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Use of an ignition facility for fusion propulsion experiments

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Abstract

The utilization of an ignition facility for a fusion propulsion experiment is proposed. An experimental setup in the facility chamber is presented along with plasma behaviors calculated by a three-dimensional hybrid code. The plasma instability in a magnetic nozzle is examined and the effect on thrust efficiency is discussed. Implications of this experiment to fields other than propulsion are also discussed. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Ignition facility; Fusion propulsion experiment; Three-dimensional hybrid code

1. Introduction

A magnetic nozzle concept in a laser fusion rocket is suitable for controlling the plasma flow and it has the advantage that thermalization with wall structures in a thrust chamber can be avoided. Thus the laser fusion rocket could realize a very high exhaust velocity of plasma as compared with existing systems. This fact makes the laser fusion rocket a promising candidate for an interplanetary transport system.

Numerical simulations of plasma behavior in the magnetic nozzle have been performed to estimate thrust efficiency of the laser fusion rocket [1,2] and to examine the effects of an instability occurring between the plasma and ambient magnetic field on the efficiency. Experimental work has also began to check the numerical results [3].

Ignition facilities such as the National Ignition Facility (NIF) could provide many experimental opportunities to advance research in such areas as new basic science applying high power lasers as well as inertial fusion energy production [4]. Peterson et al. [5] have calculated the X-ray and debris emission from direct and indirect NIF targets by using a one-dimensional (1D) code and Peterson [6] also calculated the responses of NIF first wall to the target X-rays and debris.

Here we propose to use the facility to examine the feasibility of the magnetic nozzle concept and also to identify the plasma instability expected in

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the nozzle, since the facility could realize the same plasma conditions as supposed for the fusion rocket in terms of the magnetization parameter *LB*. *LB* is an important parameter for understanding the instability involved [7] and it is defined as ρ_i/R_b, where ρ_i is the directed ion Larmor radius and $R_b = (3\ \mu_0 E_0/2\ \pi B^2)^{1/3}$ magnetic confinement radius at which the kinetic energy of the expanding plasma balances the excluded magnetic energy.

In the present paper, as an illustrative purpose, we will report the results from numerical simulations of plasma behavior for a proposed configuration of the nozzle in the ignition chamber and discuss the technical issues for designing the experiments.

The plan of the present paper is as follows: in the next section the calculational method and model adopted here are presented along with an experimental setup proposed. Typical values for the design parameters are given. The analysis of plasma behavior in the magnetic nozzle is presented in Section 3 together with discussions and the conclusion is given in Section 4.

2. Computational method and model

The NIF target chamber is a 10-cm thick aluminum sphere with a 5-m radius. The fusion targets will be held at the chamber center by the positioner. The indirect cryotargets will have a small DT fuel/CH ablator capsule inside a gold hohlraum, the target mass (113 mg) being dominated by gold. The cylindrical hohlraum is 10 mm long and 5.5 mm in diameter with 2.8-mm diameter laser entrance holes in the end faces. The target is irradiated by lasers with an energy of 1.8 MJ through beam ports located at the top and bottom sides of the chamber. A value of 20 MJ is adopted here for a representative fusion yield, 20% of which is carried by plasma.

To accommodate the magnetic nozzle concept to the NIF chamber, a solenoidal coil is inserted through a port located on the mid-section of the chamber. The configuration is based on the magnetic nozzle of a laser fusion rocket proposed by Hyde [1]. The coil would be supported by a rigid pedestal structure as proposed for a 'mini-chamber' concept [8]. The solenoidal super-conducting coil is assumed to have a radius of 1 m and to carry a current of 4.1 MA. The coil produces a magnetic field intensity of 2.57 T at the coil axis and stores approx. 20 MJ. A schematic layout of the setup is shown in Fig. 1.

To calculate the plasma behavior in the magnetic nozzle, we have developed a three-dimensional (3D) hybrid code [9]. The hybrid model treats ions as particles and electrons as inertialess fluid. The Darwin limit or non-radiative Maxwell equations are solved for electromagnetic field calculations.

The calculational model adopted here is illustrated in Fig. 2. The initial plasma is assumed to have a radius (r_p) of 0.3 m and is entirely composed of gold the mass (m_p) of which is 110 mg. Its ionic charge is calculated from the data of Peterson et al. [10] by using the Thomas–Fermi model [11]. A value of 16.81 is obtained for the ionic charge of gold at a temperature of 100 eV and density of 1.0 g/cm^3. The initial kinetic energy of the plasma debris (E_p) derived from the fusion reaction is assumed to be 4 MJ, i.e. one-fifth of the magnetic field energy E_B. The density and velocity distributions are assumed as uniform. An angle θ (cone angle) subtended from the initial plasma position at the Z axis to the solenoidal coil is taken to be 45°. (The thrust efficiency reaches its maximum value at approx. 50° [12].) The dimensions ($X \times Y \times Z$) of the calculational region are (7 m)^3.

The parameter *LB* is estimated as 1.82×10^{-2} with, $\rho_i = 1.29$ cm and $R_b = 0.71$ m. Thus, the *LB* value is much less than one as in the magnetic nozzle of the laser fusion rocket where a value of 4.96×10^{-4} is expected for the *LB* [1]. In this condition, a conventional MHD theory could be applied: the expanding plasma excludes the ambient magnetic field and diamagnetic cavity is formed. The plasma expanding into the magnetic field can undergo conventional Rayleigh–Taylor instability as the heavy fluid (plasma) is decelerated by the light fluid (magnetic field).

3. Results and discussions

The plasma behaviors calculated by the 3D

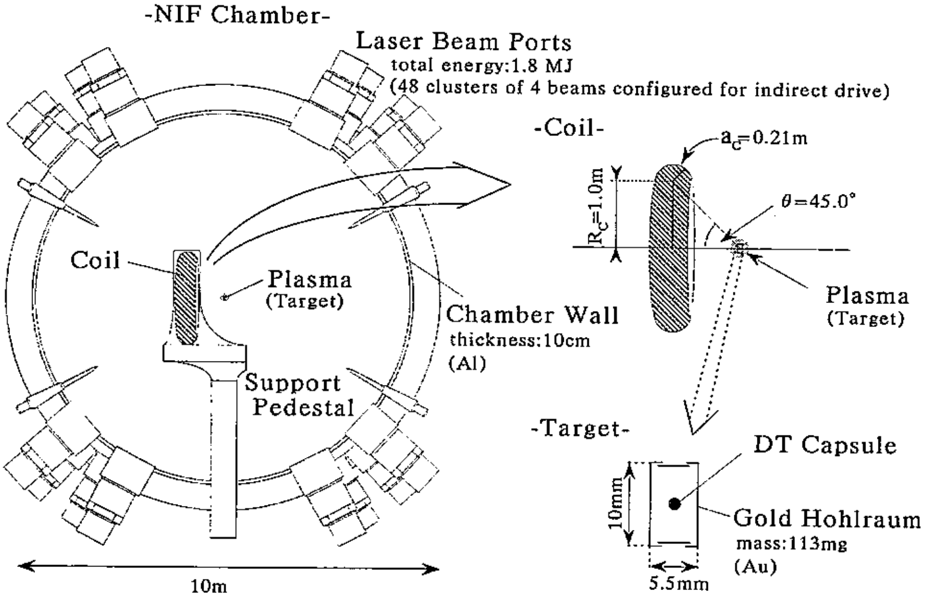

Fig. 1. Schematic layout of the experimental setup in the NIF chamber.

hybrid code is shown in Fig. 3, in which we plot a series of the contours of plasma density. The plasma initially expands isotropically, and then it is reflected back from the compressed magnetic field, resulting in thrust. The figure shows that development of the instability is so weak that the

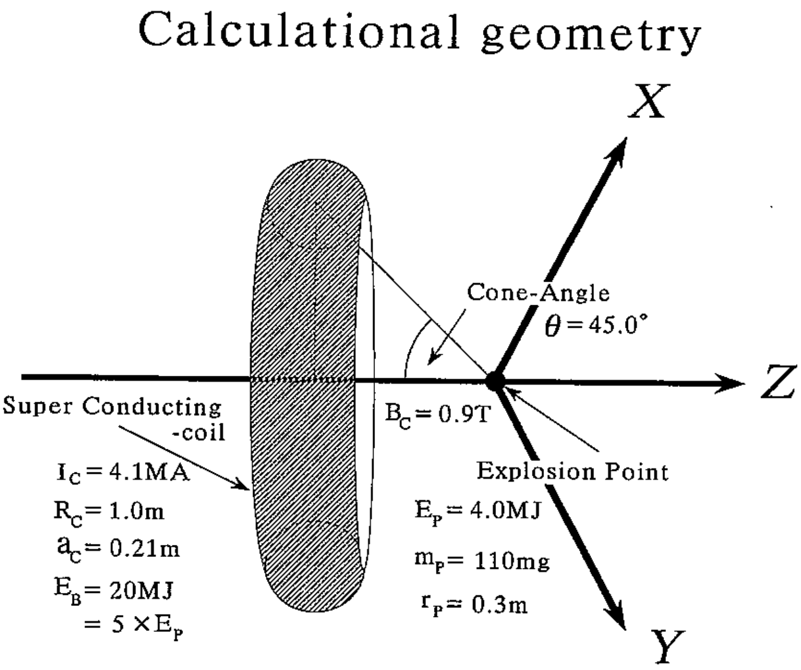

Fig. 2. Schematic illustration of the calculational model.

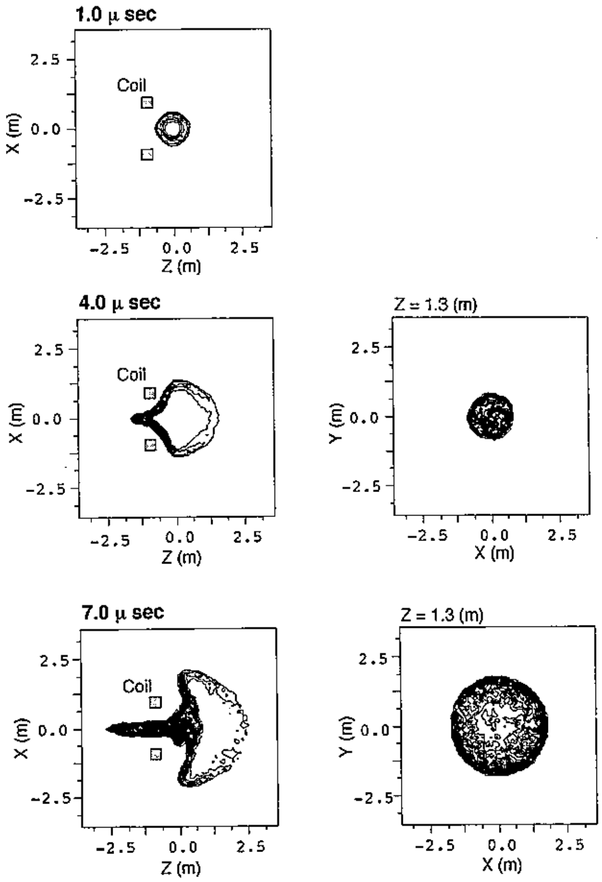

Fig. 3. Contour plots of plasma density.

instability would not degrade the thrust efficiency seriously. Fig. 4 shows the magnetic field distribution around the expanding plasma. The magnetic field is excluded from the plasma region: the diamagnetic cavity is formed.

The facility could also provide opportunities to answer the 'detachment problem' [13] and to test ideas such as 'shaped charge' for momentum concentration to improve the thrust efficiency. Utilization of the facility to the fields other than propulsion can be considered.

3.1. Direct energy conversion

Shoyama et al. [14] examined the possibility of inertial fusion energy utilization based on the interaction of D^3He plasma with various magnetic field systems. With such a system as a pickup coil one could provide the direct energy conversion of fusion energy into electrical energy with an efficiency as high as 80%. We also found from 2D simulations [15] in the pickup coil system that the amplitude of the irregular surface caused by Rayleigh–Taylor instability would be so large that plasma could not maintain its integrity after the plasma was reflected back by the compressed magnetic field. Some preliminary data about the plasma instabilities were obtained at the 'KI-1' simulation facility [3] in experiments with 'usual' laser-produced plasma clouds. Ignition facilities could also be used to check the simulation results and to examine the possibility of the direct energy conversion concept.

3.2. Asteroid protection

If the solenoidal coil is arranged to reproduce a magnetic dipole of the earth, we could simulate the dynamics of plasmas under conditions of near-earth anti-asteroidal explosions. It is proposed to use high energy explosives at a geostationary altitude for protecting the Earth from the Near-Earth Objects, which may result in enormous ecological consequences in the form of global changes of the magnetosphere, etc. [16,17]. The analytical method developed by Nikian and Ponomarenko [17] is useful for choosing optimal parameters of the simulation experiments proposed here (S.A. Nikian, private communications, 1996).

3.3. Technical issues

The super-conducting coil system should be as compact as possible so as not to interfere with the laser irradiation system. That could be a challenging problem. The coil system will become radioactive following shots producing neutrons. It is therefore recommended to use low activation materials for the construction (e.g. aluminum as conductor and carbon fiber as structural material). It seems very difficult to directly measure the thrust. Thus, measuring the velocity and density distributions of plasma must be detailed enough

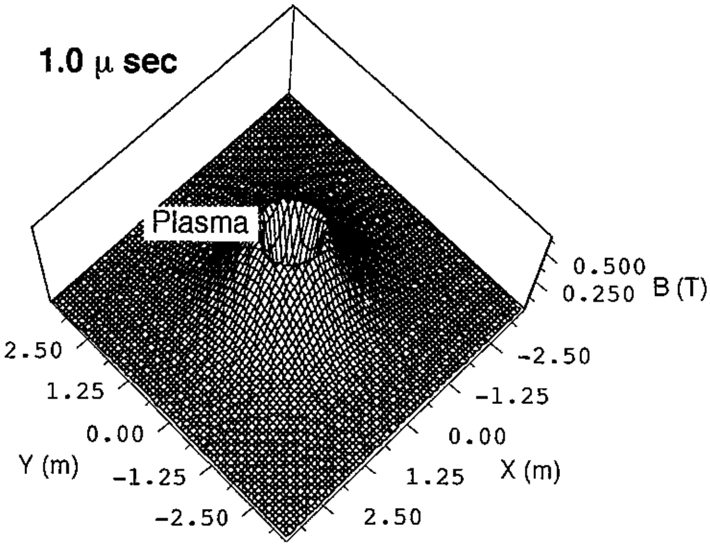

Fig. 4. Magnetic field distribution in X–Y plane at $Z = 0$.

to compare with the results from simulation calculations and to obtain the information on the thrust.

4. Conclusions

A proposal was made to use the NIF to examine the feasibility of the magnetic nozzle concept in the laser fusion rocket and also to identify the plasma instability expected in the nozzle, since the facility could realize the same plasma conditions as supposed for the fusion rocket in terms of the magnetization parameter L_B. As an illustrative purpose, the plasma behaviors were analyzed by using a 3D hybrid code for a proposed configuration of the nozzle in the NIF chamber and it is found from the preliminary calculations that the instability would not degrade the thrust efficiency seriously for the design parameters adopted. A further study is needed for choosing optimal parameters of the simulation experiments.

Implications of this experiment to direct energy conversion of plasma kinetic energy, asteroid protection, etc. were also discussed.

The computations were performed with the VPX-210/10 at National Institute for Fusion Science.

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