Trans. Japan Soc. Aero. Space Sci.
Vol. 48, No. 161, pp. 180–182, 2005

Technical Note

Thrust Efficiency Calculation for Magnetic Nozzle in Laser Fusion Rocket

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(Received March 22nd, 2005)

Key Words: Laser Fusion Rocket, Magnetic Nozzle, Thrust Efficiency

1. Introduction

Analysis of plasma behavior in a magnetic nozzle would be very useful for designing plasma propulsion systems such as inertial confinement fusion rockets and laser thermal propulsion. A 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. Some conceptual designs for a laser fusion rocket (LFR) have been proposed. The rocket has a magnetic nozzle and 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.

Hyde designed an LFR and proposed a magnetic nozzle using two SCM coils.[1)] He then proposed a new design and estimated its thrust efficiency using two-dimensional (2D) magnetrohydrodynamics (MHD) code for one coil system; the thrust efficiency was reported to be 65%.[2)] Nagamine and Nakashima[3)] calculated plasma behaviors and thrust efficiency using three-dimensional (3D) hybrid code for a magnetic nozzle using one coil, and examined how the thrust efficiency varies with certain parameters. Since these efficiency estimates were performed for magnetic nozzles using one coil, we investigated plasma behaviors and thrust efficiency for a model with two coils by using the 3D hybrid code, and conducted optimization of thrust efficiency for the magnetic nozzle.

Thrust efficiency is defined as follows in terms of momentum η:

$$\eta = \frac{\sum m v_z}{\sum m |v_0|} \tag{1}$$

where m is the ion mass, v_z is the z-component of its 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 the $+Z$ component of ion velocity as shown above.

2. Numerical Model

To calculate the plasma behavior in a magnetic nozzle, we developed a 3D hybrid code based on the model given by Horowitz.[4)] 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. The adopted calculation model is shown in Fig. 1. The model is based on Nagamine's model and a rear (R) coil is added to improve thrust efficiency. The parameters for the R coil are adopted by scaling down the parameters from Hyde.[1)] The position of the R coil is varied from -2 m to $+3$ m and the coil current is varied from 0.595 to 2.38 MA. The current of the front coil is fixed at 3.57 MA; the initial plasma is assumed to have a radius r_p of 0.3 m and is composed entirely of gold with a mass m_p of 110 mg. The initial plasma kinetic energy is assumed to be 4 MJ and the electron temperature is 0 eV. The ratio of plasma kinetic energy to the energy of the magnetic field is typically 0.1. This magnetic field energy is the sum of the energies of both coils. The other calculation parameters are the same as in Nagamine and Nakashima.[3)]

3. Results and Discussions

The calculation results for thrust efficiency are shown in Fig. 2 as functions of the R coil position (Z) and current (I). The maximum obtained thrust efficiency is 75% for $Z = -0.5$ m and $I = 1.19$ MA. Placing the R coil at $Z = +1.0$ m decreases thrust efficiency.

As an illustration, the velocity vector distributions projected on to the XZ plane at 8 μs are shown in Fig. 3(a) for the case of one coil, (b) for the case of $Z = +1.0$ m and $I = 1.19$ MA and (c) for the case of $Z = -0.5$ m and $I = 1.19$ MA, respectively. It seems that although the plasma expands isotropically at the initial stage, many particles are collimated and directed along the $+Z$ direction for case (b), but the efficiency is only 61% and lower than the 75% of case (c).

Figure 4 shows the magnetic field distributions at the initial time and 0.5 μs later for the case of $Z = -0.5$ m and $I = 1.19$ MA. The magnetic field is excluded from the plasma region and compressed at 0.5 μs compared with the initial time and then the magnetic field acts like a spring to push back the plasma. This effect can be seen in all cases.

Figure 5(a) shows the phase space of v_z at 8 μs for the one-coil case; Fig. 5(b) for the two-coil case of $Z = 1.0$

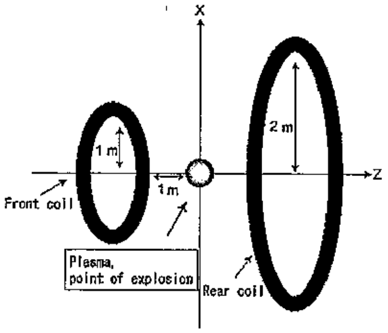

Fig. 1. Scheme of calculation model.

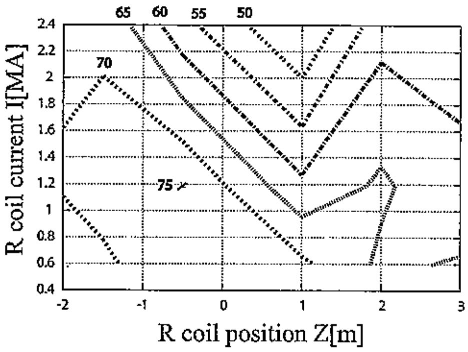

Fig. 2. Thrust efficiency (%) as functions of Z (m) and I (MA).

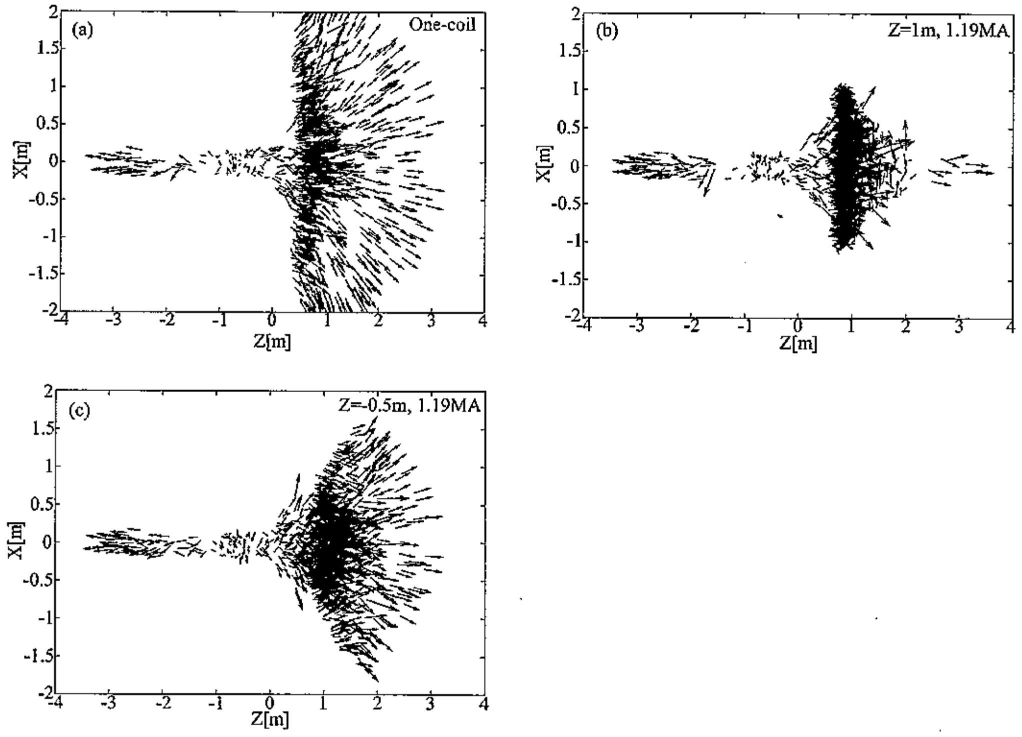

Fig. 3. Velocity vector distributions projected on to XZ plane: (a) one-coil case, (b) two-coil case of $Z = 1.0\,\mathrm{m}$ and $I = 1.19\,\mathrm{MA}$, (c) two-coil case of $Z = -0.5\,\mathrm{m}$ and $I = 1.19\,\mathrm{MA}$.

m, and Fig. 5(c) for the two-coil case of $Z = -0.5\,\mathrm{m}$.

In Fig. 5(a), there are two velocity components around $Z = 1.0\,\mathrm{m}$. It is expected that this placing of the R coil would strongly affect the components. From Fig. 5(b), it is found that the lower component is decelerated compared to case (a). On the other hand, Fig. 5(c) shows that the lower component is accelerated because the secondary coil is moved to $Z = -0.5\,\mathrm{m}$.This is why we obtained the lower efficiency for case (b). The increase in thrust efficiency obtained by using two coils must be balanced by an increase in the mass associated with the additional coil, radiation shield, and radiator panel for waste-heat removal. A preliminary assessment using the expressions in Hyde[1] for mass calculation indicates that a thrust value efficiency greater than 73% is needed to outperform the one-coil system in terms of specific power defined as the ratio of the thrust power to the power plant mass.

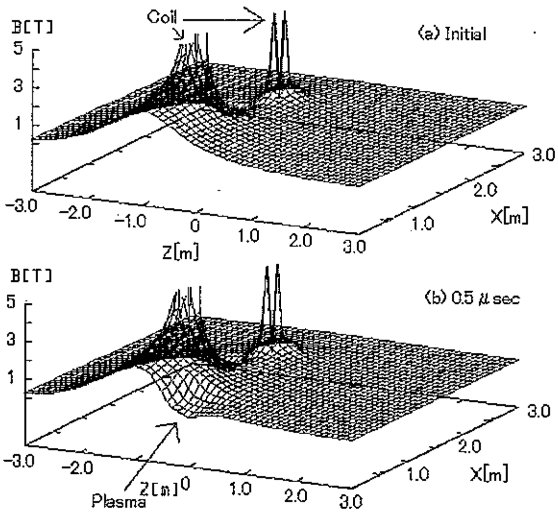

Fig. 4. Magnetic field distributions: (a) initial time, (b) 0.5 μs, case of $Z = -0.5\,\mathrm{m}$ and $I = 1.19\,\mathrm{MA}$.

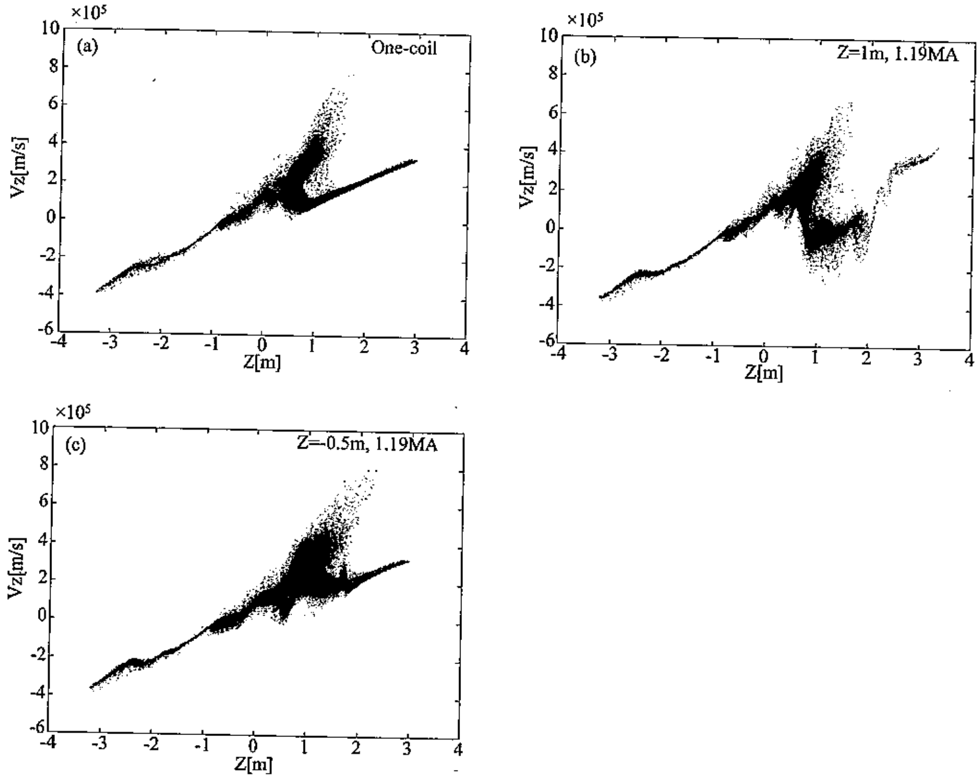

Fig. 5. Phase space of v_z: (a) one-coil case, (b) two-coil case of $Z = 1.0$ m and $I = 1.19$ MA, (c) two-coil case of $Z = -0.5$ m and $I = 1.19$ MA.

4. Conclusions

The LFR uses a magnetic nozzle to control the isotropically expanding plasma into a directed flow. A thrust efficiency calculation was performed for a magnetic nozzle using two coils using a 3D hybrid code. The maximum obtained thrust efficiency is 75% compared to 65% attained by the one coil system. It was also found that placing the second (rear) coil at the $+Z$ position decreased the thrust efficiency due to deceleration by the coil magnetic field.

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