Control of Dense Laser-Produced Plasma Flow Using a Magnetic Nozzle

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ABSTRACT

The emission of laser plasma expanding along a magnetic nozzle has investigated by high temporal resolved spectroscopy in order to consider the possibility of control by a magnetic nozzle for laser ion source plasma. Changes in temporal distribution of plasma emission spectrum were observed in the various position, strength or shape of magnetic field.

Keywords

heavy ion fusion, laser ion source, laser-ablation, high-density plasma flow, magnetic nozzle

1. Introduction

The driver accelerators for heavy ion fusion (HIF) reactors require ion sources that can provide high current, low emittance, *i.e.* high brightness ion beams. The laser ion source is considered one of the candidates because laser can produce dense plasma directly from solid and ions travel ballistically from a point source to an extraction gap, leading to high current, highly directed ion flow. On the other hand, the laser ion source has some disadvantages such as rapid reduction of ion flux during three-dimensional plasma expansion and ion flux variation during beam extraction. To resolve these problems, control of laser-produced plasma flow by magnetic fields has been recently proposed and demonstrated [1].

Plasma flow control by a magnetic nozzle has been attempted also in the studies of plasma thrusters, where a current free plasma such as helicon plasma or inductively coupled plasma passes through a divergent magnetic field [2]. In contrast, Harilal *et al.* observed that a transverse magnetic field can suppress the expansion of a laser-produced plasma [3].

When a strong divergent magnetic field is applied to a laser-produced plasma expanding from the laser target, it is also expected that the plasma is transversely suppressed and longitudinally accelerated. Because the magnetic field cannot diffuse into the plasma in the early stage of interaction, ion trajectories in the plasma core are not disturbed by Larmor motions, which maintains the highly directive ion flow of the laser-produced plasma.

The purpose of this study is to examine the feasibility of laser-produced plasma control by a magnetic nozzle. We perform temporally and spatially resolved observation of light emissions from a laser-produced plasma modulated by a magnetic field.

2. Experimental Setup

A schematic of the experimental setup is given in Fig. 1. The plasma production chamber was evacuated down to about 10^{-5} Pa by a turbo molecular pump. To produce a plasma, a KrF excimer laser (λ=248 nm, 200-300 mJ, 30 ns FWHM) was focused by a plano-convex lens through an optical window onto a plane copper target with an incident angle of 45°. The target was mounted on an automatic two-axis stage to change the laser irradiation position on the target without breaking vacuum. We changed the target position every 10-20 shots to prevent the degradation of plasma production reproducibility caused by target surface deformation.

A single turn coil was located near the laser target to apply a magnetic field. A pulse current of 550 A (peak) from a LCR circuit induced a magnetic field of 245 mT on the center axis of the coil at maximum. The coil was located 1 mm or 3 mm downstream from the target. Because of skin effect, the magnetic field cannot penetrate the Cu target in the early stage of magnetic field excitation. We calculated the shape of the field lines by COMSOL Multiphysics®. The calculated magnetic field distributions 10, 20, and 40 μs after the triggering of the circuit are shown in Fig. 2.

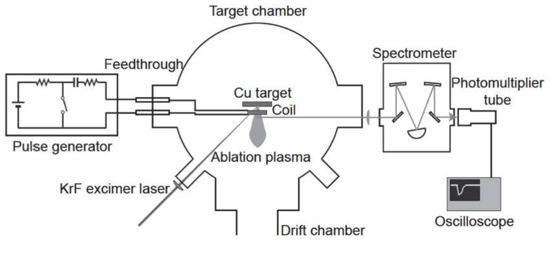
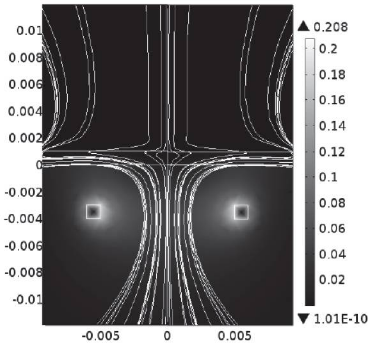
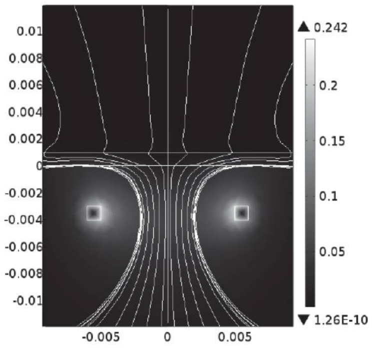


Fig. 1: A schematic of experimental setup.

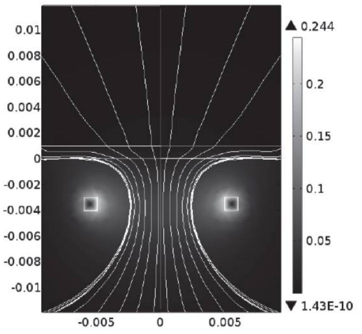
We evaluated magnetic field strength necessary to balance the magnetic pressure with the plasma pressure. Thermal pressure of laser-produced plasma was calculated as a function of the distance from the



(a) 10 μs



(b) 20 μs



(c) 40 μs

Fig. 2: Time evolution of the magnetic field induced by a single turn coil near the target.

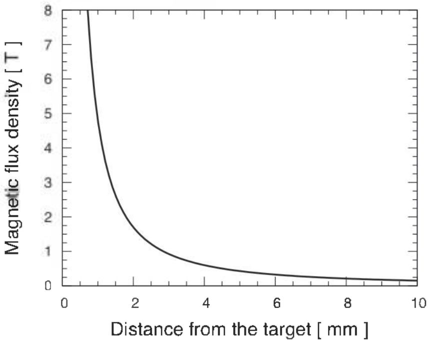


Fig. 3: Required magnetic flux density estimated from the balance between magnetic pressure and plasma pressure.

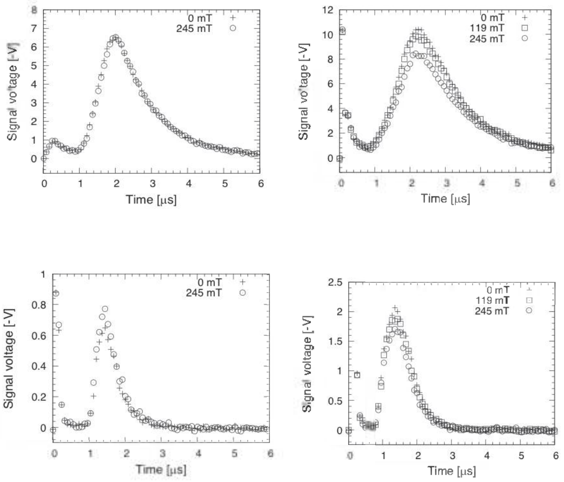


Fig. 4: Temporal change of spectral line intensities (upper row: λ=521 nm from Cu I, lower row: λ=490 nm from Cu II) observed at 20 mm downstream with two different target and coil gap lengths (left column: 1 mm, right column: 3 mm).

target along the plasma expansion axis with the following assumptions: plasma spherically and uniformly expands from the laser spot; plasma temperature is 1 eV; ten percent of laser pulse energy (250 mJ) is used for plasma production. Figure 3 plots the magnetic flux density as a function of the distance from the laser target, which is required to establish the balance between the plasma pressure and the magnetic pressure. Near the target (~1-2 cm), a magnetic flux density of hundreds of mT to a few T is required.

For spatially resolved plasma spectroscopy, light from a laser-produced plasma was focused by a plano-convex lens onto the entrance slit of a monochromator. Certain spectral lines of from atoms or ions in the plasma are observed separately by the monochromator. The temporal transition of the light intensity was recorded by an oscilloscope after the signal magnification by a photomultiplier-tube.

3. Results and Discussion

Temporal evolutions of spectral line intensities (λ=521 nm (Cu I) and λ=490 nm (Cu II)) observed in two different magnetic field configurations; the gap lengths between the target and the coil were 1 mm and 3 mm) are shown in Fig. 4. The observation point is 20 mm downstream from the target. The light intensity from Cu II was obviously enhanced by applying the magnetic field when the coil was located 1 mm from the target. In contrast, when the coil was located at 3 mm from the target, the signal was depressed. In both cases the plasma ions are modulated by the magnetic field. These results indicate that when the coil is located 1 mm from the target, the ions are transversely confined by the magnetic field, leading to the increase in the plasma density. In contrast, when the coil is located 3 mm from the target, some ions may be pushed back towards the target by the converging magnetic field in the gap between the target and the coil. Interestingly, when the coil is located 3 mm from the target, the light intensities from neutral atoms are also depressed. Since neutral atoms are not affected directly by the magnetic field, this

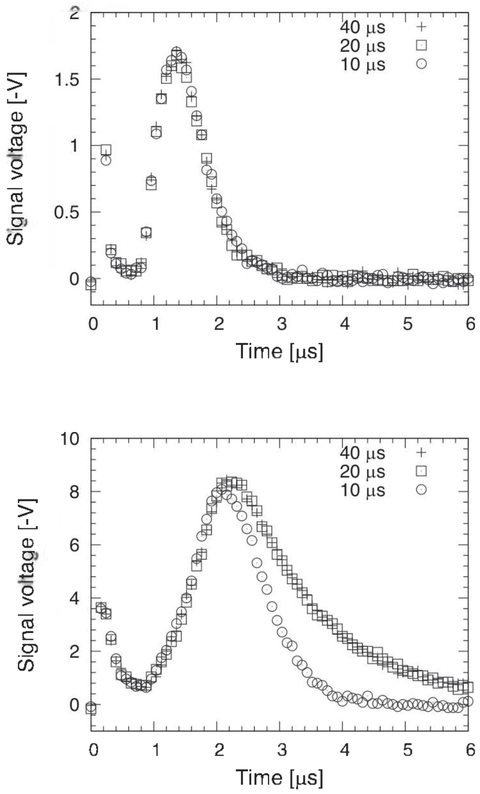


Fig. 5: Time evolutions of spectral line intensities (upper: λ=490 nm from Cu II, lower: λ=521 nm from Cu I) observed under various timing of laser irradiation.

result indicates that the flow of the neutral atoms are impeded by collisions between neutral atoms and ions.

To investigate the effect of the magnetic field shape on the behavior of the plasma, spectral line intensities were observed by changing the timing of laser irradiation with respect to the excitation current. As shown in Fig. 3, the shape of the magnetic field near the target changes depending on the delay times (10, 20, and 40 μs). On the other hand, as for emissions from Cu^+ ions (Fig. 5, upper), there is no significant difference among the waveforms with different delay times. In contrast, light intensities from the neutral copper atoms attenuates rapidly with a delay time of 10 μs (Fig. 5, lower), when the converging structure of the magnetic field near the target was more remarkable.

4. Conclusion

We investigated the behavior of a laser-produced plasma flow passing through a magnetic nozzle, which has converging and diverging field structure with a maximum magnetic flux density of 245 mT, using temporally and spatially resolved spectroscopy. When the position of the magnetic nozzle is relatively far from the target, the force pushing back the plasma seems to remarkable. By inducing the magnetic nozzle more closely to the target, the directivity of the plasma ions seems to be improved. Surprisingly the flow of the neutral atoms was found to be affected by the magnetic nozzle even though they are not directly modulated by the magnetic field, which indicates collisional interactions between the ions and the atoms in the small space between the coil and the target. In the present study, the modulations observed in the waveforms of spectral line intensities were not so large probably because the applied magnetic pressure was not enough to overcome the thermal pressure of the laser-produced plasma particularly in the initial stage. Thus, stronger magnetic field is necessary to observe more significant effect of the magnetic nozzle on dense laser-produced plasma.

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