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NUMERICAL SIMULATION OF FUSION PLASMA BEHAVIOS IN A MAGNETIC NOZZLE FOR LASER FUSION ROCKET

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In this paper, we focus on methods to control a steering angle more effectively for a Laser Fusion Rocket (LFR). We propose a new coil configuration which is virtually one ring coil formed by a lot of small square coils and these coils make a flexible magnetic nozzle to control the reflection of fusion plasma for obtaining thrust in the space. We investigate the fusion plasma behaviors in this magnetic nozzle by using 3D hybrid simulation code and evaluate the thrust efficiency and the steering angle for several coil configurations. We found that new coil configuration proposed has desirable features from technical view points.

I. 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 fusion plasma means the ionized propellant obtained from the laser fusion. An analysis of fusion plasma behavior in a magnetic nozzle would be very useful for designing plasma propulsion systems using the laser fusion. In this paper, we examine by using a 3-dimensional (3D) hybrid code how a thrust vector varies in several coil configurations.

In our recent simulations, Nagamine and Nakashima simulated fusion plasma behaviors and calculated thrust efficiency for a magnetic nozzle by using 3D hybrid code for one coil system, and examined how the thrust efficiency varies with certain parameters[1]. Sakaguchi et al., by using the same simulation code, have investigated the behaviors of fusion plasma for two-coil system by changing the current and position of a rear coil and they have concluded that the maximum thrust efficiency is 75[%][2]. Furthermore, we examined how a thrust vector varies with changing positions of the fusion explosion (off-axis explosion) for the one-coil system and we also examined how the thrust vector varies by tilting the rear coil in the two-coil system[3].

In the present paper, we propose methods for obtaining the steering angle more easily and more efficiently than the previous method which used one or two simple ring coils. Firstly, we propose a magnetic nozzle for one-coil system, which is formed by a lot of small square coils. We simulate the fusion plasma behaviors in the magnetic nozzle, and examine how the thrust vector varies by changing the current of each small coil. Secondly, in the two-coil system using the simple ring coils, we examine how the thrust vector varies by not tilting the rear coil but moving the rear coil in the normal direction against the axis of two coils. We also compare the steering angle and thrust efficiency among the present results from one and two-coil system and those from the two-coil system previously proposed. We propose a more effective method of controlling the steering angle in LFR including the considerations of the attractive or repulsive force given between coils.

II. SIMULATION MODEL

To calculate the plasma behaviors in a magnetic nozzle, we developed a 3D hybrid code. The code treats ions as individual particles and electrons as a fluid. This approach is valid when the system behavior is dominated by ion physics. Figure 1 shows a schematic layout of magnetic nozzle in LFR .This configuration for LFR is "VISTA" type[4,5]. We here propose a new magnetic nozzle formed by a lot of square coils indicated in the dashed box in this figure. We can obtain the steering angle by controlling the magnetic field asymmetry generated by different currents in the square coils. It seems an easy method from technical viewpoints to control the steering angle.

III. INITIAL CONDITION AND CASES

A calculation geometry in a scaled-down model and three simulation cases are shown in Figs. 2 and 3. In CASE 1, the same current 14 [kA] are given in all square coils, and in CASE2, the current 14 [kA] are given in upper coils and a half of the current for lower coils. In CASE3, the current 14 [kA] are given only for the upper coils. The initial calculation parameters are listed in Table 1. The ratio of plasma kinetic energy to the energy of the magnetic field is around 0.5. The calculation time is 13.85[μ s] which corresponds to around 250 ω_{ci}^{-1} (50000 time steps).

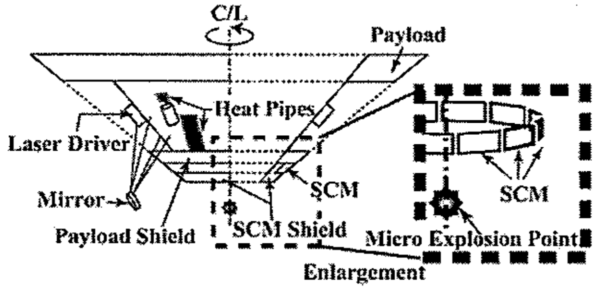
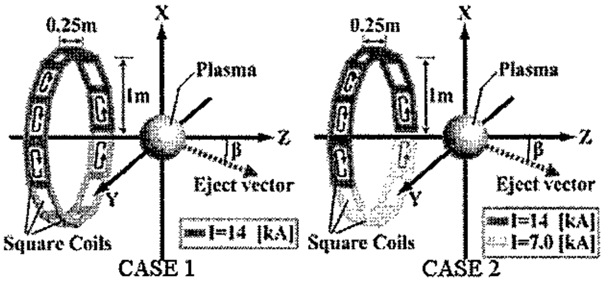
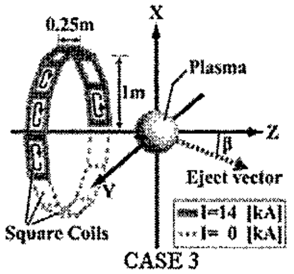


Fig 1: Schematic layout of magnetic nozzle in LFR.



CASE 1 CASE 2

Fig 2: Scheme of calculation model (CASE1 and 2)



CASE 3

Fig 3: Scheme of calculation model (CASE3)

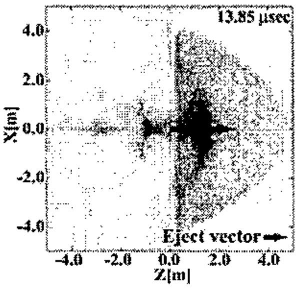


Fig 4: Ion particle positions of CASE1

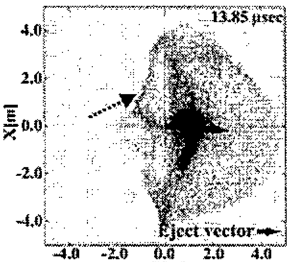


Fig 5: Ion particle positions of CASE2

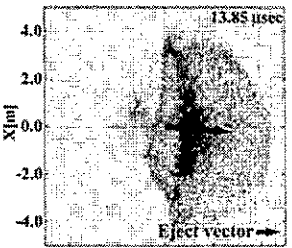


Fig 6: Ion particle positions of CASE3

IV. SIMULATION RESULTS

IV A. Results for Square Coil System

The vector plot of magnetic field and ion particle distribution projected onto the XZ plane at 13.85 [μ s] are shown in Fig.4 for CASE1, Fig.5 for CASE2, and Fig.6 for CASE3. The magnetic field acts like a spring to push back the fusion plasma. This effect can be seen in all cases. We stopped the calculation in each case when the thrust efficiency had reached an almost constant value. In CASE1, a part of the fusion plasma moved in the –Z direction across the center of the structured ring coil. This is because the same current are given in all square coils and the magnetic field generated by each coil is canceled at the center of the structured ring coil. This plasma amounts to about 2 [%] of the total fusion plasma.

TABLE 1. Simulation Parameters

Initial plasma radius [m]	0.3
Initial plasma energy [MJ]	4.0
Initial plasma mass [mg]	110.0
Atomic mass [AMU] and number	197 and 79
Time step [ns]	0.277
Simulation region [m]	12.0×12.0×14.0
Mesh number	120×120×140
Number of particles	100,000

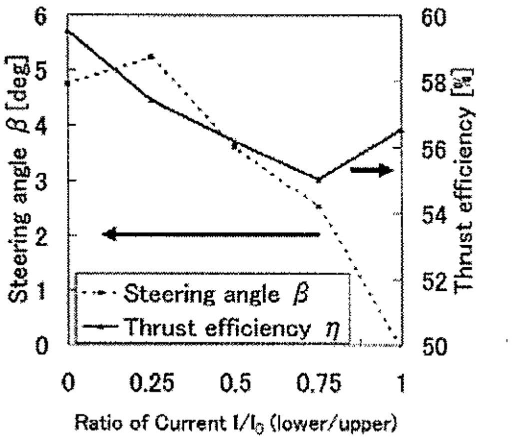


Fig 7: Dependence of the ratio of currents (I/I_0) on steering angle β and thrust efficiency.

In CASE2, the currents of upper coil and lower coil are different. The strength of magnetic field in −X region (lower region) is weaker than that in + X region (upper region), so the fusion plasma tend to push the weak magnetic field generated by the coils in the lower region, but the fusion plasma are finally reflected and some of the fusion plasma moves along the strong magnetic field line generated by the upper coils (as shown by a dashed arrow in Fig.5). The total amount of this reflected plasma depends on the current intensity of coils in lower region. In CASE3, the current is given only for the upper coils, so the magnetic field is generated in perpendicular to the Z direction. Thus, the fusion plasma can not cross this perpendicular magnetic field and almost all fusion plasma particles are collimated and directed along the +Z direction. As the current of lower coil is increasing, the reflected fusion plasma by the magnetic field is increasing. This fusion plasma is reflected along the magnetic field generated by the upper coils and collides the upper coils directly or goes through the inside of the upper square coils. This is the reason why the thrust efficiency decreases as the current of lower coils increases. The calculation results for thrust efficiency and steering angle are shown in Fig. 6 as functions of the ratio (I/I_0) between the lower current (I) and upper current (I_0). The steering angle is calculated as the sum of components of momentum vectors. The thrust efficiency in terms of momentum 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 plasma (ion) velocity and $|v_0|$ is the absolute initial velocity. The sum Σ is carried over all the plasma particles. The maximum thrust efficiency obtained is 59.5[%] at $I/I_0=0$, and the maximum steering angle is obtained as 5.2 [deg] for $I/I_0=0.25$.

IV B. Results for Two-coil System

A calculation geometry is shown in Fig. 8. The initial calculation parameters are the same as in our previous paper[3]. We have changed a distance L of the rear coil in the normal direction against the axis of two coils and calculated the steering angle and the thrust efficiency. We simulated five cases with different distances for L (L=0～1.0[m]). The calculation time is 11.08 [μ s] which corresponds to around 200 ω_{ci}^{-1}.

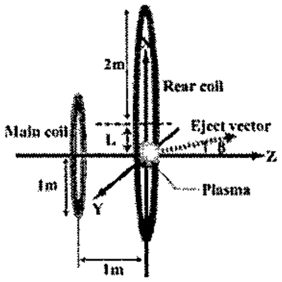


Fig 8: Scheme of calculation model.

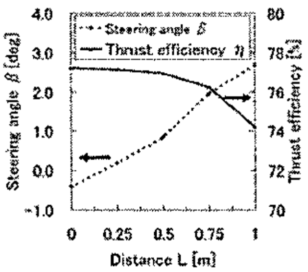


Fig 9: Dependence of distance (L) on steering angle β and thrust efficiency.

The steering angle obtained by this method and the thrust efficiency are shown in Fig. 9. We found that we could not obtain enough steering angle (such as 3.0 [deg]) by using this method. However, the thrust efficiency in these cases are more than 74 [%]. These values are much higher than the efficiency obtained by the previous method.

In our previous paper [3], we have changed a tilting angle of rear coil and calculated the steering angle and the thrust efficiency. In the paper, the maximum thrust efficiency obtained is 78.0 [%] for tilting angle 0 [deg], and the maximum steering angle is 6.0 [deg] for tilting angle 45 [deg] with the thrust efficiency of 64.0 [%]. We have to consider which parameters are more important for the operation of the spaceship, thrust efficiency or steering angle. As an another important aspect, in the two-coil system, the strength of attractive force given to the rear coil from the other coil is 500 [kN] because the coils current is around 1 [MA]. This is a quite large force, so the structure to support this force is required. On the other hand, in the one-coil system formed by a lot of square coils, the current of the coil is about 10 [kA], so the strength of repulsive force given to the coil from the neighboring coil is 1 [kN]. Supporting this force would be easier. Thus, we think that this new configuration of coils for controlling the fusion plasma flow is more desirable. However, we should improve the configuration of the coil to obtain a higher thrust efficiency in the future.

V. CONCLUSION

We have investigated the fusion plasma behaviors in the magnetic nozzle by using a 3D hybrid simulation code and evaluated the thrust efficiency and the steering angle in several cases. We found that the proposed new coil system formed by a lot of small square coils is more desirable than the other two-coil system. However, we also should take into account of the total mass of coil system and other system required for spaceship operation, when comparing its feasibility. In the new coil system, we have to improve the coil configuration in order to avoid the collision of fusion plasma with the square coils.

Finally, we are planning to propose a new method for controlling the steering angle by shaping the initial propellant configuration. For this purpose, we are developing a scheme to calculate the initial velocity distribution of fusion plasma obtained from the laser fusion for various kinds of propellant shape.

REFERENCES

[1] Y. NAGAMINE, H. NAKASHIMA, "Analysis of Plasma Behavior in a Magnetic Thrust Chamber of a Laser Fusion Rocket", *Fusion Technology* **35**, 62 (1999).

[2] N. SAKAGUCHI, Y. KAJIMURA, H. NAKASHIMA, "Thrust Efficiency Calculation for Magnetic Nozzle in Laser Fusion Rocket", *Trans. Japan Soc. Aero. Space Sci.* **48**, *161*, 180 (2005).

[3] Y. KAJIMURA, R. KAWABUCHI, H. NAKASHIMA, "Control Techniques of A Thrust Vector for Magnetic Nozzle in Laser Fusion Rocket", submitted to *Fusion Engineering & Design* (2005).

[4] C. D. ORTH, "VISTA - A Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion", *UCRL-TR-110500* (2003)

[5] H. NAKASHIMA, et al., "A Laser Fusion Rocket based on Fast Ignition Concept", *56th Int. Astronautical Congress,* IAC-05-CIAC-05-C4.4.02 (2005)