Optimizing a Magnetic Field Strength of a Magnetic Thrust Chamber

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Abstract: A magnetic thrust chamber is a propulsion system which obtains a thrust by transferring the random velocity components of high-temperature plasma into the momentum with magnetic field. To investigate the influence of magnetic field on the behavior of laser-produced plasma, the spatial distribution and the self-emission of laser-produced polystyrene plasma in magnetic field of 1.0 T are investigated in an experiment. The plasma is generated by a single Nd:YAG laser-beam with the energy of 7.5±0.2 J and the pulse width of 9.4±0.1 ns. It is found that laser-produced plasma is redirected into the other side by magnetic field and the strong magnetic field of 0.8 T at the target is required in the experimental condition.

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I. Introduction

MARS exploration is expected to elucidate the formation process of the earth since Mars is the nearest terrestrial planet such as the earth. However, the round trip to Mars with existing rockets takes more than 500 days. The long mission time causes the physical and the mental damages on astronauts, for example, i) a loss of a muscle and a bone mass due to a state of zero gravity, ii) the mental damage due to living in a small room for a long time, and iii) the exposure of the cosmic ray. The problem of a muscle and a bone loss can be solved to some extent by a continuous exercise and taking a protein and vitamin D.[1] The mental damage can be also relieved to some extent by taking an exercise and a tasty meal. However, with present-day technology, the complete solution of the cosmic-ray exposure is difficult. Therefore, a rocket with high-power and low-fuel-consumption is preferable in order to shorten the mission time.

Laser fusion rocket (LFR) is expected to be used for manned interplanetary flights because of its potential to generate a large thrust with a high specific impulse. LFR is a laser propulsion which utilizes laser-driven fusion plasma and converts the fusion energy into the kinetic energy. As the design concept, a Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion (VISTA) is proposed by Lawrence Livermore National Laboratory (LLNL).[2] It is estimated that the mission time of the round trip to Mars can be reduced up to 100 days using VISTA. The LFR design for the realization of VISTA has been studied numerically to date, for example shielding from the neutron radiation.[3-6]

A magnetic thrust chamber, a propulsion system obtaining a thrust by controlling plasma with magnetic field, has been proposed to be used for the propulsion system of VISTA. It obtains a thrust by transferring the random velocity components of high-temperature plasma into the momentum with magnetic field. Since fusion plasma has high energy, the damage on the chamber wall due to the collision of plasma is concerned. A magnetic thrust chamber controls the charged particles not to collide with the chamber wall and the lifetime can be improved. We aim for the practical applications of a magnetic thrust chamber.

For the practical application, several numerical simulations have been conducted. Nagamine *et al.* simulated a plasma behavior in magnetic field using a three-dimensional (3D) hybrid code, treating ions and electrons as particles and fluid, respectively.[7] Kajimura *et al.* examined the control of a thrust vector by changing the initial target position using the above code.[8] Matsuda *et al.* examined a thrust efficiency with various shaped targets.[9] Maeno *et al.* combined a one-dimensional (1D) radiation hydrodynamic code with a 3D hybrid code.[10] The 1D radiation hydrodynamic code simulates the creation process of laser-produced plasma. In addition, they investigated the effect of the magnetic field strength on a plasma behavior.[11] The simulation codes will provide a milestone to construct an optimum electromagnetic coil in case of higher laser energy.

To validate the simulation codes, some experiments with the laser systems with the energy of ~ 10 J and 1 kJ have been conducted. Maeno *et al.* demonstrated a magnetic thrust chamber by using a permanent magnet and laser-produced plasma instead of fusion plasma and verified the thrust generation.[12] Moreover, Yasunaga *et al.* investigated the interaction between magnetic field of a permanent magnet or a coil and laser-produced plasma and observed the diamagnetic cavity.[13]

In this paper, we examine the spatial distribution of laser-produced plasma in a magnetic thrust chamber and the effect of magnetic-field strength on it. It is found that the low-energy ions, which are dominant on the laser-irradiation side in case of no magnetic field, increase in the other side by the increase of the magnetic-field strength. We report that laser-produced plasma on the laser-irradiation side is redirected into the other side by magnetic field of greater than 0.8 T in the experimental condition.

II. Mechanism of Magnetic Thrust Chamber

A magnetic thrust chamber generates a thrust by transforming the thermal random motion of plasma into a direction with magnetic field. The mechanism of the thrust generation of a magnetic thrust chamber is described in Fig.1. (a) Plasma is generated and expands in magnetic field of an electromagnetic coil. (b) Then, the charged particles undergo Larmor motion in magnetic field, resulting in a diamagnetic current formation. Consequently, diamagnetic field is formed

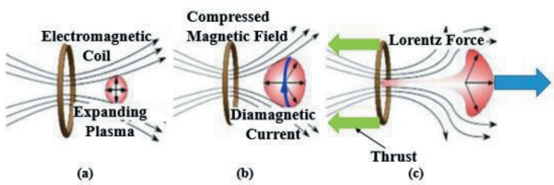

Figure 1. Mechanism of thrust generation of magnetic thrust chamber.[11]

(a) Plasma is generated and expands in magnetic field of an electromagnetic coil.
(b) The expanding plasma generates a diamagnetic current, resulting in the generation of diamagnetic field.
(c) Plasma is accelerated by Lorentz force due to the diamagnetic current and magnetic field of the coil. In contrast, the coil obtains a thrust as Lorentz force due to the coil current and diamagnetic field

to cancel out initial magnetic field. (c) Plasma obtains Lorentz force and is extruded rightward. As reaction of this, the coil obtains Lorentz force due to the coil current and diamagnetic field. Magnetic thrust chamber can control the charged particles with magnetic field without the collision with the chamber wall. Therefore, the lifetime improvement is expected.

III. Experimental Setup

The experiment was conducted at Extreme Ultra-Violet (EUV) database facility of Institute of Laser Engineering (ILE) in Osaka University. Figure 2 shows the layout of an experimental setup in a vacuum chamber. A single-beam neodymium: yttrium aluminium garnet (Nd:YAG) laser with the wavelength of 1,064 nm focuses on the polystyrene ([-CH_2-$CH(C_6H_6)$-]$_n$) spherical target pellet with the laser spot diameter of 500 µm. The diameter of the target pellet is 500 µm. It was suspended by a carbon fiber attached to a glass rod in order to reduce the effect of ablation plasma from the glass rod. An electromagnetic coil was placed 11 mm apart from the target pellet and the laser irradiates the target through the coil. The laser energy was 7.5±0.2 J and the pulse width was 9.4±0.1 ns.

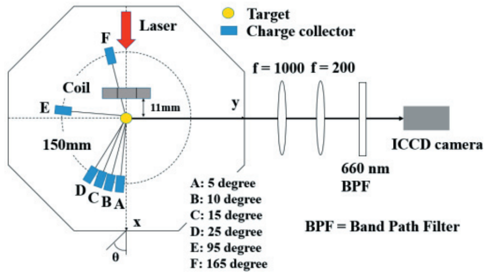

Figure 2. Layout of experimental setup in vacuum chamber. *Charge collectors are placed downward (A-D) and upward (F) to investigate the spatial distribution of ion current in the back of the target and to measure the ion going through the coil, respectively. Plasma emission with the wavelength of 660±5 nm is observed from + y-direction.*

An electromagnetic coil with the inner radius and the outer radius of 13 mm and 25 mm, respectively, was used as the source of magnetic field in this experiment as shown in Fig.3. A capacitor bank shown in Fig.4 was used to drive the coil. The graph shown in Fig.3 is the time variation of magnetic flux density of the coil when applying a voltage of 500 V on the capacitor bank. The coil can generate up to about 1.1 T at the target position (i.e. 11 mm from the coil). The magnetic-field strength is variable by changing the applied voltage on the capacitor bank.

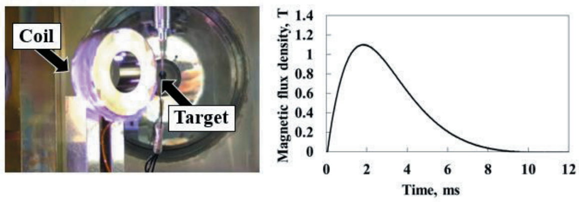

Figure 3. Time varitation of magnetic flux density at target.

The spatial distribution of laser-produced plasma in magnetic field is measured by means of charge collectors. Charge collector has been widely used because of its simple structure.[14-16] It measures the time variation of charged particles colliding with a conductor as a current. The ion velocity can be easily estimated by time-of-flight technique. This method assumes that the ions go straight ahead a charge collector after its generation. If the direction of the ion motion is changed before arriving at the charge collector, the flight distance is underestimated.

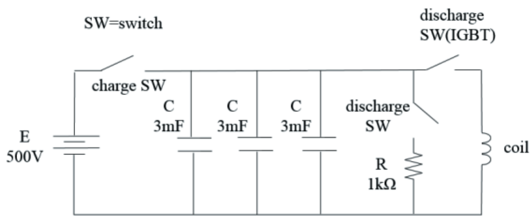

Figure 4. Schematic diagram of capacitor bank to flow current into coil.

A charge collector consists of SMA connector, Faraday cup made of cupper, and pin-hole cup as shown in Fig.5. The ions enter through the aperture with the diameter of 1 mm on the Pin-Hole cup. The ions which collide with the Faraday cup are measured as ion current. A negative biased voltage of -30 V was applied on the Faraday cup to repel electron. The ion current was converted into a voltage by a resistor. The ion signal with the frequency greater than 2 MHz was eliminated to reduce the noise in this experiment.

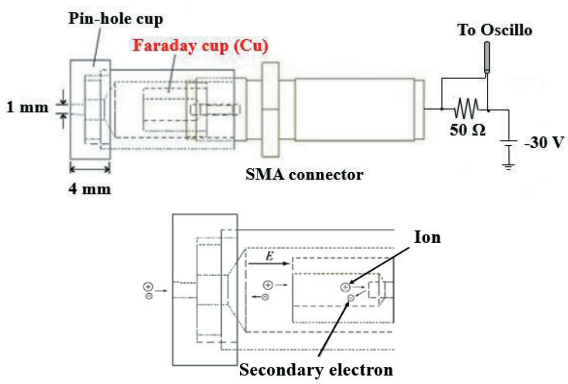

Figure 5. Layout of charge collector. *It measures the time variation of an ion current by the collision of ion with the Faraday cup made of cupper (Cu). The voltage of -30 V is applied on the Faraday cup to repel electron.*

Charge collectors are intensively placed downward (at A-D) to investigate the spatial distribution of the ion current in the back of the target as shown in Fig.2. In addition, a charge collector is placed upward (at F) to measure ions going through the coil. The angle θ is the angle from the +x-axis.

In addition, to investigate the expansion of the laser-produced plasma in magnetic field, the light emitted from plasma (plasma emission) with the wavelength of 660±5 nm is observed from the +y-direction by Intensified Charge Coupled Device (ICCD) camera as shown in Fig.2.

IV. Results

Figure 6 shows the time variation of the ion voltage, measured by the charge collector at 15 degree (see Fig.2), with and without magnetic field of 1.1 T. The little ion signal is recorded without magnetic field. On the other hand, the ion signal appears by applying magnetic field. The first and second peaks correspond to the estimated velocity of 150 km/s and 100 km/s, respectively. This result explains that the ion signal appeared by applying magnetic field shows plasma whose direction of motion is changed by magnetic field. Namely, the appearance of the ion signal in the back of the target implies that a magnetic thrust chamber works.

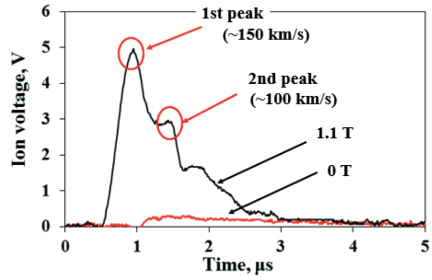

Figure 6. Time varitaion of ion voltage at 15 degree with and without magnetic field. *Almost no ion signal is recorded without magnetic field while the signal appears with magnetic field. With magnetic field, the first and second peaks appear and they correspond to the estimated velocity of 150 km/s and 100 km/s, respectively.*

The velocity component of laser-produced plasma without magnetic field is shown in Fig.7. It shows the velocity distribution of the ion current at 10, 95, and 165 degree without magnetic field. The ion velocity is estimated by time-of-flight technique. It shows that the ions with the velocity less than 100 km/s are dominant in the ion current profile at 165 degree. On the other hand, the ions with the velocity greater than 100 km/s are dominant in the ion current profile at 95 degree. The ion current at 10 degree is changed a little compared to that upward.

Then the effect of magnetic field on the spatial distribution of ions is investigated in Fig.8. It represents the spatial distribution of the time integrated ion current with magnetic field of 0 T, 0.67 T, and 1.1 T. Without magnetic field, little ion current is measured at small angle (5-25 degree) while large ion current is measured at large angle (at 165 degree). By applying magnetic field, the ion currents both at small angle, having the peak at 10 degree, and large angle increase. The ion currents at 5 and 10 degree increase by about 520% and 40% from 0.67 T to 1.1 T, respectively. This increase implies that laser-produced plasma is redirected and is extruded by magnetic field.

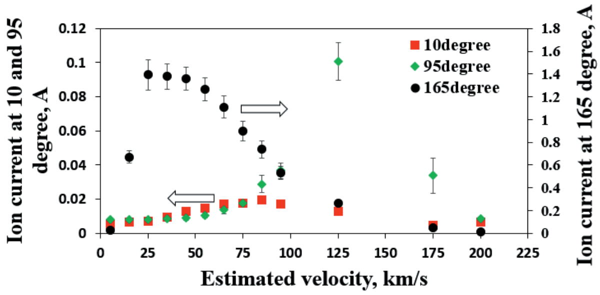

Figure 7. Velocity distribution of ion current at 10, 95, and 165 degree without magnetic field. *The ions with low velocity (< 100 km/s) is dominant at 165 degree while the ions with high velocity (> 100 km/s) is dominant at 95 degree.*

On the other hand, the ion current at 165 degree increases by about 112% and 136% from 0 T to 0.67 T and 1.1 T, respectively. The reason of the increase would be that the ions are compressed by magnetic field and go through the inner hole of the coil. While the ions go through the coil, the ions are compressed by strong magnetic field and spreads after going through the coil. As a result, the spatial distribution upward becomes narrower than that downward. Therefore, the ion current at 165 degree increases by applying magnetic field.

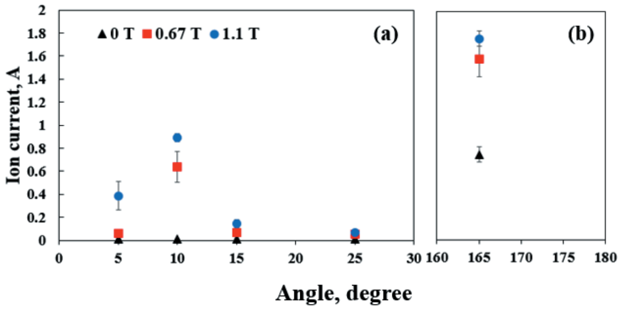

Figure 8. Spatial distribution of ion current (a) downward and (b) upward with respect to magnetic field. *Plasma expands upward without magnetic field. The ion currents both downward and upward increase by applying magnetic field.*

The change of the direction and suppression of plasma expansion by magnetic field can also be observed in the image of plasma emission. Figure

9 shows the plasma emission with magnetic field of 0 T and 0.67 T at 1.0 µs after the plasma generation. Without magnetic field, large portion of plasma expands to –x-direction and the plasma widely spreads in z-direction. In contrast, with magnetic field, the plasma expands to +x-direction and the plasma expansion in z-direction is suppressed.

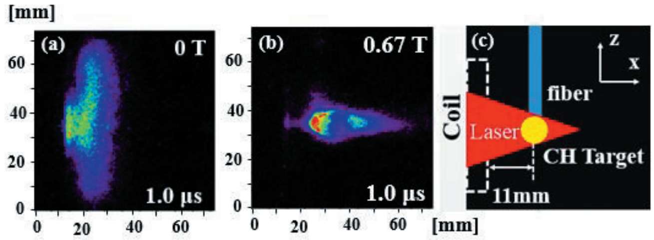

Figure 9. Plasma emission, the wavelength of 660±5 nm, with magnetic field of (a) 0 T and (b) 0.67 T at 1.0 µs after the plasma generation and (c) the setup of the target. *The plasma expansion is suppressed by magnetic field.*

According to the thrust vector, it is efficient that the divergence of plasma discharge is small, that is, it is efficient that large portion of plasma is collected at smaller angle by magnetic field in Fig.2. Therefore, the effect of magnetic field on the ion current at 5 degree is focused on. As shown in Fig.8, the ion current at 5 degree increases as magnetic field becomes stronger. Then, the velocity distribution of the ion current with respect to magnetic field is investigated in Fig.10. It shows the velocity distribution of the ion current at 5 degree with magnetic field of 0 T, 0.4 T, 0.6 T, 0.8 T, and 1.1 T. The high-velocity ions (> 100 km/s) are dominant with weak magnetic field (< 0.6 T). In contrast, the low-velocity ions (< 100 km/s) are dominant with strong magnetic field (> 0.8 T).

V. Discussion

The first remarkable point is that the ion current at small angle increases by magnetic field as shown in Fig.8. Without magnetic field, most ions are detected in the large angle (165 degree). It reflects the formation process of laser-produced plasma from laser-solid interaction.[17] When a laser irradiates a solid, the solid surface is ionized and ablated perpendicular to the surface by absorbing the incident laser energy. Then a heat wave and a shock wave due to heat conduction transmit through the solid and the other side is ionized. Therefore, high-density plasma is formed on the laser-irradiation side (upward), and low-density plasma is formed on the opposite side (downward) in the similar manner shown in Fig.8. The ion current downward increases by applying magnetic field as shown in Fig.8. The increase is due to the change of the direction of laser-produced plasma by magnetic field. The images of plasma emission shown in Fig.9 also show that the plasma downward increases by applying magnetic field. These results show that a magnetic thrust chamber works and found that the ion current downward increases.

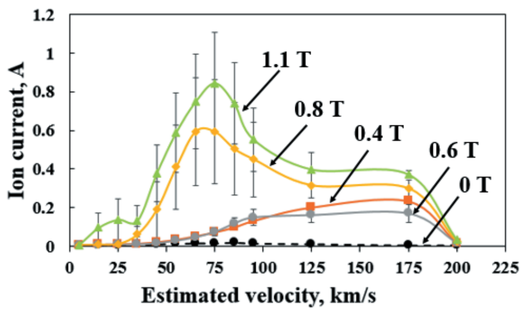

Figure 10. Velocity distribution of ion current at 5 degree with respect to magnetic field. *The lines are connected just for the ease to see. The high-velocity ions (> 100 km/s) increase with weak magnetic field (< 0.6 T). Then the low-velocity ions (< 100 km/s) increase with strong magnetic field (> 0.8 T). The increase of the low-velocity ions is because plasma generated on the laser-irradiation side is redirected into the other side since the low-velocity ions are dominant upward without magnetic field.*

The second remarkable point is the requirement of magnetic field of a magnetic thrust chamber. As mentioned earlier, it is efficient that plasma ablated upward is redirected into smaller angle by magnetic field. Investigating the velocity distribution of the ion current at 5 degree as shown in Fig.10, it shows that the ion current with the low velocity (< 100 km/s) sharply increases with magnetic field of greater than 0.8 T. The velocity distribution of laser-produced plasma without magnetic field indicates that the low-velocity ions are dominant at 165 degree as shown in Fig.7. Namely, the ion current with the low velocity measured downward with magnetic field originates from plasma ablated upward. Therefore, the direction of plasma ablated upward can be changed into small angle with magnetic field of greater than 0.8 T with this experimental condition.

VI. Conclusion

The spatial distribution and the plasma emission of laser-produced plasma with magnetic field of 1.0 T are investigated in the experiment. A single beam Nd:YAG laser with the energy of 7.5±0.2 J and the pulse width of 9.4±0.1 ns irradiates a spherical polystyrene target with the focal diameter of 500 µm. The ions are measured by means of charge collectors and the effect of the magnetic-field strength on the spatial distribution is investigated. It is found that the ion current at small angle increases by applying magnetic field and the direction of plasma ablated on the laser-irradiation side is changed in the other side with magnetic field of greater than 0.8 T in the experimental condition.

Acknowledgments

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