Experimental Demonstration of Magnetic Thrust Chamber for a Laser Fusion Rocket

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In order to validate the concept of a magnetic thrust chamber for laser fusion rockets, the interaction between laser-produced plasma and the magnetic field produced by a permanent magnet/coil is investigated. Time variation in magnetic flux density in the magnetic thrust chamber was observed by means of several loop probes. The magnetic flux density at the midpoint between the permanent magnet and the target was found to decrease, approaching zero at 50 ns after laser ignition; it then recovers to its initial value after 1 µs. This result demonstrates the concept of the magnetic thrust chamber; the diamagnetic cavity was observed. The impulse bit of the magnetic thrust chamber is estimated from the time variation of the magnetic flux density; it is 0.6 µNs at a laser energy of 0.6 J and laser pulse duration of 2 ns. The estimated impulse bit is in good agreement (order of magnitude) with that measured using a pendulum thrust stand.

Key Words: Laser Fusion Rocket, Laser Produced Plasma, Magnetic Thrust Chamber, Interaction between Magnetic Field and Plasma

Nomenclature

\begin{align*}
A & : \text{surface area of loop coil sensor} \\
B & : \text{magnetic flux density} \\
d & : \text{diameter of permanent magnet} \\
F & : \text{thrust} \\
I_{\text{bit}} & : \text{impulse bit} \\
I_c & : \text{current through electromagnetic coil} \\
k & : \text{Nagaoka coefficient} \\
l & : \text{length} \\
L & : \text{inductance of loop sensor} \\
N & : \text{number of turns of loop coil sensor} \\
N_c & : \text{number of turns of electromagnetic coil} \\
M & : \text{remanence of magnet} \\
m_c & : \text{magnetic moment of electromagnet coil} \\
m_m & : \text{magnetic moment of permanent magnet} \\
m_p & : \text{magnetic moment of plasma} \\
R & : \text{resistance of the circuit} \\
r & : \text{distance} \\
r_c & : \text{radius of electromagnetic coil} \\
r_m & : \text{distance between } m \text{ and } m_p \\
r_p & : \text{distance between plasma and loop probe} \\
V & : \text{induced voltage} \\
S & : \text{surface area of permanent magnet} \\
V_{\text{det}} & : \text{observed voltage crossing resistance} \\
t & : \text{time} \\
\theta & : \text{angle between magnetic moment and probe} \\
\tau_{\text{b}} & : \text{interaction duration period} \\
\mu_0 & : \text{permeability}
\end{align*}

1. Introduction

Rocket development began in earnest with the space race between the United States and the Soviet Union in the 1960s. At that time, large chemical rocket propulsion systems were developed for departure from the gravitational field of the Earth, and compact propulsion technologies were designed for orbital maneuvering and altitude control. In recent years, great progress has been made through the development and construction of the International Space Station and the design of the Manned Mars Explorers Program.3,4

Manned interplanetary flights will require large thrust with high specific impulse, to minimize the length of crew exposure to cosmic radiation. In conventional chemical propulsion, the exhaust velocity of high temperature gas is at most a few km/s. This means that some of the manned missions with chemical propulsion are impossible because required increment of velocity cannot be offered. Electric propulsions enable the high velocity increment due to high specific impulse. It, however, will take long time to get necessary velocity, since the only limited thrust is available through electric propulsion, however, due to the limits of space-based power generation.5 Various other types of propulsion systems, including thermonuclear rockets, nuclear pulse propulsion, and magnetic sails, among others, have been proposed and are being studied.3,5

One of the candidates for the main propulsion system of manned interplanetary flights is the Laser Fusion Rocket (LFR).
In the LFR, plasma control technology is applied using a magnetic field in the form of a magnetic thrust chamber. High density and high temperature plasma produced by inertial confinement fusion can be controlled by the magnetic field and convert a large amount of energy to large thrust with high specific impulse through the magnetic thrust chamber. The detailed description of the magnetic thrust mechanisms are described in Refs. 8 and 9.

Figure 1 shows a conceptual picture of a LFR. The geometry is a half-angle cone; this shape reduces the requirements for massive radioactive shielding and also reduces the interaction between fusion neutrons or x-rays and the vehicle. The magnetic coil is located at the bottom of the space vehicle and a fuel pellet is positioned at the apex of the cone, with several laser focusing mirrors being used to irradiate the pellet.

Our previous studies of LFR have focused on the plasma particle motion and changes in the magnetic field in the magnetic thrust chamber. These studies demonstrated that the diamagnetic cavity is formed against the applied magnetic field and impulse is produced. These earlier studies were based, however, on numerical simulation using a three dimensional hybrid code. In this study, therefore, the time variation in the magnetic flux density in the magnetic thrust chamber is measured by means of a magnetic loop coil sensor to detect the changing of the magnetic field by laser produced plasma. Since the interaction period between the plasma and the magnetic field was estimated to be 1 μs, the integrated circuit was not used in this study and the time variation of the voltage in the loop coil sensor was numerically integrated over time.

Magnetic flux density at position P (see Fig. 2) is written as,

\[ B = \frac{m}{4\pi r^3} \sqrt{1 + 3 \cos^2 \theta} \]  

Therefore, from Eq. (5), the magnetic moment of the plasma, \( m_p \), can be obtained as

\[ m_p = \frac{4\pi r^3 B}{\sqrt{1 + 3 \cos^2 \theta}} \]  

The magnetic moment of a column permanent magnet can be expressed as,

\[ m_m = MLS \]  

The neodymium permanent magnet used in this experiment is assumed to be \( 1.5 \times 10^{-5} \) Wb·m, since the remanence, the diameter, and the length of the permanent magnet are \( 1.26 \) Wb/m², 16 mm, 60 mm, respectively.

The magnetic moment of the electromagnet coil is written as,

\[ m_c = \mu_0 N_i \pi r_c^2 l_c \]  

The repulsive force between \( m_p \) and \( m \) (\( m \) is \( m_m \) or \( m_c \)) is written as Eq. (9), since we assume that diamagnetic current flows axisymmetrically in the permanent magnet or the electromagnetic coil axis and that the position of the current center remains on the target, and, therefore, the two magnetic moments face each other.

\[ F = \frac{m_p}{4\pi \mu_0 r_m^2} \frac{m}{2} \frac{2}{I_m} \]  

Impulse bit can be obtained by integrating the time variation of the thrust.

\[ I_{bit} = \int_0^{\tau_s} F dt \]
3. Experimental Setup

All of the experiments were conducted in the Institute of Laser Engineering, Osaka University, Extreme Ultra Violet (EUV) generation facility. Table 1 shows the specifications of the laser. The laser we used is 1064 nm single-beam Nd:YAG laser with a pulse width that can be changed from 2 ns to 10 ns. The spot size at the target of the incident laser can be changed by changing the position of the focal lens, which was fixed at 500 μm in this study. The laser beam is focused through a focusing lens (f = 200 mm). Plasma is generated from a target irradiated by the laser, which is a 500 μm diameter polystyrene sphere. The target is suspended at the end of a carbon fiber attached to a glass stick, in order to reduce the effect of the ablation plasma of the glass stick. In this experiment, the vacuum is kept below 5 × 10⁻³ Pa.

A magnetic field is applied using a permanent magnet and an electromagnetic coil. The permanent magnet (columnar neodymium permanent magnet, diameter: 16 mm, length: 60 mm) is set 11 mm away from the target, as shown in Fig. 3. The angle between the incident axis of the laser beam and the magnet axis is 45 degrees. The magnetic field profile along the magnet axis is shown in Fig. 4. The magnetic flux density at the target is 0.12 T. The loop coil sensors are set at 5 mm and 25 mm from the surface of the permanent magnet, as shown in Fig. 5. The magnetic flux density at the loop coil sensors at 5 mm and at 25 mm is 0.3 T and 0.027 T, respectively. The diameter of the loop is 2 mm and the number of turns is two. From the calibration, the observed voltage is 0.64 times smaller than the theoretical voltage, as shown in Eq. (1). This is due to the imperfections in the sensor loop, and this value is used as a calibration coefficient.

Figure 6 shows a schematic of the electromagnetic coil configuration. A magnetic field is generated by flowing current through the electromagnetic coil, as shown in Fig. 7. The inner diameter, the outer diameter and the width of the loop coil are 8 mm, 18 mm and 5 mm, respectively. The number of turns is 5. The laser beam passes through the coil loop and focuses on the central axis of the coil. The target is set 6.5 mm downstream from the front surface of the coil. The loop coil sensor is set perpendicular to the electromagnetic loop coil and the laser axis, as shown in Fig. 7. The distance between the loop coil sensor and the target is 20 mm. The diameter and the number of turns of the coil loop sensor are 5 mm and one turn, respectively. The applied magnetic field can be changed by changing the current through the coil. Figure 8 shows the calculated magnetic field configuration at a coil current of 5 kA.

Table 1. Specifications of laser.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nd:YAG Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length</td>
<td>1064 nm</td>
</tr>
<tr>
<td>Pulse width</td>
<td>2 - 10 ns</td>
</tr>
<tr>
<td>Energy</td>
<td>0.1 - 5 J</td>
</tr>
</tbody>
</table>
Figure 9 shows the current trace flowing through the loop electromagnet coil. The current through the coil flows in the form of a relatively square pulse of comparatively short duration (about 40 μs) using a pulse forming network (PFN). The current is monitored by measuring a potential drop of a 0.02 Ω current shunt resistor. A previous study has shown that the observed interaction period between the magnetic field and the plasma is at most 5 μs. Therefore, the magnetic field is assumed to be almost constant during the interaction between the laser produced plasma and magnetic field.

4. Results and Discussion

4.1. Impulse bit measurement using permanent magnet

Figure 10 shows the time variation of magnetic flux density at the middle point between the target and the permanent magnet. The incident laser energy is 0.62 J and the duration period is 2.7 ns. The target is irradiated with a laser at t = 0 ns. The magnetic flux density in the magnetic chamber is decreased and goes almost to zero at 50 ns after laser ignition, and then recovers to the initial value after 1 μs. This result shows that the diamagnetic current presses the applied magnetic field outward (therefore, the magnetic flux density is decreased) and the compressed magnetic field pushes back the plasma (therefore, the magnetic flux density recovers), like a spring.

Figure 11 shows the thrust history estimated from the magnetic flux density history at 25 mm from the permanent magnet. The maximum thrust is estimated to be 2.5 N at t = 50 ns, and then the thrust decreases to -0.17 N at t = 1.25 μs and eventually recovers to zero. Most of the interaction between the magnetic field and the plasma occurs within 1.8 μs, which is a short enough time that the magnetic field is assumed to be almost constant. According to Eq. (10), the estimated impulse bit at this condition is 0.44 μNs.
Figure 12 shows the relationship between incident laser energy and impulse bit for two pulse durations: 3 ns and 10 ns. The uncertainty in the impulse bits comes from the combination of the statistical variation of the measurement value, the uncertainty of the calibration coefficient of the loop sensor, and the error of the position and angle of the loop coil sensor. With an increase in pulse duration, the impulse bit is increased: 0.63 $\mu$Ns at 3 ns and 0.95 $\mu$Ns at 10 ns for a laser energy of 0.5 J. These results are in good agreement with the theoretical analysis; that is, the impulse is theoretically proportional to the third root of the pulse duration. The impulse bit increases with laser energy for both duration periods. This tendency is also in good agreement with the theoretical analysis; the impulse is theoretically proportional to the two-thirds power of the laser energy, if the pulse duration is constant.

Figure 13 shows a comparison between the estimated impulse bit deduced from the loop coil sensor results and the impulse bit measured by means of a pendulum thrust stand. The impulse bit measured by the thrust stand is about three times larger than that estimated from the loop coil sensor, but the merely approximate estimation using the loop coil sensor results is sufficient for order of magnitude estimation. The difference will be due to several assumptions: the position of the magnetic moment of diamagnetic current stays on the initial target position during the interaction, the thickness of the diamagnetic current is infinitely thin, and the form of the loop coil sensor is a true circle. The relative simplicity of this estimation as compared to that using the thrust stand data is attractive. Of course, some improvement is needed for quantitatively agreement; using several loop sensors simultaneously will reduce the uncertainty in the measurement of the position of the diamagnetic current.

### 4.2. Impulse bit measured using the electromagnetic coil

The relationship between the current through electromagnetic coil and the impulse bit was investigated. The laser energy is intended to be fixed at 3 J, but it in fact fluctuates between 3 J and 4 J due to instability in the seed laser. The pulse width is fixed as 10 ns. The loop coil sensor, however, detects the change of magnetic flux density caused by the electromagnetic coil. Therefore, this effect was eliminated by subtracting the change in the magnetic flux density due to the electromagnetic coil and by assuming the interaction duration period to be 700 ns.

Figure 14 shows the relationship between the electromagnetic coil current and the impulse bit. The impulse bit at $I_c = 4800$ A is estimated to be 9.6 $\mu$Ns. The impulse bit using the electromagnetic coil is larger than that using the permanent magnet, in part because of the distance between the two magnetic moments -- 6.5 mm for the electromagnetic coil case and 11 mm for the permanent magnet case. According to Eq. (9), the repulsive force is proportional to $r_m^{-3}$.

The impulse bit increases with an increase in the current through the electromagnetic coil, and the impulse bit is proportional to square of the current. This shows that the magnetic moment of the diamagnetic current is proportional to the strength of the magnetic field, since the magnetic moment of the electromagnetic coil is proportional to the current through the electromagnetic coil. This is natural, since the diamagnetic current counteracts the applied magnetic field. These results show that the energy of the plasma is larger than that of magnetic field produced by the electromagnetic coil current.
5. Conclusion

The interaction between the magnetic field and a laser induced plasma was observed using a loop coil sensor. The diamagnetic cavity was observed; the magnetic flux density at the middle point between the target and the permanent magnet decreased and then recovered 1 μs after laser ignition.

The loop coil sensor was shown to be a useful tool for the estimation of the impulse bit. Though the estimated impulse bit is almost one third as large as the impulse bit measured by means of a thrust stand, it agrees qualitatively with the thrust stand measurements and the theoretical analysis. That is, the impulse bit increases with an increase in the laser energy and the pulse duration period.

For more accurate measurement, some improvements will be required; the position and the magnitude of the magnetic moment of the plasma could be detected more accurately by observing optical emissions from the plasma or by using multiple sensors.

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