Gradient Field Imploding Liner Fusion Propulsion System
Phase I Study

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Human deep space exploration requires high energy propulsion systems

\[ \frac{m_f}{m_0} = e^{-\frac{\Delta v}{v_e}} \]

- Solar system destinations require \( \Delta v \approx 10^4 - 10^5 \text{ m/s} \)
- High exhaust velocity required for reasonable payloads

Multiple studies show the benefits of fusion energy for rapid trip times to Mars and the outer solar system...

- High exhaust velocity (specific impulse)
- High specific power (kW/kg) to reduce trip times

...once we get it to work

Rocket equation: \((m_f/m_0) = \text{fraction of initial mass delivered to destination; } \Delta v = \text{required mission velocity; } v_e = \text{propellant exhaust velocity}\)
Take advantage of current ground-based research in Magnetoinertial Fusion (MIF)

Multiple approaches: Z-pinch, Θ-pin, Liner-driven FRC, etc.

- Pulsed current in an external coil generates strong axial magnetic field, induces azimuthal current in target liner
- Radial $j_\theta B_z$ Lorentz force implodes the liner to compress the target fuel
- At maximum compression, pressure is balanced between the stagnating liner material, external magnetic field, trapped internal magnetic field, and fuel pressure


Energy storage, resistive coil, pulse repetition all present challenges
Reformulate the θ-Pinch Concept

• Replace the time changing magnetic field generated by the pulsed current coil with a target moving rapidly into a steady-state magnetic field gradient
  
  \[ \mathbf{I} \propto \mathbf{B}_z = \mathbf{v}_z \frac{\partial \mathbf{B}}{\partial z} \]

• The rapidly changing magnetic field observed in the target frame of reference induces a strong azimuthal current in the target liner

• The combination of axial magnetic field and azimuthal liner current generates a radial Lorentz force that rapidly compresses and heats the target, similar to a θ-pinch
NIAC Phase I Concept

Preliminary Concept

Target Accelerator

Fuel Target

Magnetic Field Coil

Conversion to Directed Thrust (magnetic nozzle not shown)

Compress

Burn

Expand

External field pressure + liner material pressure = Internal field pressure + gas kinetic pressure
Potential Benefit

How Does This Help?

• Replaces pulsed drive coil with steady-state superconducting magnet, mitigating issues with repetitive, high current pulse generation
  - Reduces energy storage requirements, coil resistive losses
  - Reduces demands on switches, power components, etc.

• Fairly compact linear geometry for in-space applications
  - Strong gradient field produced by small bore magnet
  - Readily incorporates magnetic nozzle for directed plasma thrust

• Moves the challenge from pulsed coil to target accelerator
  - However, the target can be accelerated over a longer time period

• Opportunity for relatively low cost ground testing
  - Validate target acceleration, preheating, and compression physics
  - Adaptable once MIF conditions for fuel breakeven are demonstrated
Phase I Study Goals

- Model target injection and compression dynamics
- Evaluate fusion fuel target designs (geometry, density, liner)
- Evaluate high velocity target acceleration options (several km/s)
- Evaluate magnetic field requirements and solenoid coil designs
- Incorporate MIF concepts of target preheating and internally compressed magnetic fields to reduce particle thermal transport
- Estimate performance (yield, specific impulse, average thrust)

Pull it all together into an initial vehicle design and comparative mission analysis
Phase I Study Approach

• Semi-analytic model (backup charts)

• Preliminary choices
  - Fuel: D+T -> $\alpha$ (3.5 MeV) + n (14.1 MEV)
    • easiest to ignite, but issues with neutrons
  - Accelerator: laser ablation to accelerate target
    • achieve high velocity, also useful for preheating target

• Performed several trades on target design, injection velocity, fuel density, magnetic field values, coil size, etc.

• Optimized design for maximum energy release, used to define vehicle performance for mission analysis
Summary of Results

Optimum Initial Parameters

<table>
<thead>
<tr>
<th>Initial Fuel Density</th>
<th>Initial Target Radius</th>
<th>Aspect Ratio</th>
<th>Injection Velocity</th>
<th>Preheat Fuel Temp</th>
<th>Coil Axial B-Field</th>
<th>Initial Target B-Field</th>
<th>Axial B-field Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07 kg/m^3</td>
<td>1.0 cm</td>
<td>6</td>
<td>10 km/s</td>
<td>400 eV</td>
<td>30 T</td>
<td>1.0 T</td>
<td>100 T/m</td>
</tr>
</tbody>
</table>

Corresponding Engine Performance

<table>
<thead>
<tr>
<th>Specific Impulse (s)</th>
<th>Impulse (N·s)</th>
<th>Yield (J)</th>
<th>Gain (100% efficiency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Liner</td>
<td>Be Liner</td>
<td>Li Liner</td>
<td>Be Liner</td>
</tr>
<tr>
<td>32,200</td>
<td>17,145</td>
<td>780</td>
<td>1445</td>
</tr>
</tbody>
</table>

Assumes 70% magnetic nozzle conversion efficiency (plasma energy into directed kinetic energy)

Results are extremely optimistic, but demonstrate the concept is feasible and may provide performance values of interest for deep space exploration.
Mission Analysis: Mars

Example: Initial vehicle mass of 320 mT with a 100 mT payload would take 45 days and use 50 mT of propellant for a 1-way trip to Mars with the Li lined target system, and approximately 75 days with the Be lined target system.
Mission Analysis: Saturn

Example: Initial vehicle mass of 400 mT with 100 mT payload would take 200 days and use 190 mT of propellant for a 1-way trip to Saturn with the Li lined target system, and approximately 320 days with the Be lined target system.
### Rapid Mars trip with Orion module and deep space habitat

**System** | **Mass (mT)**
---|---
Prop Tanks | 5.0
Thermal | 13.6
Propulsion | 75.4
Structural | 17.3
Avionics | 3.5
Mass Growth Allowance | 58.4
**Inert Mass** | 173.2
Payload | 50.0
**Dry Mass** | 223.2
Ullage | 1.5
**Inert Mass** | 224.7
Propellant | 48.5
**IMLEO** | 271.6

**Mass parameters based on related prior work:**


Future Work

Advanced 3D multi-physics simulation (SPFMax)

• Smooth Particle Hydrodynamics with Maxwell equation solver developed by UAH for MIF and fission/fusion hybrid research
• Preliminary results show induced surface current generated due to $v_z(\partial B_z/\partial z)$ term

Ground-based experiment options (validation models)

• Experimentally demonstrate target compression physics
  - Available 2-stage light gas gun, hollow or filled projectiles, instrumented
  - Use water cooled coils to generate various magnetic field geometries
• Pulsed laser ablation studies of liner materials
  - Available kW-class pulsed laser, thrust stand

Currently evaluating approaches for a possible Phase II proposal
Acknowledgements

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The Phase I final report will be available on the NIAC website

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BACKUP CHARTS
Phase I Study Approach

Semi-Analytic Model

Based on MIF model of McBride and Slutz (2015)

- Adiabatic heating
- Optional fuel preheating (laser absorption)
- Fusion byproduct ($\alpha$) energy deposition within target
- Radiative losses from high temperature plasma
- Radial ion and electron thermal conduction losses
- Mass and energy end losses from the compressed target
- Fusion cross sections and reaction rates
- Energy yield and gain, energy balance calculations
- Initial model modified for high velocity target injection
- Partially validated with adiabatic compression model

Numerous trade studies performed to evaluate optimum engine performance

Sample Model Results

-Isp as a function of initial fuel density
-Isp as a function of initial target radius
-Isp as a function of initial target velocity
-Isp as a function of fuel preheat temperature
Results, continued

Isp as a function of external magnetic field

Isp as a function of internal target magnetic field

Isp as a function of magnetic field gradient

Isp as a function of liner material (Al, Be, Li)
In Development: SPFMax Simulation
*Smooth Particle Hydrodynamics with Maxwell equation solver*

Code in development at the University of Alabama, Huntsville

- Tabular equations of state to model variable levels of ionization
- Thermal conduction, radiation emission and absorption
- Shock capturing
- Real viscosity
- Electromagnetic field propagation and forces in the plasma
- Self-consistent circuit model
- Nonlocal absorption of fusion ion product energy
Sequence of target propagation through the entrance of a magnetic field coil