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Pulsed Fusion Propulsion System for Rapid Interstellar Missions

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An inertial-confinement fusion system that utilizes a self-generated magnetic field is examined as a potential propulsion system that would allow interstellar missions to be carried out in relatively short times. The system in question is the magnetically insulated inertial confinement fusion (MICF) concept, which combines the favorable aspects of both inertial and magnetic fusion into one. Physical containment of the hot plasma in this device is provided by a metal shell, whereas its thermal energy is insulated from that wall by a self-generated magnetic field. Fusion reactions in MICF can be triggered by a laser or a particle beam that enters the target pellet through a tiny hole and ablates the inner surface. The lifetime of the resulting plasma is dictated by the time it takes the shock wave to traverse the thickness of the shell. This confinement time is typically two orders of magnitude longer than that of implosion-type inertial fusion and leads to a very large energy multiplication. When employed as a propulsion system, MICF can produce a specific impulse and a thrust that make interstellar destinations reachable in acceptably short times.

Nomenclature

C_1 = coefficient for the energy transfer rate to the electrons
C_2 = coefficient for the energy transfer rate to the ions
D = linear distance
E = instantaneous energy
E_T = pellet energy content
$E_{\rm th}$ = thermal energy
E_0 = initial energy
$\bar{E}_\alpha$ = mean alpha energy
F = thrust
$I_{\rm sp}$ = specific impulse
M_i = ion mass
m_f = final vehicle mass
m_i = initial vehicle mass
m_T = pellet mass
N_α = alpha particle density
n = particle density
Q = pellet energy gain
R = ratio of alpha density to plasma density
S_f = destination distance
T = temperature
v_e = exhaust velocity
v_f = final vehicle velocity
τ = confinement time
$\tau_{\rm th}$ = thermalization time
ω = repitition rate

Introduction

A QUESTION that has been asked quite frequently in recent years has to do with the human desire to explore interstellar space and to be able to accomplish it in a lifetime. The answer clearly lies in finding a system that has the propulsive capability to achieve this objective and still be amenable to development in a time frame such as the early part of the next century. Such a system should produce a specific impulse in the range of 10^5–10^6 s and a large enough thrust, in the ten to hundreds of kilonewtons, to be able to meet these requirements. This automatically eliminates from consideration conventional propulsion systems and some of the advanced concepts such as nuclear thermal and gas core fission systems due to the small specific impulses they produce. With pure antimatter annihilation propulsion systems still very far in the future, fusion reactions with the next largest energy production per unit mass, offer the most promising approaches to this challenge. One particular scheme, namely, the magnetically insulated inertial confinement fusion (MICF) concept, has the capability of meeting these demanding requirements and simultaneously lends itself to near-term development due to a present-day reasonable understanding of its underlying physics principles.

The MICF concept[1,2] combines the favorable aspects of magnetic and inertial fusion in that physical containment of the plasma is provided by a metallic shell such as tungsten or gold, and its thermal energy is insulated from that shell by a self-generated magnetic field as shown in Fig. 1. Fusion reactions in this device are triggered by a laser or a particle beam that enters the target pellet through a small hole to ablate the inner wall and form the hot plasma. Upon striking the wall, a plasma is created with a density and a temperature gradient that are nearly perpendicular to one another. When that happens, an electric field is formed that, according to the generalized Ohm's law, gives rise to a time-varying magnetic field.[3,4] This field does not serve the same purpose as it does in magnetic confinement systems; rather, it provides a thermal insulation of the plasma from the metal wall. As a result, the plasma confinement time in MICF is much longer than in implosion-type inertial fusion and generates much more energy as reflected by the energy multiplication factor Q. In contrast to implosion-type inertial fusion, where the plasma lifetime is dictated by the sound speed in the plasma itself (the time it takes a pulse to propagate from the shell to the plasma core), the lifetime in MICF is dictated by the time it takes the shock to propagate across the metal shell once it is formed when the incident beam strikes the inner wall. The shock speed in the latter case is much slower because of the larger atomic mass of the metal shell and its lower temperature that arises from the thermal insulation provided by the magnetic field. It is estimated[2] that the confinement time in MICF is about two orders of magnitude longer than implosion-type systems, that is, about 10^{-7} s, and that can result in very large Q values. Moreover, the beam plasma coupling is much more efficient because the energy is put directly into the plasma rather than in an imploding pusher. The Rayleigh–Taylor instability, which is known to plague implosion-type inertial fusion, is totally eliminated in MICF because the lighter fluid (the plasma) is supported by the heavier fluid (the shell) in the presence of a gravitational field. These unique properties allow for the large energy gain that, as we shall note shortly, will result in very impressive propulsive capability. As

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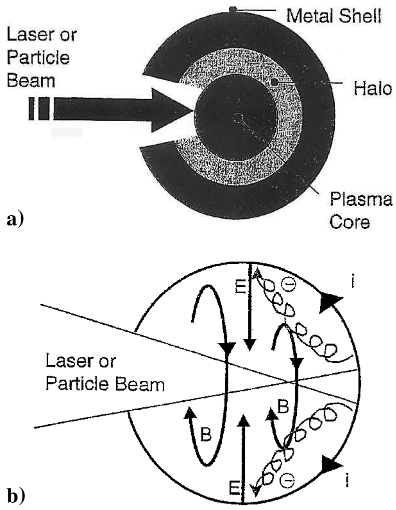

Fig. 1 Schematic of formation in MICF of: a) plasma and b) magnetic field.

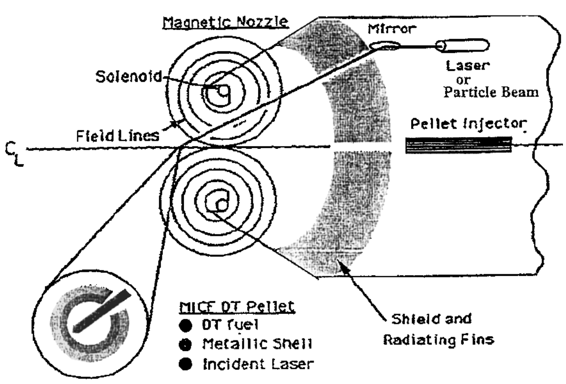

Fig. 2a MICF fusion propulsion system.

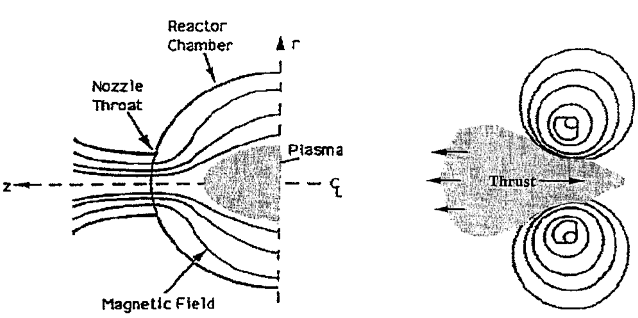

Fig. 2b MICF-driven rocket.

a propulsion system,[5] (Fig. 2), it is envisaged that MICF pellets injected into a burn chamber will be triggered by an incident laser or a particle beam at the center, and the reaction products along with the ionized shell material will be exhausted through a magnetic nozzle, which will be an integral part of an externally applied magnetic configuration that also serves to cushion the chamber walls from the microexplosion shock. In the next sections, we will examine the plasma dynamics in MICF and see how that might impact its performance as a propulsion system.

Note that another approach that makes use of magnetized targets is being studied at the Los Alamos National Laboratory and is referred to as magnetized target fusion (MTF). In this scheme the magnetic field employed is, however, externally generated (instead of being self-generated as in MICF) and is utilized to compress a preformed field-reversed compact torus (FRC). This approach has its own unique challenges, such as forming a stable FRC and translating it into the region where magnetic compression is to take place. No proof of principle experiments on MTF have yet been carried out, and for the purposes of this paper it should be pointed out that MTF does not appear to lend itself to antiproton drivers, as will be discussed later.

Plasma Dynamics in MICF Pellets

A true assessment of the plasma dynamics in an MICF pellet requires an elaborate, complex computational scheme that solves the time-dependent particle and energy conservation equations of all of the species in the system. For a deuterium–tritium (DT) fuel, the fusion reactions produce neutrons that simply escape the system and play no major role in heating the pellets, and alpha particles, with 3.5-MeV energy, which deposit their energy in the plasma to keep it hot and sustain the reactions. Once they are created, these alpha particles begin to slow down through coulomb collisions with not only the ions and the electrons of the background plasma, but also with the other alpha particles that preceded them and had already reached some of form of thermalization. Hence, conservation equations must be written not only for the ions and electrons of the plasma, but also for fast and thermal alphas taking into account interactions between all of these species and the radiation, for example, bremsstrahlung, emitted by the electrons. This radiation can cause ionization in the remaining solid fuel region (the halo in Fig. 1) and in the metal shell, and the resulting fuel ions, particularly, can find their way to the plasma core through diffusion across the magnetic field. These incoming ions serve as a fueling source for the burning plasma in the core, but by the same token some of the core ions will also diffuse across the magnetic field to the halo region to cause further ionization, and the cycle repeats itself. Although a relatively small number of metal ions find their way to the core plasma, if they do they can result in enhanced production of bremsstrahlung radiation due to their large charge number. The resulting radiation, once again, causes further ionization in the halo and in the metal shell and that in turn increases the back pressure on the core plasma causing its density to increase and correspondingly its energy production to increase as well. The diffusion of charged particles across the magnetic field in both directions can be purely classical (in the manner of coulomb collisions) or anomalous, as induced by plasma instabilities such as those associated with density and/or temperature gradients.[6,7] It is not unreasonable to imagine the presence of such gradients, particularly in small pellets as considered in MICF, and as a result, these so-called drift instabilities might very well take place. These oscillations can be shown to be marginally unstable, but the anomalous diffusion associated with them can be especially beneficial because it leads to a more efficient fueling of the burning plasma by the relatively cold ions arriving from the halo without seriously degrading its temperature. Preliminary investigations appear to confirm this salutary effect.

For the purposes of this paper we can make a reasonable evaluation of energy production in a target pellet and assess its impact on the propulsion capability it generates. The model we employ, though meaningful and indicative of what might be expected of an MICF propulsion system, is clearly simpler and less complicated than the one described earlier. It does, nevertheless, contain the main elements of energy production in MICF targets and the energy content of these pellets as they finally disassemble and emerge from the nozzle to produce the thrust.

The central theme in this analysis is the role of the alpha particles generated by the DT fusion reactions for the duration of the burn. Once they are born, these particles almost immediately begin to slow down on the electrons and ions of the core plasma formed initially by an incoming laser or particle beam. This means that the alpha particles will have an energy distribution that spans the range from birth energy E_0, of 3.5 MeV, down to E_{th}, a thermal energy equal to that of the background plasma. Mathematically this is represented by[8]

$$n_\alpha(E) = \frac{\left(n_i^2/4\right)\langle\sigma v\rangle}{\mathrm{d}E/\mathrm{d}t}\exp\left[-\int_E^{E_0}\frac{\mathrm{d}E}{(\mathrm{d}E/\mathrm{d}t)\tau(E)}\right] \qquad (1)$$

where n_i is the plasma ion density, E the instantaneous alpha energy, $\mathrm{d}E/\mathrm{d}t$ the energy loss per unit time arising from interaction with plasma particles, $\tau(E)$ the confinement time of alphas in the system, and $\langle\sigma v\rangle$ the velocity averaged fusion reaction cross section. As we shall see shortly, the alpha thermalization time τ_{th} is much shorter than the confinement time, and as a result, the exponential term in expression (1) can be safely set equal to unity. For alphas whose initial energy is much larger than those of the field particles, the power loss can be expressed by[8]

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\left(C_1 E + \frac{C_2}{\sqrt{E}}\right) \tag{2}$$

where

$$C_1 = \frac{2\times 10^{-12} n_e(\text{cm}^{-3})}{T_e^{\frac{3}{2}}(\text{keV})} \tag{3}$$

$$C_2 = \frac{9\times 10^{-10} n_i(\text{cm}^{-3})}{M_i(\text{amu})} \tag{4}$$

and $n_e = n_i = n$ is the electron density, $T_e = T_i = T$ the electron temperature, and M_i the ion mass, which in the DT case is taken to be 2.5 atomic mass units (amu). Integrating Eq. (2) from E_0 to E_{th}, we readily obtain τ_{th} or

$$\tau_{\text{th}} = \frac{2}{3C_1}\ln\left[\frac{1 + (C_1/C_2)E_0^{\frac{3}{2}}}{1 + (C_1/C_2)E_{\text{th}}^{\frac{3}{2}}}\right] \tag{5}$$

Because generally $E_{\text{th}} \ll E_0$, it can be ignored, and the result reduces to

$$\tau_{\text{th}} = (2/3C_i)\ln\left[1 + (E_0/E_c)^{\frac{3}{2}}\right] \tag{6}$$

where we have introduced $E_C = (C_2/C_1)^{2/3}$, known as the equipartition energy, which represents the alpha energy at which the power loss to the electrons and to the ions is the same. To obtain the alpha number density N_α in the system, we write

$$N_\alpha = \int_{E_0}^{E_{\text{th}}} n_\alpha(E)\,\mathrm{d}E = -\int_{E_0}^{E_{\text{th}}} \frac{\left(n_i^2/4\right)\langle\sigma v\rangle}{C_1E + C_2\big/\sqrt{E}}\,\mathrm{d}E \tag{7}$$

and it is straightforward to demonstrate that this result reduces to

$$N_\alpha = \left(n_i^2/4\right)\langle\sigma v\rangle\tau_{\text{th}} \tag{8}$$

where use was made of Eq. (6). In addition to these results, it is important that we calculate the mean alpha energy $\bar{E}_\alpha$ during the slowing down process because that quantity will be used in determining the heating of the plasma by these particles. It is given by

$$\bar{E}_\alpha = \frac{1}{N_\alpha}\int_{E_0}^{E_{\text{th}}} E n_\alpha(E)\,\mathrm{d}E \tag{9}$$

which becomes, after performing the necessary mathematical operations,

$$\bar{E}_\alpha = \frac{(C_2/C_1)^{\frac{2}{3}}}{C_1\tau_{\text{th}}}\left\{\varepsilon^2 - \left[\frac{1}{3}\ln\left(\frac{\varepsilon^2-\varepsilon+1}{\varepsilon^2+2\varepsilon+1}\right) + \frac{2}{\sqrt{3}}\tan^{-1}\left(\frac{2\varepsilon-1}{\sqrt{3}}\right)\right]\right\} \tag{10}$$

where

$$\varepsilon = (C_1/C_2)^{\frac{1}{3}}E^{\frac{1}{2}} \tag{11}$$

Equation (10) has to be evaluated between the limits E_0 and E_{th}, corresponding to birth energy E_0 and thermal energy E_{th}, respectively. Plasma heating by the alpha particles can then be obtained from the expression

$$\tfrac{3}{2}\Delta T = R(E_0 - \bar{E}_\alpha) \tag{12}$$

where $R = N_\alpha/n_i$ on the assumption that the electrons and the ions have been heated equally. This is clearly an approximation because we recall from Eq. (2) that the rate of transfer to each of these species is different. The answer will not be drastically different if we calculated these quantities separately and eventually considered the thermalization between the electrons and the ions to obtain the final plasma temperature.

If we now apply these results to an initial plasma in the core formed by the incident beam to be with a density of 5×10^{22} cm^{-3} and a temperature $T = 20$ keV, then we find from Eq. (6) that $\tau_{\text{th}} = 1.56\times 10^{-9}$ s and from Eq. (8) that $N_\alpha = 4.10\times 10^{20}$ cm^{-3}. If we utilize these values in Eq. (10), we find that the mean alpha energy in a plasma with 50–5% mixture of DT to be 1465 keV. When substituted in Eq. (12), it reveals that the average plasma particle increased its energy by 16.71 keV as a result of the alpha slowing down. The fusion reaction time is given by $1/n\langle\sigma v\rangle$, and for the DT density and temperature under consideration here, it yields a value of 5×10^{-8} s. Because the thermalization time is much shorter than the reaction time and the plasma confinement time of about 10^{-7} s, about two generations of such alphas will have been generated during the lifetime of the pellet. If we assume that plasma heating by alphas in each generation is unaffected by the one that preceded it, then clearly the plasma heating will be that of the first generation multiplied by the number of generations. Equation (2) tells us, however, that energy transfer from the alpha particle to the field particle decreases as the latter's energy increases. That is why true assessment of this affect can only be obtained by solving the governing coupled, time-dependent equations alluded to in the earlier discussion. To proceed with the present simplified approach, we shall assume that the plasma heating as calculated takes place in the generations noted earlier, that is, 2. As a result, our calculation of the energy content of the pellet at the end of the burn might be somewhat conservative. With the initial plasma particle energy being $\frac{3}{2}(20) = 30$ keV, its energy at the end of the burn will be about 64 keV, and the energy content in the 1-cm pellet associated with the plasma component will be 1.4×10^{25} keV or 2.23×10^{9} J.

The other contributor to the energy content is the alpha particles themselves, which now can be viewed as another species in the system with an average energy of 1465 keV. Multiplying this by the number of generations, by the density as given by N_α, and by the volume of the pellet, we obtain 0.81×10^{9} J. In view of this, the energy content of a target pellet E_T at the end of the burn becomes

$$E_T = 3.0\times 10^{9}\ \text{J} \tag{13}$$

If we now assume that this energy results in propelling the pellet through the nozzle, then the velocity acquired by such a pellet with a mass m_T of 3.5 gm (Ref. 9) is given by

$$v_e = \sqrt{2E_T/m_T}, \qquad v_e = 1.32\times 10^{6}\ \text{m/s} \tag{14}$$

giving rise to a specific impulse $I_{\text{sp}} = 1.32\times 10^{5}$ s. The pellet mass was arrived at by a design that divides the 1 cm radius into a hollow core region of 0.25 cm, a tungsten shell of 0.45 cm thickness, and an intermediate region of DT fuel. Also note that the velocity is about 0.004 of the speed of light so that no relativistic effects need be considered. Moreover, the result as given by Eq. (14) assumes the target pellet remains nearly intact (a lump of charged particle debris) at the end of the burn obviating the need for evaluation of the escape velocity of each species involved. This may, once again, lead to an underestimation of the performance of the system. Finally, we find out how efficient these MICF targets are by calculating their energy gain factor, the Q value. We recall that the energy input E_{in} consists of the initial plasma at a density of 5×10^{21} cm^{-3} and a temperature of 20 keV in a core of 0.25 cm radius. This readily gives a value of $E_{in} = 1.57 \times 10^6$ J, which yields a Q value of about 1911. Note, however, that, whereas an initial plasma density of 5×10^{21} cm^{-3} was used in obtaining E_{in}, a plasma density of 5×10^{22} was employed throughout this analysis to obtain the propulsive parameters. This reflects that the plasma density in MICF immediately rises to perhaps several orders of magnitude of the initial value, but subsequently decays to a value at the end of the burn that may be lower than the initial value. Our choice of 5×10^{22} may, therefore, represent quite a reasonable mean value in the absence of a time-dependent analysis. In fact, preliminary computer results indicate that Q values of several thousands are achievable when mildly turbulent diffusion is invoked.

The large energy gain just seen is a direct consequence of the role of the magnetic field in insulating the metal wall from the burning plasma. For the field to be effective in performing this, it must persist for a time equal to or longer than the plasma lifetime. For the temperature noted earlier, the plasma is said to possess high conductivity, and that makes the magnetic field decay time quite long. It can be shown[4] that the decay time in the example is about three times longer than the confinement time.

Mission Analysis

We assess the propulsive capability of MICF by applying the results to several interstellar missions and to missions to some planets in the solar system. As illustrated in Fig. 2, pellets containing DT fuel are injected into the reaction chamber, where they are zapped by an incident laser or a particle beam. Because of the large input energy, laser beams that can deliver such energy will require massive and complicated driver and optical systems that may make the dry mass of the system substantial even if it proves to be technically feasible. Rather we will employ antiproton beams because of the large annihilation energy they produce and on the assumption that the mass of such a system is negligibly small in comparison to the laser driver system. Hence, we will assume that the dry mass of the MICF propulsion system would be that of a comparable laser-fusion propulsion[10] but without the driver component, or about 220 mT. We will also assume that 10 MICF pellets per second are injected and zapped because such a repitition rate is considered quite feasible and readily allows for evacuation of the debris between detonations.[5] Because each annihilation produces 1876 MeV of energy, then the number of antiprotons $\bar{p}$ required to produce the input energy per pellet is 5.23×10^{15} and at the repitition rate of interest, this amounts to 5.23×10^{16} $\bar{p}$ per second. Of course, this implies a 100% efficiency of converting annihilation energy into the creation and heating of the initial plasma utilized in this analysis. The proton–antiproton annihilation reaction yields neutral pions and positively and negatively charged pions. The neutral pions immediately decay into high-energy (~ 150 MeV) gamma rays, which completely escape this system and do not contribute to the plasma heating. This means the given number of required antiprotons is somewhat underestimated. However, it is more relevant that the charged pions can indeed heat the plasma before they decay even in such a small pellet with a relatively thin tungsten shell. This comes about because of the presence of a strong magnetic field. In the absence of such a field, these pions (with kinetic energy of about 250 MeV) have a range of about 9 cm in tungsten, but for several megagauss fields commensurate with high-temperature plasma, the path length is reduced to a fraction of a centimeter.[9] The thrust produced by the system will, therefore, be given by (at a repetition rate of $\omega = 10$)

$$F = \omega m_T, \qquad v_e = 10 m_T v_e \tag{15}$$

where m_T is the mass of the pellet (3.5 gm) and v_e the exhaust velocity given by Eq. (14).

The missions we consider are 1) flyby, where the vehicle simply passes by the destination; 2) rendezvous, where the vehicle ultimately slows down to a zero velocity as in the case of simply landing at the destination or to a very small velocity commensurate with a predetermined orbit; and 3) round trip, where the vehicle lands at its destination and then turns around and comes back to Earth. If we denote by S_f the distance to the destination and by t_f the time it takes to reach it, then from the standard nonrelativistic rocket equation we can write for the fly-by mission[11]

$$t_f = [(m_i - m_f)/F]v_e \tag{16}$$

$$S_f = \left(m_i v_e^2 / F\right)[1 - m_f/m_i + (m_f/m_i)\ln(m_f/m_i)] \tag{17}$$

$$v_f = v_e \ln[1/(1 - F t_f / m_i v_e)] \tag{18}$$

where m_i and m_f are the initial vehicle mass and its final (dry) mass, respectively, and v_f is the velocity of the vehicle when it reaches its destination assuming it started from rest.

If we denote by D the linear one-way distance from Earth to the destination in question, and if we also assume a continuous burn acceleration/deceleration type of trajectory at a constant thrust, then the time it takes for a rendezvous mission may be written as[12]

$$\tau_{RD} = (D/v_e) + 2\sqrt{D m_f / F} \tag{19}$$

whereas that for a round-trip mission is given by

$$\tau_{RT} = 4D/v_e + 4\sqrt{D m_f / F} \tag{20}$$

It must be kept in mind that in all of the scenarios the underlying premise is that just enough propellant is carried onboard to achieve the mission.

The two interstellar missions we consider are one to a distance of 10,000 AU (1.5×10^{15} m), which puts it somewhere within the Oort cloud, and the other is to the nearest star, that is, Alpha Centauri at 4×10^{16} m. The results are given in Table 1. For comparison we have included in Table 1 a case, which we consider as optimistic because it is based on a pellet gain of 2623. We recall that such a gain appears to be feasible when mildly turbulent diffusion characterizes the cross magnetic field transport in MICF. In any case we see from the results that the Oort missions, which may be viewed as precursor to the Alpha Centauri missions, are achievable in relatively short times, indeed well within a human's lifetime. The flyby and rendezvous missions to Alpha Centauri may be viewed also as quite acceptable especially for robotic missions intended to send back information about our nearest star.

We have applied the analysis to three interplanetary missions, one from Earth to Mars, one to Jupiter, and the third to the outermost planet in the solar system, Pluto. Only the conservative scenario was employed, and the results are shown in Table 2, where we have also included the mass of the propellant m_p required for the mission. We see that these missions are quite fast with MICF, and because of its high specific impulse the amount propellant required is relatively modest in almost all cases.

Table 1 Interstellar missions with MICF

	Conservative		Optimistic	
Mission	Trip time, yr	Amount of $\bar{p}$	Trip time, yr	Amount of $\bar{p}$
Oort flyby	37	102 gm	8.47	23 gm
Oort rendezvous	41	114 gm	10.44	29 gm
Oort round trip	155	427 gm	36.74	101 gm
α Centauri flyby	968	2.67 kg	213	587 gm
α Centauri rendezvous	988	2.73 kg	224	619 gm
α Centauri round trip	3899	10.76 kg	872	2.41 kg

Table 2 Interplanetary missions with MICF

Mission	Trip time, day	Propellant mass m_p, mT	Amount of $\bar{p}$
Mars flyby	10	30	74 mg
Mars rendezvous	15	45	112 mg
Mars round trip	31	94	234 mg
Jupiter flyby	32	97	243 mg
Jupiter rendezvous	46	138	345 mg
Jupiter round trip	102	309	774 mg
Pluto flyby	123	373	932 mg
Pluto rendezvous	172	520	1.30 gm
Pluto round trip	445	1345	3.36 gm

Note that the speeds gained during the propulsive maneuver will be smaller than those predicted by the equations used, for example, Eq. (18), due to the effects of solar gravity. An upper bound on the loss can be obtained by considering the rocket to thrust radially away from the sun. Because the solar accelerations are about 0.0006 g and the thrust-to-mass ratio of the MICF engine is about 0.065 g, the rocket will climb away from the sun. In fact, it can be shown[11] that the solar gravity losses for the Oort and Alpha Centauri missions are 2×10^{-3} and 2.6×10^{-6}, respectively. It can, therefore, be safely said that the results presented in Tables 1 and 2 are reasonably accurate and sufficiently indicative of the MICF propulsive capability for interstellar and other missions.

Conclusions

We have demonstrated that a novel fusion scheme that combines inertial and magnetic fusions into one has the propulsive capability to make interstellar missions in acceptably short times. This MICF system makes use of fuel targets that are zapped with antiproton beams through tiny holes giving rise to an initial hot plasma and a magnetic field that serves to insulate this plasma from the metal shell that surrounds the pellet. Energy production due to fusion reactions that ultimately contribute to the energy content of the pellets are attributed to the alpha particles generated by the DT reactions. These particles are shown to slow down in the plasma in times much shorter than the confinement time and, thus, provide generations of energy buildup that manifest themselves in the large exhaust velocity and the corresponding large specific impulse. When applied to several missions to the Oort cloud and Alpha Centauri, it is shown that the MICF propulsion system can make these journeys in relatively short times.

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