Lateral confinement of laser ablation plasma in magnetic field

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Abstract

The propagation of a copper laser produced plasma directed along a uniform magnetic field was investigated with the aim of confining the lateral expansion of the plasma. Time-resolved optical imaging and time-of-flight Langmuir ion probe measurements were used to study the plasma dynamics. Thin films of copper were deposited without and with the magnetic field. It was observed that the magnetic field gives rise to substantial confinement of the plasma, leading to 2.6 times increase of the deposition rate on axis.

Introduction

Pulsed laser deposition (PLD) is a widely used technique for deposition of complex materials, from superconductors to nanoparticles.[1,2] It would be beneficial for PLD to reduce the lateral expansion of the ablation plume, leading to an increase of the deposition rate. There are several reports of experiments where a magnetic field has been demonstrated to strongly influence the flow of laser produced plasma.[3-8] This paper describes the results of an experiment to investigate the flow of a low temperature copper LPP along a uniform magnetic field. Time resolved imaging of the plasma self-emission clearly showed that, in comparison with the free ablation case, the magnetic field strongly limits the lateral expansion. Consequently, in presence of the magnetic field, a much higher deposition rate was measured, which is of interest in PLD.

Experimental methods

The magnetic field was produced by 2 Nd-Fe-B ring magnets attached to an iron yoke. The dimensions of each magnet were: 20 mm height, 45 mm external diameter and 15 mm diameter hole. The distance between the magnets was 35 mm. Along the z direction the field increases rapidly from a value of 11 mT at the magnet surface to 320 mT at 8 mm from the surface and remains constant at this value over a region spanning 20 mm. The copper (Cu) target was placed at 8 mm from the surface of one of the magnets, thus the plasma is produced in, and expands into, a region of uniform field.

A 248 nm, 20 ns excimer laser was used to irradiate a Cu target in a vacuum chamber at ~10^{-4} mbar. The laser spot area was 0.02 cm^2 giving a fluence ~4 J/cm^2. The target was rotated to reduce drilling. The ion flux was measured using a negatively biased (-10 V), 2×2 mm^2 planar ion probe placed on the z axis at 2 cm from the target and oriented to face the target. The evolution of the shape of the plasma plume was measured by recording time-lapse optical images of self-emission parallel to the target surface using an intensified charge coupled device (ICCD) which was triggered at various delays after the laser pulse. Depositions on glass substrates were made at 2 cm from the target to investigate how the magnetic field influences the amount and spatial distribution of ablated material.

Results and discussion

Figure 1 shows the ion current per unit area at 2 cm from the target recorded on the Langmuir ion probe without and with magnetic field. In a vacuum environment, without magnetic field, the ion flux measured can be understood in terms of the adiabatic, isentropic expansion model developed by Anisimov et al.[9,10] At the end of the laser pulse, after an initial acceleration, the semi-ellipsoidal plume expands inertially while remaining self-similar. In the inertial phase, the ion flow velocity at the probe can be approximated as the ratio of the target-probe distance and the ion time-of-flight (TOF) measured from the time of laser irradiation. In Fig. 1 the TOF at the maximum ion flux for the free ablation is 1.2 μs, which corresponds to an ion velocity of 1.7×10^6 cm s^{-1} and ion energy of 94 eV. In the presence of the axial magnetic field, the peak ion current density is ~6 times higher than the free ablation case, indicating substantial concentration of the plasma flow in the forward direction. Assuming the ions are mainly singly charged, the signals in Fig. 1 can be used to find the number of ions per cm^2 at the probe position; the values are 1.15×10^{14} without the field and 7×10^{14} with the field.

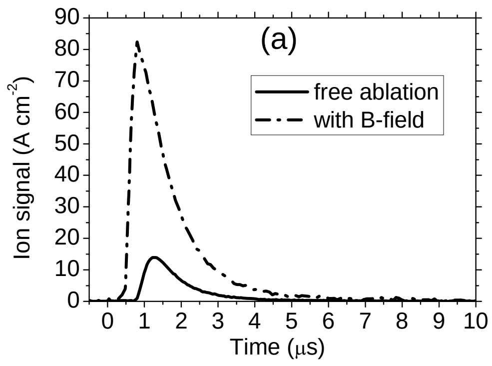

Figure 1: Ion time-of-flight signal at 2 cm from the target, with and without magnetic field.

Figure 2 shows images of the plasma self-emission 600 ns and 1 μs after the laser pulse. For free ablation the plume shows the normal, approximately semi-ellipsoidal, shape. The plume front moves out from the target at $\sim3\times10^6$ cm s^{-1}, which is in good agreement with the ion probe signal. In the presence of the magnetic field the plume is distinctly different. Up to delays of ~300 ns the two cases are quite similar, but at 300 ns the plume in the magnetic field begins to look more cylindrical. The plume size at which the magnetic field is expected to begin to

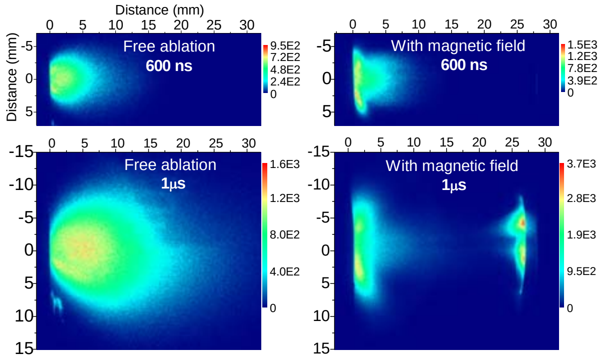

Figure 2: Time resolved images of the plasma self-emission at 600 ns and 1 μs after the laser pulse, without and with magnetic field. The gate widths of the images at 600 ns and at 1 μs were 100 ns and 1 μs, respectively.

influence the plasma flow can be estimated by equating the ram pressure, due to the plasma flow, to the magnetic pressure. The magnetic pressure is $P_B = B^2/2\mu_0 = 4\times10^4\ \mathrm{N\,m^{-2}}$. For the free plume, the ram pressure in the *z* direction at the probe position, at the time of maximum ion flux, is $P_R = n_i\, m_i\, v^2 = 1.5\times10^3\ \mathrm{N\,m^{-2}}$, where n_i is the ion density, m_i is the ion mass and *v* is the plasma velocity. For a 3-D inertial expansion, the ram pressure scales as (plume radius)$^{1/3}$. Thus, taking into account the plume shape,[9] it is estimated that the ram pressure in the transverse direction (*x* or *y*) will be equal to the magnetic pressure when the plume transverse radius is ~0.15 cm. This is close to the value of the transverse radius at 300 ns when influence of the magnetic field is first observed. From 300 ns onwards a rather flat conical flare is observed near the target surface. From 600 ns onward a cylindrical plume shape becomes more evident and the flare structure continues to develop. The emission from the region beyond 10 mm remains weak, but clearly plasma is moving through this region since its arrival at the hole in the magnet in front of the target can be observed. The light emission from the region at the surface of the magnet in front of the target first appears at ~600 ns, indicating a plasma velocity of ~ 5×10^6 cm s^{-1}, which is again consistent with the ion probe signal. In this region the magnetic field lines turn sharply from axial to a more radial direction. Thus, there is field component normal to the plasma velocity and the resulting MHD activity will decelerate the axial flow and heat the plasma. It seems that the flare emission may be due to an interaction near the target surface of the radial component of plasma velocity with the magnetic field. This interaction will induce an azimuthal current which heats the plasma in that region.

To investigate the influence of the magnetic field on the amount and distribution of ablated material flowing away from the target, thin film depositions were made on glass slides placed at 2 cm from the target. For free ablation 3000 laser shots were used, while in the magnetic field, where the deposition rate is higher, 750 shots were used. The deposition profile was found by measuring the optical transmission, around 515 nm, of the film with a calibrated flatbed scanner. The film thickness was found by comparing the measured transmission with a calculation using

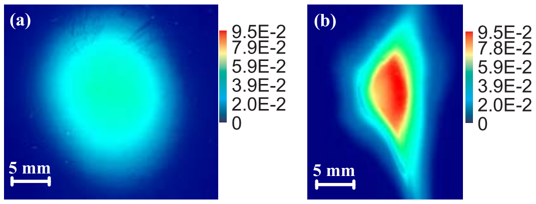

Figure 3: Images showing distribution of Cu deposition per laser pulse on glass slides at 2 cm from target; (a) without magnetic field, and (b) with magnetic field.

the XOP program[12] and assuming the bulk values for the complex refractive index of Cu. Figures 3(a) and (b) show the images of the depositions without and with magnetic field, respectively. It can be seen that in the magnetic field the deposition is restricted to a significantly smaller area and the deposition rate in the centre of deposit is increased by a factor of ~2.6. In the magnetic field the shape of the deposition is less regular and shows fluted projections along the vertical direction, which may indicate the development of a plasma instability.[13]

Conclusion

It has been shown that when a low temperature LPP is directed along moderate (0.3 T) magnetic field the lateral expansion of the plasma is severely constrained. Both the ion flux and the deposition rate in the forward direction are strongly enhanced. These features are of interest for the development of laser plasma ion sources and PLD of thin films. A novel and intriguing conical flare develops near the ablation target. It will be of interest to use MHD modelling to find a deeper understanding of this interesting feature.

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