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Control techniques of thrust vector for magnetic nozzle in laser fusion rocket

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Abstract

An analysis of plasma behavior in a magnetic nozzle would be very useful for designing plasma propulsion systems using a laser fusion. We examine by using a three-dimensional (3D) hybrid code how a thrust vector varies with changing positions of the fusion explosion (off-axis explosion) for the one-coil system of a laser fusion rocket. Furthermore, we investigate plasma behaviors and the thrust efficiency, and optimize the thrust efficiency by changing the current and the position of a rear coil for two-coil system. We also discuss the possibility of control techniques of the thrust vector for a two-coil system.

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Keywords: Laser fusion rocket; Magnetic nozzle; Thrust vector; Thrust efficiency

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1. Introduction

A laser fusion rocket (LFR) has a magnetic nozzle that controls the plasma flow resulting from laser fusion by using a superconducting magnetic (SCM) coil, obtaining thrust by exhausting the plasma flow from the back of the rocket. The magnetic nozzle would achieve a high exhaust velocity (high propellant utilization efficiency), because plasma would not contact wall structures directly when exhausted from the nozzle. Analysis of plasma behavior in a magnetic nozzle would be very useful for designing plasma propulsion systems. Several estimations of thrust efficiency have been conducted, for example, Hyde et al. designed an LFR [1] and estimated thrust efficiency using two-dimensional magnetrohydrodynamics (2D-MHD) code for one-coil system; the thrust efficiency was reported to be 65% [2]. Nagamine and Nakashima simulated plasma behaviors and calculated thrust efficiency for a magnetic nozzle using 3D hybrid code for one-coil system, and examined how the thrust efficiency varies with certain parameters [3]. These studies have been conducted only for the estimation of thrust efficiency and it was assumed that the initial explosive plasma was located along the central axis of the nozzle. Here we try to control the thrust vector of the LFR using two methods. Firstly, we will examine by using 3D hybrid code [4] how the thrust vector varies

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with changing positions of the fusion explosion (off-axis explosion) for one-coil system. Secondary, we will investigate plasma behaviors and the thrust efficiency for the two-coil system in comparison with one-coil case and conduct the optimization of thrust efficiency by changing the current and the position of the rear coil, and also examine how the thrust vector varies by tilting the rear coil.

The thrust efficiency in terms of momentum η is defined here as follows:

$$\eta = \frac{\sum m v_Z}{\sum m\,|v_0|} \qquad (1)$$

where v_Z is the Z-component of the plasma (ion) velocity and $|v_0|$ is the absolute initial velocity. The sum $\sum$ is carried over all the plasma particles. Consequently, to increase the efficiency, we must increase +Z component of the ion velocity.

2. Simulation code

To calculate the plasma behavior in a magnetic nozzle, we used a 3D hybrid code based on the model given by Horowitz et al. [4]. Vchivkov et al. investigated the thrust conversion process of an LFR in a scaled-down model using this hybrid code, and they compared the numerical results with experimental ones and obtained a good agreement between these two results [5]. So we could obtain results with enough reliability by using this code.

3. Control techniques of thrust vector for one-coil system (method 1)

3.1. Numerical model

Calculation geometry in a scaled-down model is shown in Fig. 1. The initial calculation parameters are listed in Table 1. We have changed the position of initial plasma located at X-axis by changing angle α with respect to Z-axis. The ratio of plasma kinetic energy to the energy of the magnetic field is 0.16. The other calculation parameters are the same as in Nagamine and Nakashima [3]. We simulated five cases with different five angles α which are $\alpha = 0°, 10°, 20°, 30°$ and $45°$, and obtained the steering angle β to Z-axis. The calculation time was 11.08 μs which corresponds to around $200\omega_{ci}^{-1}$ (40,000 time steps), where ω_{ci} is the ion cyclotron frequency.

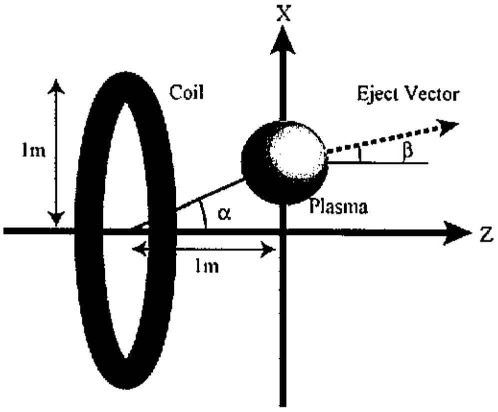

Fig. 1. Calculation geometry for method 1.

Table 1
Simulation parameters

Coil radius (m)	1.0
Coil current (A)	3.57×10^6
Coil position along Z (m)	−1
Plasma coordinates (m)	0, 0, tan α
Plasma radius (m)	0.3
Plasma energy (MJ)	4
Plasma mass (mg)	110
Atomic mass (AMU)	197
Atomic number	79
Time step Δt (ns)	0.277
Calculation region (m)	$12.0 \times 12.0 \times 14.0$
Mesh number	$120 \times 120 \times 140$
Number of particles	100000

4. Results

The plasma behaviors in a magnetic nozzle and the eject vector are shown in Fig. 2, where we plot ion particle positions in the X–Z plane at $Y=0$ in the case of $\alpha = 45°$. This figure shows that the initial plasma expands in a direction (in this case, $\beta = 37°$) because plasma is asymmetrically deflected by the magnetic field that is generated by the coil. Since the broken line plotted in Fig. 2 shows a vehicle structure, it is expected that plasma will collide with the wall of the vehicle. Therefore, we found that the limitation on α by this method is less than 45°. The dependence of initial

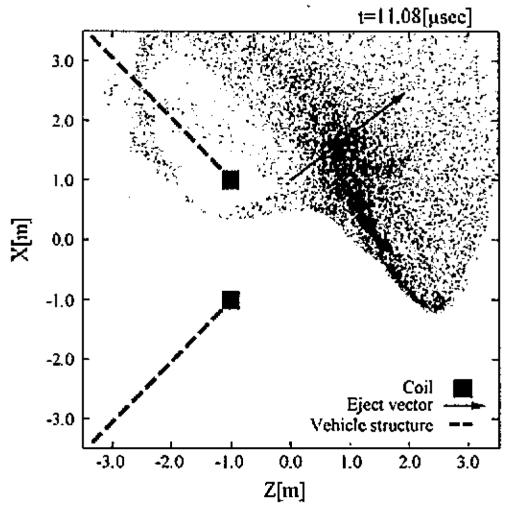

Fig. 2. Ion particle positions at 11.08 μs and eject vector (arrow) in the X–Z plane at $Y=0$ in the case of $\alpha=45°$.

plasma position α on steering angle β is shown in Fig. 3. The relationship of α to the thrust efficiency is also plotted in Fig. 3. The steering angle β increases with increasing α, while the reverse trend is found for the thrust efficiency. We can easily calculate the steering angle β using the following formulas for the arbitrary initial plasma position α in the range 0–45°:

$$\beta = 0.0023\alpha^2 + 0.7254\alpha \qquad (2)$$

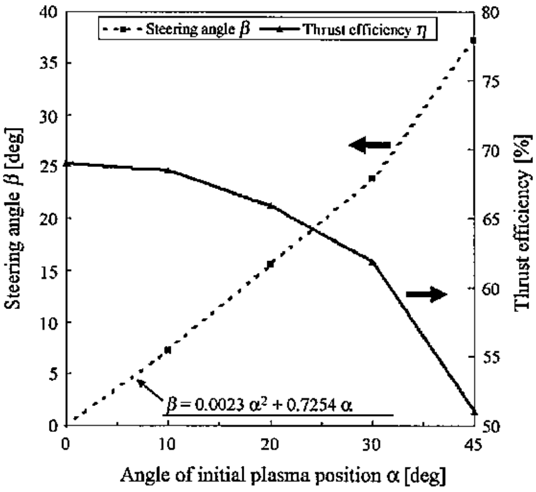

Fig. 3. The dependence of initial plasma position α on steering angle β and thrust efficiency.

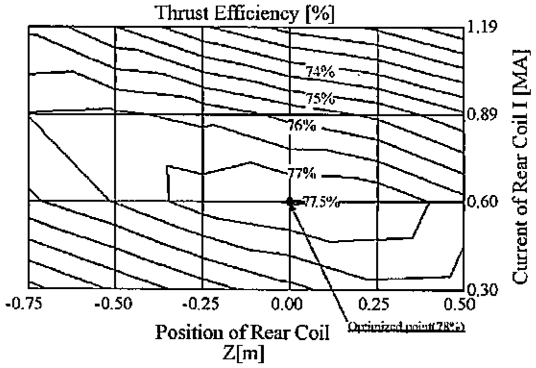

Fig. 4. The contour of thrust efficiency for currents of rear coil ranging from 0 to 1.19 MA and for rear coil positions ranging from $Z=-0.5$ to 0.25 m.

In addition, the coefficient of the determination (R^2 value) in the above formula (2) is 0.99.

5. Control techniques of thrust vector for two-coil system (method 2)

5.1. *Optimization of thrust efficiency*

Sakaguchi et al. [6], using the same simulation code, have investigated the behavior of fusion plasma for the two-coil system by changing the current and position of a rear coil. They have concluded that the maximum thrust efficiency is 75%. We investigated the thrust efficiency in data points around the maximum thrust efficiency and found the highest thrust efficiency was 78% with the current $I=0.595$ MA and position $Z=0.0$ m for the rear coil. This means that the center of the rear coil was the same position as in the initial plasma. Fig. 4 shows the contour plot of thrust efficiency obtained. We have studied, using these optimized parameters, the possibility of controlling the thrust vector by tilting the rear coil.

5.2. *Numerical model*

The calculation geometry is shown in Fig. 5. The initial calculation parameters are the same as in Sakaguchi et al. [6]. The ratio of plasma kinetic energy to the energy of the magnetic field is typically 0.1. We have changed the tilting angle γ as illustrated in Fig. 5 and

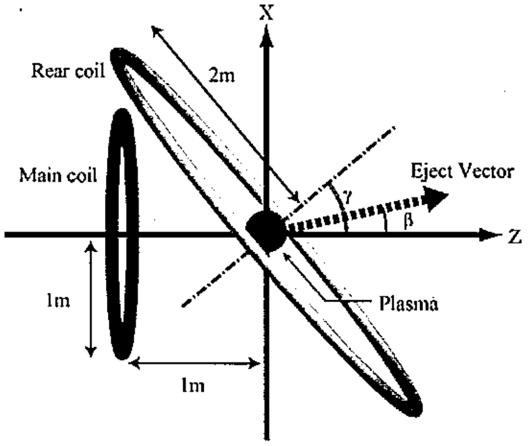

Fig. 5. Calculation geometry for method 2.

calculated the steering angle β and the thrust efficiency. We simulated four cases with different four angles for γ ($\gamma = 0°$, 15°, 30° and 45°). The calculation time was 11.08 μs which corresponds to around $200\omega_{ci}^{-1}$, where ω_{ci} is the ion cyclotron frequency.

6. Results

The steering angle β obtained by this method and the thrust efficiency are shown in Fig. 6. We found that we could not obtain the enough steering angle by using this method as compared with the above method 1. However, the thrust efficiency in these cases is more than 65%. So these values are much higher than the efficiency obtained by the method 1. The plasma behaviors in a magnetic nozzle and an eject vector are shown in Fig. 7, where we plot ion particles in the X–Z plane at $Y = 0$ in the case of $\gamma = 45°$. This figure shows that the steering angle is very small although the tilting angle is large, the LFR could not obtain the enough steering force by tilting the rear coil. When we control the thrust vector of the LRF, we have to choose and consider an effective method: the easier method to control the thrust vector (method 1) or the method which can be obtained higher thrust efficiency, but the small steering angle (method 2). Its choice also depends on the total mass of the LFR, and Sakaguchi et al. discussed it in their paper [6].

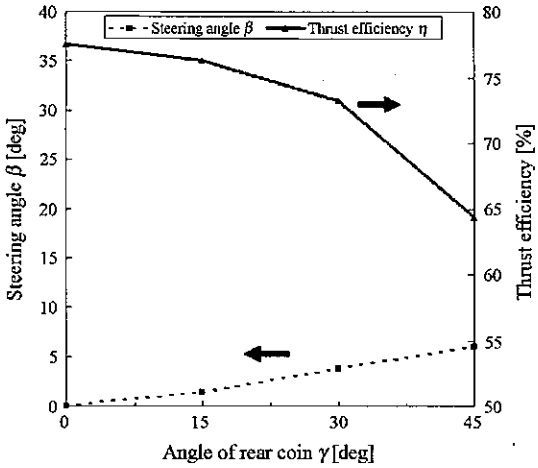

Fig. 6. The steering angle obtained by method 2 and thrust efficiency.

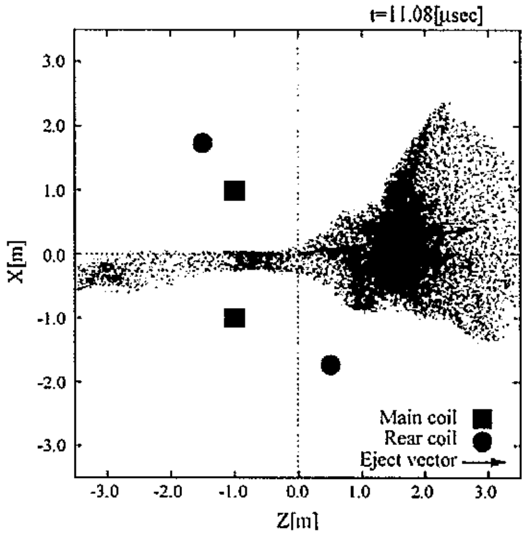

Fig. 7. Ion particle positions at 11.08 μs and eject vector (arrow) in the X–Z plane at $Y = 0$ in the case of $\gamma = 45°$.

7. Conclusion

In this study, we found that an LFR can obtain the steering angle β in proportional to α in the method 1 although there was the limitation on the maximum steering angle. In the method 2, the steering angle obtained by tilting the rear coil is small compared with the method 1, but the thrust efficiency is still high because of the usage of two coils optimized for obtaining higher thrust efficiency. It is important for controlling the thrust of an LFR to consider the tradeoff between the steering angle and the thrust efficiency. It is also necessary to solve the following subjects newly emerged by using the control method 1. The first is precise injection techniques of a fuel pellet to the arbitrary position. The second is the establishment of the steering techniques of laser beam to irradiate the fuel pellet when the pellet position is moved.

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