# Antimatter Driven P-$B^{11}$ Fusion Propulsion System

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**Abstract.** One of the major advantages of using P-$B^{11}$ fusion fuel is that the reaction produces only charged particles in the form of three alpha particles and no neutrons. A fusion concept that lends itself to this fuel cycle is the Magnetically Insulated Inertial Confinement Fusion (MICF) reactor whose distinct advantage lies in the very strong magnetic field that is created when an incident particle (or laser) beam strikes the inner wall of the target pellet. This field serves to thermally insulate the hot plasma from the metal wall thereby allowing the plasma to burn for a long time and produce a large energy magnification. If used as a propulsion device, we propose using antiprotons to drive the system, which we show to be capable of producing very large specific impulse and thrust. By way of validating the confinement properties of MICF we will address a proposed experiment in which pellets coated with P-$B^{11}$ fuel at the appropriate ratio will be zapped by a beam of antiprotons that enters the target through a hole. Calculations showing the density and temperature of the generated plasma along with the strength of the magnetic field and other properties of the system will be presented and discussed.

## INTRODUCTION

The Magnetically Insulated Inertial Confinement Fusion (MICF) concept, illustrated in Fig. 1, has been studied extensively (Kammash, 1988 and 1990) as a potential propulsion device for use in human exploration of the solar system and beyond. It has also been examined for potential utilization of antimatter annihilation reactions to trigger fusion reactions in a deuterium (D) –tritium (T) fueled device (Kammash, 1992 Cassenti, 1997). This concept combines the favorable aspects of both magnetic and inertial fusion in that physical containment of the hot plasma is provided by a metallic shell while its thermal energy is insulated from the material wall by a strong, self-generated magnetic field as shown in Fig. 2. Unlike conventional implosion-type inertial fusion schemes, energy production in this approach does not require compression of the fusion fuel to many times solid-state densities and simultaneous delivery of energy to the core to initiate the burn. Instead, the fusion plasma is created through wall ablation by an incident laser or particle beam that enters the target through a hole. A side benefit of the ablation process is generation of the strong magnetic field through the "thermoelectric" effect whereby it can be shown that such a field can be created in a hot plasma when its density gradient is perpendicular to its temperature gradient. We have seen that MICF is capable of producing specific impulses of tens of thousands of seconds at substantial thrusts, a capability that would allow round trips to Mars, for example, in a few months instead of years even when it is driven by lasers that require massive power supply systems. These travel times can be drastically reduced if beams of antiprotons are used to initiate the D-T fusion reactions since moderately sized "traps" can be utilized for this purpose. The use of the D-T fuel cycle has the undesirable consequence of producing high-energy neutrons that can induce radioactivity in many components of the propulsion vehicle. One way to completely circumvent this problem is to use a fuel cycle that produces no neutrons at all, either as a direct reaction product or in side reactions as might happen if deuterium- helium 3 (D $H_e^3$) fuel cycle is used. The most obvious candidate is the proton (P)-boron ($B^{11}$) cycle which produces only charged particles in the form of three alpha particles. The major drawback to the use of P-$B^{11}$ is the high temperature requirement, which leads to enhanced radiation loss that might prevent ignition of the system (Nivens, 1998). However, the use of antiprotons p-bar to create such a hot plasma and ignite it in an MICF propulsion system, appears promising and should be explored. In this paper will present a proposed experimental study that will serve as a basis for potential use of P-$B^{11}$ in an MICF propulsion device.

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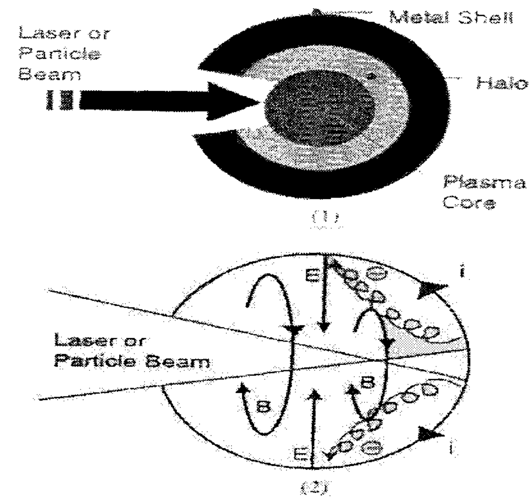


**FIGURE 1.** Schematic of (1) Plasma Formation and (2) Magnetic Field Formation in MICF.

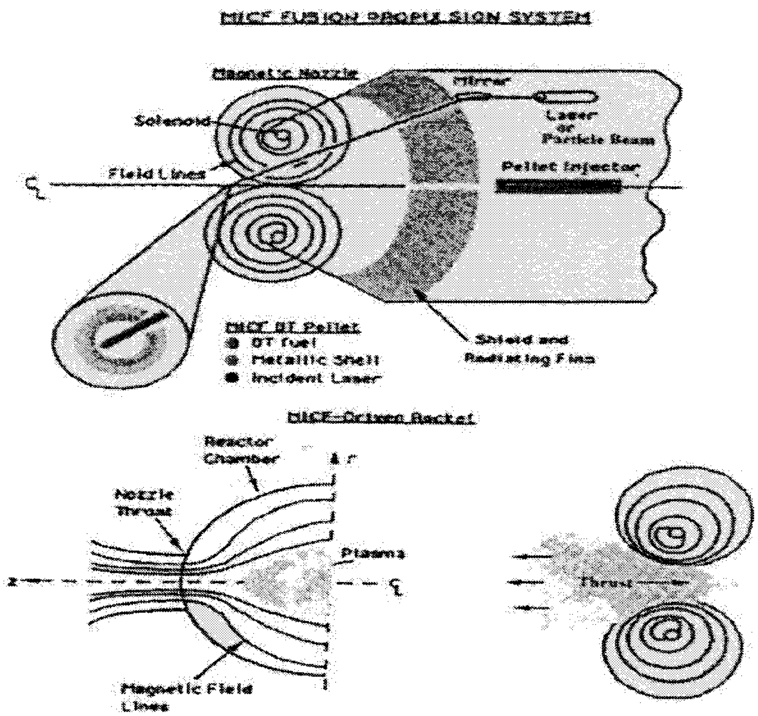


**FIGURE 2.** MICF Fusion Propulsion System.

# ANTIPROTON-GENERATED PLASMA IN MICF

It is expected that the p-bar trap constructed at the Marshall Space Flight Center will deliver up to $10^{12}$ particles at a mean energy of 10 keV to an MICF target in about a microsecond. We shall assume that the inner walls of the target contain a hydrogen Boron mixture at a ratio of 5 to 1 respectively. In order to calculate the parameters of the plasma created inside an MICF pellet whose core radius $r_c$=0.25 cm, and whose fuel thickness is 0.05 cm we first must calculate the penetration depth or range of 10 keV p-bar in the hydrogen-boron fuel mixture. For incident protons (p) or antiprotons (p-bar) with kinetic energy between 1 and 10 keV, the stopping power can be determined from (Ziegler, 1977).

$$\frac{1}{n}\frac{dE}{dx} = A_1 E^{1/2}\left[\frac{eV}{10^{15}\ \mathrm{atoms/cm^2}}\right] \tag{1}$$

where E is the energy of the incident particle in keV/amu, n the number density of the target material, and $A_1$ is a coefficient that depends on the target material. $A_1$= 1.262 for hydrogen and $A_1$=2.474 for boron, and with E = 10 keV/amu and n= $10^{23}/cm^3$, we find that

$$\frac{dE}{dx} = 3.99\mathrm{x}10^{8} \quad \mathrm{eV/cm}\ \ (\mathrm{Hydrogen})$$

$$\frac{dE}{dx} = 7.82\mathrm{x}10^{8} \quad \mathrm{eV/cm}\ \ (\mathrm{boron}) \tag{2}$$

If we further assume that the p-bar loses energy continuously as it penetrates the material then we can readily obtain for the range R, the value

$$R = E_{ave} / \left(dE/dx\right) \tag{3}$$

with this equation we find for a purely hydrogen target $R_H$=2.51x$15^{-5}$ cm, while for a purely boron target $R_B$= 1.28x$10^{-5}$. However, assuming that the shape of the dE/dx curve is independent of the stopping medium, then the range in a compound target can be written as (Knoll, 1979).

$$R_c = \frac{M_c}{\sum_i n_i \left(A_i / R_i\right)} \tag{4}$$

where $R_i$ = range in element i, $n_i$,= number of atoms of element i in the molecule, $A_i$ = atomic weight of element i, $M_c$= molecular weight of the compound. Using the following values: $n_H$ = 5, $n_B$ = 1, $A_H$ = 1.007825 amu, $A_B$ = 11.009305 (for $B^{11}$) amu, $M_c$ = 12.01713 amu and substituting in Eq (4) the individual ranges obtained above we find that $R_{PB}$=1.51.x$10^{-5}$cm. The well-known Bethe formula also produces similar results as the empirical (experimentally–based) formula given Eq (1). The relativistic Bethe formula is given by (Evans, 1995).

$$\frac{dE}{dx} = \frac{4\Pi e^2 z^2}{m_o v^2} NZ\left[\ln\frac{2m_0 v^2}{I} - \ln\left(1 - v^2/c^2\right) - v^2/c^2\right] \tag{5}$$

Where I = Ionization energy (13.6 eV for H, and 8.3 eV for B), e = electron charge, $m_o$ = electron mass = 0.511 MeV/$c^2$, z = incident particle atomic number (1 for p and p-bar), N = Number density of target ($10^{23}$ for solid state density), Z = atomic number of target (1 for H, and 5 for B) v = velocity of incident particle, c = speed of light.

Noting that the relativistic kinetic energy can be written as

$$KE = \frac{M_o c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - M_o c^2 \tag{6}$$

where $M_o$ is the rest mass of the incident particle, then

$$\left(v/c\right)^2 = 1 - \left(\frac{KE}{m_o c^2} + 1\right)^{-2} \tag{7}$$

which for 10 kev antiprotons yields

$$\left(v/c\right)^2 = 2.13\mathrm{x}10^{-5} \tag{8}$$

Putting these results in Eq (5) we find that

$$dE/dx = 1.13x10^9 eV/cm \tag{9}$$

for a pure hydrogen target and

$$\frac{dE}{dx} = 1.16x10^{10} eV/cm \tag{10}$$

in a pure boron target. These results give rise to $R_H$= 8.85x10$^{-6}$ cm and $R_B$=8.62x10$^{-7}$, and using Eq (4) we find that $R_{PB}$=1.20x10$^{-6}$ cm. If we assume that an antiproton beam with a diameter d=1.0x10$^{-3}$ cm (size of hole in target through which beam enters) containing 1.0 x10$^{10}$ p-bars strikes an area A in target whose density is n then the number of ablated ions $N_i$ is given by

$$N_i = R_{PB} A n \tag{11}$$

and the plasma density $n_p$ is given by $N_i/V_c$ where $V_c$ is the volume of the core. The temperature of the generated plasma T can be obtained from

$$T = \frac{2}{3}\frac{Ein}{N_i} \tag{12}$$

where Ein = 10$^{10}$x1876MeV on the assumption that all the annihilation energy appears in the plasma temperature. These results are summarized in table 1. It would be interesting to see what kind of a fusion plasma can the above-described antiproton beam give rise to in the experimental MICF pellet. This can be assessed by calculating the Q-value which is the ratio of

**TABLE 1.** Antiproton-Generated Plasma in MICF.

| Formula | Range (cm) | Total number of ablated Ni | Plasma density $n_p$ (cm$^{-3}$) | Plasma temperature (eV) |
|---|---|---|---|---|
| Ziegler | 1.51x10$^{-5}$ | 1.43x10$^{12}$ | 2.21x10$^{13}$ | 8.72x10$^{6}$ |
| Bethe | 1.20x10$^{-6}$ | 1.14x10$^{11}$ | 1.75x10$^{12}$ | 1.10x10$^{8}$ |

fusion power $P_f$ to injection power Pinj. These are given respectively by

$$p_f = \frac{n_p^2}{5} <\sigma v> E_f V_c \tag{13}$$

$$Pinj = N_{\bar{p}} E_{\bar{p}} / \tau \tag{14}$$

where $E_f$= 8.7 MeV is the energy produced in P-B$^{11}$ reaction, <σv> the fusion reaction rate, Np the total number of injected antiprotons, τ the pulse length of the p-bar beam, and $V_c$=0.065 cm$^3$, the core volume in the MICF target. If we use the conservative figures produced the Ziegler formula, as shown in table 1, and assume that the <σv> value does not change significantly from that at 2 Mev temperature (for which numerical value is available) then

$$Q = \frac{P_f}{Pinj} = 0.17\% \tag{15}$$

Clearly no ignition takes place at this Q-value, but perhaps increase in Ni and T as shown in Eqs. (11) and (12) could very well lead to ignition in a future propulsion device. As pointed out earlier, the excessive radiation losses at these high-temperatures constitute the major obstacle to ignition, but in the proposed experiment it is expected that the radiation emitted will provide the basis for diagnostic assessment of the plasma within the target. It should also be noted that the magnetic field generated by the above plasma inside MICF would be about 125 MG as predicted by the formula (Cassenti, 1997).

$$B_{MG} = 3.6\left(\frac{T}{keV}\right)^{1/2}\left(\frac{10\mu m}{d}\right)\left[\frac{A^{1/2}(Z+1)^{-1/2}}{1.1}\right] \tag{16}$$

where Z and A are respectively the atomic and mass numbers of the target fuel.

## SUMMARY AND CONCLUSIONS

We have demonstrated in this paper that a proposed experiment [first to be conducted anywhere] on the use of antiprotons to initiate fusion reactions in an inertial confinement concept is feasible with the current antiproton trap designed and built at NASA's Marshall Space Flight Center. We have also shown that with a proposed beam of $10^{10}$ antiprotons, which would be available in the existing trap, sufficiently dense, hot plasma will be created in the MICF target that would allow verification of the confinement properties of this fusion scheme. When extrapolated to an operating propulsion device, this antiproton—driven MICF system will be capable of producing a specific impulse of more than $10^5$ seconds at tens of kilonewtons of thrust-a capability that will clearly open up the solar system to human exploration.

## ACKNOWLEDGMENTS

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