Z-pinch Discharge in Laser Produced Plasma

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ABSTRACT

Z-pinch effects in a laser produced aluminium plasma were investigated with a relatively low current fast coaxial electrical discharge. The ion flux in the laser produced plasma (LPP) was monitored with a Langmuir ion probe and the line density was controlled by using an aperture to select the portion of the LPP which enters the discharge cell. The Z-pinch dynamics were recorded using time-resolved imaging of the visible self-emission; the plasma was pinched to about one-third the initial radius. Both the laser and Z-pinch plasmas were diagnosed using time- and space-resolved spectroscopy; substantial heating was observed. The measured behaviour of the pinch was compared with the predictions of the slug model.

INTRODUCTION

Currently there is great interest in producing efficient, sources of extreme ultraviolet (EUV) radiation for lithography, Z-pinch plasmas have been shown to be intense emitters of EUV and x-ray radiation [1]. Z-pinch structures are created by driving a high electric current through a cylindrically symmetric plasma so that the Lorentz force compression of the plasma column produces the imploding structure.

The portion of LPP under discharge in this experiment was selected and collimated through a 3 mm circular aperture in the cathode as seen in Fig. 1 (a). The value of the measured pinch radius was found in a good agreement with the value predicted by the slug model[2]..

EXPERIMENTAL SETUP

In this work a LPP under free expansion from a rotating aluminium target, as shown in Fig. 1 (a), approached a discharge cell where it was collimated by an aperture in the cathode of the cell. A 248 nm, 20 ns excimer laser pulse was focused on the target to a 1mm diameter spot, giving a laser fluence of 4 J cm^{-2}. The cathode was 1 cm from the target and the inter electrode gap was 1 cm. Two 5 mm x 10 mm windows were cut in the discharge cell to allow viewing the plasma along the axis orthogonal to the discharge axis.

When the column of plasma contacts the anode it triggers the discharge. The coaxial discharge cell was connected to a low inductance DC circuit (L ≈ 60 nH) consisting of a 1.5 μF capacitor which was charged to a maximum of 1 kV.

The voltage drop across the capacitor was measured using a potential divider and the current flow through the anode was measured with a Rogowski coil. The discharge cell and target were placed in a vacuum chamber at 10^{-4} mbar.

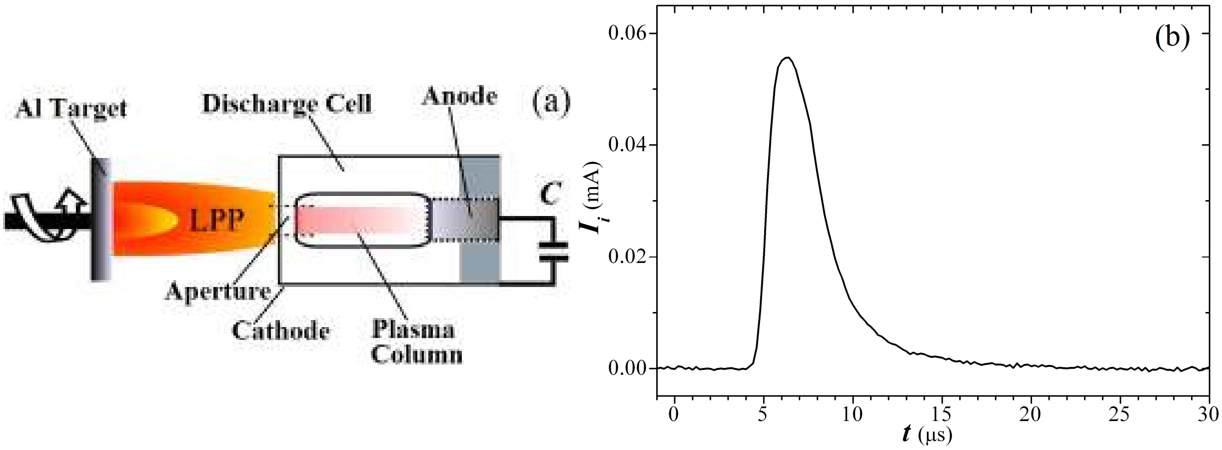

Fig. 1 (a) Schematic of LPP and cylindrical discharge cell. (b) Ion probe signal.

The dynamics and conditions of both the laser plasma and the Z-pinch were measured using a 3x6 mm^2 planar Langmuir ion probe biased at -30 V to reject electrons and placed 15.5 cm from the target perpendicular to the plasma plume. Time-resolved imaging of the visible self-emission was recorded using a fast gated ICCD camera and time- and space resolved visible spectroscopy was recorded with a 1/4 meter spectrometer equipped with a 300 lines/mm grating and ICCD camera. The spectrometer was also absolutely calibrated using a 100 W quartz halogen lamp.

RESULTS AND DISCUSSION

The ion signal in Fig. 1 (b) was first used to characterise the plasma flow in the ablation plume and determine the ion line density entering the discharge cell. Owing to the 3D self-similar and inertial expansion [3] of the plasma we can also find the time at which the plume will reach the anode to be 0.9 μs.

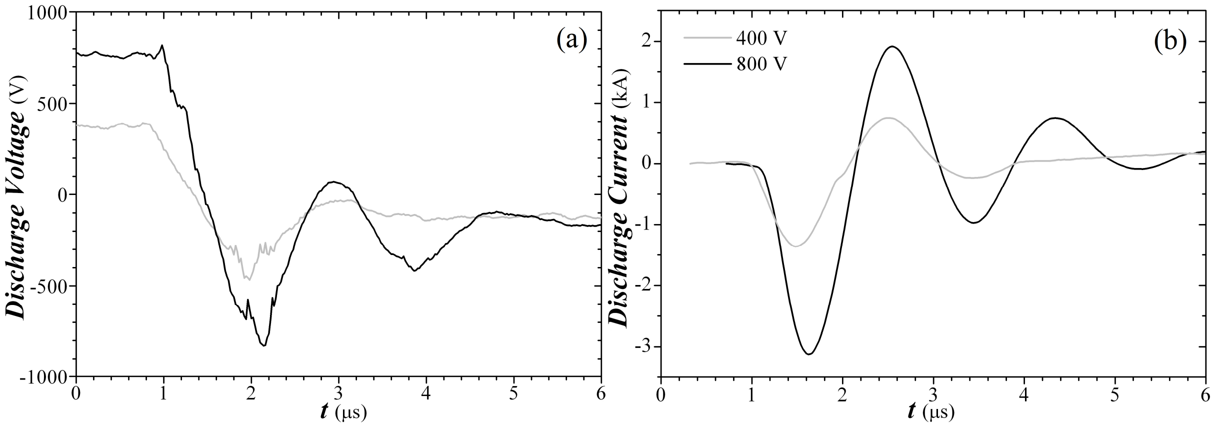

Fig.2 (a) Voltage discharge signals. (b) Current discharge signals.

The voltage and current signals recorded are shown for 400 V and 800 V discharges (Fig. 2). The current flow commences at ~0.8 μs, as expected from the ion signal. Both voltage and current signals are moderately damped oscillations with a period of 1.8 μs. Fitting the discharge characteristics with the capacitance of 1.5 μF gives values of 0.1 Ω and 60 nH for the total resistance and inductance of the setup. The current rise rate was found to be 6 x10^9 A s^{-1} for the 800V discharge.

Fig.3 (a) shows an ICCD image of the visible self-emission for a 400 V discharge at 900 ns after the laser pulse. Emission was observed from the plume immediately outside the cathode, the plasma column inside the cell and the plasma accumulating on the live electrode. Fig.3 (b) shows the column pinched along its length with a kink instability developed on it. The diameter near the cathode is ~1.4 mm, compared to the 3 mm diameter of the column in Fig. 3 (a).

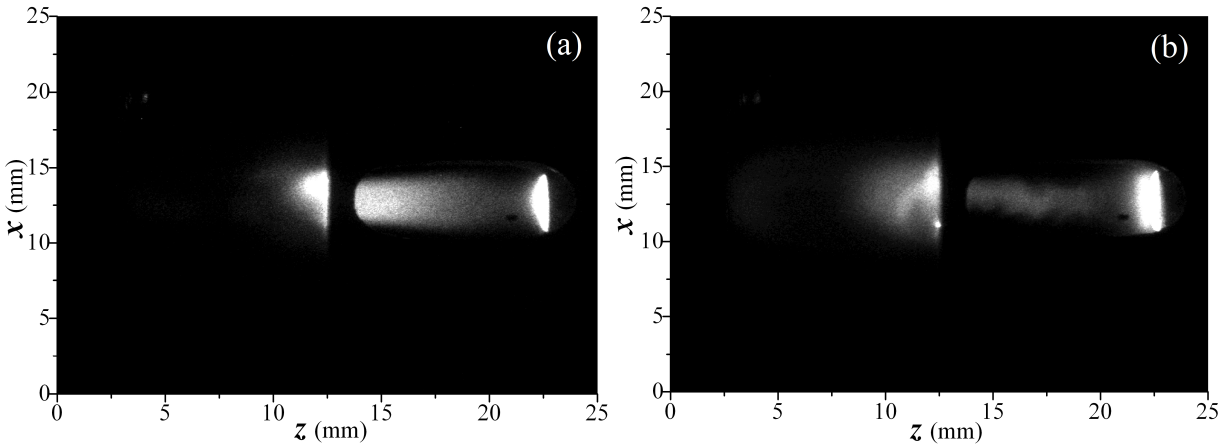

Fig. 3 (a) ICCD image of plasma at t = 900 ns. (b) ICCD image at t = 1.1 μs showing kink instability.

To diagnose the plasma conditions in the ablation and discharge plasmas we analysed the time- and space-resolved spectra. In Fig. 4 we see line outs from these spectra taken at z ≈15mm and z ≈17mm respectively inside the discharge cell for 0 V and 400 V. Only neutral aluminium lines are seen for the 0 V case where as for the 400 V case the spectrum is dominated by singly ionised aluminium lines. The electron temperature, T_e, was estimated with and without discharge using the plasma spectral synthesis code PrismSPECT [4], along with the absolute intensity measurements, the ion density and the plasma thickness. From this T_e was inferred to be 0.3 eV without discharge and 1.8 eV with a 400 V discharge.

Fitting the absolute intensity measurements with a plasma thickness of 2 mm gives an ion density of ~10^{15} cm^{-3} which is much greater than the 2 x10^{14} cm^{-3} expected from the geometrical compression. It is not clear why there is this discrepancy but it could be due to the apparent tendency of the Z-pinch to propagate backwards from the anode to cathode.

There was also strong emission observed on several singly ionised aluminium lines which suggests the pinch plasma has inhomogeneous temperature.

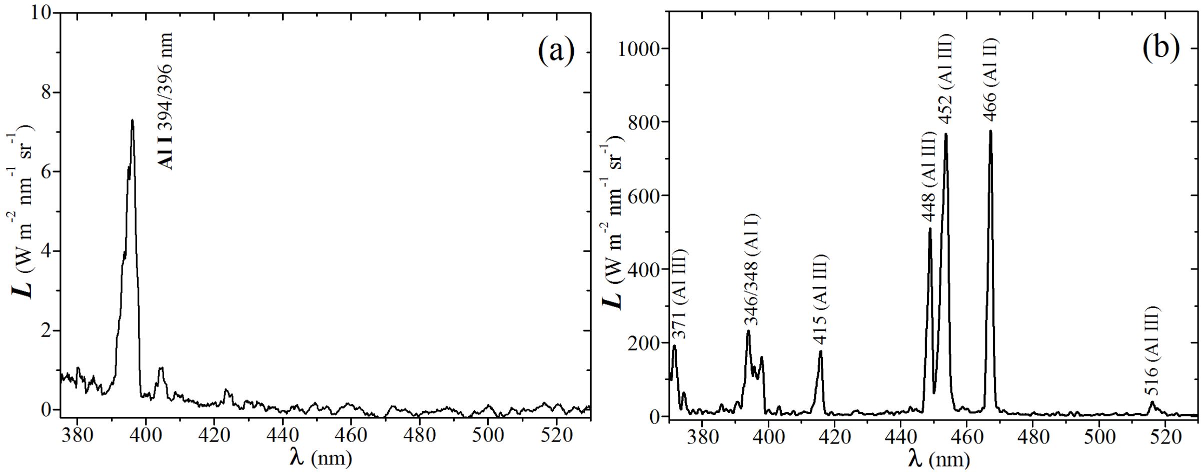

Fig. 4 (a) ICCD spectroscopic line out taken at z ≈15mm at 0 V. (b) Line out taken at z ≈17mm at 400 V.

This is consistent with the predictions of the slug model. The analysis in Ref.3 shows that efficient EUV generation at 13.5 nm will require a Z-pinch discharge which yields a pinched plasma of ~0.5 mm radius with a $T_e \approx 30$ eV and an electron density of $\sim 2 \times 10^{18}$ cm^{-3}, which corresponds to an ion line density of $\sim 1.5 \times 10^{16}$ cm^{-1}.

Clearly the peak current in the discharge must be higher to observe significant EUV emission. Accumulation of the laser ablation plasma on the anode was observed, suggesting that it may be necessary to obtain close matching of the time scales describing the ablation plume expansion and the rise time of the discharge current.

CONCLUSION

It has been observed that a 1kA discharge in a LPP produces a Z-pinch effect. The ion line density in the discharge column was controlled by using an ion probe to monitor the ion flux in the LPP and an aperture was used to select a portion of the laser ablation plume. The pinch time, pinch radius and plasma heating correlate well with the slug model of Z-pinch dynamics. The onset of the kind instability was clearly observed.

ACKNOWLEDGEMENT

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