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A LASER FUSION ROCKET BASED ON FAST IGNITION CONCEPT

Hideki Nakashima, Yoshihiro Kajimura
Department of Advanced Energy Engineering Science
Kyushu University, Japan
nakasima@aees.kyushu-u.ac.jp
Yasuji Kozaki
Institute of Laser Engineering
Osaka University, Japan
Yuri P. Zakharov
Institute of Laser Physics, Novosibirsk, Russia

A propulsion system driven by a laser-induced fusion called laser fusion rocket (LFR) is an attractive candidate for future interplanetary missions since it could provide both large specific impulse and power. So far, some conceptual design studies have been performed based on a conventional fusion ignition scheme [i.e. central ignition (CI) scheme]. We here propose a LFR design based a new scheme - fast ignition (FI) scheme. The scheme is based on recent experimental and theoretical researches which show that a high gain is achievable with small laser energy. When viewed from a propulsion standpoint, such facts could realize a very compact LFR. In this paper, we show the masses contributed by main components such as thrust chamber, laser driver, etc. for the new design and compare the results from the conventional design. It is found that a reduction by a factor of 7 in power plant (dry) mass is possible with fast ignition scheme as compared to the conventional central ignition scheme with concomitant reduction of the scale as shown for the coil radius (13m in CI vs. 5m in FI).

1. Introduction

A propulsion system driven by a laser-induced fusion called laser fusion rocket (LFR) is an innovative concept and it is an attractive candidate for future interplanetary missions since it could provide both large specific impulse and power. So far, some conceptual design studies have been performed for LFR based on a conventional fusion ignition scheme (i.e. central ignition scheme)

Hyde[1] designed a LFR for the first time and then he also proposed a new design[2]. Orth et al.[3] extended Hyde's concept and proposed a spacecraft concept called VISTA which will be capable of manned Mars mission 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. Recently, extensive additions and improvements to the original study have been made in Ref. 4

Figure 1 shows a schematic layout of the LFR which derives thrust from laser-induced fusion microexplosions. LFR's overall geometry is that of a 50 deg.-half - angle cone. This shape is required to avoid massive radiation shielding and to keep fusion neutrons (and x rays) from striking and heating vehicle surface. The 50 deg. half angle maximizes thrust efficiency[3][5].

We here propose a LFR design based on a new scheme-Fast Ignition scheme. The scheme is based on recent experimental and theoretical researches which show that a high gain is achievable with small laser energy [6][7]. When viewed from a propulsion standpoint, such facts could realize a very compact LFR.

In this paper, we show the masses contributed by main components such as thrust chamber, laser driver, etc. for the new design and compare the results from the conventional design.

We also identify the major technological problems to be solved to realize the LFR.

2. Central ignition vs. fast ignition

Fast ignition (FI) is a newly proposed scheme to separate the laser systems for implosion and heating[8]. For implosion the requirement is such that the a fuel shell should be compressed with the use of long (< 20 nsec) laser pulse beams to more than 1000 times the solid density. Compared to the central ignition (CI) scheme which requires formation of a hot igniting spot in the center of the compressed fuel, all required is to achieve the high density for fast ignition. This relaxes the requirements such as laser irradiation uniformity and power balance: strictly required for the central ignition scheme. For forced heating the requirement is to deliver certain amount of energy to heat the core to ignition temperature within an inertial time of the fuel assembly at the maximum density. For the heating, high energetic micro particles such as electrons generated by a second ultra-intense laser beam are expected to be transported into the compressed fuel and to heat it successfully enough beyond the ignition temperature. A new scheme utilizing the hydrodynamic impact-Impact Ignition- has recently been proposed[9]. Simple physics, high-energy coupling efficiency, low cost, not needing a PW laser, and affordability of investigation in laboratories under rather well-established physical understanding and experimental know-how are considered to be the notable advantages of the new scheme. Figure 2 compares the two schemes.

Pellet gains (defined as the ratio of fusion energy to laser energy) for DT fuel are plotted in Fig.3 as a function of laser energy for the two schemes[10]. Fast ignition scheme would produce much higher gain with smaller driver energy.

3. System design and mass calculation

The mass and energy flows in LFR are given in Fig. 4. 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 in the magnetic chamber. The mechanism of thrust production in the chamber is given in Fig.5. Some of the fusion energy is picked up to power-supply the laser for next shot. The waste heats arising from inefficiencies in the driver and power system are ejected by heat pipe radiators.

The mass of each component is calculated by using the expressions given in Ref. [1]. Table 1 lists the parameters adopted in the calculation. Optimistic values are adopted for the pellet gains of the DT fuel, i.e., G=1500 at E=5 MJ[11] for CI and G=450 at E=0.5 MJ for FI, respectively, where G is the pellet gain and E is the laser energy. The radius of coil adopted in the magnetic thrust chamber is decreased from 13m in CI to 5m in FI. The driver (KrF laser) efficiency is assumed as 6 %. Other parameters such as driver repetition rate are the same as adopted in Ref.3. As for a mission, a round trip to Mars with mission duration of roughly 80 days is assumed (a stay on the planet is neglected here). The expellant mass is tentatively calculated under the assumptions that the expellant mass is constant and the coasting during the trip is neglected. An analytic trajectory code was written by using the rocket equations.

The results are summarized in Table 2 and Fig.6. It is found from Fig.6 that a reduction by a factor of 7 in power plant (dry) mass is possible with fast ignition scheme as compared to the conventional central ignition scheme with concomitant reduction of the scale as shown for the coil radius. Such a small radius of 5m for the magnetic coil is almost the same as adopted in the ITER design for magnetic confinement scheme. Such compactness will save the development cost and time, and realization of the IFR will be made earlier.

These facts indicate advantages of FI scheme over CI scheme in developing the LFR. However, there are some technological problems to be solved. Firstly, although the pellet gain is the most important parameter, we must admit that there exists ambiguity in the pellet gain adopted.

The magnetic thrust chamber is the heart of the LFR design, in which the charged plasma-debris energy from a pellet is converted into vehicle thrust[4]. An experiment was conducted to study the thrust conversion process in a scaled-down manner[12]. It was found that a thrust conversion efficiency as high as 60 % is possible in the scaled-down model. Large-scale simulative experiments are needed and they are being proposed for the GEKKO facility [13] and for National Ignition Facility[14].

Thirdly, the direct energy conversion efficiency by the pick-up coil system is estimated to be only a few percents[15], whereas a value of 4% is required in CI and a greater value of 17% is required in FI, which results from the pellet gain assumed. Thus, the design of pick-up coil system should be upgraded and tested in the experiments.

4. Conclusion

In comparison with CI scheme LFR, we show that the FI scheme would provide a more compact and feasible LFR, if the technological issues such as energy conversion method are solved.

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Fig.1 Schematic layout of laser fusion rocket

Fig.2 Central ignition vs. fast ignition

Fig.3 Pellet gain of DT fuel

Fig.4 Mass and energy flow diagram in laser fusion rocket

Fig.5 Thrust generation mechanism

Fig.6 Summary of component mass

Table 1 Parameters adopted

Table 2 Distribution of mass in units of ton

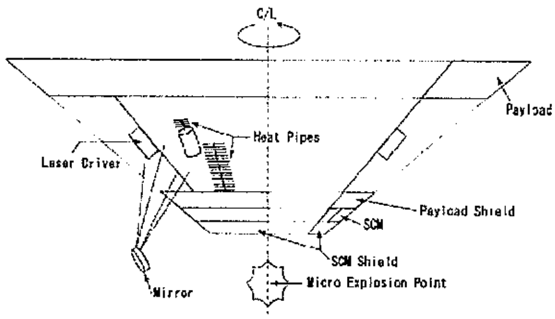

Fig.1 Schematic layout of laser fusion rocket

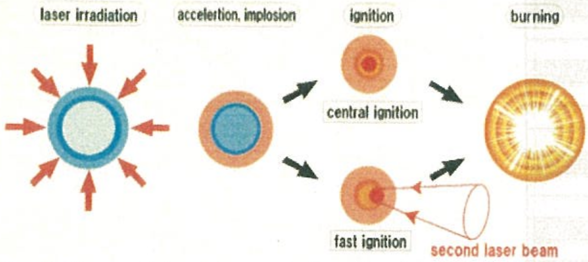

Fig.2 Central ignition vs. fast ignition

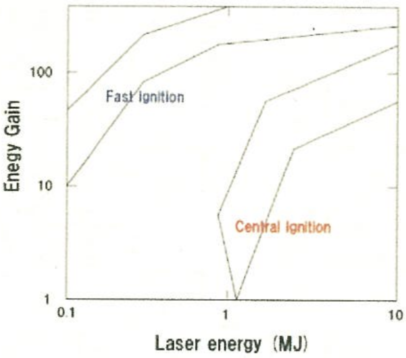

Fig.3 Pellet gain of DT fuel

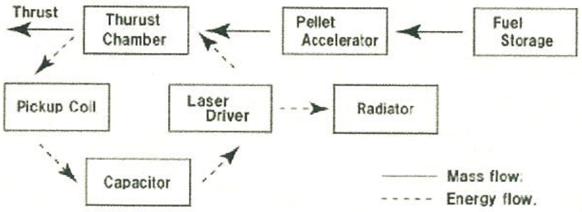

Fig.4 Mass and energy flow diagram in laser fusion rocket

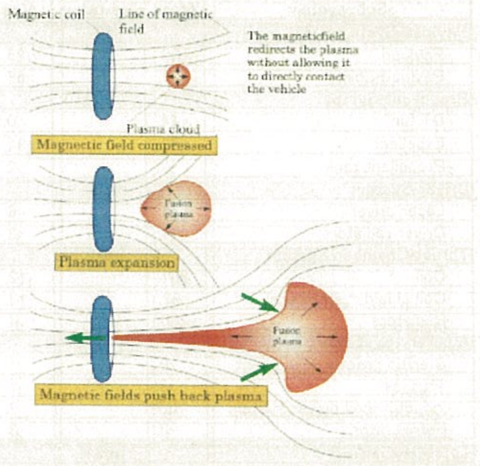

Fig.5 Thrust generation mechanism

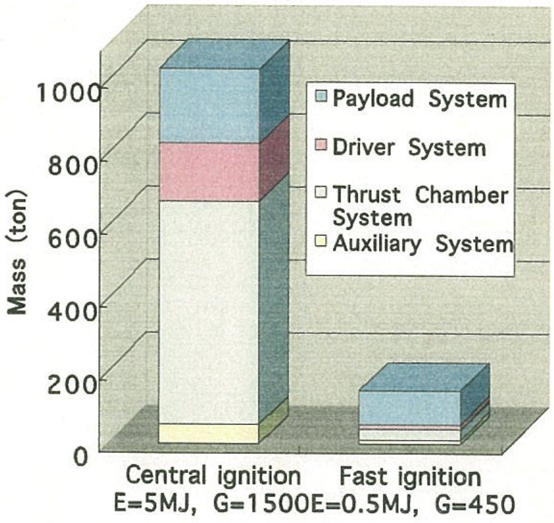

Fig.6 Summary of component mass

Table 1 Parameters adopted

	Central ignition	Fast ignition
Driver energy : E (MJ)	5	0.5
Driver efficiency : ς_{driver}	0.06	
Energy per module : E_L (kJ)	220	15
Fuel type	DT	
Fuel capsule gain : G	1500	450
Jet efficiency [Momentum]	0.65	
Maximum repetition rate : f (Hz)	30	
Magnet coil radius : R_c (m)	13	5
Payload mass (ton)	100	25
Total length (m)	125	48
Distance to Mars (m)	7.83E+10	
Round trip time (day)	80	

Table 2 Distribution of mass in units of ton

	Central ignition		Fast ignition	
Sub-system	Mass	Total Mass	Mass	Total Mass
Payload System		204		93.
Payload	100.		25.	
Payload Shield	104.		68.	
Propellant System		98.		97.
DT fuel	14.		0.53	
Expellant	82.		94.	
Propellant tank	2.		2.	
Driver System		160.		14
Laser driver	66.		6.	
Driver radiators	94.		8.	
Thrust Chamber System		613		29.
Coil	301.		12.	
Coil shield + structure	82.		13.	
Radiators	230.		4.	
Auxiliary Systems		54		12
Startup reactor equipment	9.		1.	
Trusses	3.		1.	
Inductor-coil power system	39.		7.	
Refrigerator	3.		3.	
Total DRY MASS		1031		148.
TOTAL WET MASS		1129.		245.