Progress on Plasma Lens Experiment at the Final Focus Test Beam*

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Abstract. The Plasma Lens Collaboration proposed and has been approved to perform the Plasma Lens Experiment at the Final Focus Test Beam (SLAC E-150*bis*). The experiment is a revised and simplified proposition which reflects the pertinent scientific and technological advances since an earlier proposal (1) was submitted. The goals of the experiment are to study plasma focusing of high energy, high density particle beams; to investigate plasma beamsstrahlung suppression; and to develop technologies for plasma lens applications in present and future linear colliders.

INTRODUCTION

Plasma focusing devices are compact, simple, and very strong focusing elements. The focusing strengths for typical parameters are equivalent to focusing magnets with gradients of 10^9 Gauss/cm. In principle, such strong fields are capable of focusing beams to very small spot sizes (2-7) and perhaps even capable of avoiding (8) the inherent (Oide) limitation (9) in discrete strong focusing. Several proof-of-principle experiments using low density particle beams have demonstrated plasma focusing (10-12). Our goal is to demonstrate the effectiveness of plasma lenses in the parameter regime of interest for SLC and the next generation of high energy linear colliders. The experience gained is expected to yield new final focus designs capable of generating spot sizes smaller than ever produced before.

A facility such as the FFTB offers a unique environment to test all aspects of plasma focusing for high energy, low emittance beams. In our earlier proposal (1) we intended to test plasma focusing with both round and flat beams. In the latter case, the intention

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was to demonstrate a focused beam size which would be even smaller than that achieved by the FFTB. We believe that the plasma lens can indeed deliver such an unprecedented beam size at the FFTB. With that in mind we will test the plasma focusing of round beams and concentrate on demonstrating the power of a plasma lens through its demagnification power, as a first step of experimentation.

We will perform a round beam focusing experiment at the FFTB. It would utilize the round beam aspect ratio of $\varepsilon_{nx} = \varepsilon_{ny} = 3 \times 10^{-5}$ m-rad from the FFTB (13), and a charge of 10^{10} particles per bunch. The plasma lens would have electron densities adjustable from 10^{16} to 10^{18} cm^{-3} and a thickness of 3 mm. The plasma will be generated by laser ionization immediately prior to the arrival of the beam. With optimized conditions, the plasma lens will be capable of demonstrating the focusing of a 5 µm round beam to a final spot size of less than 2 µm in both dimensions, or a luminosity enhancement factor of about 10. The simplicity and economy of such a scheme will prove the plasma lens to be a worthy add-on device for luminosity enhancement in linear colliders (7).

PARAMETER STUDIES

The prospect of testing plasma lens concepts at the FFTB was investigated (14). In the study, plasma lens parameters for round beam focusing, flat beam focusing, and "adiabatic focusing" (8) were provided. Here we refine our treatment and limit ourselves to round beam focusing only. We consider beam energies of 50 and 30 GeV, which correspond to the current configuration of the accelerator and its future configuration as the PEP-II (B factory) injector, respectively. In either case, the effectiveness of the plasma lens can be demonstrated.

Ignoring the effects due to the return current, the focusing strength K for underdense plasma lenses is governed by the plasma density n_p,

$$K = \frac{2\pi r_e}{\gamma} n_p \ , \tag{1}$$

where r_e is the classical electron radius and γ is the relativistic kinetic energy factor of the beam. For overdense plasma lenses the strength is determined by the beam density n_b,

$$K = \frac{2\pi r_e}{\gamma} n_b \ . \tag{2}$$

The plasma return current tends to reduce the focusing effect of the lens (15). The effect is approximately given by

$$K_{rc} = \frac{K}{1 + (k_p \sigma_r)^2} \ , \tag{3}$$

TABLE 1. Parameters for Round Beam Focusing.

Beam Parameters	**Case A**		**Case B**		**Case C**	
E_0 [GeV]	30	50	30	50	30	50
N [10^{10}]	1	1	1	1	1	1
ε_n [10^{-5} m-rad]	3.0	3.0	3.0	3.0	3.0	3.0
β_0^* [mm]	45	75	45	75	45	75
σ_{r0}^* [μm]	4.74	4.74	4.74	4.74	4.74	4.74
β_0 [mm]	48.1	80.3	48.1	80.3	48.1	80.3
σ_0 [μm]	4.91	4.91	4.91	4.91	4.91	4.91
σ_z [mm]	0.47	0.47	0.47	0.47	0.47	0.47
n_{b0} [10^{16} cm^{-3}]	5.3	5.3	5.3	5.3	5.3	5.3
Lens Parameters	**Case A**		**Case B**		**Case C**	
n_p [10^{16} cm^{-3}]	2	2	10	10	100	100
$k_p\sigma_z$	12.5	12.5	28	28	88.5	88.5
s_0 [mm]	-20	-20	-20	-20	-20	-20
ℓ [mm]	3	3	3	3	3	3
f [mm]	22.8	47	17.4	35.7	21.6	36
Focused Beam	**Case A**		**Case B**		**Case C**	
β_r^* [mm]	22.2	37	12.6	21	20.4	34
σ_r^* [μm]	2.01	3.35	1.53	2.55	1.94	3.23
s^* [mm]	2.8	28.5	-2.6	10.7	1.6	17.5

where σ_r is the rms size of the beam and $k_p = \sqrt{4\pi r_e n_p}$ is the plasma wave number. The effect is appreciable only when the plasma is considerably denser than the beam.

The response of the plasma occurs in a time $\tau_p = 1/\omega_p$ and therefore in the overdense regime the requirement for response within the time of a beam pulse is $\tau_p \ll \tau_b \sim \sqrt{2\pi}\sigma_z$, or $k_p\sigma_z \gg 1/\sqrt{2\pi}$, where σ_z is the rms bunch length. In the underdense regime, the wave breaking limit is quickly reached and the focusing is less subjected to the limit.

For the plasma lens experiment, the FFTB emittance is adjusted to a round beam configuration of $\varepsilon_{nx} = \varepsilon_{ny} = 3 \times 10^{-5}$ m-rad for a bunch population of 10^{10}. With the relaxed beam properties, many of the chromatic corrections at the FFTB can be less stringent as well. A laser ionized plasma with a thickness of 3 mm and adjustable plasma density from 10^{16} to 10^{18} cm^{-3} is placed at a distance of 2 mm from the vacuum focus.

Parameters for three typical cases with different plasma densities are shown in Table 1. Here, E_0 is the beam energy, N is the number of particles per bunch, ε_n is the normalized emittance, and the bunch length is σ_z. The focused beam size in vacuum is σ^*_{r0} with corresponding beta function β^*_0. The density of the plasma lens is n_p, and the focal length is $f = s^* - s_0 - \ell/2$, where s^* is the distance of the new focal point from that of the vacuum, ℓ is the lens thickness, and s_0 is the location of the entrance to the plasma lens with respect to the vacuum focal point. At the entrance to the plasma lens, the beam size, beta function, and beam density are σ_0, β_0, and n_{b0}, respectively.

In Case A, an underdense plasma lens with $n_p = 2 \times 10^{16}$ cm^{-3} focuses the beam from about 5 µm to 3.4 µm and to 2.0 µm, for 50 GeV and 30 GeV beams, respectively. Increasing the plasma density to 10^{17} cm^{-3}, as shown in Case B, allows the study of overdense plasma focusing without degradation due to return currents. In this case, the plasma focusing is strongest in this experiment, and the beam size decreases from 5 µm to 2.6 µm and to 1.5 µm, for 50 GeV and 30 GeV beams, respectively. In Case C, the plasma is much denser than the beam, and the beam-plasma interaction is in the extreme overdense regime, where the focusing strength diminishes due to return currents. It is important to note that the extreme overdense regime in Case C is the basis for the concept of "plasma beamsstrahlung suppression" (3,15).

In addition, a completely new particle-in-cell code has been developed by the plasma lens collaboration (16) to augment the numerical calculations discussed. Results from the new simulations have confirmed the parameters and provides refined guidance to the research and development of the experimental design.

EXPERIMENTAL DESIGN

The apparatus for the plasma lens experiment is to be installed at Station 1027 on the FFTB (13). The location is within the final focus region of the FFTB and has ample space available for installation of all accessories. The design is to minimize the impact on the existing FFTB beam line, as well as to allow simultaneous presence of other scheduled experiments. At the conclusion of the plasma lens experiment, it will be possible to revert the FFTB beam line configuration to its original state.

The arrangement consists of a plasma chamber sandwiched between two identical differential pumping systems, and has ports for ionization laser, plasma diagnostics, gas supply, and beam size measuring devices. The differential pumping stages are separated by thin beryllium windows, with millimeter-sized holes for electron beam passage, to maximize pumping efficiency. The ionization laser is the same 1 µm wavelength laser system as was used for the non-linear Compton scattering experiment at the FFTB (E-144) (17). A small portion of the laser will be doubled in frequency for plasma diagnostics using Thomson scattering. Conventional wire scanners will be used for all beam size measurements, and the bremsstrahlung signal is monitored by the existing detectors downstream. Hydrogen gas will be used as the plasma source to minimize background radiation from beam-plasma interaction. The outline of the plan is shown as Figure 1.

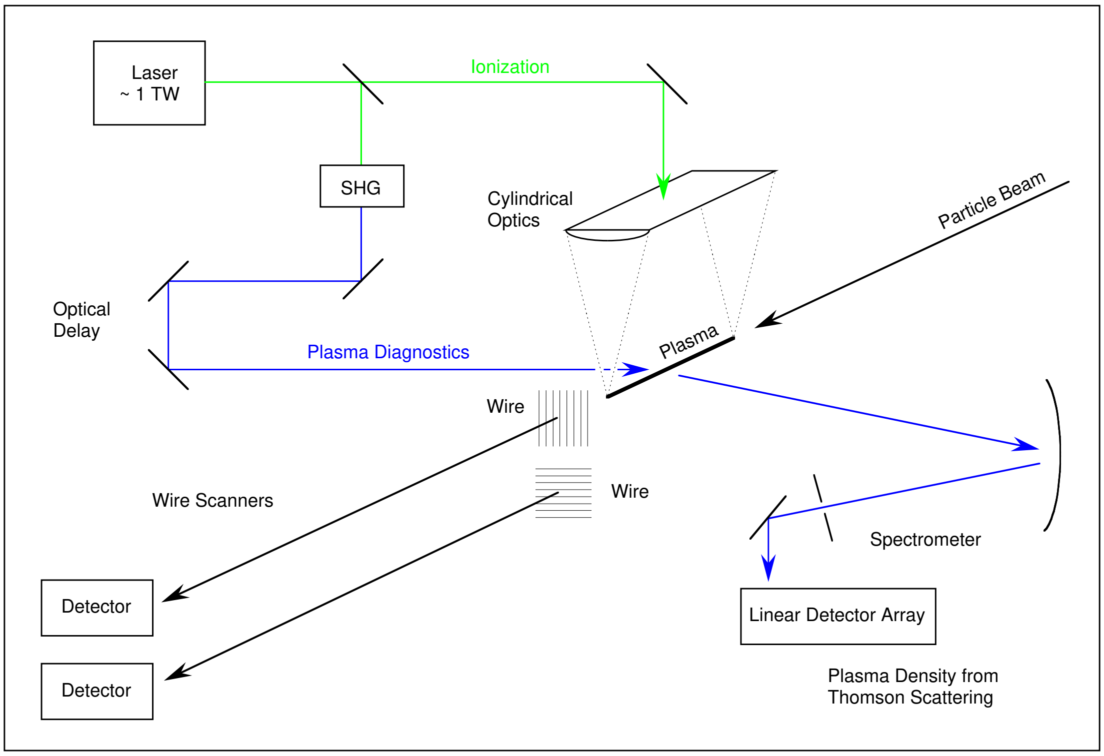

FIGURE 1. Outline of the Plasma Lens Experiment at the FFTB.

RECENT DEVELOPMENTS

Detailed designs of the experiment began in October 1997, immediately after the approval from SLAC Experimental Program Advisory Committee. With guidance from the new particle-in-cell simulations (16), a preliminary design was constructed and reviewed in March 1998.

At the March 1998 review, plasma diagnostics compatibility issues were raised. It was suggested that laser interferometry should be used in place of Thomson scattering for plasma density measurements, the former which is much easier to setup and provides more reliable performance. However, the change requires pathways free of high pressure gas for the interfering laser beams. Consequently, a minor change has to be made to the gas delivery method.

With the change in plasma diagnostics, a pulsed gas nozzle is used as the plasma gas source now in place of a static gas cell as suggested in the proposal. The gas nozzle is procured from a commercial enterprise, which cuts development time significantly. A similar nozzle has been proven to perform satisfactorily at LBL (18) in the parameters of interest to the plasma lens experiment.

As synchrotron radiation induced by plasma focusing provides essential information on focusing strength, the collaboration is developing a synchrotron radiation monitor as an additional diagnostic tool.

ACTIVITIES IN PROGRESS

As the planned operational date of April 1999 for the plasma lens experiment is approaching rapidly, the activities of the plasma lens collaboration are intensifying. Currently, the testing of the new gas nozzle is underway, along with the commissioning of the vacuum system, and will be completed by the end of August 1998. The experimental design will be completed following the gas nozzle test, which is expected to be near the close of September 1998.

Meanwhile, other systems such as plasma diagnostics, beam size measurements, and data acquisition are being developed independently. Fabrication of the plasma lens chamber, and the laser transport system is expected to take three months from October through December 1998. All systems will be integrated and installed in the first quarter of 1999.

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REFERENCES

1. Barletta, W., et al., "SLAC Proposal E-150," SLAC, 1993.
2. Chen, P., *Part. Accel.* **20**, 171 (1987).
3. Chen, P., et al., *IEEE Trans. Plasma Sci.* **15**, 218 (1987).
4. Rosenzweig, J. B., and Chen, P., *Phys. Rev. D* **39**, 2039 (1989).
5. Chen, P., Rajagopalan, S., and Rosenzweig, J. B., *Phys. Rev. D* **40**, 923 (1989).
6. Su, J. J., et al., *Phys. Rev. A* **41**, 3321 (1990).
7. Chen, P., *Phys. Rev. A* **45**, R3398 (1992).
8. Chen, P., Oide, K., Sessler, A., and Yu, S., *Phys. Rev. Lett.* **64**, 1231 (1990).
9. Oide, K., *Phys. Rev. Lett.* **61**, 1713 (1988).
10. Rosenzweig, J. B., et al., *Phys. Rev. Lett.* **61**, 98 (1988).
11. Nakanishi, H., et al., *Phys. Rev. Lett.* **66**, 1870 (1991).
12. Hairapetian, G., et al., *Phys. Rev. Lett.* **72**, 2403 (1994).
13. Tenenbaum, P., et al., "SLAC-PUB-6593," SLAC, 1994.
14. Betz, D., et al., *Proc. IEEE Part. Accel. Conf.* **88-647453**, 619 (1991).
15 Whittum, D. H., et al., *Part. Accel.* **34**, 89 (1990).
16. Masuda, S., et al., Wkshp. Adv. Accel. Concepts, 1998.
17. Heinrich, J. G., et al., "SLAC PROPOSAL E-144," SLAC, 1991.
18. Leemans, W., Private Communications, 1998.