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Title
Measurement of plasma structure in a Magnetic Thrust Chamber

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Chapter 1: Introduction

1.1. Background research

In 1961, President John F. Kennedy announced the Apollo program, a project to land a man on the Moon and return him to the earth safely by the end of the 1960s. On Apollo 11 mission, astronauts Neil Armstrong and Buzz Aldrin landed on the Moon and walked on the lunar surface. Since the mission, five subsequent Apollo missions landed on the Moon by 1972. The Apollo program contributed the development of the technologies relating to a rocket and a manned space flight, especially electronics and telecommunications. In addition, the space exploration has been greatly developed and many discoveries have been found to date.

In 2010, a half of a century later since the announcement of President John F. Kennedy, President Barack Obama announced the manned flight to Mars by the middle of 2030s [1]. The Mars exploration is expected to provide new information to elucidate the planet formation process. One of the reason that the planet formation process has not been elucidated yet is that the initial conditions of the primitive solar nebula (mass, temperature, and elemental composition) is still unknown. However, the evidence of the primitive solar nebula has been already lost. Therefore, it is important to know the chemical composition and the isotopic composition of a terrestrial planet, such as the earth and Mars, to approximate the initial conditions. Mars is the nearest terrestrial planet from the earth so that the Mars exploration is a realistic plan and is expected to elucidate the planet formation process.

The Mars exploration is also expected to forecast what will happen on the earth in the future. Opportunity, an American unmanned Mars probe landed on Mars in 2004, found a convincing evidence that water existed on Mars in the past [2]. To exist a liquid water stably, the thicker layer of the atmosphere than that at present is necessary, so that it is thought that the thicker layer existed on primitive Mars and it was blown away. By elucidating the reason of the disappearance of the Mars atmosphere, we can forecast the possibility that the atmosphere of the earth will disappear in the future and plan the measures. The Mars exploration is expected to provide an information about the past and future earth.

In recent years, Mars is interested for not only the exploration but also the destination of the human settlement. Mars One, a Not-for-Profit Organization (NPO) in the Netherlands, proposed to send four astronauts to Mars by 2025 and to settle them there.
permanently [3]. Mars One recruited the members in 2013 and plan to start the training in 2015. Mars is getting to be a familiar with us.

However, the round trip to Mars with conventional rockets, mainly categorized into a chemical rocket (high-thrust and low specific impulse) takes more than 500 days. The long mission time causes the physical and the mental damages on the astronauts, 1) a loss of a muscle and a bone mass due to a state of zero gravity, 2) the mental damage due to living in a small room of a spaceship for a long time, and 3) 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 [4]. However, with present-day technology, the complete solution of a mental damage and the exposure of the cosmic ray is not found. Therefore, a high-speed interplanetary spaceship is preferable for a manned Mars exploration mission in order to shorten the mission time as much as possible.

1.2 Laser Propulsion

As an interplanetary spaceship, a sail propulsion [5], a nuclear electric propulsion [6], and so on have been developed. In recent years, a laser propulsion has taken an attention as the development of laser technology. Laser propulsion is a system obtaining a thrust by controlling an exhaust direction of a laser-driven plasma. It has a unique characteristic, being able to control individually the energy source and the propellant mass, resulting in the controllability of thrust parameters, such as specific impulse, in wide range [7, 8].

With a conventional chemical rocket, its momentum per propellant mass is determined constantly because the generated energy of a propellant depends on its chemical potential. Therefore, the performance of the rocket can be determined automatically by selecting the propellant.

On the other hand, with laser propulsion, the energy injected into a propellant can be determined voluntarily. That is, it can determine either utilizing a lot of a fuel or getting a lot of the exhaust velocity (i.e. energy) to obtain a momentum. For example, a high specific impulse mode can be set for an orbital transfer vehicle, requiring the saving of a propellant. And a high momentum coupling coefficient mode can be set for a ground launch vehicle, requiring a high thrust instead of a high specific impulse. For an interplanetary flight, the required thrust and specific impulse are varied depending on the orbit of the spacecraft. Therefore, laser propulsion can be designed to be optimized during transferring an orbit.
1.3. Laser Fusion Rocket and Magnetic Thrust Chamber

Laser Fusion Rocket (LFR) is one of the laser propulsion which utilizes a laser-driven fusion plasma and converts the thermal energy into the kinetic energy. According to Einstein’s mass-energy equivalence, written as \( E = mc^2 \), a fusion reaction releases the energy of 10 MeV which is a hundred thousand times larger than that released by a chemical reaction. Therefore, LFR can achieve large thrust, and reduce the mission time of the round trip to Mars up to 100 days. As a design concept, a Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion (VISTA) is proposed by Lawrence Livermore National Laboratory (LLNL) [9]. Since then, the study for the realization of LFR, such as shielding from the neutron radiation, has been conducted [10-14].

As the propulsion system of LFR, a “Magnetic Thrust Chamber” is being thought in the proposal. Magnetic thrust chamber obtains a thrust by transferring the random velocity components of the high-temperature plasma into the momentum with magnetic field. Since a fusion plasma has high energy, the damage on the chamber wall due to the collision of the plasma is concerned. However, magnetic thrust chamber can control the plasma to avoid the damage on the chamber wall. As a result, the lifetime improvement of the propulsion system can be expected. The mechanism of the thrust generation of magnetic thrust chamber is described in the next section.

Finally, the merits of LFR are summarized below.

1) Since a fusion plasma releases a high energy, LFR can generate a high thrust and voyage with high speed, resulting in the reducing the mission time of the interplanetary flight.

2) The relation between the laser energy and the propellant mass is independent with a laser-produced plasma, so that the plasma exhaust velocity and mass can be controlled in wide range. The plasma mass can be controlled by controlling a ratio of propellant mass to a total target mass. Therefore the system can be arranged depending on missions (i.e. a variability of the impulse bit).

3) The damage on the chamber wall can be reduced by controlling the direction of the fusion plasma, resulting in the lifetime improvement of the magnetic thrust chamber.
1.4. Principle of Magnetic thrust chamber

Figure 1.4 shows a mechanism of a thrust generation of a magnetic thrust chamber.

(a) An electromagnetic coil generates a magnetic field. The plasma expands in the magnetic field of the coil.
(b) Diamagnetic current cancel out the initial magnetic field of the coil. The plasma compresses the magnetic field around the plasma.
(c) The compressed magnetic field pushes back the plasma and the spaceship is accelerated by the reaction.

For a realization of LFR, demonstrating magnetic thrust chamber is essential. However, magnetic thrust chamber has never been demonstrated in the proposal of LLNL. Therefore, our group aims to demonstrate a magnetic thrust chamber and our final goal is to construct the magnetic thrust chamber obtaining a thrust with a fusion plasma.

Fig. 1.4 The mechanism of thrust generation of magnetic thrust chamber [4]. (a) Laser irradiates a target pellet to generate nuclear reaction. The fusion plasma expands in a magnetic field generated by electromagnetic coil. (b) The plasma induces a diamagnetic current to sweep aside the magnetic field and magnetic field is compressed. (c) The compressed magnetic field pushes back the plasma and the spaceship is accelerated by the reaction.
1.5. Purpose of research

Our group has utilized the simulation codes, 3-D hybrid PIC code and a 1-D radiation hydrodynamic code [15-17]. 3-D hybrid PIC code simulates the movement of a plasma in a magnetic field by treating ion and electron as a particle and a fluid, respectively. A radiation hydrodynamic code simulates the formation process of a laser-produced plasma. Miwa modified the 1-D radiation hydrodynamic code into 2-D radiation hydrodynamic code and simulated the behavior of the laser-produced plasma depending on the shape of the target pellet [18]. Tominaga used 3-D hybrid PIC code and 2-D radiation hydrodynamic code to simulate the spatial distribution of the ion current in a magnetic thrust chamber and could simulate the plasma behavior in the rear area (See Fig. 1.5) [19]. However, the thrust deduced from the numerical code is three times larger than that measured by experiment. In addition, the ion current profile at high angle of simulation codes behaves differently with that of experiment. Moreover, the ion current at low angle of simulation codes has not matched with that of the experiment quantitatively yet.

Our group has also conducted the experiments of a magnetic thrust chamber. Maeno et al confirmed that magnetic thrust chamber generated a thrust due to the interaction between the plasma and the magnetic field of a permanent magnet [20]. Yasunaga et al measured the time variation of the magnetic flux density between a magnet and a target and found the diamagnetic cavity [21]. Maeno et al investigated the dependence of the incident laser wavelength and energy on the impulse of a magnetic thrust chamber [22]. They found that the impulse with the laser frequency of \( \omega \) (the fundamental wavelength of 1,053 nm) was smaller than that of \( 2\omega \) and \( 3\omega \), which the impulses of \( 2\omega \) and \( 3\omega \) were similar. They also found that the impulse increased as the incident laser energy increased, however, the experimental values of the impulses were far from the theoretical values. Therefore, to unravel the difference, the state of the plasma and a magnetic field (e.g. density, temperature, spatial distribution of plasma, and time variation of magnetic flux density) needs to be observed. Yasunaga et al. have examined the interaction between magnetic field and laser-produced plasma, and observed the diamagnetic cavity [23]. Hinaga used Faraday type charge collectors to measure the ions and observed that the momentum of the ions was changed by a magnetic field. He also conducted the experiment using Thomson parabola and measured the carbon ion with the degree of ionization of 3, 4, and 5 [24]. However, the plasma structure in a magnetic thrust chamber has never been observed experimentally, so we examine the plasma structure in a magnetic thrust chamber by observing the light emission of a laser-produced plasma with several magnetic field strength and electron density with several magnetic field.
Chapter 2

Laser absorption rate and plasma deceleration

2.1. Laser intensity

Laser intensity, $I$, is an index representing a performance of a pulsed laser [25-32]. When a laser (with the laser pulse width of $\tau$, the laser energy of $E_L$, and the laser spot radius of $r_{\text{spot}}$) irradiates a solid as shown in Fig. 2.1, laser intensity represents the laser power per unit area, written as Eq.(2.1).

$$I = \frac{E_L}{\pi r_{\text{spot}}^2 \tau}$$  \hspace{1cm} (2.1)

After the laser irradiates a solid, the incident laser is reflected at the point of the critical density (See Section 2.1.2). This critical density, $n_c$, is written as,

$$n_c = \frac{4\pi^2 m_e}{\mu_0 e^2 \lambda^2},$$  \hspace{1cm} (2.2)

where $m_e$ is the electron mass, $\mu_0$ is a magnetic permeability at vacuum, $e$ is an elementary charge, and $\lambda$ is a laser wavelength. Then, the laser wavelength can be written as,

$$\lambda = \frac{2\pi c}{\omega},$$  \hspace{1cm} (2.3)

where $c$ is the speed of light.
2.2. Absorption Process and Absorption Rate

If the high-power laser irradiates a solid, the electron oscillates by electric field of the incident laser. The oscillation of the electron gives the ion the photon energy of the incident laser due to a collision of electron with the photon or the ion \([25-32]\). As Fig. 2.2 shows, the plasma, with the electron density decreasing in \(+x\) direction exponentially, is produced by the incident laser coming from left. This absorption process is called inverse bremsstrahlung. The absorption rate of the incident laser energy is derived here.

Fig. 2.2. The diagram of irradiating a solid with a laser: The electron density decreases exponentially as leaving from the solid. The critical point is where the electron density is equal to the critical density.

When the laser with its electric field, \(E\), irradiates a plasma, the equation of motion of the electron can be written as Eq.(2.4), including the effects of the dispersion and collision with the ion.

\[
m_e \frac{dv}{dt} = -eE - m_e \nu_{ei} v
\]  
(2.4)

where \(v\) is an electron velocity and \(\nu_{ei}\) is collisional frequency of ion and electron. Assuming that the ion is at rest, the current density, \(j\), can be written by only electron motion.

\[
j = -n_e e v = \sigma E
\]  
(2.5)

where \(\sigma\) is the electrical conductivity.

Assuming that the electric field changes as \(E = E \exp(-i \omega t + i k \cdot r)\), where \(k\) is a wavenumber vector and \(r\) is a position vector. Eq.(2.4) can be rewritten as follows.

\[
\frac{dv}{dt} + \nu_{ei} v = - \frac{eE}{m_e} \exp(-i \omega t + i k \cdot r)
\]

Solving this equation for \(v\).

\[
v = - \frac{eE}{m_e (\nu_{ei} - i \omega)}
\]  
(2.6)
Substituting Eq.(2.6) into Eq. (2.5), $j$ and $\sigma$ can be obtained as follows:

$$j = \frac{i\omega^2_{pe}e_0E}{\omega + iv_{ei}}$$  \hspace{1cm} (2.7)

$$\sigma = \frac{i\omega^2_{pe}e_0}{\omega + iv_{ei}}$$

where $\omega_{pe}$ is a plasma frequency, which can be expressed as $\omega^2_{pe} = n_e e^2 / \varepsilon_0 m_e$.

The laser intensity can be written by using a group velocity of an electromagnetic wave, $v_g$.

$$I = v_g e_0 E^2$$  \hspace{1cm} (2.8)

The energy conservation law holds between an energy provided by a laser and a joule heat consumed by a plasma. With using Eq.(2.7) and Eq.(2.8), the following equation can be derived.

$$\nabla \cdot v_g e_0 E^2 = -Re(j \cdot E^*)$$

$$= -Re\left(\frac{i\omega^2_{pe}e_0}{\omega + iv_{ei}} E \cdot E^*\right)$$

$$= -\frac{v_{ei}(\omega^2_{pe}e_0 E^2)}{\omega^2 + v^2_{ei}}$$

$$= -\alpha_c e_0 E^2,$$  \hspace{1cm} (2.9)

where $\alpha_c$ is an energy absorption rate in a plasma and * stands for complex conjugate.

Equation (2.9) implies that a plasma is not heated up if $v_{ei}=0$ (i.e. no dispersion and collision due to the ion, resulting in no joule heat). Define an absorption coefficient, $K_a$, by the following equation. The absorption coefficient is an index how much light is absorbed into a medium when light irradiates into the medium.

$$K_a = \frac{\alpha_c}{v_g}$$  \hspace{1cm} (2.11)

The following equation describes the propagation equation of the electromagnetic wave varied with $\exp(-i\omega t + i\mathbf{k} \cdot \mathbf{r})$ from Maxwell equation. Here, Fourier transform ($\partial / \partial t = -i\omega$) is used.

$$\nabla \times (\nabla \times E) - \mu_0 e_0 \omega^2 E + \mu_0 e_0 \frac{\omega^2_{pe} \omega}{\omega + iv_{ei}} E = 0$$

$$\nabla^2 E - \nabla (\nabla \cdot E) + \frac{\omega^2}{c^2} \varepsilon E = 0,$$  \hspace{1cm} (2.12)

where $\varepsilon$ is a permittivity of plasma and is expressed as,

$$\varepsilon = 1 - \frac{\omega^2_{pe}}{\omega(\omega + iv_{ei})}.$$

The dispersion relation to an electromagnetic wave can be derived from Eq.(2.12) and
can be written by the following equation. The propagation direction of the wave and the direction of the electric field are perpendicular, resulting in $\mathbf{k} \cdot \mathbf{E} = 0$. Fourier transform ($V = i\mathbf{k}$) is used.

\[
\left( \frac{ck}{\omega} \right)^2 = 1 - \left( \frac{\omega_{pe}}{\omega} \right)^2 \frac{\omega}{\omega + iv_e} \quad (2.13)
\]

By solving Eq.(2.13) for $k$, the real part $k_r$, the real wavenumber, and the imaginary part $k_i$, a spatial decrement, are obtained. In addition, the group velocity of an electromagnetic wave, $v_g$, can be obtained from $k_r$. Assuming $\omega \gg v_e$, Eq.(2.13) becomes as,

\[
k_r = \frac{\omega}{c} \sqrt{1 - \left( \frac{\omega_{pe}}{\omega} \right)^2} \quad (2.14)
\]

\[
v_g = \frac{\partial \omega}{\partial k_r} = c \sqrt{1 - \left( \frac{\omega_{pe}}{\omega} \right)^2}
\]

\[
k_i = \frac{1}{2} \frac{v_e}{c} \left( \frac{\omega_{pe}}{\omega} \right)^2 \sqrt{1 - \left( \frac{\omega_{pe}}{\omega} \right)^2} . \quad (2.15)
\]

Equation (2.14) implies that the incident laser reflects at the point of the critical density. When $\omega > \omega_{pe}$ (i.e. $k_r > 0$), the incident laser propagates in the region of a low density plasma with being absorbed as shown in Fig. 2.2. However, at the point of the critical density when $\omega = \omega_{pe}$ (i.e. $k_r = 0$), the electromagnetic wave cannot propagate forward anymore and reflects at this point.

The collisional frequency of electron and ion can be expressed as

\[
v_{ei} = \frac{Z^2 e^4 n_i \ln \Lambda}{3(2\pi k T_e)^{3/2} \varepsilon_0^2 \sqrt{m_e}} , \quad (2.16)
\]

where $Z$ is the degree of ionization, $n_i$ is the ion density, $\ln \Lambda$ is a Coulomb logarithm, and $T_e$ is the electron temperature.

Absorption coefficient has a relation of $K_a = 2k_i$. The absorption coefficient $K_a$ could be obtained by using this relation, Eq.(2.15), and Eq.(2.16).

\[
K_a = \frac{Z^2 e^4 n_i \ln \Lambda}{3(2\pi k T_e)^{3/2} \varepsilon_0^2 \sqrt{m_e}} \frac{1}{c} \frac{n_e e^2}{\varepsilon_0^2 \varepsilon_0 c \omega^2 m_e} / \sqrt{1 - \left( \frac{\omega_{pe}}{\omega} \right)^2}
\]

\[
= \frac{Z^2 e^6 n_e n_i \ln \Lambda}{3 \omega^2 c \varepsilon_0^3 (2\pi n_e k T_e)^{3/2}} [1 - (\omega_{pe}/\omega)^2]^{1/2}
\]

Then the absorption fraction, $\eta_a$, could be derived from the absorption coefficient. Assuming the plasma whose electron density on the surface of a solid is linearly varied with $n_e = n_e(1 - x/L)$ as shown in Fig. 2.3 and that the laser irradiates the plasma with the incident angle $\theta$ against the direction of the electron density gradient. The variation of the laser intensity in the x direction can be expressed by Lambert-Beer law as,

\[
\frac{dl}{dx} = -K_a l . \quad (2.17)
\]
By considering that the incident laser reflects at the point of the critical density (i.e. the path of the incident laser is $2L$), the absorption fraction can be obtained by integrating Eq. (2.17).

$$\eta_a = 1 - \exp \left(-2 \int_0^L K_a dx \right),$$  \hspace{1cm} (2.18)

where $L$ is the characteristic length of the density gradient.

![Diagram](image)

Fig. 2.3. The incident laser propagating in plasma with incident angle of $\theta$:
Assuming that the electron density decreases linearly, the incident laser is reflected at
the critical point and the most laser energy is absorbed there.

Next, the electric field of the incident laser is modified by $E = Re \left( E(x) \exp(-i\omega t + ik_y y) \right)$ [27]. The propagation equation to the electric field can be obtained by WKB (Wentzel-Kramers-Brillouin) approximation.

$$\frac{dv_{gx}}{dx} E(x) + 2v_{gx} \frac{dE(x)}{dx} + \nu_{ei} E(x) = 0$$

$$v_{gx} = \frac{k_x c^2}{\omega}$$

$$k_x = \frac{\omega}{c} \sqrt{1 - \frac{\omega_{pe}^2}{\omega^2} - \sin^2 \theta}$$

where $v_{gx}$ is a group velocity in $x$ direction, and $k_x$ is a wavenumber in $x$ direction, and $k_y$ is a wavenumber in $y$ direction. $k_x$ is expressed as $k_y = (\omega/c) \sin \theta$.

The absorption fraction can be derived in the same way with the derivation of the former absorption fraction. Then, the absorption fraction can be obtained as follows.

$$\eta_a = 1 - \exp \left\{-\frac{32\nu_{ei} L}{15c} \cos^5 \theta \right\},$$

where $\nu_{ei}$ is a collisional frequency of electron and ion at the critical point.

When the incident laser irradiates in perpendicular to the surface of the solid (i.e. $\theta=0$), the absorption fraction can be simplified as
\[ \eta_a = 1 - \exp\left\{ -\frac{32 \nu_{ei} L}{15 c} \right\}. \]

The absorption fraction can be represented as a function of laser intensity in W/cm\(^2\) as follows [27].

\[ \eta_a \ln(1 - \eta_a)^{-1} = 10^{11} \frac{L \omega}{c I} \quad (2.19) \]

Assuming \( L = 50 \) μm, the absorption fraction as a function of the incident laser intensity is obtained by Eq.(2.19), as shown in Fig. 2.4.

![Graph](image)

**Fig. 2.4.** The absorption fraction with respect to incident laser intensity.

### 2.3. Plasma deceleration

Parameter \( \kappa \) shows plasma deceleration in a magnetic field. Nikitin et al. have discussed the dynamics of the 3D expansion of a spherical cloud of rarefied plasma into a vacuum in the presence of a non-uniform external magnetic field of dipole structure, in the framework of ideal MHD approximation, and described how to determine the configuration and location of the plasma front which are caused by the retardation effect [34]. In addition, they defined an energetic criterion \( \kappa \) that characterizes the interaction between the expanding plasma and the dipole field, which is the same as adopted here and \( \kappa \) is given as

\[ \kappa = \frac{E_p}{E_M} = \frac{12 \pi E_0 R_0^3}{\mu_0 |\mu_d|^2}, \]

where \( E_p \) is the kinetic energy of ions, \( E_M \) is the field energy integral of the dipole beyond the spherical radius \( R_0 (E_M = (\mu_0/4\pi)|\mu_d|^2/(3 R_0^3)) \), \( R_0 \) the distance from
the magnetic coil to the explosion location, $\mu_0$ is the vacuum magnetic permeability, and $|\mu_d|$ the magnetic moment magnitude. The critical value $\kappa_c$ was found by Nikitin et al. for different plasma locations. When $\kappa$ is lower than $\kappa_c$, substantial plasma deceleration will occur in all directions from the explosion location. (When the plasma is located at the axis, the critical value is $\kappa_c = 0.4$) [34]
Chapter 3
Measurement of plasma self-emission

3.1. Laser facility

This experiment was conducted at the Extreme Ultra-Violet (EUV) database facility of the Institute of Laser Engineering (ILE) at Osaka University. Fig. 3.1 shows a vacuum chamber. A single beam irradiates a target to produce a plasma.

![Fig. 3.1 The vacuum chamber of EUV facility](image)

3.2. Source of magnetic field

Magnetic field was generated by flowing current into an electromagnetic coil with 96-turn cupper wire with the inner radius of 13 mm, outer radius of 25 mm and the thickness of 10 mm. The current was generated by a capacitor bank, in which three 32 mF capacitors were connected in parallel as shown in Fig. 3.2. The magnetic field of 1.1 T was generated at the initial target position by applying 500 V on the capacitor bank and flowing current of about 1100 A. The current was measured with a current probe. To calculate the magnetic field strength, a magnetic field was measured by using a Gauss meter before the experiment and a current was also recorded simultaneously. Therefore, the relation between a current and a magnetic field can be obtained. Then, by recording the current flowing in the coil during the experiment, the
magnetic field can be calculated by using the relation.

Figure 3.3(a) shows the coil we used and Fig. 3.3(b) is the field strength at a target position as a function of time. The field lasts about 10 ms. In the experiment, the laser irradiates the target at the peak of the magnetic field strength. The time-scale of the experiment is in micro-second which is much smaller than the time duration of the magnetic field. Therefore, the field strength can be considered as constant during the plasma expansion.

Figure 3.4 shows the initial magnetic field configuration generated by the electromagnetic coil. Initial target position corresponds to the coordinate \((x, y) = (0, 0)\).

![Fig. 3.2 Capacitor bank for generating current](image)

![Fig. 3.3 The electromagnetic coil and the time variation of magnetic field: The size of the coil used in this experiment is inner radius of 13mm, outer radius of 25 mm, and thickness of 10 mm.](image)
3.3. Experimental setup and conditions

The experimental setup is shown in Fig. 3.5. A plasma was created by focusing a 1064 nm Neodymium: Yttrium Aluminum Garnet (Nd:YAG) laser onto a polystyrene ([-CH2-CH(C6H6)-]n spherical target with a diameter of 500 µm (Fig. 3.6). The pulse width of the laser is 9.5±0.5 ns and the laser energy is 6.0±0.8 J as shown in Table. 3.1. The target is suspended by a carbon fiber attached to a glass rod to reduce the plasma formation of the glass rod. The distance between the coil surface and the target is 11 mm.

The emission from the plasma was collected with a lens (focal length of 200 mm) and imaged onto intensified charge coupled devices (ICCDs) at a wavelength of 660 nm with a band-path filter with the width of 10 nm (FWHM). Two ICCDs were used to take images of different delay times in a single laser-shot. The self-emission is composed of H-α and thermal bremsstrahlung emissions.

The relation between the magnetic field strength and parameter κ are as shown in Table. 3.2. Plasma deceleration was assumed to occur in the magnetic field of over 0.46 T.
Fig. 3.5 Experimental setup

Fig. 3.6 Polystyrene target pellet with the diameter of 500 μm.

Table 3.1 Condition of Nd: YAG Laser

| Condition          | Value       |
|--------------------|-------------|
| Number of incident laser | 1 beam/shot |
| Wavelength         | 1064 nm     |
| Pulse width        | 9.5 ± 0.5 ns|
| Laser energy       | 6.0 ± 0.8 J |

Table 3.2 Parameter $\kappa$ with several magnetic field strength

| The magnetic field strength [T] | $\kappa$ |
|---------------------------------|----------|
| 0.23                            | 0.67     |
| 0.46                            | 0.17     |
| 0.67                            | 0.077    |
| 0.89                            | 0.044    |
| 1.1                             | 0.029    |
3.4. Results

Figures 3.7-3.12 show the light emission from the plasma at 0.1 µs, 0.2 µs, 0.3 µs, 0.5 µs, 1.0 µs, 1.5 µs after plasma generation with the magnetic field of 0, 0.23, 0.46, 0.67, 0.89, and 1.1 T, respectively. In these figures, the target is set at the coordinate (x,y) = (0,0) and is irradiated with the laser from left side through the hole of the coil. The center axis of the magnetic field corresponds to the x-axis at y = 0.

Without the magnetic field, the plasma expands to -x direction and ±y directions. With the magnetic field, the plasma expansion to -x and ±y direction is suppressed. Comparing the plasma emission in +y direction with that in –y direction, the plasma intensities in +y direction is higher than that in –y direction. Since the high-energy plasma hit the carbon fiber attached to a glass rod, the fiber is ablated and the ablation plasma emits light.

![Figures 3.7-3.12 showing the light emission from the plasma with and without the magnetic field at different times.](image)

Fig. 3.7 The light emission from the plasma without and with the magnetic field of 0.23 T, 0.46 T, 0.67 T, 0.89 T, and 1.1 T at 0.1 µs after laser irradiation.
Fig. 3.8 The light emission from the plasma without and with the magnetic field of 0.23 T, 0.46 T, 0.67 T, 0.89 T, and 1.1 T at 0.2 μs after laser irradiation.

Fig. 3.9 The light emission from the plasma without and with the magnetic field of 0.23 T, 0.46 T, 0.67 T, 0.89 T, and 1.1 T at 0.3 μs after laser irradiation.
Fig. 3.10 The light emission from the plasma without and with the magnetic field of 0.23 T, 0.46 T, 0.67 T, 0.89 T, and 1.1 T at 0.5 μs after laser irradiation.

Fig. 3.11 The light emission from the plasma without and with the magnetic field of 0.23 T, 0.46 T, 0.67 T, 0.89 T, and 1.1 T at 1.0 μs after laser irradiation.
Fig. 3.12 The light emission from the plasma without and with the magnetic field of 0.23 T, 0.46 T, 0.67 T, 0.89 T, and 1.1 T at 1.5 μs after laser irradiation.
3.5. The image of line plots along x and y direction

Left figures in Figs. 3.13 (a)-(f) show the light intensities from the plasma averaged from \( y = -4 \) to \( 4 \) mm along the x direction as shown in Fig. 3.7-Fig. 3.12 with six different magnetic field strength. Black line shows the plasma intensity without the magnetic field. The red, green, blue, light blue, and pink lines show the plasma intensity with the magnetic field strength of 0.23 T, 0.46 T, 0.67 T, 0.89 T, 1.1 T, respectively. The small peak of intensity without and with the magnetic field of 0.23 T observed at \( x = -11 \) mm because the high speed plasma reaches the surface of the coil at 0.2 \( \mu s \). The intensity with the magnetic field of 0.23 T is not as high as that without magnetic field, meaning the plasma is decelerated. Plasma expands to \( -x \) direction as time passes, but the shift of intensity is small and not so different among the magnetic field strength over 0.67 T. This shows the energy of magnetic field is much larger than the kinetic energy of plasma. More plasma expands to \( +x \) direction, as magnetic field strength is larger from 0.5 \( \mu s \). Second peak is also observed in \( +x \) direction from 1.0 \( \mu s \). This means that the plasma increases in the direction which contributes to obtaining the thrust.

Right figures in Figs. 3.14 (a)-(f) show the light intensities from the plasma averaged from \( x = -5 \) to 0 mm along the y direction as shown in Fig. 3.7-Fig. 3.12 with six different magnetic field strength. The width of plasma expansion to \( \pm y \) direction with magnetic field is smaller than that without magnetic field. The intensity at \( x = 0 \) is higher as magnetic field strength is larger. This shows the plasma is suppressed by the magnetic field in y direction and does not expand across the magnetic field.
Fig. 3.13  The light intensities from the plasma along x direction at (a) 0.1 μs, (b) 0.2 μs, (c) 0.3 μs, (d) 0.5 μs, (e) 1.0 μs, (f) 1.5 μs after laser irradiation.
Fig. 3.14  The light intensities from the plasma along y direction at (a) 0.1 μs, (b) 0.2 μs, (c) 0.3 μs, (d) 0.5 μs, (e) 1.0 μs, (f) 1.5 μs after laser irradiation.
Chapter 4
Measurement of Electron density

4.1. Laser facility

The measurement of electron density was conducted at laser facility in Osaka University, called “Gekko XII facility”. Figure 4.1 shows a vacuum chamber. GXII facility is one of the biggest laser facility in the world. Plasma is generated by the spherical symmetric irradiation of lasers to target. (They have twelve beams and one or six beams irradiate target in this experiment).

![The vacuum chamber of GXII facility](image)

**Fig. 4.1** The vacuum chamber of GXII facility

4.2. Experimental setup

Electron density was measured by using Mach-Zehnder interferometer. Experimental setup is shown in Fig. 4.2. Mach-Zehnder interferometer is a device used to determine the relative phase shift variations between two collimated beams derived by splitting light from a single source. A light beam from a probe laser (Verdi V5, DPSS laser, wavelength: 532 nm) is split by first beamsplitter. One of them passes through the plasma and the other passes through the vacuum. And then two beams are recombined by second beamsplitter. These two beams interfere with each other and make fringes. These fringes are measured by two ICCDs. We also use
Digital Delay and Pulse Generator (DG535) to adjust the laser timing and shutter timing of two ICCDs. Laser energy is 2 W in this experiment, so we could get enough light intensity to measure fringe shift by the light refraction through the plasma.

Fig. 4.2  Experimental setup (Mach-Zehnder interferometer)

4.3. Experimental conditions

In this experiment, electron density with several laser energy was measured without and with the magnetic field strength of 1.1 T on the target position. Glass laser was used to generate plasma and laser condition is as shown in Table 4.1. Number of incident laser is 1 beam or 6 beams. The wavelength of laser is 1053 nm. Pulse width is 1.3 ns. Laser energy is 10, 50, 100, 600 J/beam. Target is polystyrene spherical target with the diameter of 500 μm and the thickness of 7μm as shown in Fig. 4.3. The ratio of plasma energy to magnetic energy, κ is calculated and shown in table. 4.2. κ is obtained by using the equation as shown the chapter of 4.2. Laser energy is converted to the kinetic energy of plasma as shown in Table. 4.3.

| Table 4.1  The condition of Glass laser |
|----------------------------------------|
| Number of incident laser | 1 beam or 6 beam |
| Wavelength | 1053 nm |
| Pulse width | 1.3 ns |
| Laser energy | 10, 50, 100, 600 J/beam |
Fig. 4.3  Target composed of polystyrene

| Laser energy and number of laser | Parameter $\kappa$ |
|---------------------------------|---------------------|
| $10 \text{ J} \times 6$         | 0.29                |
| $50 \text{ J} \times 6$         | 1.11                |
| $100 \text{ J} \times 6$        | 1.75                |
| $600 \text{ J} \times 6$        | 4.73                |
| $600 \text{ J} \times 1$        | 0.79                |

Table 4.3 Conversion of laser energy to kinetic energy of plasma

| Laser energy and number of laser | Laser intensity [W/cm²/beam] | Conversion efficiency of laser energy to kinetic energy of plasma [%] | Total kinetic energy of plasma [J] |
|---------------------------------|------------------------------|---------------------------------------------------------------------|------------------------------------|
| $10 \text{ J} \times 6$         | $3.9 \times 10^{12}$         | 100                                                                 | 60                                 |
| $50 \text{ J} \times 6$         | $2.0 \times 10^{13}$         | 76                                                                  | 228                                |
| $100 \text{ J} \times 6$        | $3.9 \times 10^{12}$         | 100                                                                 | 360                                |
| $600 \text{ J} \times 1$        | $2.4 \times 10^{15}$         | 27                                                                  | 162                                |
| $600 \text{ J} \times 6$        | $2.4 \times 10^{15}$         | 27                                                                  | 972                                |

4.4. Mach-Zehnder interferometry

Assuming target is ionized perfectly, refractive index is represented as follows.

$$N = \left[ 1 - \frac{\omega_{pc}^2(r)}{\omega^2} \right]^2 = \left[ 1 - \frac{n_e(r)}{n_c} \right]^2$$  \hspace{1cm} (4.4.1)

Probe laser irradiates plasma in parallel to x-axis apart y from x-axis as shown in Fig. 4.4. $n_e$ is number density of electron. $n_c = \varepsilon_0 m_e \omega^2 / e^2$ is cut-off density against electromagnetic wave angular frequency is $\omega$. In this condition, $n_c = 1.1 \times 10^{15} \lambda^{-2} \text{ [m}^{-3}]$. $\lambda$ [m] is the wavelength of probe laser in vacuum.

If spatial variation of refractive index of plasma is slow against incident wavelength, Phase difference $\phi(y)$ is represented as follows by using
WKB(Wentzel-Kramers-Brillouin) approximation.

\[ \phi(y) = \int_{z_1}^{z} (k_0 - k_p) dx = \frac{2\pi}{\lambda} \int_{z_1}^{z} (1 - N) dz \] (4.4.2)

\[ k_p = \frac{2\pi}{\lambda} \] and \( k_0 \) is wave number in plasma and vacuum. \( N \) is refractive index of plasma. \( \phi(y) \) is obtained as follows in the case of \( n_e \ll n_c \).

\[ \phi(y) = \frac{\pi}{\lambda n_e} \int_{z_1}^{z} n_e(r) dz \approx \frac{2\pi}{\lambda n_e} \int_{y}^{a} n_e(r) (r^2 - y^2)^{\frac{1}{2}} r dr \] (4.4.3)

\( n_e \) is obtained from \( \phi(y) \) by using abel inversion assuming plasma is cylindrical symmetric against the x-axis.

\[ n_e \approx -\frac{\lambda n_e}{\pi^2} \int_{r}^{a} \frac{d\phi(y)}{dy} (y^2 - r^2)^{\frac{1}{2}} dy \] (4.4.4)

![Probe Laser](image)

**Fig. 4.4** Optical path of probe laser in plasma

### 4.5. Analysis method of Mach-Zehnder interferometry

**Fig. 4.5(a) and (b) are the fringe images detected by the ICCDs.** Figure 4.5(a) is the image of reference shot which shows the distribution of fringes before plasma generation. Fig. 4.5(b) is the image of main shot which shows the distribution of fringes at 200 ns after laser irradiation. Fringe shifts were measured in Fig. 4.5(b) because refractive index of air and plasma is different. Phase difference is calculated from these fringe shift. Phase difference between light fringes is \( 2\pi \).
Fig. 4.5  The images of fringes measured by Mach-Zehnder (a) The distribution of fringes before laser irradiation in Reference shot (b) The distribution of fringes at t = 200 ns after laser irradiation in main shot

“Neutrino” is used for the calculation of the phase shift from the distribution of fringes. At first, the number of fringes is calculated by wavelet transformation. At second, the phase map is obtained by unwrapping the phase data. These work are done in reference data and main data. At third, the phase difference is calculated by subtracting the reference data from main data as Fig. 4.6(a). Finally, electron density is calculated as shown Fig. 4.6(b) by using abel inversion assuming plasma is cylindrical symmetry with z-axis.

Fig. 4.6  (a) The distribution of phase difference at t = 200ns after laser irradiation (b) The distribution of electron density at t = 200ns after laser irradiation
4.6. Electron density

4.6.1. Time development of electron density with several laser conditions

Figure 4.7 and 4.8 show time development of electron density with six laser irradiation of 10 J/beam with the magnetic field strength of 1.1 T and without the magnetic field, respectively. Electron density is measured in this experiment, but plasma behavior including ion can be measured because electron follows ion. In Fig. 4.7, plasma is stopped by the magnetic field and formed the structure like a shell at t = 200 ns and 300 ns. Electron density is about 5.0×10^{17} \text{ cm}^{-3} there. The electron density decreases and that structure almost vanishes at 400 ns. In Fig. 4.8, shell structure like a shell by electron is not observed. Electron already expands outside of the field of view. Black region is a region where neutral atoms exist because neutral particle show phase difference opposite to electron deducted by electrons. Similar structure of black region was found with and without magnetic field, that is, neutral particle doesn’t interact with magnetic field, of course.

![Fig. 4.7](image_url)  
Fig. 4.7 Time development of electron density with six laser irradiation of 10 J/beam with the magnetic field of 1.1 T at (a) 50 ns, (b) 100 ns, (c) 200 ns, (d) 400 ns after laser irradiation.
Fig. 4.8 Time development of electron density with six laser irradiation of 10 J/beam without magnetic field at (a)50 ns, (b)100 ns, (c)200 ns, (d) 400 ns after laser irradiation to CD target shell of without and with the magnetic field strength of 1.1 T as shown in Fig. 4.9 and Fig. 4.10. CD shell target composed of carbon and deuterium with the diameter of 500 μm and the thickness of 7μm was used in this shot because of the shortage of polystyrene shell target. Electron is stopped by the magnetic field and formed the structure like a shell at t = 200 ns and 300 ns. Electron density is about 5.0×10^{17} cm^{-3} there. The electron density decreases and that structure almost vanishes at 400 ns. Then, electron expands to +x direction which contributes to obtain thrust. In Fig. 4.10, structure like a shell by electron is not observed. Electron already expands outside of the field of view.
Fig. 4.9  Time development of electron density with six laser irradiation to CD target of 100 J/beam with the magnetic field strength of 1.1 T

Fig. 4.10  Time development of electron density with six laser irradiation to CD target of 100 J/beam without the magnetic field
4.6.2. Electron density with several laser energy

The distribution of electron density with several laser energy, 10 J×6, 50 J×6, 100 J×6 with the magnetic field strength of 1.1 T at 50 ns and 200 ns is shown in Fig. 4.11. The distribution of electron density with several laser energy, 10 J×6, 50 J×6, 100 J×6 without the magnetic field at 50 ns and 200 ns are shown in Fig. 4.12. With the magnetic field strength of 1.1 T, plasma expands wider as laser energy is higher at 50 ns after laser irradiation. Then, plasma forms shell structure at 200 ns. The shell structure extends more to +y direction as laser energy is higher. Without magnetic field, plasma is generated and expands at 50 ns, but plasma expands outside of the field of view at 200 ns as shown in Fig. 4.12.

- At 50 ns after laser irradiation
  - (a) 10J×6
  - (b) 50J×6
  - (c) 100J×6

- At 200 ns after laser irradiation
  - (d) 10J×6
  - (e) 50J×6
  - (f) 100J×6

Fig. 4.11  The distribution of electron density with several laser energy with the magnetic field strength of 1.1 T at 50 ns and 200 ns (a) 50 ns and 10 J×6, (b) 50 ns and 50 J×6, (c) 50 ns and 100 J×6, (d) 200 ns and 10 J×6, (e) 200 ns and 50 J×6, (f) 200 ns and 100 J×6
Fig. 4.12  The distribution of electron density with several laser energy without the magnetic field at 50 ns and 200 ns (a) 50 ns and 50 J\times 6, (b) 50 ns and 100 J\times 6, (c) 50 ns and 100 J\times 6, (d) 200 ns and 10 J\times 6, (e) 200 ns and 50 J\times 6, (f) 200 ns and 100 J\times 6

4.6.3. Electron density with one or six beams irradiation

The distribution of electron density with one or six beams irradiation with the magnetic field strength of 1.1 T at 50 ns and 200 ns (a) 50 ns and 600 J\times 1, (b) 50 ns and 100 J\times 6, (c) 200 ns and 600 J\times 1, (d) 200 ns and 100 J\times 6 is as shown in Fig. 4.13. The distribution of electron density with one or six beams irradiation without the magnetic field at 50 ns and 200 ns (a) 50 ns and 600 J\times 1, (b) 50 ns and 100 J\times 6, (c) 200 ns and 600 J\times 1, (d) 200 ns and 100 J\times 6 is as shown in Fig. 4.14. Plasma is expanding in a magnetic field at t = 50 ns and is stopped by the magnetic field at t = 200 ns. Kinetic energy of plasma with 100 J\times 6 irradiation is larger than that with 600 J\times 1, so the distribution of plasma with 100 J\times 6 irradiation is larger than that with 600 J\times 1 irradiation.
At 50 ns after laser irradiation

Fig. 4.14 The distribution of electron density with one or six beams irradiation without the magnetic field at 50 ns and 200 ns (a) 50 ns and 600 J×1, (b) 50 ns and 100 J×6, (c) 200 ns and 600 J×1, (d) 200 ns and 100 J×6

At 200 ns after laser irradiation

Fig. 4.15 shows the comparison of plasma expansion between two experiments about the measurement of plasma self-emission and electron density by using Mach-Zehnder interferometer. Fig. 4.15(a) shows light intensity of plasma self-emission with the magnetic field of 0.23 T with one beam of 6 J at 200 ns after laser irradiation (κ=0.67). This figure is calculated from light intensity of plasma self-emission by using Abel inversion. Fig. 4.15(b) shows the distribution of electron density with the magnetic field strength of 1.1 T with one beam of 600 J at 200 ns after laser irradiation (κ=0.79). Similar surface of the plasma expansion is observed in both figures with similar κ. Fig. 4.16 shows the peak positions as a function of the angle θ derived from Fig. 4.15. Both results show similar tendency in the range 0 < θ < 60°, while the peak positions from 600 J case are further than those from 6 J case at 60° < θ. It is because plasma energy in the range (0 < θ < 60°) is estimated by laser energy and laser absorption rate and plasma interacts with magnetic field in the range (60° < θ).

4.7. Comparison the results between two experiments

Fig. 4.15 shows the comparison of plasma expansion between two experiments about the measurement of plasma self-emission and electron density by using Mach-Zehnder interferometer. Fig. 4.15(a) shows light intensity of plasma self-emission with the magnetic field of 0.23 T with one beam of 6 J at 200 ns after laser irradiation (κ=0.67). This figure is calculated from light intensity of plasma self-emission by using Abel inversion. Fig. 4.15(b) shows the distribution of electron density with the magnetic field strength of 1.1 T with one beam of 600 J at 200 ns after laser irradiation (κ=0.79). Similar surface of the plasma expansion is observed in both figures with similar κ. Fig. 4.16 shows the peak positions as a function of the angle θ derived from Fig. 4.15. Both results show similar tendency in the range 0 < θ < 60°, while the peak positions from 600 J case are further than those from 6 J case at 60° < θ. It is because plasma energy in the range (0 < θ < 60°) is estimated by laser energy and laser absorption rate and plasma interacts with magnetic field in the range (60° < θ).
Fig. 4.15 Comparison of the plasma expansion between two experiments in the similar value of $\kappa$. (a) Light intensity of plasma self-emission with the magnetic field strength of 0.23 T with one beam of 6 J at 200 ns after laser irradiation (b) The distribution of electron density with the magnetic field of 1.1 T with one beam of 100 J/beam at 200 ns after laser irradiation.

Fig. 4.16 The peak positions as a function of the angle $\theta$ derived from Fig. 4.15
Chapter 5: Summary

Plasma emission with and without an external magnetic field was measured to investigate the interaction between plasma and magnetic field in a magnetic thrust chamber. The plasma expansion in both $-x$ and $\pm y$ direction is suppressed by the magnetic field. In addition, the light intensity in $+x$ direction is higher as magnetic field strength is larger. Therefore, more plasma expands to $+x$ direction, which contributes to obtain thrust as magnetic field strength is larger. We also calculated the criterion $\kappa$ and plasma deceleration was measured with magnetic field of over 0.23 T. Electron density was also measured by using Mach-Zehnder interferometer with several laser energy. Electron is suppressed by magnetic field and forms the structure like a shell in a magnetic field of 1.1 T at 200 ns and 300 ns after laser irradiation. Then, plasma expands to $+x$ direction. Electron expansion for $+y$ direction is smaller, as laser energy is larger.

Comparison of the plasma expansion in a magnetic field between two experiments are conducted in similar $\kappa$. As a result, similar structure of the plasma expansion is observed in both figures with similar $\kappa$. It means that the structures obtained from both experiments show more or less same, under the condition of the similar ratio of the plasma energy to the magnetic field energy. It shows $\kappa$ is the important factor to establish the scaling rule for Laser Fusion Rocket.
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