Some Design Aspects of Laser Fusion Rocket

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Abstract

A rocket powered by a laser-induced fusion microexplosion is an attractive spacecraft for manned exploration of the solar systems, because it has potential advantages of high specific impulse and low specific mass, relative to chemical rockets.

We discuss here fusion pellet design and describe a magnetic nozzle concept for thrust conversion.

The main purpose of the present study is to obtain the data base that makes a viable rocket design possible.

As for fusion pellet employing advanced fuel, it seems difficult to obtain a high pellet gain with a reasonable driver energy. Thrust chamber utilizing a magnetic nozzle could efficiently convert plasma energy into thrust.

1. Introduction

Fusion rockets have potential advantages over conventional rockets such as chemical ones. These advantages include(1)high characteristics exhaust velocity (or specific impulse),(2)high engine thrust-to-weight ratio, (3)high power level and(4)long mission life. These features make the fusion rockets potentially attractive for manned exploration of the solar systems.

In a conceptual design study by Hyde(Ref.1), the fusion rocket could permit missions ranging from occasional 9 days "VIP"service to Mars, to routine 1 year, 1500ton, Plutonian cargo runs. Recently, Orth et al. (Ref.2) have extented Hyde's concept and proposed a new spacecraft concept called VISTA which will be capable of manned Mars missions with a payload of 100 tons, and a total mission duration of roughly 100 days, including a stay on the planet of about 10 days.

Figure 1 shows the schematic layout of the fusion rocket which derives thrust from laser-induced fusion microexplosion. The mass and energy flow are given in Fig.2. Fusion pellets are injected into a magnetic thrust chamber. At the same moment ,the laser is fired to induce the microexplosion in the pellets. The resulting fusion output is converted into thrust. Some of the fusion energy is picked up to power-supply the laser for next shot. The waste heat arising from inefficiences in the driver and power systems is ejected by a heat pipe radiator.

This paper discusses some design aspects of a laser fusion rocket. Included are preliminary discussions of the design for two major components of the rocket-fusion pellet and thrust chamber. The main purpose of the present study is to obtain the data base that makes a viable rocket design possible.

2. Fusion Propulsion System

Fusion pellet

The pellets considered here are DT ignitor and DD major fuel (DT/DD) pellet and DT/D^{3}He one (Fig.3). We take up here these advanced fuel pellets because they have advantages of (1)low

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ignition temperature of 4 kev, comparable to a pure DT pellet, and(2)large hot-plasma fraction. The energy deposited in hot plasma can potentially be converted to thrust by a magnetic nozzle as described later. A typical value of the fraction is ~60% for the DD pellet and ~70% for the D^3He pellet(Ref.3).

According to the work of Rosen and Lindl(Ref.4)done on a DT pellet, we have obtained a pellet gain(defined as the ratio of fusion energy to laser energy)for the DT/DD pellet as a function of laser driver energy. The starting point is an assembled DT/DD fuel configuration,i.e., one that is about to burn as shown in Fig.3. A hot-DT ignitor region (hot spot)of radius R_H is surrounded by nearly Fermi-degenerate(cold)DT fuel of radius R_{CDT} and cold DD fuel of radius R_{DD}. (Once the DT ignitor core is ignited by a small central spark having a temperature of several keVs, the surrounding DD or D^3 He fuel is heated to sufficiently high temperature to ignite the DD or D^3He fuel through the bootstrap process by charged particle heating and neutron heating.) The assembly is assumed to have internal energy ηE, where E is the original driver energy and η represents a coupling efficiency. Figure 3 also shows variation of ρ(density), P(pressure) and T(temperature)with R(radius) in the Meyer-Ter-Vehn(MTV)model. The isobaric MTV model enforces a constant pressure throughout the assembled fuel.

The pellet gain G is given by

$$G = \frac{f_{DT} q_{DT} M_{CDT}}{E} + \frac{f_{DD} q_{DD} M_{DD}}{E} \quad (1)$$

,where q_{DT}=339 is the fusion output from DT reaction in units of MJ/mg, while q_{DD}=345 MJ/mg from DD reaction. M_{CDT} is the cold fuel mass of DT and M_{DD} that of DD, respectively.

The burn-up fraction is given by

$$f_{DT} = \frac{\rho R}{6.3 + \rho R} \quad \text{for DT fuel} \quad (2)$$

and

$$f_{DD} = \frac{\rho R}{65 + \rho R} \quad \text{for DD fuel(Ref.3), respectively} \quad (3)$$

,where ρR is the total sum of the density-radius product, expressed in g/cm^2,

$$\rho R = (\rho R)_H + \rho_{CDT}(R_{DD} - R_H) \quad (4)$$

,where again $(\rho R)_H$=0.4g/cm^2 is assumed for the hot spot.

The gain calculated by eq. (1) is shown in Fig.4, as a function of χ where the parameter χ is defined as

$$\chi = \frac{R_{CDT}}{R_{DD}} \quad (5)$$

,indicating a DT fuel fraction of the pellet. α(the factor by which the cold fuel is non-degenerate)=2, and η=0.1 are assumed in the gain calculation. The gain is degraded from that of pure DT pellet (χ=1) as the DD fraction increase. (i.e., as χ decreases).

We also performed implosion-burn simulation to check the gain curve by employing 1D hydro code MEDUSA(Ref.5). During the simulation, We found it very difficult to obtain ρR value above 10g/cm^2 with a reasonable driver energy such as a few tensMJ for a direct drive target. Such a high value of ρR is necessary for efficient burn of advanced fuel pellet(Ref.3)and then for high gain. Thus, we feel that the development of new target design is a crucial factor for realization of fusion rocket.

MEDUSA code is now being modified to include such important process as suprathermal fusion, transport of recoil ions after neutron and proton nuclear scattering. These process will affect the burn performance of the advanced fuel pellet.

Moderator

The exhaust power of the rocket is expressed as

$$P = \frac{1}{2} a w M \tag{6}$$

,where a is the acceleration, w exhaust velocity,M mass of the rocket. Since P is constant during the time of propulsion, the acceleration is adjustable for each mission by changing the w. This change in w can be accomplished by placing excess propellant mass ,i.e., moderator outside of the fusion pellet as shown in Fig.5. The extra material lower the exhaust velocity of the pellet, while increasing its impulse, thus, the accerelation of the rocket.

Thrust chamber

The thrust chamber adopts a magnetic nozzle concept for efficiently converting the hot plasma from the fusion pellet microexplosion into thrust. The plasma is a good conductor, so when the magnetic field is applied, the plasma particles move along a magnetic field line, i.e., Larmour motion starts. This circular motion induces diamagnetic current, sweeping aside the field of the chamber. The compressed field, however pushes on the plasma, and finally redirects the plasma to produce thrust.

Thus, the main concerns of the present study are focused on the interaction between the hot plasma from the pellet microexplosion and the moderator mass, and the interaction between the resulting low speed plasma and the magnetic field in the thrust chamber. We will also compare the spherical moderator and shaped one which can concentrate the momentum towards a specified direction.

A two dimensional(r-z)fluid particle-in-cell-(PIC)code is written to analyze the interaction between the hot plasma and the moderator, and the resulting output such as location of plasma particle, and their speeds are the input to a two-dimensional collisionless PIC code, which can treat the interaction between the low speed plasma and the magnetic field to estimate the thrust conversion efficiency.

Collisionless PIC code

Accoding to the work by Dickman, et al.(Ref.6), the electromagnetic fields are assumed to be entirely described by the θ component of the magnetic vector potential A_θ, which means that the magnetic field components B_r and B_z and the inductive electric fields E_θ are computed, but B_θ and all electrostatic fields are assumed to be zero.

A_θ is computed from the Maxwellian field equation which is

$$\frac{\partial}{\partial r}\frac{1}{r}\left[\frac{\partial (rA_\theta)}{\partial r}\right] + \frac{\partial^2 A_\theta}{\partial z^2} = -\frac{4\pi}{c} J_\theta \tag{7}$$

The motions of plasma particles are followed according to the equation given by

$$m\frac{dv_r}{dt} = \frac{q}{c} v_\theta B_z \qquad \text{for r-component} \tag{8}$$

$$m\frac{dv_z}{dt} = -\frac{q}{c} v_\theta B_r \qquad \text{for z-component} \tag{9}$$

The θ-component of velocity V_θ for each particle is obtained directly from the conservation of its canonical angular momentum P_θ,

$$P_\theta = mr\left(v_\theta + \frac{q}{mc} A_\theta\right) = const. \tag{10}$$

The θ-motion of the plasma particle induces the current given by

$$J_\theta = \frac{q v_\theta}{V_c} = \frac{q P_\theta}{mr V_c} - \frac{q^2 A_\theta}{mc V_c} \tag{11}$$

, where V_c is the cell volume.
When eq(11)is substituted into the implicitly differenced form of eq(7), the resulting set of coupled equations for A_θ is solved by MICCG method(Ref.7). B_r and B_z are computed from

$$B_r = -\frac{\partial A_\theta}{\partial z} \tag{12}$$

$$B_z = \frac{1}{r}\frac{\partial}{\partial r}(rA_\theta) \tag{13}$$

We used here the collisionless PIC code in calculating thrust conversion efficiency because, for a typical plasma ($n=3\times10^{21}cm^{-3}$, T=100eV) resulting from the interaction between the hot plasma and moderator, N_D, the number of particles in a Debye cube, is ~30(Ref.8), implying that the plasma is collisionless.

3. Results and Discussions

As a sample calculation, the following parameters are adopted :Fusion pellet, plasma energy=1280MJ, X-ray energy=330MJ, Moderator, 8.3gm hydrogen. Given the above input parameters, the thrust conversion efficiency is calculated by combination of the fluid and collisionless PIC codes for the geometry shown in Fig.6.

The vector potential and locations of particles at 11 μsec after microexplosion are given in Fig.7.

A thrust conversion efficiency of~50% is finally obtained with a single coil (No.1). When a second coil(No.2)is added for supression of the plasma motion along the axis,the efficiency is increased to 60%.

As an alternative method to increase the conversion efficiency, the moderator is shaped from spherical geometry to the one which could concentrate the momentum towards the coil region(θ° =60°). (θ is measured from the Z axis as indicated in Fig.8.) The shaped moderator is formed by cutting out the θ=60° and 180° sections from the spherical geometry to blow off the plasma from these sections. The locations of plasma particles at 66.2nsec after microexplosion as calculated by fluid PIC code are shown in Fig.9.

Figure 10 compares the momentum distribution between the spherical and shaped moderators. It is clear from this figure that the momentum is concentrated around θ=60° in the shaped moderator. Figure 11 shows the particle locations and vector potential at 8.10 μsec for the shaped moderator case.

By this shaping, improvement of efficiency is calculated to be~10%.

The energy used to excite the laser is extracted from the microexplosion by a pickup coil. As the expanding plasma wave compresses the confining magnetic field, a voltage is induced in the pickup coil. For arrangement of the pick up coil given in Fig.6, the extracted energy is estimated to be~12MJ.

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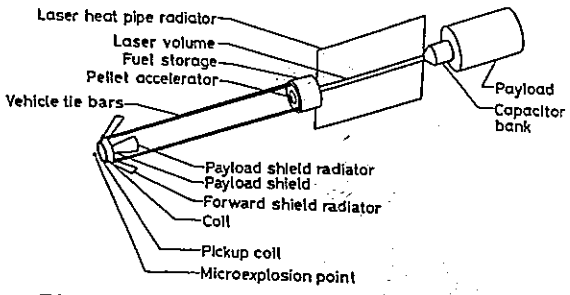


Fig.1 Schematic layout of laser fusion rocket

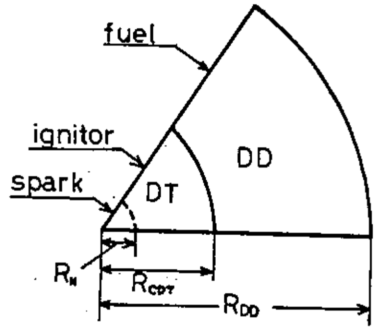


Fig.3 Configuration of DT/DD pellet

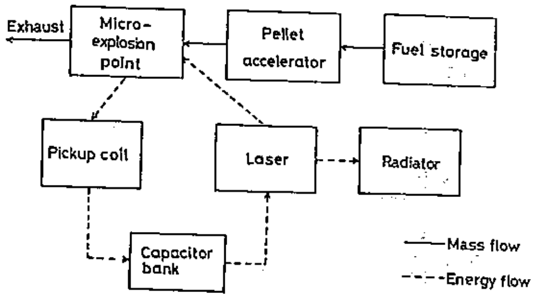
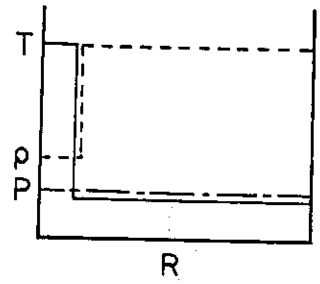


Fig.2 Mass and energy flow diagram in laser fusion rocket



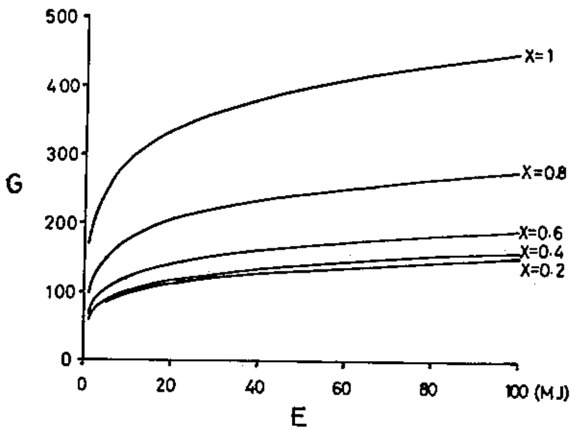


Fig.4 Pellet gain for DT/DD pellet

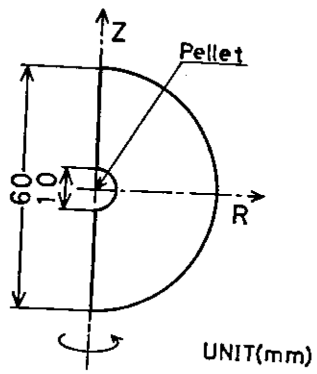


Fig.5 Spherical moderator

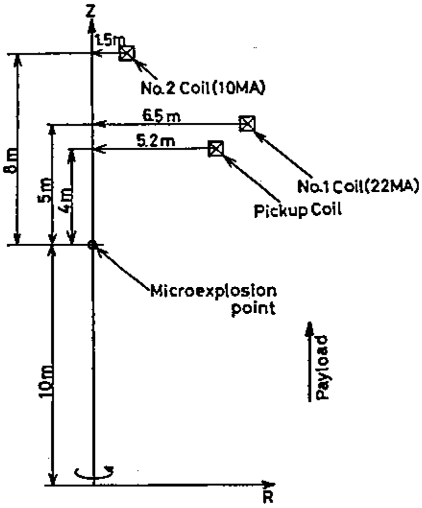


Fig.6 Calculational geometry

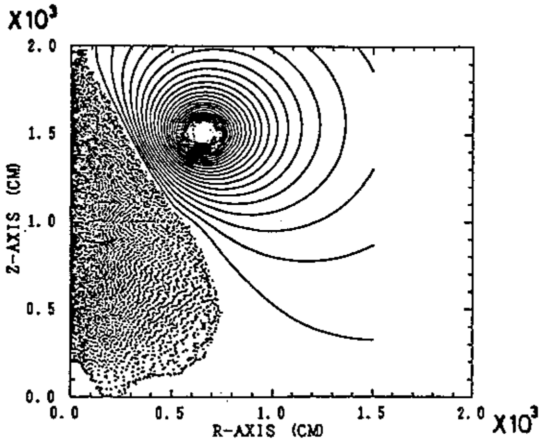


Fig.7 Vector potential and location of plasma particles at 11 μsec after microexplosion(spherical moderator)

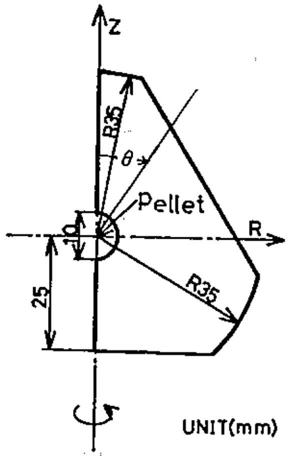


Fig.8 Shaped moderator

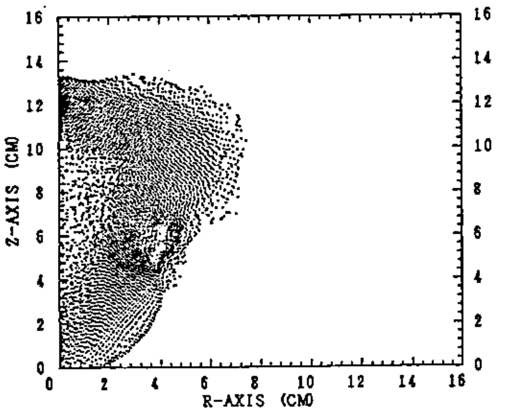


Fig.9 Location of plasma particles at 66.2nsec

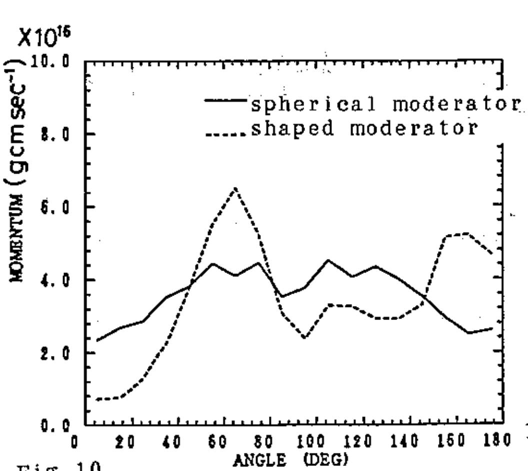


Fig.10
Comparison of momentum distribution

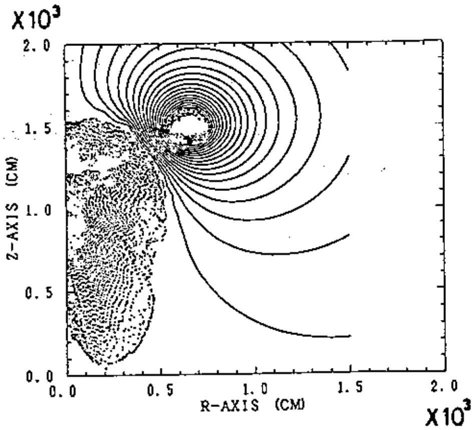


Fig.11 Vector potential and location of plasma particles at 8.1 μsec (shaped moderator)