High Density Plasma Source for Plasma Lens Experiments*

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Abstract

Experimental results of the study of a candidate source for high-energy particle beam underdense plasma lens experiments are presented. The high density plasma is based on the operation of the back-lighted thyratron. A 100% ionized hydrogen plasma with density of 1.7×10^{16} cm^{-3}, homogeneous in space and monotonically varying in time with a time scale on the order of µsecs is straightforwardly achievable. The desired plasma density for lens experiments can be achieved very simply by controlling either the applied voltage, the beam entry time or other parameters. This scheme presents a simple device with the ability to support a plasma with density ranging from 10^{12} cm^{-3} to above 10^{16} cm^{-3}. The structure also facilitates the particle beam entry and the components are vacuum compatible. The device is small, simple, robust, easy to adjust, can be operated at high repetition rates, and has a long life time.

I. INTRODUCTION

It has been proposed to use a layer of plasma as a final focusing lens for high energy particle beams. The scheme is usually termed "plasma lens".[1-5] The advantage of this approach lies in the exceptional focusing strength provided by plasma; several orders higher than conventional quadrupole magnets (10^5 T/m with plasma density of 10^{16} cm^{-3} compared with conventional quadrupole focusing lens of 10^2 T/m). Presently various plasma lens schemes have been proposed, namely, thin, thick, adiabatic and optimal plasma lens.[6,7] For both thin and thick lenses, the plasma density is uniform within the plasma slat. Adiabatic lens and optimal lens require a tailored density profile in the beam propagation direction. The adiabatic lens also offers the potential of overcoming the Oide limit on final spot size which limits all other lens designs.[8] In this paper the application of a back-lighted thyratron (BLT) or a Pseudospark is presented. The intent is to utilize the homogeneous BLT high density plasma as a plasma source for the final focusing plasma lens.

There are two regions in a passive, self-focusing plasma lens, namely underdense and overdense. In the underdense regime where the plasma density is lower than the beam density ($n_b>n_e$), the plasma electrons respond to the incoming beam by total rarefication from the beam volume. The result is a nearly uniform focusing of the beam due to the less mobile ions. The focusing strength κ for the underdense plasma lens can be written as

$$\kappa \equiv \frac{F_r}{r} = \frac{n_e e^2}{2\varepsilon_0} \qquad (1)$$

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where F_r is the radially focusing force, n_e is the plasma density and ε_0 the permittivity. The focusing strength of a underdense plasma lens is proportional to the plasma density. The focusing mechanism of a position beam can be described similarly with a major difference that the plasma electrons are now being pulled into the a positron beam instead of being rejected.[1] The space charge neutralization is provided with the incoming plasma electrons.

Experiments in Argonne National Laboratory (ANL) and University of Tokyo have confirmed that the plasma do focus low-energy ($\approx$ 20 MeV), low-density ($\approx 10^{10}$ cm^{-3}) electron beams.[9,10] In the ANL experiment a 35 cm long DC hollow cathode arc plasma source with density on the order of 10^{13} cm^{-3} is used to focus the beam size from σ=1.4 mm to σ=0.91 mm. In the University of Tokyo, a 36 cm plasma with density on the order of 10^{11} cm^{-3} is used. It has been confirmed that plasma certainly has a lens effect, even though the reduction of transverse emittance is not yet fully understood.

Presently the challenge of plasma lens experiments is to demonstrate the plasma focusing effect with high energy (10's of GeV) and high density (on the order of 10^{17} cm^{-3}) particle beams like Stanford Linear Accelerator Center (SLAC) Final Focus Test Beam (FFTB). From equation (1) a plasma with the highest possible density is required to achieve strong focusing for an underdense plasma lens design. The BLT is a potential candidate for plasma lens experiment due to its high-density plasma and other favorable features.[11] The plasma density in a typical BLT operation with a discharge current of several kA is on the order of 10^{15} cm^{-3}. Results presented in this paper indicate that plasma densities in the range of several times 10^{16} cm^{-3} can be readily achieved.

II. RESULTS AND DISCUSSION

Figure 1 shows the experimental setup for BLT high plasma density operation and density measurement. A single stage, UV flash lamp (EG&G, FX-265) triggered BLT is typically operated with a 2 µF capacitor and ultra-high purity hydrogen gas.[12] The BLT, being optically triggered Pseudosparks, can also be electrically triggered.[13] Both cathode and anode are made of molybdenum. The electrode separation is $\approx$ 3 mm. A quartz window behind the cathode allows UV light to illuminate the cathode back surface and initiates the discharge. Stark broadening spectroscopic technique was chosen to measure the plasma density.[14] With the expected plasma density variable to several times 10^{16} cm^3 the broadened line width (FWHM) of Balmer lines are on the order of several Å. An accuracy within 30% is expected with this measurement. The SPEX 1302 series spectrometer (f/7) has a resolution $\approx$ 0.9 Å with a 150 µm entrance slit width. A two-lens imaging system collects and focuses the plasma light emission onto the spectrometer entrance slit with matched f number. The measurement is taken at the mid-plane in between cathode and anode. The spatial resolution is ≈ 150 μm. Together with Hamamatsu streak camera a time-resolved plasma density measurement can be achieved. In this present experiment the jitters of BLT is ≤ 20 nsec when operated at above 7.5 kV. The triggering of BLT and streak camera were controlled separately by two different channels from a single pulse generator. The streak camera streak time setting allows one to look at a specific time interval of interest during the discharge. Not shown in the figure are the supporting vacuum and gas supply system.

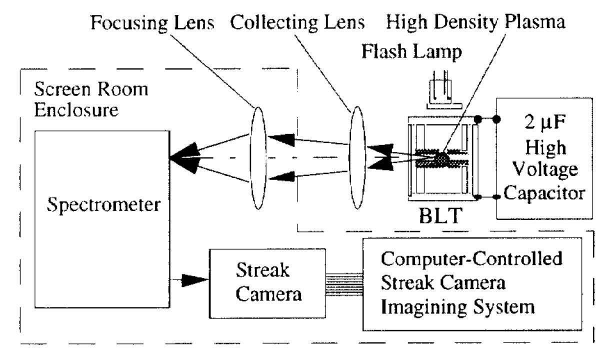

FIG. 1 Schematic for BLT high density plasma measurements

Figure 2 shows the time-resolved plasma density with two different applied voltages (7.5 kV and 10 kV). The oscillating discharge current has period ≈ 4.8 μsec and peak current proportional to the applied voltage (18.75 kA corresponding to 7.5 kV, 25 kA to 10 kV and 31.25 kA to 12.5 kV). A lumped circuit inductance of 300 nH is estimated. With a working gas of 275 mTorr hydrogen the maximum plasma density is ≈ 1.76×10^{16} cm^{-3}. The streak camera streak time was set at 20μsec/15mm with a full screen time of 13.3 μsec. With a 100 μm entrance slit the temporal resolution is ≈ 150 nsec. The plasma density is measured through H_α line broadening. As shown in Figure 2, the plasma density increases with increasing

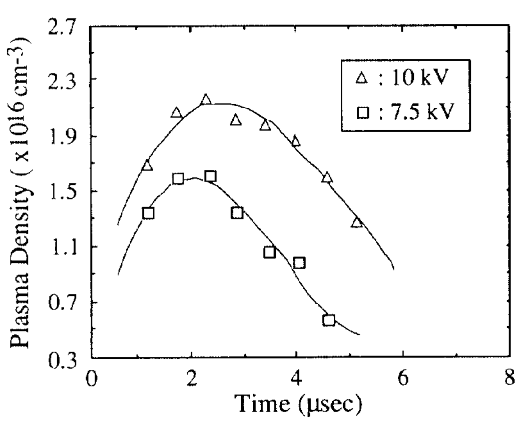

FIG. 2 Time-resolved plasma density measurements

applied voltage from 7.5 kV to 10 kV. The electron temperature is estimated to be of the order of 1 eV.[11] With 10 kV applied voltage a peak density of 2.0×10^{16} cm^{-3} is measured with ions assumed mobile.[15] With the possible 30% error, the plasma is believed to be fully ionized. Another supporting evidence is that when the voltage is further increased to 12.5 kV the peak plasma density did not increase accordingly. Theories assuming ions immobile tend to over-estimate the plasma density and is not suitable for the present measurement since the time scale of discharge is long compared with the ion plasma period.[14]

There are different ways to achieve the desired plasma density during lens experiments. One is to vary the discharge current through different applied voltage as has been done in this present experiment. Figure 3 shows the peak plasma

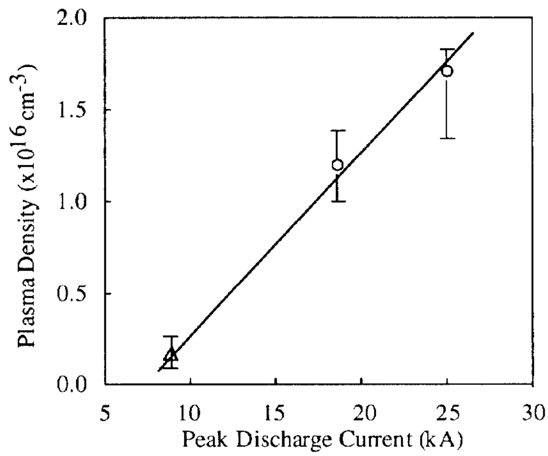

FIG. 3 Peak plasma densities with various discharge currents. Δ was taken with a slightly different discharge condition (180 mTorr hydrogen, C=0.7 μF, R=0.5 Ω, L=400 nH at 12 kV). The error bar represents the intrinsic accuracy of the measurement method, not the reproducibility of the plasma.

density obtained with various peak discharge current. With a single device the plasma density can be varied to above 10^{16} cm^{-3}. A second way is by injecting the particle beam at different time during the discharge with a fixed applied voltage since the particle beam bunch length (typically on the order of psec) is much shorter than the time scale of density variation so within the beam bunch the plasma density can be regarded as constant. It is also possible to vary the pressure, gas, and geometry thus achieving a broad range of operating conditions for a uniform, pulse repeatable, homogeneous plasma.

As indicated above the maximum plasma density is determined by the available neutral density. For this reason a circuit with one switching BLT (low pressure gas) and one lens BLT (high pressure gas) has been constructed and tested. The results indicate that the plasma density increases with increasing neutral density when operated with same discharge current. The measurements at two different positions (on discharge axis and 3 mm away from axis) also indicate a homogenous plasma, with a macroscopic density variation ≈ 15%. For a μm beam size the plasma can be regarded as uniform. Thus operating the lens with a modulator is a simple way to achieve variable plasma density.

As a numerical example of this plasma source in SLAC FFTB underdense plasma lens experiment it has been shown that, for a round beam, the final beam size can be reduced from 4.1 μm to 1.9 μm by a 2 cm thick plasma of density 6×10^{15} cm^{-3} inserted at 6 cm before the natural beam waist.[16] The normalized beam emittance is assumed to 30 mm-mrad. With a three times higher density (1.8×10^{16} cm^{-3}) the same electron beam can be focused to less than 1 μm.

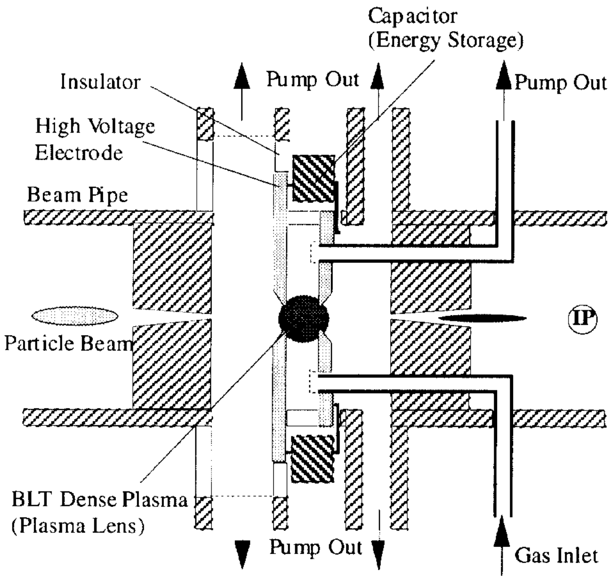

FIG. 4 Conceptual design for the BLT-based SLAC FFTB plasma lens experiments.

Figure 4 shows a conceptual design of BLT-based plasma lens design for SLAC FFTB. Many other geometries are also possible. An intuitive choice will be using the electrode central holes for beam entry and exit. Working gas will flow into the cathode-anode gap and be pumped out through electrode holes. The beam line apertures (for both beam entry and exit) need to be small enough to minimize the gas flow conductance while large enough (for example, $\geq 20\sigma$) to avoid a vacuum wake field. The pumping requirement can also be significantly reduced if a puff gas valve is used.

III. CONCLUSION

In conclusion, the results of a study of BLT high plasma density operation and proposed application to SLAC FFTB plasma lens expriment are presented. A homogeneous, reproducable hydrogen plasma with variable density from 10^{12} cm^{-3} up to 1.7×10^{16} cm^{-3} was achieved. At density 1.7×10^{16} cm^{-3} the plasma is believed to be fully ionized. With this single device the density can be easily varied by changing the applied voltages or by various other means. The plasma source is suitable for underdense plasma lens experiments. The operation and the structure of BLT have several features which are optimal for plasma lens experiments. These include (a) central holes to facilitate beam entry and exit, (b) vacuum compatible components that will not degrade the FFTB vacuum system, (c) precision timing and reproducibility, (d) variable plasma density and thickness. The device is robust and extremely simple in structure, and long lived.

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