Fusion-Enabled Pluto Orbiter and Lander

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Why Fusion Propulsion?

1. Get there **FASTER**
   - Faster can mean CHEAPER if it’s also the same size or smaller

2. Do more **SCIENCE**
   - Payload capabilities and data rates depend on POWER
The fusing plasma acts as the **heating source** for propellant flowing outside the confinement region. This process of **thrust augmentation** gives us substantial thrust with high exhaust velocity!
Pluto Explorer Mission with DFD

Single launch from Earth, fly directly to Pluto with constant thrust.

Put a 1000 kg spacecraft in orbit around Pluto, beam 30 kW to a lander using optical transmission, return high-definition video – and get there in only 4 years!
Pluto Explorer Vehicle Design

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engines</td>
<td>2 @ 1350 kg</td>
</tr>
<tr>
<td>Fuel ($D_2$)</td>
<td>6000 kg</td>
</tr>
<tr>
<td>Helium-3</td>
<td>0.5 kg</td>
</tr>
<tr>
<td>Liquid $D_2$ tank</td>
<td>2.1 m radius</td>
</tr>
<tr>
<td>Gas $^3$He tank</td>
<td>0.95 m radius</td>
</tr>
<tr>
<td>Fuel Tanks</td>
<td>300 kg</td>
</tr>
<tr>
<td>Radiator Area</td>
<td>50 m$^2$</td>
</tr>
<tr>
<td>Radiators</td>
<td>134 kg</td>
</tr>
<tr>
<td>Lander</td>
<td>230 kg</td>
</tr>
<tr>
<td>Structure</td>
<td>200 kg</td>
</tr>
<tr>
<td>Orbiter payload</td>
<td>436 kg</td>
</tr>
<tr>
<td><strong>Launch Mass</strong></td>
<td><strong>10000</strong></td>
</tr>
</tbody>
</table>
STOP RIGHT THERE.
Why is a fusion drive suddenly achievable?
DFD is DIFFERENT from other fusion reactor concepts

1. Unique heating method
2. Simple configuration
3. Small size
4. Clean operation – low radiation

→ FRC has 10x better confinement than tokamak

These features make it uniquely suited for use in space!
DFD Technology is **Simple, Small, Clean**

- Based on a PPPL experiment
- **Simple** array of magnetic coils
  - Easily direct ion flow for thrust
- **Small** size promotes **Clean** operation (very few neutrons)
  - D-³He fuel
  - Tritium exits before it can fuse
  - 1-10 MW per minivan-sized engine
- Enabled by new RF magnetic plasma heating method
  - “odd-parity” heating
  - Closed field lines FRC region
  - Steady-state operation
NIAC Study

PHASE I RESULTS
Engine design
Mass and energy breakdowns
Trajectory analysis

PHASE II PLANS
## What did we learn from Phase I?

<table>
<thead>
<tr>
<th>Area</th>
<th>Progress</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust Model</td>
<td>Use PPPL’s UEDGE* fluid code results to generate thrust and Isp model as a function of power and flow rate</td>
<td>Feasible envelope for operation, ~5 N/MW</td>
</tr>
<tr>
<td>Trajectories</td>
<td>Develop new trajectories using constant thrust, Isp, and efficiency results from UEDGE model</td>
<td>Pluto mission is feasible!</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Departing from LEO takes ~60 days and expands launch options</td>
</tr>
<tr>
<td>Magnet Model</td>
<td>Modeled the magnet mass and discovered tradeoff between HTS and LTS, materials and operating temperature, component mass</td>
<td>New NASA STTR</td>
</tr>
<tr>
<td>RF Subsystem</td>
<td>Idea for switching amplifiers (class E) to lower RF subsystem mass and approach 100% efficiency</td>
<td>New NASA STTR</td>
</tr>
</tbody>
</table>

Analyzing Key DFD Subsystems

Assess TRL and feasibility of all supporting subsystems, and increase fidelity of specific power estimates
Parametric Engine Model in MATLAB

Assumptions
- Gas box power
- RMF power and efficiency
- Synchrotron reflection
- Superconductor properties

Fusion Parameters
- Temperatures and densities
- Length & radius
- Beta
- Fuel ratio

Subsystems
- Shielding
- Thermal conversion system
- Radiator mass
- Coil cooling

Fusion Power Model
- Neutron load
- Synchrotron
- Bremsstrahlung
- Thrust power
- Thermal power

Fusion cross-sections
1 MW Engine Energy Balance

Total power

Power to sustain heating

Power available to spacecraft

Electric specific power = 0.16 kW/kg
Thrust specific power = 0.34 kW/kg
Fusion specific power = 0.74 kW/kg
Engine Mass Analysis

Fusion Engine Mass (1.0 MW / 1350 kg)

1 MW Engine | 1350 kg
---|---
Shielding thickness | 5 cm
Magnets | 558 kg
Shielding | 339 kg
Power Generation | 178 kg
Structure | 122 kg
RMF system | 108 kg
Radiators | 27 kg
Coil cooling | 18 kg
Specific Power | 0.74 kW/kg
UEDGE Plasma Transport Software

Power Input to e⁻

Radial (m)

Axial Distance (m)

Gas Flow (D₂)

Calculate thrust
Numerical Simulation of Energy to SOL

- New fluid code results confirm 5-10 N/MW thrust input power (power carried in SOL)
Thrust and Velocity Model

Results indicate a feasible range of flow rates for the SOL to absorb the energy from the fusion products.

This gives us a numerical model to trade thrust and specific impulse.
Earth Departure from LEO

- 30 days with 20 N
- 60 days with 10 N
- Short amount of time in radiation belts
- 7 km/s DV is small portion of mission total
- Expands launch options
Constant-Thrust Trajectories

Straight-line, planar and 3D trajectories all confirm feasibility of Pluto mission concept

Trajectory

Planar Orbit
Powered Injection into Pluto Orbit

- Feasible
  - Uses twice the velocity change of an impulsive burn at closest approach
- 2-3 days

Mass = 2500 kg
Thrust = 10 N
DV = 977 m/s
Phase II Plans

- Thrust augmentation experiment
  - Explore dynamics of adding plasma to the scrape-off-layer
- Synchrotron loss modeling
  - Existing models are based on tokamaks
  - Theoretical effort to create model specific to FRC
- Additional subsystem models
  - Superconducting coils
    - Subcontract with MIT’s Dr. Joseph Minervini
    - MIT has a new HTS magnet in-house
  - RF heating system
- Closed-loop no-thrust power generation equipment
I want one now!

- Caveat: We have NOT yet demonstrated fusion
- PFRC-3 requires $50M and superconducting magnets
  - Demonstrate fusion in 5-7 years
- Engineering of the space subsystems can occur in parallel with the fusion science experiments
- Once fusion near breakeven has been demonstrated, commercial development can take place
- Best-case timeline: 15 years to a space reactor
Thank You

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Backup

ADDITIONAL TECHNICAL INFORMATION
Confirmed: Field-reversal, high-beta, long-term stability (300 ms pulses), electron heating (>500 eV with 20 kW input power).

In progress: Ion heating

Next up: Particle exhaust, high power and field operation, demonstrate fusion

<table>
<thead>
<tr>
<th>Machine</th>
<th>PFRC-1</th>
<th>PFRC-2</th>
<th>PFRC-3A</th>
<th>PFRC-3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objectives</td>
<td>Electron Heating</td>
<td>Ion Heating</td>
<td>Heating above 5 keV</td>
<td>D–He3 Fusion</td>
</tr>
<tr>
<td>Fuel</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>D–3He</td>
</tr>
<tr>
<td>Goals/Achievements*</td>
<td>3 ms pulse* 0.15 kG field* e-temp = 0.3 keV*</td>
<td>0.1 s pulse* 1.2 kG field i-temp = 1 keV</td>
<td>10 s pulse 10 kG field i-temp = 5 keV</td>
<td>10 s pulse 80 kG field i-temp = 50 keV</td>
</tr>
<tr>
<td>Plasma Radius</td>
<td>4 cm</td>
<td>8 cm</td>
<td>16 cm</td>
<td>16 cm</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$2M</td>
<td>$6M</td>
<td>$20M</td>
<td>$20M</td>
</tr>
</tbody>
</table>
Thrust Augmentation

- H or D is used as a **propellant** - it flows along the magnetic field lines outside of the separatrix; scrape-off layer (SOL) e- are heated by the fusion products that are ejected into the SOL; e- energy transferred to ions in plume expansion
- This reduces the exhaust velocity of the fusion products from 25,000 km/s to ~50 km/s and increases thrust to >20 N
- Thrust/I_{sp} is adjustable based on rate that gas is injected into the gas box
- The exhaust plume is directed by a magnetic nozzle, consisting of a throat coil and nozzle coils to accelerate the flow.
Rotating Magnetic Fields (RMF)

- Parity refers to the symmetry of the magnetic field mirrored across the z=0 midplane
- Frequency is a fraction of the ion cyclotron frequency for the helium-3
  - Would be 0.3 to 2 MHz
- Provides all the startup power and a fraction of the heating power during operation
- RF antennas shown to the right
Specific Power

- Plot on right based on work done assuming direct insertion
- Other electric propulsion systems
  - Solar – not applicable to outer planet missions
  - Fission Electric

![Graph showing specific power vs. mass for various spacecraft missions and propulsion systems.](image-url)
Fusion “Cross-Sections”

Reactor operating temperatures

Reaction Rates

Mean Sigma V (m$^3$/sec)

Temperature (KeV)

Neutron Reduction Mechanisms

1. Fuel – D-$^3$He
2. Size – small radius FRC
3. Fast removal of tritium in scrape-off layer
4. Low D fuel ratio:
   - D/$^3$He of 1:3
5. Non-equilibrium:
   - D heating only $\frac{1}{2}$ as much as $^3$He by $\omega_{\text{RMF}}$
   - Beam-like distributions
DFD is REALLY small

Typical tokamak reactor:
- 1000-4000 MW
- 60 m tall
- Development in 30-50 years

PFRC reactor:
- 1-10 MW
- 2 m diameter
- Development in 5-10 years
- Small enough to fit on a single launch vehicle
Computational Tools

LSP: particle in cell

RMF: heating model

UEDGE: fluid model
Heat Recycling

- Brayton cycle heat engine
  - Heat high pressure gas to do work
- Used in High Temperature Gas Cooled Fission Reactors
- Helium working fluid
- Paired compressor/turbine sets with counter-rotating turbines and compressors
- Common shaft for compressor, turbine and generator
- Need for multiple compressor and turbine stages and recuperator to be determined
- Large radiator wings