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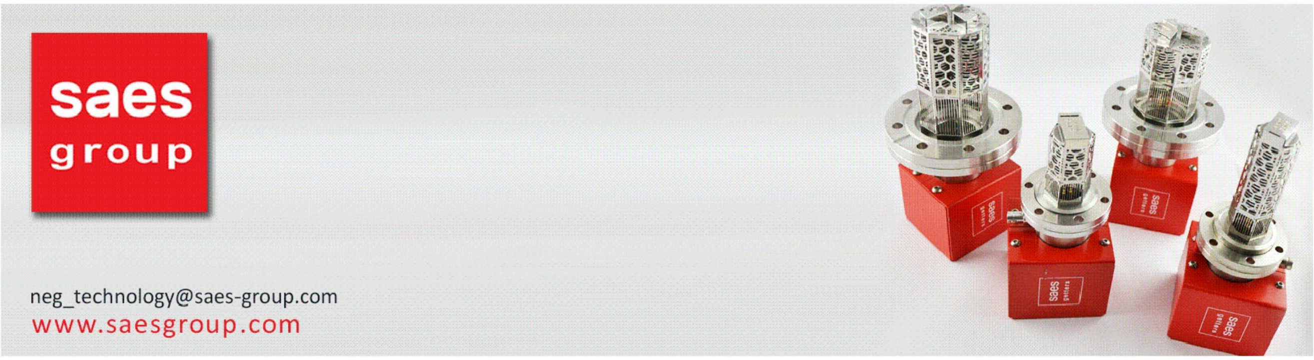

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Compression and focusing a laser produced plasma using a plasma optical system[a)]

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Axi-symmetric compression and focusing of a low temperature laser produced copper plasma with an electrostatic plasma optical system was investigated for the first time. The degree of plasma concentration was quantified using Langmuir ion measurements of the ion flow and optical measurements of the thickness distributions of copper depositions on glass substrates. Both the ion flow and the deposition measurements showed strong concentration of the ion-plasma flow towards the axis. The ion current density at the focus was compressed by a factor up to 9.The on-axis deposition rate was increased by about the same factor. © *2012 American Institute of Physics*. [doi:10.1063/1.3660261]

I. INTRODUCTION AND BASIC RELATIONS

Pulsed laser deposition is a widely used technique in research for deposition of complex materials, from superconductors to nanoparticles.[1,2] In this technique, a nanosecond pulsed laser is used vaporize a small amount of material from the surface of a solid target in vacuum and it expands away from the target as plasma moving at supersonic velocity. Since the ablation plume is significantly ionized, electromagnetic techniques can be to modify the flow in the laser produced plasma (LPP). A curved solenoidal magnetic field of ~100 mT has been used to guide the plasma on a curved path and thus avoid particulate contamination.[3] Permanent magnets have also been used to deflect the LPP.[4] The behavior of LPP injected along a magnetic field has been studied by Pagano and Lunney[5] and strong lateral confinement of the plasma expansion has been observed. Pisarczyk *et al.*[6] studied the flow of much hotter LPP along a strong magnetic field (~20 T), with the aim of laterally confining the plasma for soft x-ray laser development.

This paper describes the first results of an experiment to investigate the compression and focusing of a low temperature copper LPP using an electrostatic plasma lens (PL). The electrostatic PL is an axially symmetric plasma optical system with a set of cylindrical ring electrodes located within an external magnetic field with field lines connecting ring electrode pairs symmetrically about the lens midplane. The fundamental concept of this kind of lens was first described by Morozov and co-workers[7] and is based on the plasma optical principles of magnetic isolation of electrons and equipotentialization of magnetic field lines for the control and manipulating of an electric field introduced into the plasma medium. The plasma lens is a well-explored tool used in focusing high-current large area moderate energy heavy ion beams, where beam space charge compensation is critical.[8–10] The focal length of this kind of thin electrostatic plasma lens is given by[7]

$$F = \frac{\theta\, \varphi_b\, R}{2\varphi_L}, \tag{1}$$

where φ_b *is* the ion source extractor voltage and θ is a geometric parameter that depends on the ratio of lens radius R to lens length L and the magnetic field configuration. φ_L is the maximal lens potential. Importantly, note that the focal length of the plasma lens does not depend on the ion charge-to-mass ratio; this is a consequence of the purely electrostatic optical system, as previously mentioned.

Note that the equipotentialization condition follows from the steady-state hydrodynamic equation of motion of cold electrons, which in this case is

$$\boldsymbol{E} = -(\boldsymbol{v}_d \times \boldsymbol{B}), \tag{2}$$

where $\boldsymbol{v}_d$ is the velocity of the cold electrons and $\boldsymbol{B}$ is the magnetic field within the lens volume. The macroscopic electrostatic field $\boldsymbol{E}$ is obtained only in the presence of closed electron drift and an "insulating" magnetic field. Then the electric field is perpendicular to the magnetic field, leading to field lines that are equipotentials. Thus by using properly configured magnetic field it is possible to apply an electric field in a plasma, and use this electric field to focus an ion beam passing through the plasma lens volume. When the electrons are magnetized (Larmor radius $\ll$ plasma dimensions) they spiral along the magnetic field lines to maintain them equipotentials, but electron transport across the magnetic field lines is suppressed. Electrons in low temperature LPP are easily magnetized; for 1 eV plasma in 0.3 T field the electron Larmor radius is about 7 μm, which is much smaller than the typical plasma dimensions. The magnetic field lines connect with electrodes at various potentials, and thus a focusing electric field is maintained in the plasma volume.

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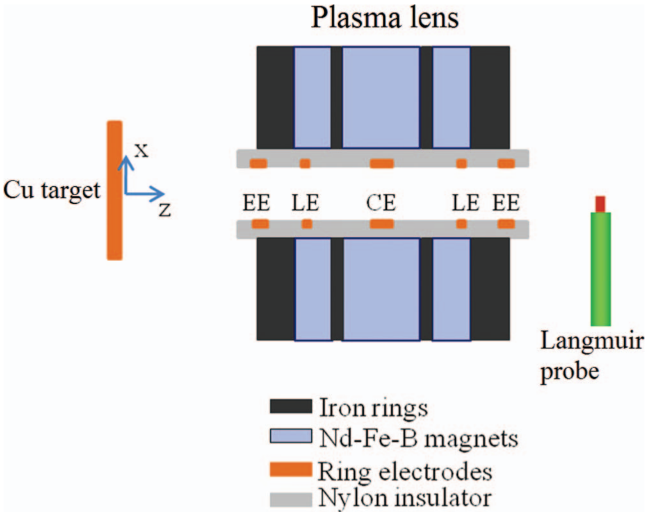

FIG. 1. (Color online) Schematic diagram of the experimental setup.

II. EXPERIMENTAL METHODS

A diagram of the experimental setup is shown in Fig. 1. The field was generated using an assembly of three Nd-Fe-B ring magnets sandwiched between five iron rings, in a manner similar to that described in Ref. 10. The magnetic field configuration was designed using the COMSOL Multiphysics computer code.[11] Both the iron rings and the magnets had external diameter of 45 mm and internal diameter of 15 mm. The overall length of the assembly was 42 mm. The magnetic field has a maximum value of 380 mT at the center of the lens. At the target position (z = 0) B = 28 mT and at the lens entrance (z = 42 mm) B = 43 mT, though at both these positions the field is in the opposite direction to the field inside the lens.

Five 10 mm diameter copper ring electrodes were positioned in the bore of the lens for electrical biasing of the lens, as shown in Fig. 1. The total length of the electrodes was 34 mm. The two outermost end electrodes (EE) were grounded in all the experiments described here. The central electrode (CE) was connected to a bias circuit and the two lateral electrodes (LEs) were connected together to another bias supply. In the bias circuit the value of the capacitor was chosen to maintain the bias voltage at a nearly constant value against the current drawn from the plasma. Normally the CE is biased at a higher value of positive voltage that the LEs in order establish a potential well on the axis. The currents drawn by the electrodes from the plasma were measured from the voltage developed across a 10 Ω load resistor. For some experiments the intermediate and central electrodes were allowed to float, and the floating voltage was measured by connecting to an oscilloscope via the high impedance coupling. A rotating copper target was ablated using a 248 nm, 20 ns excimer laser incident at 45° to the target normal and focused to a 0.02 cm^{-2} spot to give a fluence of ∼4 J cm^{-2}. The main diagnostic techniques used were Langmuir probe ion analysis and optical measurement of the spatial distribution of the deposition of the ablated material. The $2 \times 2\ \text{mm}^2$ planar Langmuir ion probe was biased at −30 V and placed on the z-axis at 10 cm from the target (i.e., at 2.4 cm from the exit of the plasma lens) and oriented to face the target.[12] Depositions on glass substrates were made near the entrance and exit apertures of the plasma lens to investigate how the plasma lens influences the amount and spatial distribution of the ablated material. The deposition profiles were obtained by measuring the film transmission at 515 nm with a calibrated flatbed scanner.

III. RESULTS AND DISCUSSION

Figure 2 shows the ion current densities at 10 cm from the target recorded on the Langmuir ion probe for free ablation, with the plasma lens in place and LE and CE floating, and with the plasma lens in place and $V_{CE} = 54$ V, $V_{LE} = 20$ V.

In the free ablation case, the maximum in the ion flux occurs at 6.4 μs, which corresponds to an ion velocity of $1.6 \times 10^6\ \text{cm s}^{-1}$ and ion energy of ∼80 eV. With the plasma lens in place the ion signal is dramatically increased. For the floating case the amplitude is increased by a factor of ∼9 the integrated signal is increased by about the same factor. Assuming the ions to be mainly singly charged, the ion fluencies are $\sim 9.8 \times 10^{11}$ ions cm^{-2} for free ablation and $\sim 9.5 \times 10^{12}\ \text{cm}^{-2}$ for the plasma lens with floating electrodes. On-axis ion signals were recorded for other potential distributions, namely $V_{CE} = 20$ V, $V_{LE} = 10$ V and $V_{CE} = 30$ V, $V_{LE} = 20$ V. However, apart from small variations in the trailing edge, the ion signal is not significantly changed. These measurements demonstrated that the ablation plume is strongly concentrated towards the axis of the plasma lens, though it seems that biasing of the electrodes up to the range indicated has little influence on the on-axis ion flux. The transverse distribution of ion flux at 10 cm from the target was measured by translating the ion probe normal to the lens axis in the y-direction. These signals were integrated to yield the transverse distribution of ion fluency. Distributions for free ablation, electrodes floating and $V_{CE} = 27$ V, $V_{LE} = 10$ V are plotted in Fig. 3. The slowly varying transverse distribution for free ablation is as expected for the usual forward-peaked plume observed for laser ablation in vacuum. With the plasma lens in place the ion fluency distribution is sharply peaked on axis. For floating electrodes the on-axis fluency is increased by ×4 over the free ablation case. Biasing the electrodes at

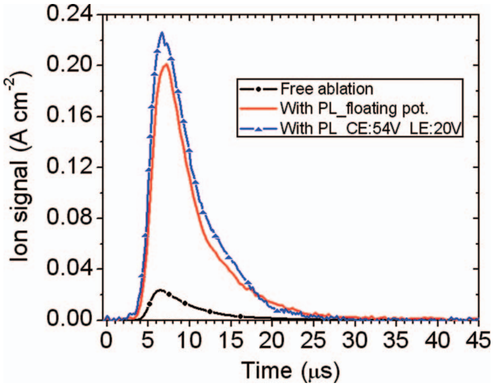

FIG. 2. (Color online) Ion current density at 10 cm from the target for (a) free ablation, (b) with the plasma lens and all electrodes floating, and (c) with the plasma lens and CE at 54 V, LE at 20 V and EE grounded.

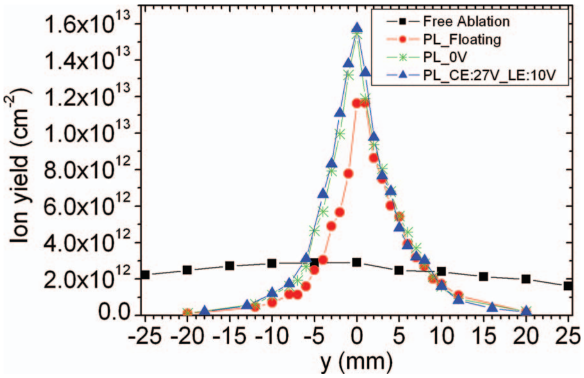

FIG. 3. (Color online) Transverse distribution of the ion fluence at z = 10 cm for free ablation and various settings of the electrode potentials.

$V_{CE} = 27$ V, $V_{LE} = 10$ V leads to ×5 increase. A similar increase and profile also observed when the electrodes were grounded.

The transverse distribution of copper deposition was measured in various locations both with and without the plasma lens. The material distribution both entering and leaving the plasma lens was analyzed by placing a glass substrate directly in front and at the exit of the plasma lens. Depositions at the plasma lens exit were done at different voltage distributions on the plasma lens electrodes. However, the analysis of the depositions confirmed that the voltage on the electrodes does not have a substantial influence on the overall plasma dynamics. Depositions were also done in the free ablation case.

Thin films were deposited at 11.5 cm from the target (3.9 cm from the exit aperture of lens) both without the plasma lens and with the plasma lens with floating electrodes. As for the ion flux the plasma lens has the effect of strongly concentrating the deposition towards the axis. The on-axis deposition rate in the center of the film is increased by a factor of ~6 compared to the free ablation case. It should also be noted that the deposition profile is highly axis-symmetric distribution, indicating that the focusing of the plasma is hydro dynamically very stable, perhaps reflecting the influence of the various circular electrodes. The floating potentials on the lens electrodes as the LPP propagates through the lens were recorded. For example a positive floating potential rising to 9.5 V appears on the CE in the interval 2–20 μs after the laser pulse, which corresponds to the transit of the LPP through the lens.

It is clear from both the ion flux and deposition measurements that the plasma lens device acts on the LPP to concentrate it on axis. It is also clear that with floating lens electrodes a potential well centered on axis established. However, at first sight it is somewhat surprising that the focusing behavior is not significantly influenced by external biasing of the electrodes. Using the formula (1) and the measured floating potential on CE, it is estimated the for a 80 eV ion the focal length is 20 mm, which is smaller than the lens length. Using the well-known formula for a magneto-static thin lens in the experimental conditions here ($B_o = 380$ mT, lens length is 4 cm, the mean ion energy is 80 eV, Cu^+) yields a focal length ~6 cm. For Cu^{++} the focal length half is this value. Thus we are not able to clearly distinguish influence of electrostatic and magnetic focusing as the LPP propagates through plasma lens. Thus, in case of experimental conditions here, the configuration crossed electric and magnetic fields, inherent in a traditional electrostatic plasma optical system, operates like magneto-electric plasma guide to limit the expansion of the ion-plasma stream and compress flux towards to axis.

IV. CONCLUSIONS

It has been shown that electromagnetic device based on the plasma optical concept with crossed electric and magnetic fields inherent to traditional electrostatic plasma lens can be used to substantially concentrate the plasma flux in LPP in a highly axi-symmetric manner. For the relatively low energy ions in the LPP it may be more appropriate to consider the lens to operate like magneto-electrostatic plasma guide which limits the expansion of the plasma flow and compresses the flux to the axis.

ACKNOWLEGMENTS

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