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

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Abstract

The proposal to perform a series of plasma lens experiments at the Final Focus Test Beam at SLAC has been described earlier. We report on our progress towards validation of concepts involved in the experiments, including the laser ionized plasma production test, development of the supersonic gas jet as the plasma source, and study on focused beam size measurement techniques. Most importantly, the effects of background events due to plasma lenses in future linear collider detectors, such as that in the NLC, are studied in details and are shown to be within detector tolerances.

I. INTRODUCTION

Although the concept of plasma lens [1] has been reasonably verified in several low energy, low density experiments [2-4], the utility of the plasma lens in high energy physics has yet to be proven. It is necessary to further demonstrate plasma focusing in a setting close to the true high energy collider with negligible induced backgrounds to the detector. The proposal to perform the plasma lens experiments at the FFTB at SLAC has been described earlier [5]. Here we report on the substantial progress that has been made in verifying the key concepts of the experiments.

II. PLASMA PRODUCTION TEST

The plasma production test was performed at the Laboratory for Laser Energetics of the University of Rochester. Plasmas suitable for the plasma lens experiments at the FFTB, with lengths of 1 mm and electron densities of order 10^{18} cm^{-3}, were produced with transverse laser illumination. The high-powered laser system employed in the test is capable of delivering up to 1 J at 1 μm with a pulse length of 1.3 ps, and is similar to the one installed at the FFTB for experiment E-144 [6]. The nominal focal spot size of the laser is ~100 μm FWHM, which corresponds to a Rayleigh length of ~3 mm. A cylindrical lens was added to produce the focusing for a 1 mm plasma.

Xenon, which has ionization potentials similar to hydrogen, was used for the test. Since xenon can have multiple charge states, a lower gas pressure can be used in the test chamber to obtain an electron density of 10^{18} cm^{-3}. The lower gas pressure minimized the defocusing of the ionization laser in the gas-filled chamber.

The plasma density was determined by measuring the recombination light with a photomultiplier tube (PMT) [7]. Dimensions of the plasma were measured using CCD image of the recombination light. With a 300 mJ laser pulse, a plasma with electron density of 0.8×10^{18} cm^{-3} and measures 1.1 mm transversely was produced (Figure 1).

The test has shown that plasma of extended size with electron density of order 10^{18} cm^{-3} can be produced using laser ionization. A hydrogen plasma with the appropriate properties should, hence, be available for the plasma lens experiments.

III. SUPERSONIC GAS JET DEVELOPMENT

In an effort to minimize background events, a supersonic hydrogen jet is under development for use with the plasma lens experiments at the FFTB. With the use of gas jets, the experimental design has been completely revised which eliminated all solid materials inside the beam pipe at the interaction point. Such gas jets offer the practical advantage during initial beam tuning, as well as suitability for application at high energy detectors.

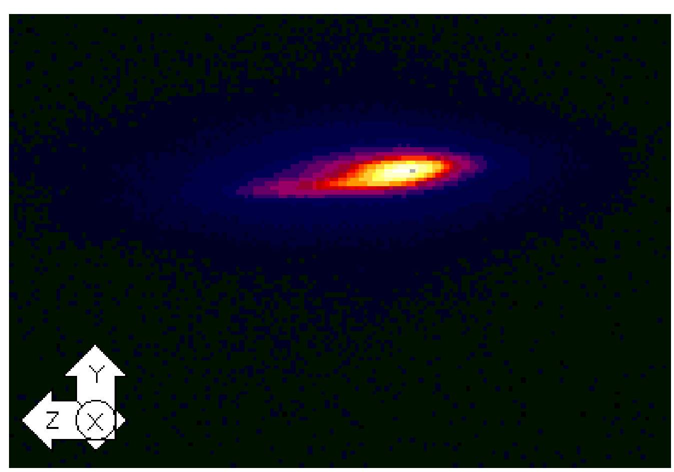

Figure 1: Artificially colored image of the plasma produced with a cylindrical lens. The laser travels in the Z-direction. The cylindrical lens was oriented to defocus the laser slightly in the Y-dimension to form a long focus.

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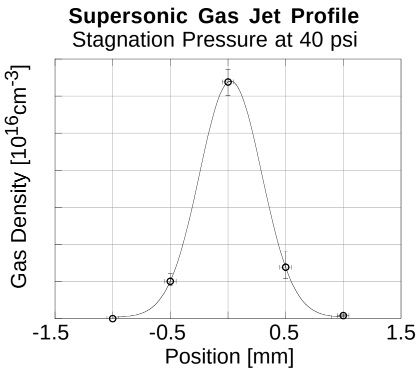

Figure 2: Transverse profile of the supersonic gas jet measured at Rochester.

The gas jet is delivered through a simple axis-symmetric converging/diverging nozzle with an opening angle of 10° and a throat diameter of 75 µm. Continuous operation of the gas jet alleviates vibration problems associated with pulsed gas jets. Nominal operating pressure of the nozzle is designed to be 2,000 psia, which gives a gas density of $\sim 2.5 \times 10^{18}$ cm^{-3} at the nozzle exit. The operating pressure can be substantially lowered with the use of liquid nitrogen pre-cooling.

The first generation nozzle design is based on a simple one-dimensional gas dynamics model that assumes an ideal gas in steady-state, isentropic flow [8]. A procedure was developed to produce the copper nozzle using conventional machining techniques combined with an extrusion process to achieve the final throat diameter.

Preliminary testing of the nozzle at low operating pressure (~40 psia) has been performed at the University of Rochester. The nozzle was moved relative to the laser so that a rough profile can be measured (Figure 2). Since the nozzle was not operating at its designed pressure, the gas density obtainable was far lower than 10^{18} cm^{-3}. However, the gas density attained agrees reasonably well with prediction.

Vacuum testing of the nozzle has started recently to check the vacuum pumping requirements for operating the gas jet in the FFTB. The nozzle was installed into a test system that approximates a differential beam line vacuum pumping system with two turbo molecular pumps giving a combined pumping capacity of 365 liter/sec. The gas from the nozzle is collected through an orifice by two mechanical pumps with a combined pumping capacity of 33 liter/sec. Initial results are not as positive as we have expected and are still under investigation. One of the concerns is the underexpansion of the gas jet due to a high exit pressure relative to the stagnation pressure, causing shock waves to disrupt the flow pattern [8].

IV. BEAM SIZE MEASUREMENTS

A. Laser-Compton Monitor

The Laser-Compton Monitor developed by Tsumoru Shintake [9] is installed in the FFTB and has been successfully operated there[10] to measure beam sizes of less than 100 nm. For the plasma lens experiments, a simplified version of the monitor is being developed for installation at the plasma lens focus (Figure 3). The Compton-scattered photons will be observed by the same detector that measures the bremsstrahlung photons from the wire scanners.

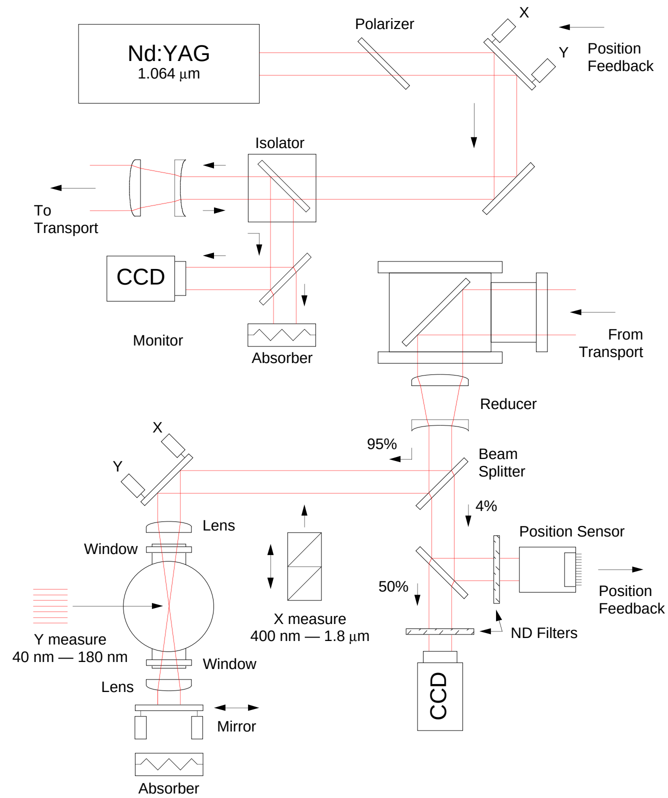

Figure 3: Schematic of the simplified version of the Laser-Compton Monitor.

B. Measurement of the Compton-Scattered Electrons

As a supplementary measurement to the Compton-scattered photons from the Laser-Compton Monitor, we intend to measure the spectrum of the Compton-scattered electrons using the existing E-144 Electron Calorimeter (ECal). The segmented calorimeter is located just downstream of the permanent dump magnets of the FFTB beam line, and provides a spectrometric analysis of the electrons.

ECal is a silicon calorimeter with tungsten as radiator, consisting of 23 layers of 3.5 mm tungsten, 1.04 mm air, and 0.300 mm silicon sandwiched between two pieces of 0.83 mm G10. The silicon wafers are subdivided into 1.6 by 1.6 cm^2 pads, where each layer has 4 such pads horizontally and 12 vertically. The silicon pads are ganged together in depth to form towers, where 4 longitudinal segments are read out separately for each tower. ECal sits on a stage which allows it to be moved up towards the beam line. Electrons from the beam will hit the center 2 (of 4) horizontal pads, so that the outer pads can possibly be used for backgrounds subtraction.

The modulation depth in the number of Compton-scattered electrons is determined by measuring the energies deposited in several rows of ECal both above and below the

Compton edge. Energies deposited would, after correction for background and shower sharing, be divided by an average energy to obtain a number of Compton electrons in the momentum range. The average energy of a selected row is determined by integrating the Compton cross section over its momentum bite.

C. Measurement with Bremsstrahlung Optics

Beam profile can be measured by converting the electron beam to bremsstrahlung photons using a thick radiator, and using collimators and slits to determine the size of the source of photons using a variant of pinhole optics [11]. The system has been tested at the MIT/Bates 1 GeV electron linear accelerator and can be used as a supplementary measurement for the plasma lens experiments.

V. DETECTOR BACKGROUNDS FROM PLASMA LENSES

Background sources for particle detectors from a plasma lens can be divided into three kinds, namely, electrons/positrons, protons, and photons. These backgrounds originate from different elementary physical processes underlying the interactions of the incoming electron or positron beams with the plasma near the interaction point. We have calculated the cross sections and angular distributions for all the processes responsible for the various sources of backgrounds [12], from which the number of background particles can be determined for any given machine parameters. Here we have chosen NLC as an example, with which the prospect of the application of plasma lenses in future linear collider detectors can be examined.

For our calculations, we have taken the NLC beam energy E_{beam} at 250 GeV, $N = 0.6 \times 10^{10}$, $\sigma_x = 300$ nm, $\sigma_y = 3$ nm, $\sigma_z = 100$ µm, the hydrogen plasma density n_p is 10^{18} cm^{-3} and $L = 2$ mm. The number of bunches in a bunch train n_b is 90. The angular cut for the scattered particles into the detector is taken to be 150 mrad. Results of our calculations are summarized in Table 1.

Background Source	Partial Cross Section (cm^{-2})	Vertex Detector	Drift Chamber
Bhabha & Møller	0	0	0
Elastic *ep*:			
electrons	0.103×10^{-45}	negligible	negligible
protons	0.613×10^{-39}	negligible	negligible
Inelastic *ep*:			
electrons	0.132×10^{-33}	negligible	negligible
charged hadrons	0.396×10^{-29}	0.23	0.23
Inelastic γp:			
charged hadrons	0.313×10^{-28}	1.8	1.8
Compton from:			
quadrupole	0.995×10^{-25}	2000 γs	2600 γs
plasma focusing	0.548×10^{-25}	990 γs	1800 γs
bremsstrahlung	0.119×10^{-24}	540 γs	270 γs

Table 1: Summary of background sources from plasma lens in NLC.

We have assumed that the resolution time for the detector is much longer than 1.4 ns, which is the separation between successive bunches in a bunch train. We have conservatively integrated the events over a train of 90 bunches, with a total time span of ~125 ns. Time separation between bunch trains is ~5 ms.

For vertex detectors, the serious range for background photons is between 4 keV and 100 keV. When imposing such energy cuts, the number of background photons is reduced to ~3,600. For drift chambers, only photons with energies greater than ~100 keV need to be considered, and the background photons total about 4,700. Drift chambers can tolerate about 10,000 incident photons, of which typically no more than 100 convert.

It can be seen from Table 1 that all the main components of the detector should survive from the plasma lens induced backgrounds. Therefore, the implementation of a plasma lens for luminosity enhancement in high energy e^+e^- collisions is feasible without hampering the normal performance of the detector.

VI. SUMMARY

Feasibility of the key concepts involved in the plasma lens experiments have been proven. The mild background events induced by beam-plasma interaction has been shown to be within tolerances for applications at high energy detectors. Further work is to be done on the supersonic gas jet, including the addition of a converging/diverging supersonic diffuser to control shock waves, as well as the development of an asymmetric (flat) supersonic gas jet to reduce vacuum pumping requirements and backgrounds.

VII. REFERENCES

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