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Optimization of thrust efficiency in laser fusion rocket by using three-dimensional hybrid particle-in-cell code

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Abstract

An optimization study on thrust efficiency of exploding plasma in the magnetic thrust chamber for laser fusion rocket is performed by using a three-dimensional hybrid particle-in-cell code. Temporal evolution of plasma clouds expanding in a dipole magnetic field is examined. The integral-in-time picture of the exploding plasma shows a cone-like geometry. The dependences of thrust conversion efficiency η and half-angle of the plasma expansion cone α on κ (the parameter characterizes the interaction between the expanding plasma and the dipole field) are examined, and optimal values of α and κ are found. The maximum thrust conversion efficiency is estimated to be about 70% from the simulation.

Keywords: Dipole magnetic field; Three-dimensional hybrid PIC code; Laser fusion rocket; Thrust conversion; Optimization study

1. Introduction

A propulsion system driven by a laser-induced fusion called laser fusion rocket (LFR) is an attractive candidate for future interplanetary missions [1]. A fusion reaction can easily produce plasma of high temperature and density. The resulting plasma flow can be controlled by a magnetic thrust chamber. In the LFR, the chamber composes of the solenoidal superconducting coil.

One of the characteristics of LFR is the thrust efficiency η, which is defined as $\eta = \Sigma m_i v_z / \Sigma m_i |v_0|$, where m_i is the ion mass, v_z is the z component of its velocity, and $|v_0|$ is the absolute value of the initial velocity. The sum Σ is carried over all the plasma particles.

Hyde [1] designed a LFR for the first time and estimated its thrust efficiency by using a two-dimensional (2D) magnetohydrodynamics (MHD) code. The efficiency was reported to be 65%.

A new spacecraft concept called vehicle for interplanetary space transport applications (VISTA) was developed by Orth et al. [2,3]. VISTA's overall geometry is a 50° half-angle cone. The 50° half-angle maximizes the thrust efficiency and is determined by selecting the optimum pellet firing position along the axis of the cone with respect to the plane of the magnetic coil, in a manner similar

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to that by Hyde [1]. The pellet is positioned at the particular site on the apex of the cone where laser beams ignite the fusion fuel. This ignition site is located behind the plane of magnetic coil. The pellet and coil are located on the spacecraft symmetric axis.

Nagamine and Nakashima [4] have investigated (a) whether Rayleigh–Taylor instability is significant for the plasma expanding in the LFRs magnetic thrust chamber and (b) how the efficiency for converting particle momentum into momentum along the rocket's thrust vector varies with certain parameters.

Zakharov et al. [5] reviewed the physical background of LFR and its laboratory verification in simulation experiments with laser-produced plasma cloud (LPC) expanding in an axially symmetric dipole magnetic field. As a result of such a kind of "Impulse" experiment under dimensionless conditions rather close to the related project of interplanetary spacecraft VISTA [2,3], the conversion efficiency of plasma momentum as high as 60% was measured in this type of magnetic thrust chamber for the first time by various independent methods.

Nikitin et al. [6] discussed, in the framework of the ideal MHD approximation, about the dependences of half-angle of plasma expansion cone α on the energetic interaction parameter κ (the parameter characterizes the interaction between the expanding plasma and the dipole field, as explained in Section 2) and of the thrust efficiency η on the cone angle α. In addition, the authors compared their estimations, with the results of numerical simulation by PIC code. According to the estimations, the thrust efficiency amounts to about 85%.

Vchivkov et al. [7] conducted a comparative analysis of the plasma behaviors in a dipole magnetic field between numerical simulation and "Impulse" experiment performed by Zakharov et al. [5]. An overall good agreement between the numerical analyses and the experimental data was found. It was also found that the thrust efficiency as high as 60% was possible in the scaled-down model considered there.

The purpose of the present paper is to analyze the exploding plasma in a magnetic thrust chamber for LFR by using a 3D hybrid PIC code and to optimize the thrust efficiency by the same approach as in Ref. [6].

The plan of the paper is as follows: in Section 2 we discuss the parameters that characterize the interaction between the expanding plasma and the dipole field. Section 3 presents the calculation model and method adopted here. The temporal evolution and integral-in-time picture of the exploding plasma in a dipole magnetic field, and estimation of the thrust conversion efficiency are presented in Section 4 along with discussion. The conclusions are given in Section 5.

2. Characteristics of plasma cloud expansion

For the given problem, the necessity to apply sophisticated PIC models to describe the plasma cloud's behavior in LFR is determined by the conditions of collisionless expansion of ions with the small but finite value of their directed Larmor radius R_L on the characteristic scale R_b of cloud deceleration by magnetic field $\mathbf{B}_{d0}$of the coil, where $R_L = m_i V_0/(Ze\mathbf{B}_{d0})$ and $R_b \approx (3\mu_0 E_0/(4\pi \mathbf{B}_{d0}^2))^{1/3}$, where again m_i is the ion mass, V_0 the initial velocity, Z the charge state, e the elementary electric charge, μ_0 the vacuum magnetic permeability and E_0 the kinetic energy. The retardation radius R_b is calculated from the condition that the kinetic energy density of all the plasma particles is equal to the density of the magnetic field energy. R_b accounts for ideal characteristics of the retardation process, and therefore some high-speed particles do not stop before R_b.

According to the results of Zakharov's experiment [8] on the interaction of LPC with uniform magnetic field, the general similarity criterion of the problem is determined from a parameter $\varepsilon_b = R_L/R_b$. The criterion for ε_b was established for the first time for exploding plasma clouds.

The cloud interacts effectively with the field only under the condition of enough ion's magnetization, i.e., $\varepsilon_b \leqslant 1$. In the opposite case, due to enhanced field penetration into plasma (with $\nu_{eff} \sim 0.3\omega_{ce}$ for electrons, where ν_{eff} is the electron turbulence frequency of the collisions and ω_{ce} is the electron cyclotron frequency), plasma cannot be decelerated by the field at all.

Nikitin et al. [9] discussed, in the framework of the ideal MHD approximation, the dynamics of a 3D expansion of a spherical cloud of rarefied plasma into a vacuum in the presence of a nonuniform external magnetic field of dipole structure and described how to find the configuration and location of the plasma front as a function of time, and also how to determine the limits of its propagation, which are caused by the retardation effect. In addition, the authors of this paper defined another energetic criterion κ that characterizes the interaction between the expanding plasma and the dipole field and is given as

$$\kappa = \frac{E_0}{E_M} = \frac{12\pi E_0 R^3}{\mu_0 |\mu_d|^2},$$

where E_0 is the initial kinetic energy of ions, E_M the field energy integral of the dipole beyond the spherical radius $R(E_M = (\mu_0/4\pi)|\mu_d|^2/(3R^3))$, R the distance from the magnetic coil to the explosion location and $|\mu_d|$ the magnetic moment magnitude. The critical value of the criterion κ_c was found by Nikitin and Ponomarenko [6,9] for different cases of plasma location. In the case where κ is lower than κ_c, a substantial plasma deceleration will occur in all directions from the explosion location ("quasi-capture" mode), meanwhile the plasma will not be captured by an ambient magnetic field, when κ is greater than κ_c ("rupture" mode). When the plasma is located at the axis, the critical value is $\kappa_c = 0.4$.

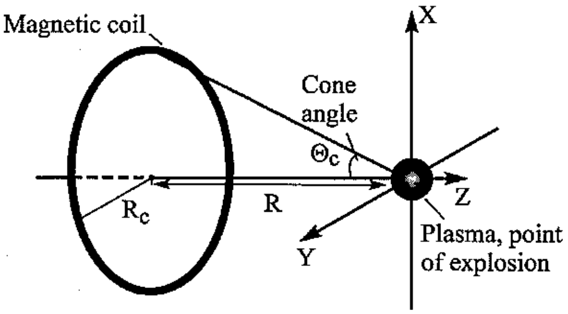

Fig. 1. Schematic of the calculation model.

3. Numerical model

The calculation model considered here is illustrated in Fig. 1, and it is based on the simulation performed by Nagamine and Nakashima [4].

Cartesian coordinates are adopted here. The magnetic coil and the initial plasma cloud are located along Z-axis. The optimal distance between the plasma and the coil R is defined according to a theoretical work of Nikitin and Ponomarenko [6] as

$$R = \left(\frac{\mu_d^2 \kappa_{opt} \mu_0}{12\pi E_0}\right)^{1/3},$$

where μ_d is the magnetic moment, E_0 the initial kinetic energy of ions and $\kappa = \kappa_{opt} \simeq 0.5 - 0.6$.

Note an angle θ_C (cone angle) subtended from the initial plasma position at the Z-axis to the magnetic coil.

The plasma behaviors are calculated by a 3D hybrid PIC code. The hybrid code treats ions as individual particles and electrons as a fluid. The equations controlling our system can be derived from Maxwell's equations and the equations of motion of the particles. The details are given in [4].

Calculations are performed for several cases with the different values of κ and ε_b. The common calculation parameters used in the simulation are shown in Table 1. The main parameters are the same with the simulation performed by Nagamine and Nakashima [4]. We have increased the

Table 1
Common calculation parameters

Coil radius R_c (m)	1.0	Effective charge (C)	16.81
Coil current (MA)	3.57	Initial magnetic field strength at the plasma (T)	0.1
Coil position along Z (m)	-1.0	Time step Δt (μs)	0.00027
Plasma radius (m)	0.3	Calculation region (m)	$6\times6\times7$
Plasma mass (g)	110×10^{-3}	Mesh size	$60\times60\times70$
Atomic mass (AMU)	197.0	Number of particles	100,000

Table 2
Interaction parameters κ for different cases

Variants	#1	#2	#3	#4	#5[a]	#6[a]
κ	0.1	0.5	0.55	0.6	0.95	1.18
ε_b	0.02	0.03	0.03	0.03	0.03	0.03
R (m)	1.0	0.80	0.83	0.85	1.0	1.0
Plasma energy (MJ)	0.42	4.0	4.0	4.0	3.9	4.9
θ_C (deg)	45	51.4	50.3	49.5	45	45

[a] From Ref. [4].

interaction parameters κ and ε_b by changing the plasma cloud energy and the distance R (see Table 2).

Initial distributions of the particle positions and velocities were assumed to be uniform. Here the simulation starts from $t = 0.8\,\mu s$ to take into account the time elapsed for the plasma expansion to 0.3 m in radius.

4. Results and discussion

In this section, we will present the simulation results along with discussion.

The numerical results for the time evolutions of particle position are shown in Figs. 2(a) and (b) for the Case 4 (see Table 2), where they are projected onto the XZ and XY planes, respectively. As we can see in these figures, the plasma shape is spherical at the initial stage, and the plasma expands almost isotropically, and then the ions in the direction of the coil are reflected back by the magnetic field, and its shape changes to follow the dipole magnetic field line. On the other hand, as shown in Fig. 2(b) the shape of the plasma is symmetric at all the stages in the XY plane.

Fig. 3 shows a time-integrated picture of plasma cloud, which was obtained by simulation. The simulation results were obtained by superimposition of plasma particle positions. The picture of the exploding plasma shows a cone-like geometry. The half-angle of the plasma expansion cone α is estimated to be about 50°.

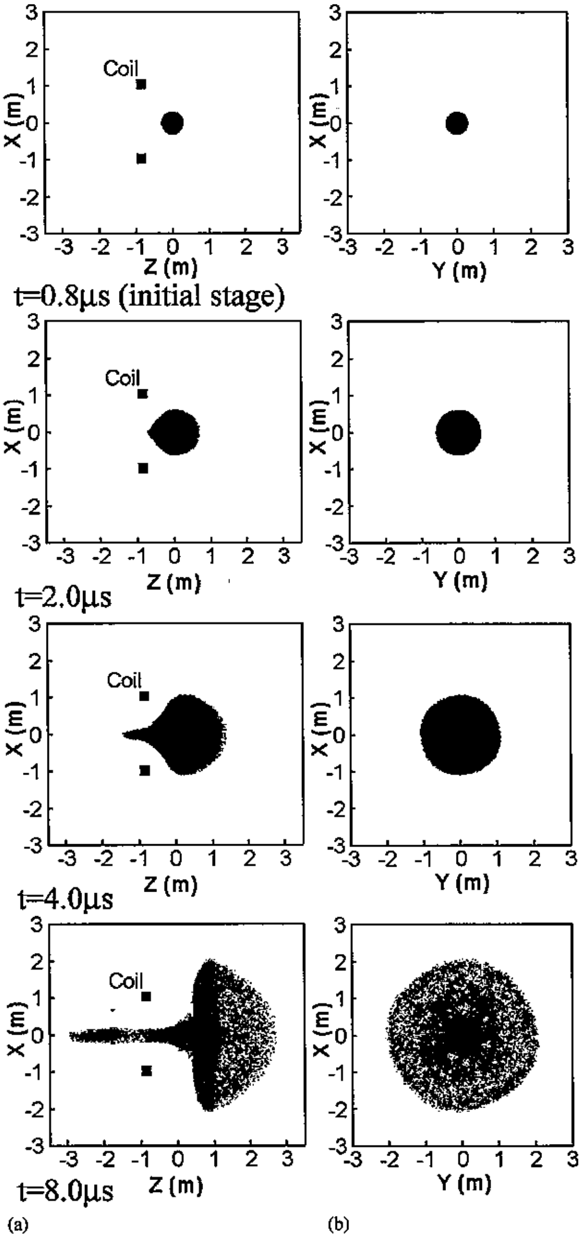

Fig. 2. Simulation results of particle positions projected onto the (a) XZ plane and (b) XY plane. (Case 4: $R = 0.85$ m, $\kappa = 0.6$).

Note that there may be some ambiguity in determining the expansion angle α because in our case we are estimating the angle by the time-integrated picture of plasma cloud (see Fig. 3). Nikitin et al. [7] estimated the plasma expansion cone from the "deceleration region" equation.

Fig. 4 shows the dependence of η on the expansion angle α, where the simulation results are shown as points, and the solid line is obtained

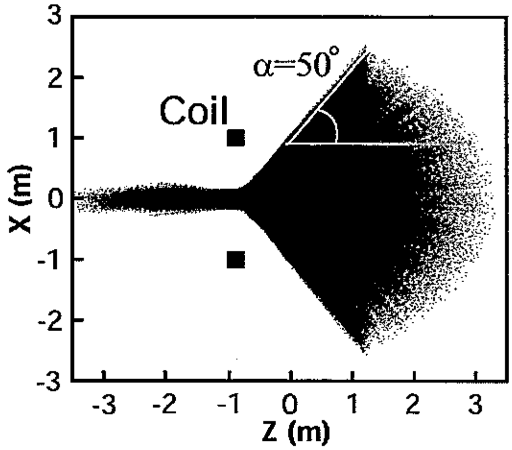

Fig. 3. Time-integrated picture of plasma cloud (simulation result, Case 4: $R=0.85\,\text{m}$, $\kappa=0.6$).

from the theoretical work of Nikitin et al. [6]. A too narrow cone ($\alpha\to 0$) as well as a too wide one ($\alpha\to\pi/2$) corresponds to the decrease in the thrust efficiency [6]. The maximum value of η reaches about 85% at $\alpha=\alpha_{opt}\simeq$45–50° in the MHD theoretical work. However, from the simulation result, we can see that its maximum value of η reaches about 70% with $\alpha=\alpha_{opt}\simeq 45°$.

The dependence η on κ is shown in Fig. 5. In this figure, the theoretical result (solid line) is given for the value of κ which is larger than κ_c, although the simulation result is considered with κ less than κ_c. In our simulation, we could not observe any clear evidence of the plasma capture, such as a substantial deceleration of plasma in all directions from the explosion location at the initial stage of the expansion, although the parameter κ was much smaller than the critical value $\kappa_c=0.4$. However, in the MHD model, the plasma will be captured for the parameter range, and then the efficiency is zero as shown by the solid line.

The maximum value of η reaches about 85% at $\kappa=\kappa_{opt}\simeq 0.5-0.6$ in the MHD theoretical work. However, from the simulation result, we can see that the maximum value of η reaches about 70% with $\kappa=\kappa_{opt}\simeq 0.5-0.6$. Points 2, 3 and 4 have the same values of η because the cone angle θ_C is about 50° for these points [4]. Points 5 and 6 were obtained from [4] and displayed here for comparison.

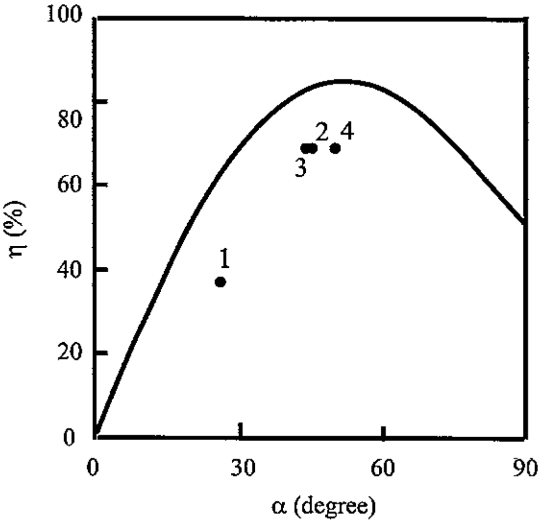

Fig. 4. Dependence of η on α. 1, $\kappa=0.1$; 2, $\kappa=0.5$; 3, $\kappa=0.55$; 4, $\kappa=0.6$. The solid line is the theoretical result [6].

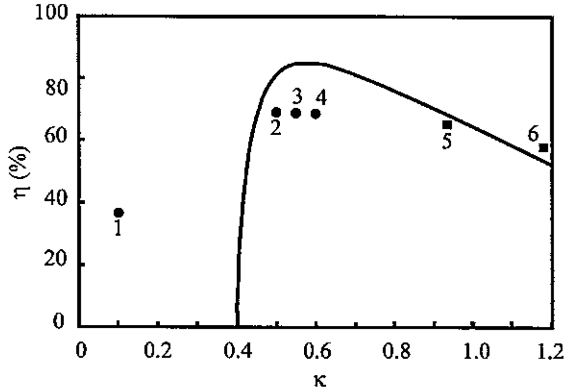

Fig. 5. Dependence of η on κ. 1, $\kappa=0.1$; 2, $\kappa=0.5$; 3, $\kappa=0.55$; 4, $\kappa=0.6$; 5, $\kappa=0.95$; 6, $\kappa=1.18$. The solid line is the theoretical result [6]. Points 5 and 6 from Nagamine and Nakashima [4].

5. Conclusions

The laser fusion rocket is a promising candidate for an interplanetary transport system. Optimization study on the thrust efficiency was performed by a 3D hybrid code. Temporal evolution of plasma cloud expanding in a dipole magnetic field was examined.

Overall qualitative agreement between the simulation and the theoretical model of Nikitin and

Ponomarenko [6] was found for the dependences of η on α and κ.

In the theoretical model η amounts to 85%, while in the simulation the maximum η is 70%.

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