AIAA 92-3023
A Laser Driven Fusion Plasma for Space Propulsion

T. Kammash and D. L. Galbraith
The University of Michigan
Ann Arbor, MI

AIAA 23rd
Plasmadynamics & Lasers Conference
July 6-8, 1992 / Nashville, TN

A LASER DRIVEN FUSION PLASMA FOR SPACE PROPULSION

T. Kammash and D. L. Galbraith
Department of Nuclear Engineering
The University of Michigan
Ann Arbor, MI 48109

Abstract

An inertial confinement fusion concept that makes use of a magnetized target driven by a laser beam is examined for potential use as a propulsion scheme that could meet the needs of the Space Exploration Initiative (SEI) of the next century. The concept in question utilizes a metal shell (e.g. tungsten) which is coated on the inside with a fusion fuel such as a deuterium - tritium (DT) mixture. A hot, fusion-grade plasma is generated inside the target through ablation by a laser beam that enters the pellet through a hole. Not only does the laser create the plasma, but it also gives rise to a strong instantaneous magnetic field that serves to thermally insulate the plasma from the material wall. Because of the self generated magnetic field, this approach is referred to as a Magnetically-Insulated, Inertially Confined Fusion (MICF) concept. The plasma lifetime in this scheme is dictated by the shock speed in the metallic shell rather than by the sound speed in the plasma itself, and as a result it burns much longer and produces a very attractive energy multiplication. When considered as a potential propulsion device, it will be shown that MICF can produce such impressive specific impulse and thrust values that a manned mission to Mars can be completed in a few months instead of a few years.

Introduction and Basic Principles

The energy produced per unit mass from nuclear fusion reactions ($\sim 3.5\times 10^{14}$ J/kg) involving hydrogen isotopes is the highest (next to anti-matter annihilation reactions) among fuels considered suitable for propulsion purposes. Although no net-power producing fusion reactors have yet been built, it is believed on the basis of the research progress made thus far that such a system will become a reality in the early part of the next century. Of the two major approaches that are being pursued world-wide, namely magnetic and inertial confinement fusions, the latter appears to be more suitable for propulsion because of its unique capability and relative simplicity[1,2]. The basic requirement for such a system, whether as a terrestrial power source or as a propulsion device, is that it possesses a large gain factor "Q". In the case of propulsion, large Q-value means high fuel (plasma) temperature, which in turn means very large specific impulse, I_{sp}, a characteristic deemed highly desirable for space exploration.

One of the most novel and promising fusion schemes that has surfaced in recent years is the Magnetically-Insulated Inertial Confinement Fusion[3] (MICF) concept illustrated in Figure 1. In this scheme, a hot plasma is generated inside a target pellet, whose walls are coated with fusion fuel such as a deuterium-tritium (DT) mixture, as a result of ablation initiated by a laser beam that enters the target through a hole. For a 10.6 μm wavelength laser (e.g. CO_2 laser), the ablation rate scaling law can be written as

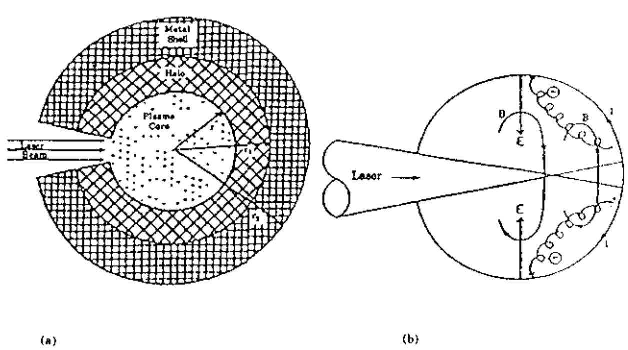

Figure 1.

Schematic Diagram of
(a) Plasma Formation and
(b) Magnetic Field Formation in MICF

$$\dot{m} = \dot{m}_0 I_{ab}^{0.85} \qquad (1)$$

where $\dot{m}_0$ has a value of about 7.1×10^5 g/cm²/sec at an absorbed laser intensity of about 10^4 W/cm². The density of the ablated material can also be expressed by

$$\rho\ (g/cm^3) = \frac{3\dot{m}_0}{R}\left(\frac{E_{ab}}{4\pi R^2\tau_L}\right)^{0.85}\tau_L\times10^{-8} \qquad (2)$$

where R (mm) is the radius of the pellet, E_{ab} (kJ) is the incident laser energy, and τ_L (ns) is the laser pulse length. The resulting plasma pressure in the cavity also assumes the form

$$P = \frac{E_{ab}(\gamma-1)}{4\pi R^3/3} \qquad (3)$$

where γ (=5/3) is the ratio of the specific heats. As noted earlier, the laser also gives rise to a magnetic field whose strength is related to the density and temperature gradients of the ablated plasma in accordance with

$$\vec{B} \sim \frac{T}{e}\frac{\vec{\nabla}n}{n}\times\frac{\vec{\nabla}T}{T}\tau_L \qquad (4)$$

where T and e are, respectively, the electron temperature and charge. Though cylindrical in geometry around the focal point of the incident laser beam, it is assumed that as the ablated plasma fills the cavity the resulting magnetic field assumes a nearly spherically symmetric geometry, and separates a hot plasma core from a colder partially ionized plasma (halo) adjacent to the solid wall. This instantaneous strong magnetic field does not provide containment since the plasma pressure is significantly larger than the magnetic field pressure; rather it serves to thermally insulate the hot plasma from the material wall. The lifetime of such a plasma is dictated by the shock speed in the shell, rather than by the sound speed in the plasma itself as is the case in the conventional implosion-type inertial fusion. This translates to about two orders of magnitude longer confinement time due to the larger atomic mass of the metal, on the one hand, and a lower shell temperature arising from the magnetic field insulation on the other. As a result, the plasma is allowed to burn much longer, producing more fusion energy and correspondingly large gain factors[4] "Q".

A full assessment of the propulsive capability of MICF requires a detailed analysis of its dynamic performance, and for that we utilize a quasi-one-dimensional, time-dependent set of particle and energy balance equations for the various species that constitute the plasma in this device[4]. We choose a deuterium-tritium (DT) fuel cycle, and allow for two populations of the alpha particles generated by this fusion reaction: a fast-alpha population born at 3.5 MeV energy, and a thermal alpha population characterized by a Maxwellian distribution at an appropriate temperature. In addition to the hot plasma in the core, the model addresses particle and energy balances in the cooler, partially ionized "halo" region, as well as a partially ionized metal region in contact with the halo region, and finally a solid non-ionized metal region which constitutes the outermost segment of the target. We treat each species as an ideal gas, for which we draw upon the thermodynamics to write the energy balance equations. Assuming the fuel ions to be represented by a single ion species with mass equal to the average masses of the deuteron and triton, we can write for the particle balance of this species:

$$\frac{d}{dt}\left\{\frac{4}{3}\pi r^3 n_f\right\} = -\frac{4}{3}\pi r^3\left\{\frac{1}{2}n_f^2<\sigma v>_f\right\} + 4\pi r^2\left\{\Gamma_r-\Gamma_f\right\} \qquad (5)$$

where n_f denotes the ion density; $<\sigma v>_f$ the velocity averaged fusion reaction cross section, which is temperature dependent; Γ_r the particle flux for the refueling ions which cross the magnetic field from the halo region to the core plasma; and Γ_f represents the flux of hot core ions in the opposite direction. In Eq.(5) the first term on the right hand side reflects the loss of ions due to the fusion reaction, and the last term represents the source term arising from the net particle flux entering the core. The energy balance for the fuel ions can be written as

$$\frac{d}{dt}\left\{\frac{4}{3}\frac{\pi r^3}{\gamma-1}n_f T_f\right\} + 4\pi r^3 n_f T_f\frac{dr}{dt} = \frac{4}{3}\pi r^3\left\{\frac{3}{2}\frac{n_f n_e}{(n\tau)_{ef}}(T_e - T_f) + \frac{3}{2}\frac{n_f n_\alpha}{(n\tau)_{\alpha f}}(T_\alpha - T_f) + n_f n_{f\alpha}\left(\frac{dE_{f\alpha}}{dt}\right)_f\right\} - \frac{3}{4}n_f^2\langle\sigma v\rangle_f + 4\pi r^2\left\{W_r - W_f\right\} \quad (6)$$

The left hand side of the above equation represents the change in the plasma thermal energy, including the spherical expansion term. The first term on the right hand side denotes the energy exchange between the electrons and fuel ions, and is characterized by the energy exchange constant $(n\tau)_{ef}$ (5). The second term represents the exchange with the thermal alpha particles, and the third term reflects the rate at which the fast alphas lose energy to the fuel ions. The fourth term denotes the energy removed from the ions due to their participation in the fusion reaction, and the last term represents the net energy flux between the refueling ions and ions escaping from the core. Similar equations are written for the other species in the core, and for all the components in the other regions of the pellet. For the electrons in the hot core, the energy conservation equation contains a term representing the X-radiation emitted by these particles; these X-rays are absorbed primarily in the inner region of the solid wall, thus contributing to the formation of the partially ionized regions in the halo and metal domains. By specifying the initial density and temperature in the core, along with the conditions that exist at the boundaries of the various regions, one can obtain a solution to the dynamic equations that describe the system which yields, among other things, the Q-value along with the densities and temperatures at the end of the burn. An interesting example of such a burn for a DT fuel in a tungsten shell is summarized in Table I.

Table 1 Pellet and Plasma Parameters

Inner radius of fusion fuel	0.25 cm
Outer radius of fusion fuel	0.30 cm
Outer radius of metal shell	0.547 cm
Input laser energy	2.59 MJ
Initial plasma density	5×10^{21} cm^{-3}
Initial plasma temperature	11.785 keV
Total pellet mass	8.75 g
Energy gain factor Q	724
Energy produced per pellet	1875 MJ

Propulsion Capability of MICF

The attractive plasma and burn properties of MICF make it especially suitable for propulsion purposes. At the end of the burn, the plasma will contain the fusion fuel ions and the electrons as well as the ions resulting from the total ionization of the tungsten shell. Upon ejection of these very energetic particles *through a nozzle, a significant amount of thrust can be generated* as well as large specific impulses as required for the space exploration missions contemplated in the next century. The main features of a propulsion device based on MICF are illustrated in Figure 2, where we envisage fusion pellets injected into a reaction chamber and zapped by a laser beam at an appropriate repetition rate. These pellets are transformed into spheres of hot plasma at the end of the burn, and that plasma is allowed to adiabatically expand to effectively fill the chamber before a appropriately designed magnetic field is energized. The resulting magnetic field will be of such a configuration as to allow the plasma to flow in one direction only, namely through a nozzle. The dimensions of the chamber and the nozzle throat area are chosen such that evacuation of the chamber can take place in a very short time, in order to allow for a high rep rate operation. Such a magnetic field forms the basis of a magnetic nozzle, which for our purposes will be long and thin and of such a configuration as to be characterized as a "Meridional" magnetic nozzle(6). It is an axisymmetric cylindrical configuration in which there are no angular components of the fluid velocity or the magnetic field. Moreover, the mean velocity of the fluid (i.e. the plasma), V, is taken to be along the magnetic field B, and the fluid flow in this system can be shown to obey the standard Bernoulli equation, namely

$$\frac{V^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho} = C \quad (7)$$

where P is the pressure, ρ is the fluid mass density, C is a constant, and γ is the ratio of the specific heats introduced earlier. For purposes of calculating the propulsion parameters of MICF, we

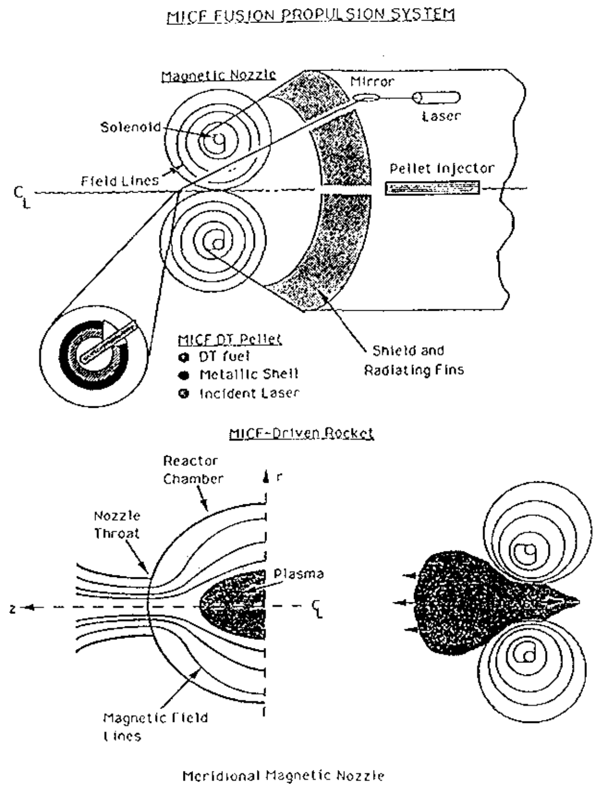

Figure 2.

Schematic of MICF Rocket and Magnetic Nozzle

identify three regions of interest, namely the reservoir, where the plasma exists at the end of the burn, the nozzle throat, and the nozzle exit; these regions will be identified respectively by the subscripts "R", "O", and "e". Using an ideal magneto-hydrodynamic description in which there is no production or conduction of heat, the flow in the system under consideration will be treated as isentropic with the sound speed C_S related to the pressure and density by $C_S^2 = \gamma P/\rho$, allowing Eq.(7) to be rewritten as

$$\frac{V^2}{2} + \frac{3}{2}C_S^2 = C \quad (8)$$

Noting that the thrust can be expressed by

$$F = \left(\frac{dM}{dt}\right)V_e \quad (9)$$

where V_e is the nozzle exit velocity and (dM/dt) is the plasma mass flow rate which can be approximated by

$$\frac{dM}{dt} = A_0\rho_0 V_0 \quad (10)$$

with A_0 denoting the nozzle throat area. Since the flow at the throat is sonic (i.e. $V_0 = C_{S0}$) it can readily be shown that

$$V_e = 2C_{S0} = \sqrt{3}C_{SR}, \qquad P_0 = \frac{1}{2}P_R \quad (11)$$

This in turn allows us to obtain for the thrust and specific impulse the following expressions:

$$F = \frac{10}{3}A_0 P_0 = \frac{5}{3}A_0 P_R, \qquad I_{sp} = \frac{V_e}{g} = \frac{\sqrt{3}C_{SR}}{g} \quad (12)$$

where g is the familiar gravitational acceleration. Equations (12) are especially useful since they allow us to compute the important propulsion parameters in terms of fluid properties at the reservoir, which we recognize to be those of the plasma at the end of the burn. For the pellet parameters given in Table 1, a reaction chamber radius of 10 cm, and a nozzle throat radius of 2.5 cm, we use Eq.(12) to obtain the propulsion parameters listed in Table 2.

Table 2 MICF Propulsion Parameters

Fuel ion exhaust speed	3.760×10^{7} cm/s
Tungsten exhaust speed	4.384×10^{6} cm/s
Charged particle energy gain	145
Firing rate ω	$\leq 6422\ s^{-1}$
Fuel ion thrust	$3.965\times10^{-3}\ \omega$ kN
Tungsten ion thrust	$4.085\times10^{-1}\ \omega$ kN
Total thrust F	$4.125\times10^{-1}\ \omega$ kN
Jet power P_{jet}	$9.699\ \omega$ MW
Effective specific impulse I_{sp}	4.512×10^{3} s

Application to a Mars Mission

We assess the potential utilization of MICF for advanced propulsion by evaluating its performance as a driver for a manned mission to Mars. We use the parameters of Table 2, taking $\omega = 100$, and employ a continuous burn acceleration/deceleration trajectory profile which assumes constant I_{sp}, F, and P_{jet} operation. If we denote the linear distance by D, and the dry vehicle mass by M_f, then the round trip time τ_{RT} under the above conditions can be written as(7)

$$\tau_{RT} = \frac{4D}{gI_{sp}} + 4\sqrt{D\frac{M_f}{F}} \qquad (13)$$

Since MICF is laser driven, the dry weight of the vehicle must include the power supply system, and at an input energy of 2.6 MJ such a system including the driver (lasers, radiators, optics, energy handling, etc.), the thrust chamber, and the overhead components are estimated to be 546 MT (8). We arbitrarily add 100 MT payload and take the dry weight of the mission vehicle to be 664 MT. With the linear distance from earth to Mars being 0.52 Astronomical units (Au) or 7.8×10^{11} m, we find from Eq.(13) that the round trip journey for this MICF-driven vehicle takes 138 days. It is also interesting to note from Eq.(13) that the travel time can be further reduced by a careful pellet design that allows for an optimum balance between the specific impulse and the thrust. This can be achieved by proper choice of the dimensions of the fuel and the metal shell (as well as the choice of the metal component itself) consistent with maximum production of fusion energy at minimum laser input energy.

Conclusion

We have examined in this paper a novel laser-driven inertial fusion concept that makes use of fuel magnetization by a self-generated magnetic field. In contrast to standard implosion-type inertial fusion, this approach allows for a much longer plasma lifetime, and correspondingly much larger energy production per unit of input energy. The initial density and temperature requirements for ignition are significantly less stringent than those for implosion schemes, and with careful pellet designs, input laser energies of less than a megajoule might prove feasible to initiate the burn. When considered as a propulsion system, MICF appears to have the desired performance characteristics that render it especially suitable for deep space missions and interplanetary travel. It is capable of producing sufficiently large specific impulses and thrusts to allow a round trip manned mission to Mars to be completed in about four months instead of several years.

References

1. T. Kammash and D. L. Galbraith, J. British Interplanetary Society **41**, 327 (1988)
2. S. K. Borowski, NASA Technical Memorandum 101354, July 18 (1987)
3. A. Hasegawa, et.al., Nuclear Fusion **28**, 369 (1988)
4. T. Kammash and D. L. Galbraith, Nuclear Fusion **29**, 1079 (1989)
5. T. Kammash and D. L. Galbraith, Nuclear Fusion **13**, 133 (1973)
6. R. A. Gerwin, et.al., Air Force Astronautics Laboratory Report AL-TR-89-092, Feb. (1990)
7. T. Kammash and D. L. Galbraith, AIAA 91-1833 27th Joint Propulsion Conference, Sacramento, CA, June 24-26 (1991)
8. R. A. Hyde, Lawrence Livermore National Laboratory Report UCRL-88857 (1983)