A Magnetic Thrust Chamber Design For A Laser Fusion Rocket Based on Impact Fast Ignition Scheme

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(Received: 4 September 2008 / Accepted: 4 December 2008)

The laser fusion rocket, which is expected as a rocket that it replaces one of the chemical propulsions, can be efficiently operated by using a shaped target. The shaped target is made of fusion pellet and the pellet is surrounded by a moderator (propellant). We here examine the applicability of the impact fast ignition scheme to the shaped target. It was found that it is difficult to increase the thrust efficiency by using a simple spherical moderator.

Keywords: Magnetic Thrust Chamber, Laser Fusion Rocket, Shaped Target, Impact Fast Ignition

1.Introduction

The laser fusion rocket (LFR) is an innovative idea proposed by Hyde et al. [1] and it is an important subject of research for future interplanetary missions since it could provides both large specific impulse and power. A fusion reaction can release a large amount of energy and easily produce plasma of high temperature and density. The resulting plasma flow can be controlled by properly designed applied magnetic field configuration, i.e., a magnetic thrust chamber. In the laser fusion rocket, the chamber is composed of a solenoidal superconducting coil.

The fusion reaction occurs by irradiation of a laser onto a fuel pellet and the resulting plasma expands isotropically. The plasma is a good electrical conductor, so when a magnetic field is applied, the plasma particles move around the magnetic field, i.e., Larmor motion starts. This circular motion induces diamagnetic currents, sweeping aside the field of the chamber. The compressed field, however, pushes against the plasma, and finally redirects the plasma to produce thrust (Fig.1). Thus the laser fusion rocket could realize very high exhaust plasma velocities when compared to existing systems. This fact makes the laser fusion rocket a promising candidate for interplanetary transport system.

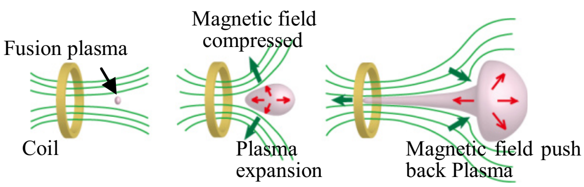

Fig.1 Magnetic thrust chamber

One of the laser fusion rocket concepts, called VISTA (Vehicle for Interplanetary Space Transport Applications), was proposed by Orth *et al.* [2]. This vehicle uses deuterium-tritium fusion. Its specific impulse is 17,000 s with a thrust efficiency about 60% (Fig.2).

A method of changing the magnetic configuration has been studied to improve the thrust efficiency of laser fusion rocket. Sakaguchi *et al.*[3] have used two coils, a rear coil being added to improve thrust efficiency, and they have obtained an improvement of thrust efficiency reaching 75%. Kajimura *et al.* examined how a thrust vector varies with changing positions of the fusion explosion [4].

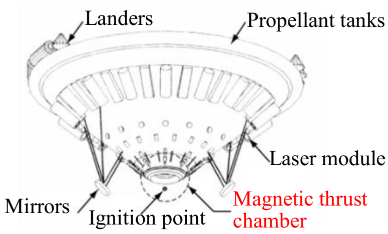

Fig.2 Laser fusion rocket VISTA

Recently we have studied a method of achieving a higher thrust efficiency with a shaped target for the laser fusion rocket [5].

2.Shaped Target

The shaped target is made of fusion pellet and the pellet is surrounded by a moderator (propellant). Plasma generated by laser fusion in the pellet collides with the moderator to produce a larger plasma. When the moderator is shaped by cutting the part of the moderator in the direction of the magnet coil (that composes the magnetic thrust chamber), the resulting high energy plasma blows off in the direction of the coil and increases the thrust efficiency (Fig.3).

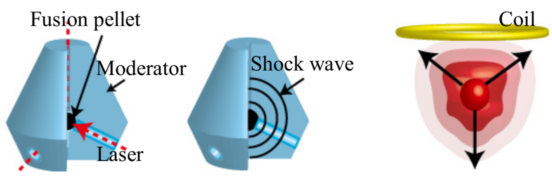

Fig.3 Expansion process for a shaped target

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In this paper we used smoothed particle hydrodynamics (SPH) code [6] for calculation of the collision between the plasma and the moderator, and three dimensional (3D) hybrid code for analyzing the plasma behavior in the magnetic field. In the SPH code, the fluid is represented by particles. 3D hybrid code is a calculation method which treat ions as particles and electrons as a fluid.

The thrust efficiency η is estimated by the following expression.

$$\eta = \frac{\sum mv_z(Total \quad Z \quad direction \quad momentum)}{\sum mv_0(Total \quad initial \quad momentum)} \qquad (1)$$

, where m is the plasma mass, v_z the plasma velocity in the direction of Z and v_0 the initial plasma velocity.

We have calculated two kinds of moderator to improve the thrust efficiency; shaped moderator and unshaped one. Energetic particles from the fusion pellet are located at the center, and the 1cm-thick moderator (Hydrogen) is placed around the fusion pellet (Fig.4). As a result of calculation, the thrust efficiency was 78 % with the shaped moderator, while it was only 66 % when the moderator was not shaped, i.e., spherical moderator.

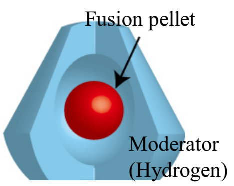


Fig.4 Shaped target

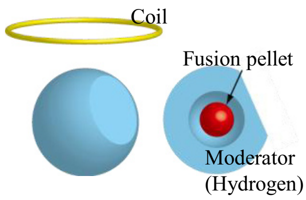


Fig.5 Shaped target for direction control

In addition, we have tried to control traveling direction by using a shaped target. We cut a part of the moderator to lose the symmetry of the expansion of plasma (Fig.5). As the result, we found that we were able to control the direction [5].

3.Impact Fast Ignition Scheme

The impact fast ignition scheme was proposed by The Institute of Laser Engineering, Osaka University [7]. The concept is very simple. The compressed deuterium (D) - tritium (T) main fuel is ignited by impact collision of another fraction of separately imploded DT fuel, which is accelerated in the hollow conical target to hyper-velocities in the order of 10^8 cm/s. Its kinetic energy is directly converted into thermal energy corresponding to temperatures > 5 keV on the collision with the main fuel, and this self-heated portion plays the role of ignitor (Fig.6).

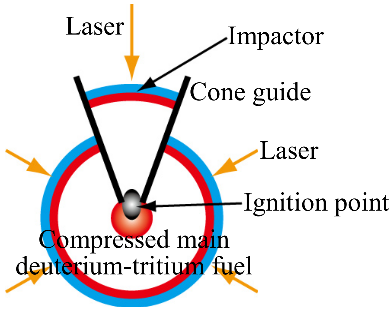


Fig.6 Initial target structure of the impact ignition target overlapped with the compressed fuel image at maximum compression.

The feature of impact fast ignition scheme is that the main physics is simple, and high energy laser such as MJ laser is unnecessary [7].

Then, we here examine the applicability of the impact fast ignition scheme to the shaped target.

4.Numerical Model and Result

4.1 Reference Model

Figure 7 is a reference model taken up here for the shaped target that adopts the impact fast ignition scheme.

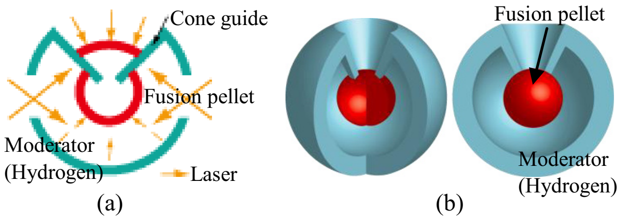


Fig.7 (a) Initial target structure
(b) Initial sate for SPH calculation

It is found from SPH calculation that a jet is produced as shown in Fig.8.

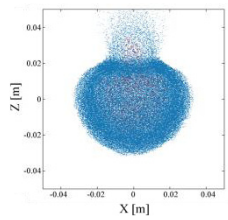


Fig.8 Result of SPH Calculation

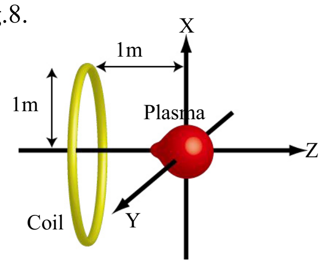


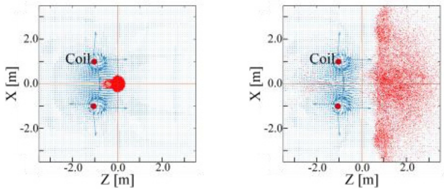
Fig.9 Numerical model

Figure 9 is a computational model for 3D hybrid calculation, and the parameters are shown in Table.1.

Table.1 Computational Condition

Coil radius [m]	1.0
Coil current [A]	3.57×10^6
Coil position along Z [m]	-1.0
Plasma coordinate [m]	(0,0,0)
Plasma mass [mg]	100
Time step Δt [nsec.]	0.277
Calculating area [m]	12.0×12.0×14.0
Number of mesh	120×120×140
Number of particles	100,000

The calculation result is shown in Fig.10. The thrust efficiency η was estimated to be 62 %. The reason why the thrust efficiency is lower than the spherical moderator case is that the plasma jet coming through the center of the coil was not deflected by the magnetic field.



(a) (b)

Fig.10 Plasma particle positions

(a) initial (b) at 11.08μsec.

4.2 Inclined Target

Then, we inclined the target by 45 degrees (Fig.11). The computational conditions are the same as in Table 1. In this model, the jet will be deflected by the strong magnetic field in the direction of the coil. In addition, it seems easier to irradiate the fuel target with the laser system laterally to induce the nuclear fusion reaction.

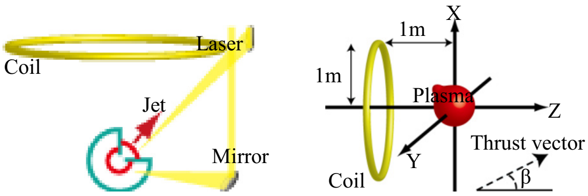
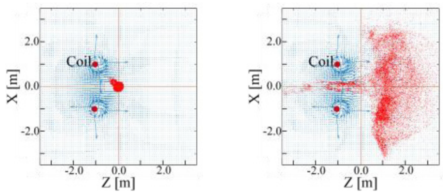


Fig.11 Numerical model



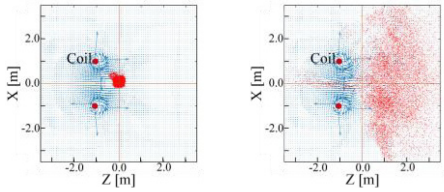
(a) (b)

Fig.12 Plasma particle positions

(a) initial (b) at 11.08μsec.

The thrust efficiency was found to be 61 %. The reason why the thrust efficiency decreases is that the number of particles that come through in the direction of -Z does not decrease so much, and the number of particles with large momentums in the direction of +X has increased.

Next, we moved the inclined target in the X direction by 10 cm. Figure 13 shows a result of calculation. The thrust efficiency was 64 %. The fraction of particles which come through in the direction of –Z is 4.5 % for the inclined target and 3.5 % when the target was moved. This decrease of the fraction increases the thrust efficiency from 61 to 64 %. However, the thrust efficiency has decreased when we moved the target further.



(a) (b)

Fig.13 Plasma particle positions

(a) initial (b) at 11.08μsec.

To decrease the expansion of plasma in the -X direction, we made a thicker part of the target to slow down the expansion speed of plasma and deflect the plasma (Fig.14). The result of calculation is given in Fig.15.

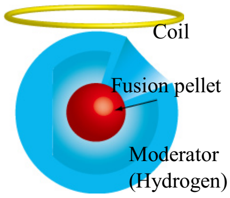


Fig.14 Shaped target to slow down the expansion speed

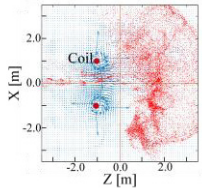


Fig.15 Result of Calculation

The thrust efficiency was found to be 67 %. The reason why the thrust efficiency has increased is that the number of particles with larger momentums in the direction of +Z has increased.

4.3 Usage of Rectangle Coil

In our past research, our group has proposed to use rectangle coils as a coil system for the magnetic thrust chamber [8]. When we use several rectangle coils, we can control the thrust vector easily by adjusting the currents of several coils and by producing a non-axisymmetric magnetic field configuration. Here, calculations are conducted for two cases where the ratios between upper coils current (I_U) and lower one (I_L), I_L/I_U are1.0 and 0.5. (Fig.16)

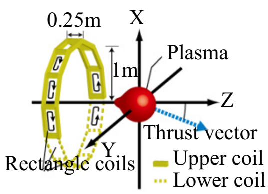
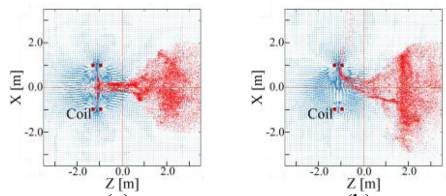


Fig.16 Numerical model

Table.2 Computational condition

Rectangle coil size [m]	0.25 ×0.536
Number of coil	12
Upper coil current [A]	32
Lower coil current [A]	16,32
Plasma coordinate [m]	(0,0,0)
Plasma mass [mg]	100



(a) (b)

Fig.17 Plasma particle positions

(a) I_L/I_U=1.0 and (b) I_L/I_U=0.5

The thrust efficiency was 71 % when I_L/I_U=1.0 and 74 % when I_L/I_U=0.5.

Next, we conducted the calculation for the inclined target as in Sec.4.2 (Fig. 18).

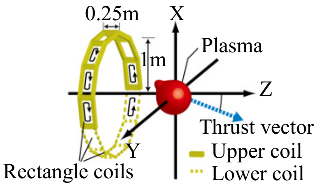
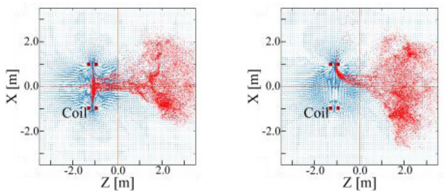


Fig.18 Numerical model



(a) (b)

Fig.19 Plasma particle positions
(a) I_L/I_U=1.0 and (b) I_L/I_U=0.5

The thrust efficiency was 70 % when I_L/I_U=1.0 and 75 % when I_L/I_U=0.5. As a result of the calculation, we have obtained the highest value for the efficiency. Especially when the ratio of the coil currents I_L/I_U is 0.5, the fraction of particles which come through in the direction of –Z is only 0.01 %.

4.4 Conical Target

As previously mentioned, we were able to improve the thrust efficiency by using the shaped target of Fig.4. Then, we take up the model which is applied to the impact fast ignition scheme (Fig. 20).

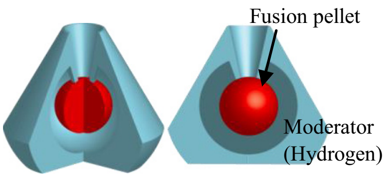
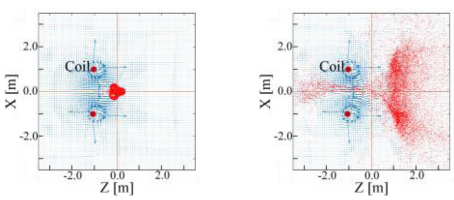


Fig.20 Shaped target



(a) (b)

Fig.21 Plasma particle positions
(a) initial (b) at 11.08μsec.

However, it is found from calculation that the thrust efficiency has decreased to 53 %. We think that the reason is attributable to an increase of particles which come through in the direction of –Z. The fraction of them was 10 %, and it was the largest value among these models.

5.Conclusion

Here, we have taken up the model that adopts the impact fast ignition scheme and it was found, from SPH and 3D hybrid calculations, that it is difficult to increase the thrust efficiency by using a simple spherical moderator.

Although the shaped target model increases the thrust efficiency, the efficiency has decreased when the impact fast ignition scheme was introduced.

The numerical model which used the rectangle coil obtained a high value for the thrust efficiency. In the case where we use rectangular coils to generate the magnetic field, even if the speed of the particle that expands as jet is fast and the particle moves toward the –Z direction, the fraction of particles which come through the coil is very low. Therefore, the high thrust efficiency can be expected and the influence of those particles on the spaceship structure can be decreased.

We are planning to design a new target model for the impact fast ignition scheme.

6.References

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