of the plasma. All curves represent of PIC simulations. Gas-jet ON/OFF is equivalent to plasma on/off.

From the divergences shown in figures 3 and 4 we estimate the plasma lens quadrupole strengths to be 4 Tesla per micron in the y direction and 0.7 Tesla per micron in the x direction [1]. This is consistent with our synchrotron critical energy estimate of 4.4 (+/- 0.3) MeV [1].

(ii) Laser-Induced Preionization and Gas Dynamics

We had also observed an intriguing dependence of plasma focusing strength on the delay timing between the arrival time of the laser pulse and beam bunch at the plasma location. The magnitude of an SRM signal (SRM #3) was used to indicate the strength of plasma focusing. Figure 5 shows this result for focusing electrons in a nitrogen plasma. The SRM signal is plotted versus the delayed beam bunch arrival time. The laser pulse arrives at zero time (within a few nsec). The displayed dynamics can be considered in two phases which are divided near the 2.2 microsecond delay time where the SRM signal is minimized.

The early phase shows a rapid rise in the SRM signal from zero to a maximum value near 400 nsec. The signal then drops (i.e. detector background level) equally rapidly to zero near the 2.2 microsecond delay time. This early phase demonstrates no observable dependence on nitrogen gas line pressure.

The late phase begins at the 2.2 microsecond delay time and shows a much slower recovery of the SRM signal to a broad maximum value and for the longest delays approaches an asymptotic level. This late phase does reveal an observable dependence on gas line pressure in two ways: (i) the timing of the peak is earlier for higher gas line pressure and (ii) the SRM signal level for the higher pressure remains above that for the lower pressure for all late phase delay times.

Similar observations have also been made with hydrogen where the SRM signals are typically much lower. This is consistent with our observation of weaker beam focusing with hydrogen plasmas. Interpreting the behaviour shown in figure 5 requires a detailed consideration of the relevant plasma and gas dynamics. In the early phase the initial laser-induced plasma density (zero delay time) was measured to be 2×10^{18} cm^{-3}. Three main processes will reduce the plasma density during this phase: (i) upward gas motion at a rate near 3×10^{4} cm/sec (the sound speed), (ii) plasma diffusion, and (iii) plasma recombination. The diffusion time is estimated to be near 3.5 microseconds at this pressure. However because of the upward gas motion alone the initial plasma density in the beamline is reduced by three orders of magnitude within the first 115 nsec of timing delay. Furthermore, the plasma recombination is significantly faster and occurs on the nanosecond time scale. Therefore, by the time the SRM signal peaks at 400 nsec the initial plasma has significantly decayed and its original volume shifted out of the beamline by about 120 microns. Finally, the zero signal level at 2.2 microseconds corresponds to the expulsion of the nitrogen gas from the beamline. We interpret this early phase behaviour to be due to shock wave formation associated with the laser ionization at zero time. However, within the first few nanoseconds of time delay part of the enhanced SRM signal could be due to a reduction of the preformed plasma density. Beyond the first few nanoseconds the enhanced SRM signal is likely due to the local enhancement of gas density associated with shock wave formation. For example, for

1030 and 730 psi nitrogen with electrons figure 5 indicates that the local density enhancements at the 400 nsec delay time are by a factor of 3.5 and 4.0 respectively . As a result, optimum focusing occurs well into the ‘afterglow’ and displaced regimes of the preformed plasma. For this reason nanosecond precision for time delay setting is adequate and represents a main advantage of this method.

We interpret the late phase behaviour to be that of a diffusion driven refill of the void created by the shock wave in the beamline. This accounts for the gas pressure dependence. The difference between the timing of the late phase peaks for 730 and 1030 psi nitrogen is consistent with this pressure difference. The peaks therefore represent transient overfill pressures prior to post-shock equilibration with ambient gas. It is worth noting that these peaks occur at delay times for which the original laser-induced plasma volume would be over 3 mm from the beamline.

It is also worth noting that for any nitrogen line pressure the asymptotic SRM signal in the late phase is almost the same as the zero time signal in the early phase. This means that the initial laser-induced plasma density had a minimal effect on the plasma focusing and that the dominant effect is impact ioniation by the beam bunch itself. The asymptotic SRM signal reveals the plasma focusing strength due to impact ionization alone. Optimum plasma densities for focusing are predicted to be near the beam bunch density. The initial preionized plasma density was about 30 times higher than this

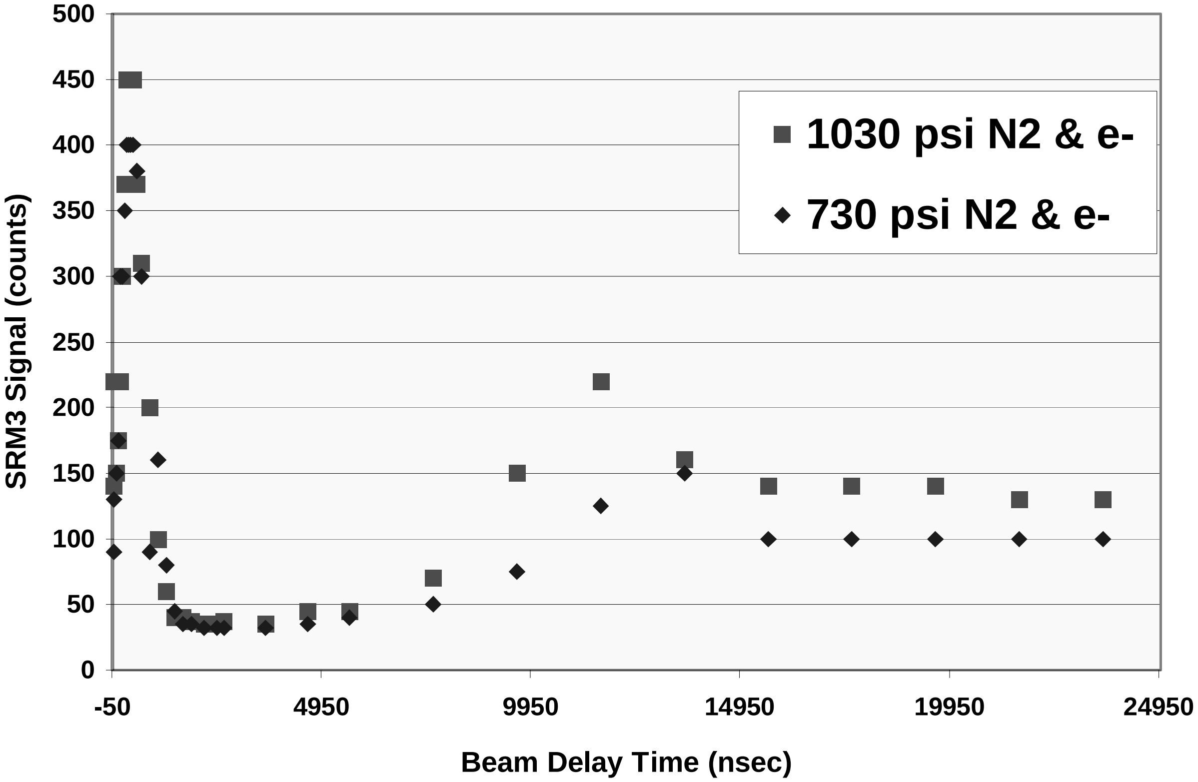

Figure 5. Variation of the strength of nitrogen plasma focusing of electrons with timing .

optimum level. Much of the focusing effect plotted in figure 5 is therefore attributed to beam-induced impact ionization of a time-dependent gas density as determined by shock wave dynamics. Much less is attributed to the preionization.

Discussion and Conclusions

The feasibility of using gaseous plasmas as final focusing elements for electron and positron bunches in linear colliders has been demonstrated at high bunch density and high energy. Simultaneous focusing in both transverse directions has been observed with spotsize reductions to one half of incident values. We anticipate greater luminosty enhancement where electron and positron beam waists coincide in a single plane.

A major benefit of the laser in this work appears to be the shock wave generation that follows gas ionization. This establishes the formation of local densities in the beamline that can be significantly greater than those permitted by static line pressure alone. As a result, gas handling can be done at reduced and safer line pressure levels. Varying the time delay for the beam bunch has allowed the electron and positron beams to be used as probes of gas dynamic behaviour.

With linear colliders in mind, one can contemplate the application of final focus plasma lenses based on either impact ionization or laser-induced preionization of gases (or some combination). For the latter case the role of shock waves could be suppressed by minimizing beam bunch time delay (to subnanosecond intervals). Furthermore, optical field ionization permits greater control of plasma densities in this prompt case. Gas densities can be controlled to make plasma and beam bunch densities comparable. Combined focusing of electron and positrons by a single plasma lens may simplify design. Furthermore, gas flow could be controlled by injecting gas into leaky structures that could be evacuated between consecutive beam bunches. A disadvantage of the preionization technique is the greater timing constraint.

Because plasma focusing is a self pinching phenomenon (regardless of how the plasma is formed) the issue of beam steering and relative displacement between electrons and positrons is a key one for linear colliders and needs to be addressed. Nonetheless, parallel development of plasmas suitable for optimum focusing of electron and positron beam bunches is warranted and should be conducted with specific linear collider parameters in mind. Tabletop experiments can be done in which plasma densities and their decay dynamics are calibrated and shock wave formation is documented.

References:

1. J.S.T Ng et al., Phys. Rev. Lett. 87[24], 244801-1 to 4 (12/10/01).

2. P. Chen, Part. Accel. 20, 171 (1987).