FULL PARTICLE-IN-CELL SIMULATION FOR ANALYSIS OF THE DEPENDENCY OF THRUST ON MAGNETIC FIELD STRENGTH IN A LASER FUSION ROCKET

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ABSTRACT

A magnetic thrust chamber is a thrust system in a laser fusion rocket. 2D-3V fully kinetic particle-in-cell calculations were performed to investigate the dependency of impulse on the magnetic field strength in a Laser fusion rocket. It is found that when we decrease the energy ratio of plasma to the magnetic field, β, from 2 to 0.2, the momentum conversion efficiency increases from 75.4% to 84.2% due to reduction of divergent angle. However, if β decreases from 0.2 to 0.02, the efficiency decreases to 79.0 % despite smaller divergent angle. These results suggest that too strong magnetic field may induces plasma attachment, resulting in decreased thrust.

KEY WORDS

Laser Fusion Rocket, Particle-in-cell simulation, Impulse, Plasma detachment

1. INTRODUCTION

In 2024, the National Ignition Facility (NIF) achieved a significant milestone in laser fusion ignition, achieving an energy gain of 5.2 MJ from an input laser energy of 2.05 MJ[1)]. This output energy is more than twice the input energy, making the practical use of fusion energy increasingly viable. One promising application of this technology is in rocket propulsion, specifically in the form of a Laser Fusion Rocket[2)], which has been conceptually designed to reduce the mission duration to Mars. Conventional propulsion systems, such as chemical propulsion, offer high thrust but low specific impulse, leading to travel times exceeding 180 days. Electric propulsion, while providing high specific impulse, offers only low thrust. In contrast, a laser fusion rocket combines high thrust with high specific impulse, potentially cutting the mission time to Mars to just 90 days.

2. RESEARCH OBJECTIVE

2.1 Mechanism of thrust generation

The laser fusion rocket generates thrust through a three-stage process, involving the ejection of propellant plasma by a divergent magnetic field within a system known as the magnetic thrust chamber. Initially, high-energy lasers irradiate a pellet to initiate inertial fusion reactions, which produce substantial amounts of energy, including high-energy neutrons and alpha particles. These particles ionize the propellant. As the ionized propellant thermally expands with divergent magnetic field, a diamagnetic current which forms on the plasma surface, particularly where the density gradient is significant. Subsequently, the averaged plasma momentum is redirected downstream by the Lorentz force, which arises from the interaction between the diamagnetic current and the external magnetic field. Finally, the plasma detaches from the magnetic field lines and exits the magnetic thrust chamber, generating thrust.

2.2 Plasma detachment and thrust.

If the plasma remains attached to the magnetic field lines, the system fails to produce thrust as the plasma is not ejected or negative particles momentum increases. Therefore, the detachment of the propellant plasma from the magnetic field lines is crucial for effective thrust generation in the laser fusion rocket.

In the past years, the dependency of thrust on magnetic field strength has been discussed under the assumption that all charged particles detach from the magnetic field lines. The optimal thrust efficiency in term of momentum has been computed to be 65% when the magnetic field energy is five times larger than plasma energy via 3D hybrid particle-in-cell (PIC) simulation[3)]. However, the hybrid PIC calculation does not include electron kinetic theory. Therefore, it is necessary to analyze dependence of thrust on magnetic field strength considering the electron attachment.

In this study, we performed 2D-3V fully kinetic PIC simulation of with different magnetic field energy to investigate the dependence.

3. METHODOLOGY

3.1 Calculation method

We use 2D-3V simulation code of Extensible PIC Open Collaboration[4)] (EPOCH) to examine the interaction between particle motion in the magnetic thrust chamber and electromagnetic field in a cartesian system. In the particle-in-cell method, super-particles combining multiple charges and masses, are introduced, and the equation of each particle motion is solved. EPOCH applies Finite Difference Time Domain (FDTD) method for field solver, Buneman-Boris method for solving the equation of motion, and Villasenor-Buneman method for computing the current density.

3.2 Simulation parameters

Figure 1 shows the schematic diagram of the simulation condition. We established a plasma with a number density $n_{\mathrm{P}} = 10^{22}\ \mathrm{m}^{-3}$, temperature $T_{\mathrm{P}} = 1\ \mathrm{keV}$, and zero flow velocity. The plasma was set at a radius of $r_{\mathrm{P}} = 0.1\ \mathrm{mm}$ at the center of the simulation domain. The mesh size is set to 1.34 times larger than the Debye length, and all of four boundaries are open. The coil current values (I_{c}) are set such that the ratio of plasma energy to the magnetic field energy (β) would be 2, 0.2, and 0.02.

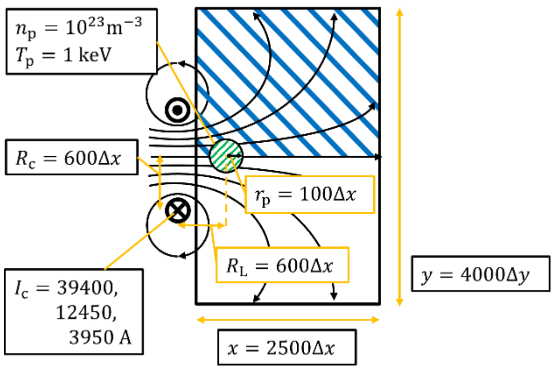

Fig.1: Schematic diagram of simulation condition.

4. RESULTS AND DISCUSSIONS

Figure 2 shows the temporal properties of impulse the case of $\beta =$ (a) 2, (b) 0.2, (c) 0.02, and Table 1 shows the momentum conversion efficiency of propellant and the ratio of the particles ejected from $x_{\max}$ and $y_{\max}$ boundary to the total ejected particles (N_{XMAX}/N and N_{YMAX}/N) at $t = 0.9\ \mathrm{ns}$ in case of $\beta = 2$, 0.2, 0.02, respectively. The impulse I and the momentum conversion efficiency η_{eff} is computed by using following formulas in the same manner as previous studies:

$$I = \Sigma m v_x \tag{1}$$

$$\eta_{\mathrm{eff}} = \Sigma m v_x / \Sigma m |v_0| \tag{2}$$

where m is the mass of super-particle, v_x the x component of particle velocity, and v_0 is the initial particle velocity. We can see that the impulse approach to 0.4-0.5 $\mu\mathrm{Ns/m}$ as time passes in all cases of β. This has a qualitative agreement with the result from the hybrid simulation and suggests that the magnetic thrust chamber generates thrust in each case of β. When comparing η_{eff} with each β,

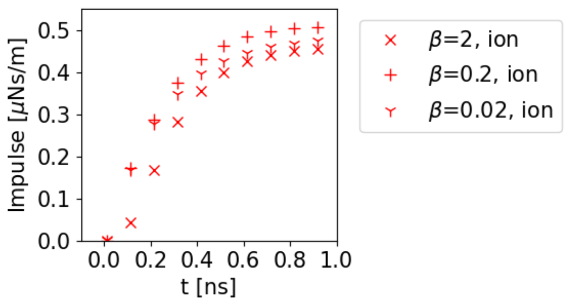

Fig.2: Temporal properties of impulse the case of $\beta =$ (a) 2, (b) 0.2, (c) 0.02.

Table 1: η_{eff}, N_{XMAX}/N, and N_{YMAX}/N at $t = 0.9\ \mathrm{ns}$ in case of β =2, 0.2, 0.02.

β	η_{eff}	N_{XMAX}/N	N_{YMAX}/N
2	75.4%	48.0%	14.2%
0.2	84.2%	69.9%	0.2%
0.02	79.0%	65.3%	0.1%

it increases as β decreases from 2 to 0.2. This is due to that the position where the plasma pressure and magnetic pressure are balanced is pushed in the y-axis direction, and the divergence angle becomes smaller. However, the increase in η_{eff} is about half of that of N_{XMAX}/N. We suspect that N_{YMAX}/N accounts for 14.2%, and particle ejected from $y_{\max}$ boundary also has x component of momentum, resulting in high η_{eff}. When β increases from 0.02 to 0.2, η_{eff} decreases by 5.2% due to the increase of N_{XMAX}/N. The reason may be that particle attachment to the strong magnetic field increase the number of particles ejected from $x_{\min}$ or $y_{\max}$ boundary which have negative v_x.

5. CONCLUSION

2D-3V fully kinetic particle-in-cell calculations were conducted in the case of β =2, 0.2, 0.02, and thrust efficiency is estimated. When β is decreased from 2 to 0.2, η_{eff} increases from 75.4% to 84.2% due to reduction of divergent angle. However, if β decreases from 0.02 to 0.2, η_{eff} decreases to 79.0 % despite smaller divergent angle. In this case, we observed more particles are ejected inverse direction to the thrust. Therefore, we suggest that too strong magnetic field may induces plasma attachment, resulting in decreased thrust. For further investigation, it is necessary to perform simulations by changing the magnetic field strength in detail or changing the system to cylindrical to consider the kinetic theory in θ direction.

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