Antiproton-Driven Magnetically Insulated Inertial Confinement Fusion (MICF) Propulsion System

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Presentation Outline

1. What is MICF Propulsion and How It Works

2. Comparison with Implosion-Type Inertial Confinement Fusion (ICF)

3. Mathematical Plasma Modeling and Basic Equations

4. Classical and Anamolous Cross Field Transport

5. Preliminary Results and Fusion Energy gain

6. Application to Propulsion

7. Phase II Proposed Investigation
Implosion-Type  Laser-Fusion

Major Issues

1. High Compression ratio \[ \eta = \frac{n}{n_{\text{liquid}}} \approx 10^3 - 10^4 \]

\[ n_{\text{liquid}} = 4.5 \times 10^{22} \text{ cm}^{-3} \]

\[ (\rho \sim 0.2 \text{ gm/cm}^3) \]

2. Pellet energy gain \[ G = \frac{E_{\text{fusion}}}{E_{\text{driver}}} \]

3. Pre-heat problems

4. Rayleigh-Taylor Instability

5. Uniform Illumination-Complicated Optics
<table>
<thead>
<tr>
<th>Implosion Laser-Fusion</th>
<th>MICF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement time $\tau$</td>
<td>$\tau = \frac{d}{U_s}$</td>
</tr>
<tr>
<td>$\tau = \frac{R}{C_s} = \tau_d$</td>
<td>$d =$ Thickness of metal shell</td>
</tr>
<tr>
<td>$R =$ Radius of pellet</td>
<td>$U_s =$ Sound speed in shell</td>
</tr>
<tr>
<td>$C_s =$ Sound speed in plasma</td>
<td>$U_s \sim \sqrt{\frac{T}{\rho}}$</td>
</tr>
<tr>
<td>$\tau_d =$ Disassembly time</td>
<td>$T =$ Temp in shell much less than that in plasma due to magnetic insulation</td>
</tr>
<tr>
<td></td>
<td>$P =$ Density of shell much larger than that of plasma due to large atomic mass</td>
</tr>
</tbody>
</table>

$\therefore U_s \ll C_s$

$\therefore \tau \gg \tau_d$

In fact $\tau_{MICF} = 10^2 \tau_d$ ⇒
I) lower plasma density
II) lower laser energy
III) better coupling to plasma
IV) higher gain
Figure 1: Schematic of (1) Plasma Formation and (2) Magnetic Field Formation in MICF
Main Features of MICF Fusion

1. Combines the favorable aspects of Inertial and Magnetic Fusions into one

2. Physical Containment of plasma is provided by a Metallic shell (e.g. tungsten or gold), and thermal Insulation of plasma energy is provided by a self-generated, strong magnetic field

3. Magnetic Field generation is due to $\nabla n \times \nabla T$ i.e. density and temperature gradients perpendicular to one another.

Generalized Ohm’s Law shows that

$\nabla n \times \nabla T \Rightarrow$ Electric field, $E \Rightarrow$ time varying magnetic field, $B$

4. Decay time of Magnetic Field > plasma confinement time
Plasma Modeling and Basic Equations

1. Examples of particle and energy balance equations for species in MICF; Each species is treated as an Ideal Gas. For DT Fuel Ions in the core

2. Particle Balance Equation

\[
\frac{d}{dt}\left\{\frac{4}{3}\pi r_n f^n_f\right\} = -\frac{4}{3} \pi r_n f^n_f \left\{\frac{1}{2} n_f^2 \langle \sigma v \rangle\right\} + 4\pi r_n \left\{\Gamma_r - \Gamma_f\right\}
\]

3. Energy Balance Equation

\[
\frac{d}{dt}\left\{\frac{4}{3}\pi r \gamma - 1 n_f T_f f f^n_f\right\} + 4\pi r_n f^n_f \frac{d r}{d t} = \frac{4}{3} \pi r_n f^n_f T_f^T_f \left\{3 n_f^2 n_e \left(T_e - T_f\right) + \frac{3 n_f^2 n_f}{2 (n\tau)_{e\gamma}} \left(T_e - T_f\right)\right\}
\]

\[+ n_f \sum_{k=1}^{k_{max}} n_k \left\{\frac{d E_k^n_f}{d t}\right\}_f - \frac{3}{4} n_f^2 T_f^T_f \langle \sigma v \rangle_f\right\} + 4\pi r_n \left\{W_r - W_f\right\}
\]

4. \(\Gamma's\) and \(W's\) are particle and energy fluxes across the magnetic field

5. \(\gamma = \text{ratio of specific heats} = \frac{5}{3}\)
Electron Balance Equations in the Core

1. **Particle Balance**

\[ n_e = n_f + 2\left(n_\alpha + n_f\alpha\right) \]

2. **Energy Balance**

\[
\frac{d}{dt} \left\{ \frac{3}{4} \frac{\pi r}{3 (\gamma - 1)} n_e T_e \right\}^{2} + 4\pi r n_e T_e \frac{dr}{dt} = \\
\frac{4}{3} \pi r \left\{ \frac{3}{2 (n\tau)_{ef}} (T_f - T_e) + \frac{3}{2 (n\tau)_{e\alpha}} (T_\alpha - T_e) \right\} \\
+ n_e \sum_{k=1}^{k_{max}} n_k \left( \frac{dE_k}{dt} \right)_{e} - P_{BC} \}
\]

\[
+ 4\pi r \left\{ \Gamma_r E_{re} - \left( \Gamma_f + 2\Gamma_\alpha \right) E_{Le} \right\}
\]
where

\[ E_{re} = \text{average energy of an electron diffusing across the magnetic field into the core} \]

\[ E_{Le} = \text{average energy of an electron diffusing out} \]

\[ P_{BC} = \text{Bremsstrahlung Radiation} \]

\[
= \left(3.340 \times 10^{-15}\right)n_{e}T_{e}^{1/2}\left[n_{e}^{n} + 4(n_{\alpha} + \sum_{k=1}^{k_{max}} n_{k})\right] \frac{keV}{cm. \sec}
\]
Classical and Anomalous Cross Field Transport

1. **Particle and Energy Fluxes**

   i) **Particle Flux** \( \Gamma = -D \frac{\partial n}{\partial r} \)
   
   where \( D = \) diffusion coefficient

   \[ \frac{\partial n}{\partial r} = \text{density gradient} \]

   ii) **Energy Flux** \( W = \bar{E} \Gamma \), where \( \bar{E} = \text{mean particle energy} \)

2. **Classical Diffusion**

   \( D = \rho^2 \nu \); \( \rho = \text{Larmor radius}, \nu = \text{Collision frequency} \)

3. **Anomalous Diffusion**

   i) **Bohm diffusion** \( D_B = \frac{T}{16eB} \)

   \[ e = \text{electronic charge} \]
   \[ B = \text{Magnetic field strength} \]

   ii) **Modified Bohm**

   \[ D = \frac{\gamma}{k^2} = \frac{\gamma}{r^2}; \gamma = \frac{\sqrt{2}}{3} W_D; W_D = \text{drift frequency} \]
Preliminary Results and Fusion Energy Gain

1. For most parameter ranges, the gain “Q” is larger for classical diffusion than for Bohm.

2. “Modified Bohm” however appears to yield highest gain; reaching a value of $Q = 2623$ at an input energy $E_{in} = 1.15$ MJ. This may be attributed to more efficient fueling of the core without degrading its temperature when “mild turbulence” exists in the system.

3. The large $Q$ values are reached when the “halo” region is totally depleted. This occurs at about 20 ns into the burn at which time the pressure in the core reaches its maximum.

4. The Bremsstrahlung radiation emitted by the core electron plays an important role in ionizing the fuel in the halo region and in the inner regions of the metal shell. This contributes to the pressure build up outside the core which in turn compresses the core increasing its density and fusion energy production.

5. The Gain generally increased as the input energy $E_{in}$ is decreased, although there seems to exist a “cut-off” input energy below which $Q$ becomes very small!
Radii $r$, $r_1$, $r_2$ and $r_3$ versus time for $E_{in} = 4.033$ MJ. $B = 100$ T, $N_0 = 5 \times 10^{21}$ cm$^{-3}$, $T_0 = 20$ keV, classical diffusion.
Gain $Q$ versus magnetic field $B$. $E_{in} = 4.907$ MJ,
$N = 5 \times 10^{21}$ cm$^{-3}$, $r_0 = 0.25$, $r_f = 0.3$, $r_{max} = 1$ cm.
Cut-off input energy $E_{in}$ and gain $Q$ versus initial cavity radius $r_0$. $B = 100$ T, $N_0 = 5 \times 10^{21}$ cm$^{-3}$. 
Fuel properties versus time for $E_{in} = 4.033$ MJ.

$B = 100$ T, $r_0 = 0.25$ cm, $N = 5 \times 10^{21}$ cm$^{-3}$, $T_0 = 20$ keV.
Cut-off input energy $E_{in}$ and gain $Q$ versus initial plasma density $N_0$. $B = 100$ T, initial cavity radius $r_0 = 0.25$ cm.
Gain $Q$ versus time for $E_{in} = 4.033$ MJ, $B = 100$ T, $N_0 = 5 \times 10^{21}$ cm$^{-3}$, $T_0 = 20$ keV, classical diffusion.
Gain $Q$ versus input energy $E_{in}$. $B = 100$ T, $N = 5 \times 10^{21}$ cm$^{-3}$, $r_0 = 0.15$ cm, $r_f = 0.18$ cm, $r_{max} = 0.6$ cm.
Gain $Q$ versus input energy $E_{in}$ for modified Bohm diffusion. Initial $N = 5 \times 10^{21} \text{ cm}^{-3}$, $r_0 = 0.25 \text{ cm}$, $r_f = 0.3 \text{ cm}$, $r_{max} = 1 \text{ cm}$.
MICF FUSION PROPULSION SYSTEM

Magnetic Nozzle
Solenoid
Field Lines

MICF DT Pellet
- DT Fuel
- Metallic Shell
- Incident Laser

Shield and Radiating Fins
Pellet Injector
Laser or Particle Beam
Mirror

MICF-Driven Rocket

Reactor Chamber
Nozzle Throat
Plasma
Magnetic Field Lines

Thrust
Application To Propulsion

\[ I_s = 1.3 \times 10^5 \text{Sec} \]

<table>
<thead>
<tr>
<th>Mission</th>
<th>conservative</th>
<th>optimistic</th>
<th>( F = 4.6 \times 10^4 \text{N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oort FB</td>
<td>37 y</td>
<td>102 gm</td>
<td>8.47 y</td>
</tr>
<tr>
<td>Oort Rend</td>
<td>41 y</td>
<td>114 gm</td>
<td>10.44 y</td>
</tr>
<tr>
<td>Oort Rd trip</td>
<td>155 y</td>
<td>427 gm</td>
<td>36.74 y</td>
</tr>
<tr>
<td>( \alpha ) Centauri FB</td>
<td>968 y</td>
<td>2.67 kg</td>
<td>213 y</td>
</tr>
<tr>
<td>( \alpha ) Centauri Rend</td>
<td>988 y</td>
<td>2.73 kg</td>
<td>224 y</td>
</tr>
<tr>
<td>( \alpha ) Centauri Rd trip</td>
<td>3899 y</td>
<td>10.76 kg</td>
<td>872 y</td>
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<table>
<thead>
<tr>
<th>Mission</th>
<th>Trip Time</th>
<th>Propellant Mass, ( m_p )</th>
<th>Amount of ( \bar{p}'s )</th>
</tr>
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<tbody>
<tr>
<td>Mars FB</td>
<td>10 d</td>
<td>30 mT</td>
<td>74 mg</td>
</tr>
<tr>
<td>Mars Rend</td>
<td>15 d</td>
<td>45 mT</td>
<td>112 mg</td>
</tr>
<tr>
<td>Mars Rd trip</td>
<td>31 d</td>
<td>94 mT</td>
<td>234 mg</td>
</tr>
<tr>
<td>Jupiter FB</td>
<td>32 d</td>
<td>97 mT</td>
<td>243 mg</td>
</tr>
<tr>
<td>Jupiter Rend</td>
<td>46 d</td>
<td>138 mT</td>
<td>345 mg</td>
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<tr>
<td>Jupiter Rd trip</td>
<td>102 d</td>
<td>309 mT</td>
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<tr>
<td>Pluto FB</td>
<td>123 d</td>
<td>373 mT</td>
<td>932 mg</td>
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<tr>
<td>Pluto Rend</td>
<td>172 d</td>
<td>520 mT</td>
<td>1.30 gm</td>
</tr>
<tr>
<td>Pluto Rd trip</td>
<td>445 d</td>
<td>1345 mT</td>
<td>3.36 gm</td>
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Proposed Phase II Investigations

To verify the confinement properties of MICF as formulated in Phase I study:

1 - To experimentally verify the generation of magnetic fields in MICF targets using the facilities of the world class “Ultra Fast” Laboratory at the University of Michigan which can deliver laser beam intensities of > $10^{20}$ W/cm$^2$ on target

2 - To measure the magnetic field in a typical target and compare with theoretical predictions

3 - To demonstrate experimentally the confinement dependence on type of metal shell; on thickness of shell and on the strength of the magnetic field

4 - To investigate above phenomena with a particle beam e.g. a proton beam generated by a laser beam impinging on aluminum foil. Experiments at U of M have shown that a laser beam of intensity of $10^{18}$ W/cm$^2$ striking a 3μm thick foil gives rise to $10^{10}$ - $10^{12}$ protons with average energy of 0.5 MeV

5 – Utilize above information for eventual use of an antiproton beam ($10^{12}$ $\bar{p}$'s at 20 keV with pulse length of 10’s of μs) from trap developed at MS FC to generate fusion-grade plasma in MICF targets
Hole Diameter: 0.6 × Shell Diameter
Larmor Diameter = 340 μm, if B = 100T.
\( T_e = 15 \text{ keV} \)

\[
\frac{B}{MG} = 3.6 \left( \frac{T}{1 \text{ keV}} \right)^{1/2} \left( \frac{10 \mu m}{d} \right) \left[ \frac{A^{1/2} (z+1)^{-1/2}}{1.1} \right]
\]

DT plasma, \( A/z = 2.5 \)
\( d = \text{Spot diameter} \)

Note if
\[ d = 10 \mu m \]
\[ T = 1 \text{ keV} \]
\[ B = 3.6 \text{ MG} \]
\[ T = 10 \text{ keV} \]
\[ B = 10 \text{ MG} \]

\[
\tau = \frac{\pi \sigma L^2}{C^2}
\]
\( L = \text{Scale Length} \)
\( \sigma = \text{Plasma Conductivity} \)
Particle Beam Driven MICF

Incident Laser Beam Intensity $\sim 10^{18}$ W/cm$^2$

Proton Beam
$10^{12}$ @ 0.5 MeV

Al Foil
thickness = $3 \times 10^{-6}$ m
d = $10 \times 10^{-6}$ m

Metal Shell

1 cm