Plasma structure and energy dependence in a magnetic thrust chamber system

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Abstract. We demonstrate a magnetic thrust chamber system, in which an expanding plasma is controlled by an external magnetic field to produce a thrust. The plasma structure and energy dependences are discussed in terms of the drive laser energy and magnetic field strength. The density distribution from two different experiments show identical structure despite the laser energy is different by two order of magnitude when the ratio of magnetic field to plasma energy is more or less same. The experimental results indicate that this ratio is one of the essential factors to extrapolate the plasma dynamics for much larger energy such as inertial confinement fusion plasmas.

1. Introduction

The interaction between high-temperature plasmas and magnetic field is observed in various physical phenomena, for example, in laboratory: magnetic confinement fusion, fusion reactor wall, and laboratory experiments to study astrophysical phenomena. Furthermore, the magnetic field can convert the plasma thermal energy to kinetic energy to generate thrust for space propulsion systems. This is one of the strong candidates as the thrust system of laser fusion rocket (LFR), in which a high-temperature fusion plasma is controlled by a magnetic field. We call this specific system for LFR as a magnetic thrust chamber[1].

Previous numerical and theoretical works have shown that it produces both large impulse and high specific impulse which are required for manned interplanetary spaceflight[2, 3]. We have recently performed experiments with laser-produced ablation plasmas to demonstrate the magnetic thrust chamber systems: the direct measurement of an impulse with a thrust stand[4], a diamagnetic cavity formation[5], and observation of plasma deceleration which result in the thrust generation[6]. Though these previous experimental researches have shown the thrust...
generation, energy dependence on the plasma structure formation and thrust generation have never been discussed. This energy dependence (energy scaling-law) is one of the important factors to design a future system LFR which utilize larger plasma kinetic energy resulting from a fusion reaction.

In this paper, we demonstrate a magnetic thrust chamber by using an electromagnet and two different laser systems. Despite the laser energies of two systems are different by two orders, the density distributions are remarkably similar when the ratio of magnetic field energy to plasma kinetic energy is similar.

2. Experiment

The experiment was performed with Extreme Ultra-Violet (EUV) database laser and Gekko-XII (GXII) laser at Institute of Laser Engineering, Osaka University. A plastic (CH) sphere target with the diameter of 500 µm was irradiated by a laser pulse (drive laser) to produce an expanding plasma as a model of an inertial confinement fusion. Figure 1 shows the schematic view of a magnetic thrust chamber consisting of an electromagnet and CH sphere target. The drive laser irradiates the left-side of the target. The plasma initially expands leftwards and it interacts with an external magnetic field. Diamagnetic current induced in the plasma \( j \) and the external magnetic field \( B \) result in a \( j \times B \) force acting on the plasma to produce a thrust on the magnet.

The experimental conditions are shown in Table 1. The laser energies are \( \sim 6 \) J in 9 ns pulse width with EUV and \( \sim 600 \) J in 1.3 ns with GXII with 500 µm focal spot diameter in FWHM. The plasmas were diagnosed with interferometry and self-emission gated optical imager (GOI) by using an intensified charge coupled device (ICCD) camera with a gate width of 10 ns. GOI measures the spatial distribution of self-emission intensity at a wavelength of 660 nm with the width of 10 nm in FWHM and interferometry gives electron density assuming that the plasma distributes axially symmetrically. In general, the emission comes from thermal bremsstrahlung and/or H-α emission at 656 nm, and strongly depends on the plasma density.

The electromagnet is a 96-turn (axially 8 turns and radially 12 turns) coil with inner and outer diameters of 26 mm and 50 mm, and with the thickness of 10 mm. The center of the coil is at \( z = -18 \) mm [\( z = -18 \) mm in Figs. 2(a) and 2(b)].

We estimate the energy conversion ratio as an absorption coefficient \( \eta_{ab} \) as a function of laser intensity \( I \) : \( \eta_{ab}/\ln(1 - \eta_{ab}) = 10^{11} \lambda \omega/cI \) [7], where \( \lambda \) is a characteristic length \( \lambda = [1/(n_e)(dn_e/dx)]^{-1} \), \( n_e \) and \( n_c \) are electron and critical densities, \( \omega \) is the frequency of the drive laser, and \( c \) is the speed of light. Both EUV and GXII experiments were performed with similar ratio of magnetic field energy \( E_B \) to plasma energy \( E_p \), where \( E_B = LI^2/2 \), \( L \) is an inductance of the coil, \( I \) is the maximum current flowing in the coil, and \( E_p = \eta_{ab}E_L \): \( E_B/E_p \sim 1.4 \) for EUV and 1.2 for GXII experiments, where \( \eta_{ab} \) is 1.0 and 0.27, respectively.
Table 1. Experimental conditions

| Parameters                                      | EUV       | GXII     |
|------------------------------------------------|-----------|----------|
| Laser Energy $E_L$ [J]                          | $\sim 6$  | $\sim 600$ |
| Pulse width (FWHM) [ns]                         | $\sim 9$  | $\sim 1.3$ |
| Wavelength [nm]                                 | 1064      | 1053     |
| Focal spot diameter (FWHM) [m]                  | 500       | 500      |
| Average laser intensity [W cm$^{-2}$]           | $4.5 \times 10^{11}$ | $2.4 \times 10^{14}$ |
| Magnetic field at the target [T]                | 0.2       | 1.1      |
| Magnetic field Energy $E_B$ [J]                  | 8.2       | 190      |

3. Results and discussions

Figures 2(a) and 2(b) show self-emission and electron density distributions obtained from EUV and GXII experiments, respectively at $t = 200$ ns. Experimental configuration is more or less axially symmetrical and we calculated the radial distributions with Abel inversion technique assuming the symmetry on $z$-axis. The drive laser irradiates the target at $z = 0$ from left-side and the plasma expands in $-z$ direction initially. The plasma stops expanding due to the interaction with the magnetic field later in time, and the plasma makes a shell-like conical structure balancing with the magnetic pressure. This conical shapes have been observed in numerical simulation by Nagamine et al. [1] with much larger energy of 4 MJ as a model of a laser fusion plasma. Here, in the EUV experiment, the magnetic skin depth is $c/\omega_{pe} \sim 5.3$ $\mu$m, which is much smaller than typical plasma size of $\sim 4$ mm. Moreover, the electron-ion collision frequency is $\nu_{ei} \sim 6.7 \times 10^{10}$ s$^{-1}$ which is similar scale to the electron gyrofrequency $\omega_{ce} \sim 3.5 \times 10^{10}$ rad/s, and the magnetic diffusion coefficient $\eta = \nu_{ei} (c/\omega_{pe})^2 \sim 1.9$ m$^2$s$^{-1}$ with typical plasma parameters in the EUV experiment: $T_e \sim 8$ eV, $n_e \sim 1 \times 10^{18}$ cm$^{-3}$, $A = 12$, $Z = 3$, and $B = 0.2$ T. The diffusion time of the magnetic field is $\tau \sim l^2/\eta \sim 8$ $\mu$s, where $l = 4$ mm is the typical plasma size. The diffusion time is much larger than plasma expansion time $\sim 200$ ns, and therefore, the magnetic cavity should be formed in the expanding plasmas as observed in the previous experiment [5].

The line-out plots are shown, for example, in Figs. 3(a) and 3(b) taken at $\theta = 60^\circ$. The origin corresponds to the initial target position ($z, r$) = (0, 0) in Fig. 2. The peak positions are at $\sim 2.3$ mm in both data.

Figure 4 shows the peak positions as a function of the angle $\theta$ derived from Figs. 2(a) (6 J)
and 2(b) (600 J). Both results show similar tendency in the range $0 < \theta < 90^\circ$, while the peak positions from 600 J case are further than those from 6 J case at $90^\circ < \theta$. In small angle $\theta < 90^\circ$, the plasma is initially produced by laser-irradiation, hence the plasma energy can be estimated by the drive laser energy and the absorption coefficient. In the range $\theta > 90^\circ$, however, the plasmas does not expand directly from the initial position but flows from the region $z < 0$ along the magnetic field lines interacting with the field. The plasma drift velocity in EUV experiment [in Fig. 2(a)] is much smaller than the other. In this case, the plasma is easily trapped by the magnetic field, resulting in smaller structure in larger angle $\theta$.

4. Summary
We have conducted two experiments to model a magnetic thrust chamber system with the drive laser energy of $\sim$6 J and $\sim$600 J with EUV and GXII laser systems. The density distributions are obtained with optical diagnostics and they show a shell-like conical structure, meaning the suppression of the plasma expansion by an external magnetic field. The structures obtained from both experiments show more or less same, under the condition of the similar ratio of the magnetic field energy to the plasma energy. This result indicates that the energy ratio is one of the essential factors in the magnetic thrust chamber system and it can help us to develop the energy scaling-law for future higher-energy experiments using fusion plasmas with such as National Ignition Facility and Laser Mega Joule. Nevertheless, there are still plenty of experimental work to be done to build an energy scaling-law in a magnetic thrust chamber: structure formation in different energy ratio, spherical irradiation, numerical analysis, and connection with thrust generation and thrust efficiency depending on the plasma and magnetic field energies.

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