Numerical Analysis of Magnetic Thrust Chamber System for Laser Fusion Rocket Considering the Creation Process of Laser-Produced Plasma

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The plasma behavior in a magnetic thrust chamber system for a laser fusion rocket is numerically simulated using a three-dimensional (3D) hybrid particle-in-cell (PIC) code and a one-dimensional (1D) radiation hydrodynamic code. The magnetic thrust chamber and an applied magnetic field with a suitable geometry generate an impulse from the interaction between the diamagnetic current in the laser-produced plasma and the magnetic field generated by a magnetic coil. A 1D radiation hydrodynamics code is used to compute the hydrodynamic evolution of a radiating plasma heated by laser beams or external radiation sources. By combining this code and a 3D hybrid PIC code, a series of numerical simulations are performed to investigate high-energy laser injection onto a fuel target and the ablated plasma behavior of the system. A thrust energy of 0.37 J and an impulse bit of 31.6 μNs are obtained for an incident laser energy of 4.0 J. This impulse bit could mostly be generated by interactions between a slowly expanding plasma (expansion velocity of ~ 20 km/s) and a magnetic field. To optimize this system, it is important to reduce the expansion velocity of the laser-produced plasma.

Key Words: Laser Fusion Rocket, Magnetic Thrust Chamber System, Laser-Produced Plasma

Nomenclature

B	: magnetic field
c	: speed of light
c_v	: specific heat
D	: diffusion coefficient
e	: elementary charge
E	: photon energy density
E	: electric field
j	: current density
m	: particle mass
n	: particle density
p	: pressure
q	: artificial viscosity
Q	: source term
t	: time
T	: temperature
v	: velocity
Z	: charge state of ion
α	: thermal relaxation coefficient
η	: emissivity
κ	: thermal conductivity
μ_0	: permeability of vacuum
ρ	: mass density
χ	: absorption coefficient

Subscripts

e	: electron
i	: ion
ν	: frequency group

1. Introduction

In the future, space propulsion systems that can generate large thrusts and high specific impulses (proportional to the exhaust velocity) will be required for manned space flights to Mars. One promising rocket is the laser fusion rocket¹⁻⁴⁾ (LFR), which was first proposed in the 1970s by Hyde.^{1,2)} This rocket employs a magnetic thrust chamber system to generate thrust. It produces an impulse (i.e., momentum per pulse) by generating a diamagnetic current in a laser-produced plasma. Figure 1 depicts the mechanism for producing an impulse in this system of a LFR. It involves the following processes:

- Inertial confinement fusion (ICF) releases large amounts of energy, creating high temperatures and high-density plasmas. The resulting fusion plasma expands in an applied magnetic field with a suitably designed geometry. The magnetic field is typically produced by a solenoid superconducting magnet (SCM).
- Since plasma is a good conductor, the charged particles in the plasma undergo Larmor motion when a magnetic field is applied. This Larmor motion induces the dia-

magnetic current sweeping the magnetic field, which compresses the magnetic field.

- (c). The compressed magnetic field pushes the plasma back in a similar manner to a spring. Consequently, the LFR produces an impulse due to the interaction between the diamagnetic current in the plasma and the magnetic field generated by the SCM.

Fig. 1. Mechanism for producing an impulse in a magnetic thrust chamber of a LFR. (a) Expanding ICF plasma in an applied magnetic field with a suitably designed geometry. (b) Compressed magnetic field and diamagnetic current induced by Larmor motion. (c) Compressed magnetic field pushing the plasma back.

The magnetic thrust chamber system of LFR has the following three advantages. First, this system is suitable for short-duration space missions because this generates large thrusts and high specific impulses. This reduces the amount of cosmic radiation that a crew will be exposed to, which is the greatest problem associated with manned space flight. Second, the thrust of the system can be easily varied during a mission by varying the laser pulse repetition rate, the plasma and magnetic field parameters. This enables the acceleration of the vehicle to be varied flexibly, which is necessary in many missions. Third, LFR has long lifetime since the plasma does not interact directly with the solid wall of the vehicle as it is confined by the magnetic field; thus, the structure of the vehicle is not affected and little plasma energy is wasted, resulting in long lifetime.

Several numerical simulations⁵⁻⁸⁾ have investigated the behaviors of various plasmas in the magnetic thrust chamber system for a LFR. They suffered from Rayleigh-Taylor (RT) instability and electron detachment. Nagamine *et al.*⁵⁾ used a three-dimensional (3D) hybrid particle-in-cell (PIC) code to show that RT instability does not pose a serious problem for a LFR since it will reduce the impulse. Kawabuchi *et al.*⁷⁾ found that electron detachment will occur by using a two-dimensional (2D) coordinate space and a 3D velocity space (2D3V) electromagnetic full PIC code. When electrons do not escape from the magnetic field of the system, a space vehicle cannot generate sufficient thrust since ions will be pulled back to the space vehicle by the charge-separation electric field generated by the motions of the ions and electrons. On the other hand, Vchivokv *et al.*⁸⁾ experimentally observed temporal plasma behaviors in an axially symmetric dipole magnetic field. Using a magnetic probe, they found that a diamagnetic cavity forms in the applied magnetic field. They also used a 3D hybrid PIC code to estimate the impulse.

However, the above numerical simulations were not sufficiently accurate because the above PIC codes can only simulate plasma behavior in a magnetic field. The results obtained by them strongly depend on the initial plasma parameters and distributions, which are input parameters. In these studies, the input parameters used arbitrary plasma parameters (hereafter, referred to as the “Maxwell case”) without considering the

creation process of the laser-produced plasma. To demonstrate a magnetic thrust chamber, it is important to perform simulations from high-energy laser injection onto a fuel target to the ablated plasma behavior in a system.

This study employs a one-dimensional (1D) Lagrangian radiation hydrodynamic code,^{9,10)} which can compute only the hydrodynamic evolution of a radiating plasma heated by laser beams. We attempt to simulate the plasma behavior in the system by inputting the results obtained into a 3D hybrid PIC code. In addition, the results obtained when the creation process for a laser-produced plasma was considered and ignored are compared.

2. Numerical Simulation Methods

2.1. 1D Lagrangian radiation hydrodynamic code

A 1D Lagrangian radiation hydrodynamic code named “Star-1D”¹⁰⁾ was developed by Sunahara. Star-1D can simulate the evolution of a wide variety of high-energy-density laser-produced plasmas. This code uses the one-fluid and two-temperature ($T_i \neq T_e$) model. Plasma is assumed to be quasi-neutrality due to co-moving electrons. Thus, the following equations are solved. Equation (1) is the equation of continuity. Equation (2) is the equation of motion in planar and spherical geometries in which q smooths the shock front. Equations (3) and (4) are energy equations for ions and electrons. The second terms on the right-hand sides of Eq. (3) and (4) represent thermal conduction due to ions and electrons, respectively. The flux-limited Spitzer-Harm model¹¹⁾ with a flux limit of 0.1 is applied. The third term in Eqs. (3) and (4) indicates electron-ion temperature relaxation. α is determined from the Spitzer relaxation time.¹²⁾ Q_i ($=-q \nabla \cdot \mathbf{v}$) is the viscous heat, which is the conversion of kinetic energy to ion thermal energy due to the viscosity. Q_e consists of a laser energy deposition term and a laser heating term for electrons. The laser energy deposited between the vacuum-plasma boundary (expansion surface) and the critical surface is calculated by ray tracing with 100 rays. The critical density is $9.8 \times 10^{20} \text{ cm}^{-3}$. Inverse bremsstrahlung is assumed to occur during the laser energy absorption process. The deposition for each calculation mesh is calculated $P = \exp(-K_a \Delta t)$, where P is the local laser power, K_a is the laser absorption coefficient, and Δt is the time taken for the laser ray to pass through each mesh size at its group velocity. In Eqs. (2) to (5), the variables p_s , c_{vs} , and p_{THs} are functions of n_i and T_s . They are obtained from SESAME equation of state (EOS) tables.¹³⁾ Here, s represents an electron or an ion.

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0 \quad (1)$$

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho} \nabla(p_i + p_e + q) \quad (2)$$

$$\rho c_{vi} \frac{dT_i}{dt} = -p_{THi} \nabla \cdot \mathbf{v} + \nabla \cdot (\kappa_i \nabla T_i) + \alpha(T_e - T_i) + Q_i \quad (3)$$

$$\rho c_{ve} \frac{dT_e}{dt} = -p_{THE} \nabla \cdot \mathbf{v} + \nabla \cdot (\kappa_e \nabla T_e) - \alpha(T_e - T_i) + Q_e \quad (4)$$

$$p_{\text{THs}} = T_s \left(\frac{\partial p_s}{\partial T_s} \right)_\rho \quad (5)$$

Equation (6) is the radiative transport equation. To evaluate the radiation transport process, the multi-group diffusion approximation model using a flux limit is applied (see Eq. (7)). The photon energy $h\nu$ ranges from 0 to 1 keV and is divided into 100 bins for ν to solve Eq. (6) numerically, where h is the Planck constant. η_ν and opacity $\kappa_\nu (= \chi_\nu/\rho)$ are based on the collisional radiative equilibrium (CRE) model. In this model, the plasma is assumed to be optically thin.

$$\rho \frac{d}{dt} \left(\frac{E_\nu}{\rho} \right) - \nabla \cdot (D_\nu \nabla E_\nu) = 4\pi\eta_\nu - c\chi_\nu E_\nu \quad (6)$$

$$D_\nu = \frac{c}{3\chi_\nu + |\nabla E_\nu|/E_\nu} \quad (7)$$

2.2. 3D hybrid PIC code

Nagamine *et al.* developed a 3D hybrid PIC code⁵⁾ to simulate plasma behavior in a magnetic field. This code treats ions as individual particles and electrons as a magnetic hydrodynamic fluid. The basic equations are given below. Equations (8) and (9) are the equations of particle and fluid motion, respectively. m_e is zero because the inertial term is neglected in this code. High-frequency plasma phenomena, the resistivity, electron motions such as electron plasma oscillation and cyclotron motion are also neglected. The plasma is assumed to be quasi-neutral (i.e., $Zn_i = n_e$). T_e is assumed to be zero because the plasma cools as it expands and its inertial energy will be converted into kinetic energy. ∇p_e is also zero from $p_e = n_e k_B T_e$, where k_B is the Boltzmann constant. Equation (10) is given by Ampere's law and $j_i = Zen_i v_i$. The transverse displacement current in Ampere's law is neglected by the Darwin approximation. The ion current density is important since it relates the ion motion to the electromagnetic field. These approaches are valid because the system behavior is dominated by ion physics.

$$n_i m_i \frac{dv_i}{dt} = -Zen_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) \quad (8)$$

$$n_e m_e \frac{dv_e}{dt} = -en_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e \quad (9)$$

$$\mathbf{v}_e = \frac{1}{en_e} \left(\mathbf{j}_i - \frac{\nabla \times \mathbf{B}}{\mu_0} \right) \quad (10)$$

3. Star-1D Numerical Simulation Conditions and Results

3.1. Calculation model of Star-1D

To simulate the laser-produced plasma of a CH target with a diameter of 500 μm , a 1D calculation model for laser ray tracing with a spherical geometry is considered (see Fig. 2(a)). The number of spatial meshes is 500. These meshes are generated radially with widths between 1 and 0.01 μm . They move with the hydrodynamic evolution of the plasma as it is heated by the laser beam. For a CH material, the atomic mass averaged over carbon and hydrogen and the mass density ρ are

assumed to be 6.5 amu and 1.06 g/cm^3 , respectively. The plasma is created by a 1064-nm single-beam neodymium:yttrium aluminum garnet (Nd:YAG) laser with a Gaussian intensity profile. The laser spot size (FWHM: full width at half maximum) is set to be 0.636π steradian on the target surface. In simulating the dynamics of this plasma with a divergence of 0.636π steradian in a 4π steradian spherical geometry, the input laser power is multiplied by 6.29 ($=4\pi/0.636\pi$). The distance between the laser focal point and the target center (origin) is set to 0.5 cm. The energy of a single pulse beam is 0.636 J; i.e., the total laser energy on a spherical target is 4.0 J. Figure 2(b) shows a Gaussian time-variable power profile of a single pulse beam. The simulation start time is set to zero. Star-1D finishes calculations at 75 ns. The peak power of 2.51×10^8 W is obtained at 25 ns. The rise and fall times of the peak are 10 and 20 ns, respectively. The time step Δt is initially set to 0.1 ps and it is subsequently varied according to the Courant Friedrichs Lewy (CFL) condition.

Fig. 2. Calculation model of Star-1D. (a) 1D Lagrangian calculation model for ray-tracing. (b) Gaussian temporal power profile of a single pulse beam.

3.2. Results of Star-1D simulation

Figure 3 shows the Star-1D simulation results at 75 ns. The horizontal axis represents the radius of the laser-produced plasma from the center of plasma. The ablation and expansion surfaces are located at radii of 0.25 and 8.9 mm. The vertical axes represent the 1D ion density, the ion expansion velocity, and the charge state of ions in the plasma. The material between the center and a radius of 0.25 mm is not considered to be ionized because the ion expansion velocity in this region is zero. The absorption energy is equal to the incident laser energy (4.0 J). The plasma has kinetic and inertial energies at 75 ns of 3.3 J (83% of incident laser energy) and 0.28 J (7% of the incident laser energy), respectively. The remaining absorption energy is the heat loss from the expansion surface. The ablated plasma mass is 2.1×10^{-8} kg (30%) for a target mass of 6.9×10^{-8} kg. The ablation plasma expanding into vacuum expands nearly isothermally.^{14,15)} Consequently, the ion expansion velocity increases to 175 km/s and the ion density decreases exponentially, as shown in Fig. 3. The charge state of ions near a radius of 5 mm is rapidly altered by shock waves. To combine with a 3D hybrid PIC code, these results are converted to 3D ion super particle density, expansion velocity, and charge state distributions. A 3D hybrid PIC code was improved to treat a 3D ion super particle charge state distribution as an input parameter to combine Star-1D and a 3D hybrid PIC code.

Fig. 3. 1D ion density, ion expansion velocity, and charge state of ion distributions of laser-produced plasma as a function of plasma radius at 75 ns.

4. Calculation Model of a 3D Hybrid PIC Code

In addition to numerical simulations, experiments were performed at *Osaka University* to observe laser-produced plasma behavior in a magnetic field. In these experiments, a pulsed power supply and an edgewise coil are used to generate a pulsed magnetic field. When the charging voltage is 5 kV, the condenser bank can supply a maximum current of 10 kA with a pulse width of 20 μ s. To model this experiment, the calculation model uses the experimental conditions shown in Fig. 4. The initial laser-produced plasma is located at the center of model. The model is a $100\Delta x \times 100\Delta x \times 100\Delta x$ cube, where $\Delta x=1$ mm is the mesh width. The edgewise coil that generates the magnetic field is formed by winding five turns of a rectangular copper wire (width: 5 mm; thickness perpendicular to the coil axis: 1 mm; external diameter: 18 mm; internal diameter: 8 mm; length: 5 mm). This coil has a high lamination factor, a small temperature difference between the inside and outside of the coil, and a high frequency response. The coil is set at a distance of 6.5 mm from the center. Figure 5 shows the magnetic field strength along the z -axis at $x=y=0$ and in the z - x plane at $y=0$ produced by the coil for a coil current of 5.2 kA. The magnetic field strength at the center is 0.51 T. The calculation start time is set to 75 ns. The calculation time is $100000\Delta t$, where $\Delta t=50$ ps (ion cyclotron frequency $\omega_{ci}=1/2047\Delta t$) is the time step. The simulation finishes at 5.075 μ s. 3D ion super particle distributions for the position and expansion velocity in the laser-produced plasma are inputted into this code. The particles have only expansion velocities; they do not have thermal velocities. The number of particles is 1000000.

5. Numerical Simulation Results for a 3D Hybrid PIC Code for Maxwell and Star-1D Cases

Numerical simulation of a 3D hybrid PIC code is performed for two initial conditions for a laser-produced plasma. The plasma parameters are inputted into a 3D hybrid PIC code. One is the Star-1D case using the results of Star-1D. The other is the Maxwell case using arbitrary plasma parameters (see below).

The 3D ion super particle expansion velocity distribution in the laser-produced plasma is assumed to be Maxwellian, as

Fig. 4. Cubic calculation model for 3D hybrid PIC code.

Fig. 5. Magnetic field strength along the z -axis at $x=y=0$ and in the z - x plane at $y=0$ produced by an edgewise coil with five turns when the current is 5.2 kA. The magnetic field strength at the center is 0.51 T.

shown in Fig. 6. The plasma radius is arbitrarily set to 9 mm. The kinetic energy is 1.2 J for an incident laser energy of 4.0 J since the absorption rate is assumed to be 0.3. The characteristic velocity is assumed to be $\langle v^2 \rangle^{1/2}=4.8$ km/s. The plasma mass is equal to the target mass (6.9×10^{-8} kg) since all the target is assumed to be ionized. The ion density is assumed to be uniform; $n_i=2.1 \times 10^{18}$ cm $^{-3}$ since the plasma radius is 9 mm and the mass density is 1.06 g/cm 3 . The charge state of the ions $\langle Z \rangle$ is 1.25 ($=C^{4+}+H^+/4$), since the ionization rate is assumed to be 0.5. Table 1 lists the characteristic plasma conditions for the Maxwell and Star-1D cases.

Fig. 6. Maxwell super particle velocity distribution for the Maxwell case. The characteristic velocity is assumed to be $\langle v^2 \rangle^{1/2}=4.8$ km/s.

Table 1. Plasma conditions for Maxwell and Star-1D cases.

	Maxwell case	Star-1D case
Kinetic energy, J	1.2	3.3
Plasma mass, kg	6.9×10^{-8}	2.1×10^{-8}
Ion density, cm $^{-3}$	2.1×10^{18}	see Fig. 3
Ion expansion velocity	Maxwell distribution	see Fig. 3
Charge state of ion	1.25	see Fig. 3

5.1. Time evolution of magnetic field

Figure 7 shows the magnetic field strength distribution in the z - x plane at $y=0$ of the calculation model at calculation times of 325, 575, 825 ns, 1.075, 1.325, 1.575, 3.075 and 3.575 μ s for the Maxwell case. Comparison with the initial magnetic field shown in Fig. 5 reveals that the magnetic field disappears inside the area indicated by the red circle in Fig. 7(a). The diamagnetic current forms a diamagnetic cavity in the magnetic field. Figures 7(a)-(d) show that the magnetic field returns to the initial magnetic field up to 3.575 μ s and that the cavity moves in the $+z$ direction by pushing the plasma back. Figure 8 shows the magnetic field strength distribu-

tion in the z - x plane at $y=0$ at calculation times of 1.325, 2.575, 3.825 and 5.075 μ s for the Star-1D case. Comparison with the initial magnetic field shown in Fig. 5 reveals that the magnetic field disappears inside the area indicated by the red circle in Fig. 8(a). The diamagnetic current forms a diamagnetic cavity in the magnetic field. Figures 8(a) and (b) show that the magnetic field returns to the initial magnetic field up to 5.075 μ s and that the cavity moves in the $+z$ direction by pushing the plasma back. The cavity size in Fig. 8(a) is larger than in Fig. 7(a). This indicates that the diamagnetic current in the laser-produced in a magnetic field generated by a coil is much larger than the Maxwell case.

Fig. 7. Magnetic field strength distribution for Maxwell case in z - x plane at $y=0$ for calculation times of 325, 575, 825 ns, 1.075, 1.325, 1.575, 3.075, and 3.575 μ s. A diamagnetic cavity forms in the magnetic field by the diamagnetic current.

Fig. 8. Magnetic field strength distribution for Star-1D case in z - x plane at $y=0$ for calculation times of 1.325, 2.575, 3.825, and 5.075 μ s. A diamagnetic cavity forms in the magnetic field by the diamagnetic current.

5.2. Thrust energy and impulse bit

The efficiencies in terms of the kinetic energy η_{kin} and the momentum η_{lbit} are calculated using Eqs. (11) and (12), where $v_{\pm z}$ is the velocity of a super particle which moves in the $\pm z$ direction. The sums are performed over all super particles. Figure 9 shows the time evolutions of the thrust energy and the impulse bit for the Maxwell and Star-1D cases.

$$\eta_{kin} = \frac{\sum \frac{1}{2} m_i v_{1z}^2 - \sum \frac{1}{2} m_i v_0^2}{\sum \frac{1}{2} m_i v_0^2} \quad (11)$$

$$\eta_{lbit} = \frac{\sum m_i v_z - \sum m_i v_{z0}}{\sum m_i |v_{z0}|} \quad (12)$$

For Maxwell case, the thrust energy increases gradually up to 3 μ s, after which it saturates at 0.36 J; the final efficiency η_{kin} is 31%. In a similar fashion, the impulse bit increases and saturates at 151 μ Ns; the final efficiency η_{lbit} is 41%. For the Star-1D case, the thrust energy increases rapidly up to 200 ns, after which it saturates at 0.37 J (12%). In a similar fashion, the impulse bit increases and then saturates at 31.6 μ Ns (41%). Figure 9 indicates that the direction of movement of many super particles is changed to the $+z$ direction by the magnetic field of the coil, as shown in Figs. 7 and 8. The plasma behaviors (including the time-variable magnetic field, thrust energy, and impulse bit) of the two cases exhibit a time difference.

6. Discussion

We compare the results obtained with and without considering the creation process of a laser-produced plasma. The

thrust energy and impulse bit for the Maxwell case increase gradually, whereas those for the Star-1D case increase rapidly. We focus on the slow expansion velocity in the range 0-20 km/s. In this region, the charge state of ions and the ion density are almost same for the two cases.

In the Maxwell case, the super particles in the slow expansion velocity region (see Fig. 6) can easily interact with the magnetic field since the interaction time is long. Consequently, the impulse bit is larger than that for Star-1D.

In the Star-1D case, super particles in the initial plasma can be divided into two groups: group A has a slow expansion velocity of about 20 km/s (kinetic energy: 0.027 J), while group B has a fast expansion velocity in the range 20-175 km/s (kinetic energy: 3.0 J). Figure 10 shows the thrust energy and impulse bit of these groups. For the B group (see Fig. 10(b)), the thrust energy and impulse bit increase rapidly up to 200 ns, after which they saturate at 0.34 J (11%) and 7.5 μ Ns (14%), respectively. The particles in the B group are too fast to push back against the magnetic field. They do not interact with the magnetic field; rather they expand the magnetic field. Consequently, the diamagnetic current in the laser-produced plasma will produce a much larger magnetic field than that of the Maxwell case (see Figs. 7 and 8). For group A (see Fig. 10(a)), the thrust energy and impulse bit increase slowly up to 1.5 μ s, after which they saturate at 0.0337 J (125%) and 24.1 μ Ns (102%), respectively. The reason for high efficiency is that the interaction force is enhanced by the diamagnetic cavity produced by the B group. There is a time lapse of 1.5 μ s before the particles in the A group interact with the magnetic field. The super particles in the slow expansion velocity region can easily interact with the magnetic field since the interaction time is long.

Fig. 9. Time evolutions of thrust energy and impulse bit. For Maxwell case, thrust energy and impulse bit saturate at 0.36 J (31%) and 151 μ Ns (41%), respectively. For Star-1D case, thrust energy and impulse bit saturate at 0.37 J (12%) and 31.6 μ Ns (41%), respectively.

Fig. 10. Time evolutions of thrust energy and impulse bit for the Star-1D case. For group A, thrust energy and impulse bit saturate at 0.0337 J (125%) and 24.1 μ Ns (102%). For group B, thrust energy and impulse bit saturate at 0.34 J (11%) and 7.5 μ Ns (14%), respectively.

7. Summary

A series of numerical simulations were performed for high-energy laser injection onto a spherical target for ablated plasma behavior in a magnetic thrust chamber system for a LFR by combining a 1D Lagrangian radiation hydrodynamic code and a 3D hybrid PIC code. The results obtained (Star-1D case: considering the creation process of the laser-produced plasma) were compared those of previous studies (Maxwell case: without considering the creation process of the laser-produced plasma).

In both cases, a diamagnetic cavity forms in the magnetic field due to the diamagnetic current of the laser-produced plasma. The magnetic field returns to the initial magnetic field up to 3.575 μ s for the Maxwell case and up to 5.075 μ s for the Star-1D case, while the cavity moves in the +z direction by pushing the plasma back. The diamagnetic cavity for the Maxwell case is larger than that for the Star-1D case. The high expansion velocity region of the Star-1D case has velocities in the range 20-175 km/s; the super particles do not interact with the magnetic field but rather expand it. Consequently, the diamagnetic current in the laser-produced plasma in the magnetic field generated by the coil is much larger than that of the Maxwell case.

The thrust energy and impulse bit saturate at 0.36 J (31%) and 151 μ Ns (41%) for the Maxwell case. The thrust energy and impulse bit saturate at 0.37 J (12%) and 31.6 μ Ns (41%) for the Star-1D case. These results suggest that the thrust energy and impulse bit have previously been overestimated.

The expansion velocity of the plasma was found to greatly affect these phenomena. In the Star-1D case, the thrust energy and the impulse bit saturate at 0.0337 J (125%) and 24.1 μ Ns (102%) for group A, respectively. The thrust energy and the impulse bit saturate at 0.34 J (11%) and 7.5 μ Ns (14%) for group B. The reason for the high efficiency is that the interaction force is made enhanced by the diamagnetic cavity produced by group B.

To optimize the thrust energy and the impulse bit in a magnetic thrust chamber for a LFR, the interaction region between the magnetic field and the plasma needs to be enlarged by using a larger coil or the velocity of the fast velocity group must be reduced by some other means. We intend to investigate the parameters for reducing the plasma expansion velocity.

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