Direct Fusion Drive provide game-changing power and propulsion in space

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JPL Advanced Space Propulsion Workshop, 2014
Talk Outline

- PFRC Reactor Design and Experiments
- Variable Thrust and Specific Impulse via Augmentation
- Missions
  - Alpha Centauri
  - L2 Space Telescope
  - Asteroid Deflection
  - Mars Mission
- Conclusions
Summary

- DFD produces power AND thrust
- FRC fusion reactor exhausts fusion products plus additional deuterium to produce thrust
- Heating method naturally limits size: 1-10 MW and size of minivan
- Low neutron radiation using $^3\text{He}$ as fuel
  - $^3\text{He}$ is in limited supply, enough for approx. 100 MW/year
- Perfect for space applications
PRFC Reactor Design
Princeton Field Reversed Configuration (PFRC)

- Field Reversed Configuration (FRC)
  - Simple geometry with fewer coils
- RF heating with odd-parity rotating magnetic fields naturally limits reactor size
  - Plasma radius in range 20-40 cm
  - Size of 1-10 MW which is ideal for space
- Confinement with high temperature superconducting coils
- Burns aneutronic D and $^3$He with beta greater than 0.8

- Linear configuration allows for configuration as a rocket engine
- Magnetic Nozzle
- Add H or D$^+$ to augment thrust
- Variable exhaust velocity
  - 50 to 20,000 km/s
  - $P = 0.5 \frac{u_E}{\eta}$, with $\eta \sim 0.5$
PFRC Experiments at PPPL

- Princeton Plasma Physics Laboratory performing experiments with DOE funding
  - Concluded PFRC-1 a, b, c in 2011
  - PFRC-2 operating now; goal is to demonstrate keV plasmas with pulse lengths to 0.3 s
  - MNX experiment on plasma detachment in nozzle

- Princeton Satellite Systems performing mission and trajectory design, space balance of plant studies under IR&D
  - Four joint PPPL/PSS patents

<table>
<thead>
<tr>
<th>Machine</th>
<th>PFRC-1</th>
<th>PFRC-2</th>
<th>PFRC-3</th>
<th>PFRC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives</strong></td>
<td>Electron Heating</td>
<td>Ion Heating</td>
<td>Heating above 5 keV</td>
<td>D–He3 Fusion</td>
</tr>
<tr>
<td><strong>Goals/Achievements</strong></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>1000 s pulse 60 kG field i–temp = 50 keV</td>
</tr>
<tr>
<td><strong>Plasma Radius</strong></td>
<td>4 cm</td>
<td>8 cm</td>
<td>16 cm</td>
<td>25 cm</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>$2M</td>
<td>$6M</td>
<td>$20M</td>
<td>$50M</td>
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</table>
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
Variable Thrust and Isp

THRUST AUGMENTATION WITH D^+
The DFD design envelope fits between traditional chemical, electric and nuclear propulsion methods.

Fusion products of the deuterium-helium-3 (D/He\(^3\)) reaction have a very high exhaust velocity: 25,000 km/s.

We can convert some of their kinetic energy into thrust by transferring energy from the fusion products.

\[
P = \frac{1}{2} \frac{T u_e}{\eta} \\
\dot{m} = \frac{T}{u_E}
\]
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/Isp 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.
Magnetic nozzle: 3D simulations in LSP

Modeling provides evidence for detachment

Expanding plasma plume at 2.18 $\mu$s

Inside nozzle:

- $n_e = 10^{11}$ cm$^{-3}$
- $T_i = 1$ eV
- $T_e = 100$ eV

At $z = 100$ cm:

- KE (H$^+$) $\sim 2$ keV
Space Plant Components
Mars Mission Energy Balance

Diagram:

- Fusion: 11.5 MW
  - RMF: 0.6 MW
  - Heat Engine: 3.58 MW
- Gas Box: 1 MW
- Bremsstrahlung: 2.05 MW
- Synchrotron: 4.57 MW
- Neutron: 0.18 MW
- Thrust: 4.2 MW
- Radiators: 3.12 MW
- Efficiency: 60%
Alpha Centauri Starship

VISIT THE STARS!
DARPA 100 YEAR STARSHIP SYMPOSIUM
2011
Synopsis: Alpha Centauri

- Stable orbits possible around stars A and B
- Deliver 500 kg payload
- Nine 10 MW engines
  - 14 N thrust
  - $u_E$ 12,000 km/s
  - 500 year transit
  - Achieve 0.15 c
- Two 10 MW engines
  - 7.5 N thrust
  - $u_E$ 3200 km/s
  - 700 year transit
  - 3He 564.7 kg
Final Orbit Insertion

- Go into 1 AU orbit around star A or B
- Then transfer into polar orbit around (potential) planet
L2 Space Telescope

INTERPLANETARY SPACE TUG
IAC 2012
Mission: Telescope to Sun-Earth L2

- 1 MW engine
  - Electrical power 1.25 MW
  - Propulsion power 1.13 MW
- Transit ~40 days from GPS
- Payload mass 6200 kg
- ΔV 3.1 km/s
- 40 N thrust
- \( u_E \) 56.5 km/s
- 3He 50 g
- D 353 kg
Deploying the James Webb Telescope

Circular restricted three-body simulation
Asteroid Deflection

SAVE THE WORLD!

IEPC 2013
Synopsis: Asteroid Deflection

- Must reach an asteroid and apply DV to it to avoid orbital keyhole
- $\Delta V$ to Apophis 10-30 km/s in 175-270 days
- $\Delta V$ to asteroid 0.3 m/s
- 10 MW engine
- Thrust: 500 N
- Burn time: 23 days
- Mass flow 0.02 kg/s
  - 41000 kg propellant
Asteroid Deflection Maneuvers

- Example Keyhole
- Orbit-normal direction of hyperbolic orbit
- Actual or "Earth-Perturbed" Closest Point of Approach
- Asteroid Trajectory
- Unperturbed Closest Point of Approach
- $b$-Plane
- Relative velocity of the Asteroid with respect to Earth.
- Computed using the asteroid's velocity from its unperturbed orbit at the predicted closest point of approach.
- Incoming Asymptote
- $V_{\infty}$
Deflection Capability Analysis

- Use Apophis 2029 encounter with Earth
  - Consider an asteroid half the size of Apophis
- Maximize separation at time of impact
  - Maximize distance
  - Vary delta-v
  - Vary thrust level
- Investigate tradeoff of deflection distance vs. fuel mass

“Knee” at 500 N
Consider two maneuvers
- Along-Track (vertical)
- Cross-Track (horizontal)

Goal is to move ellipse away from keyhole and Earth focus

Along-track deflection is always much easier
Example Deflection Maneuver

- Maximizing deflection distance (with $\Delta V$ limit)

Apply 23 day **along-track** burn at perigee to optimally change SMA and create drift
Mars Mission

HUMAN EXPLORATION
IAC 2014
Synopsis: Mars Roundtrip

- Humans to Mars, orbit for several weeks and return to LEO
- Total ΔV of 50 km/s
- Trip time 310 days
- 30 MW engines
- Thrust ~ 300-400 N
- Total mass of 124 MT fits within SLS envelope
Mars Trajectory and SLS

- Modified Lambert trajectory
  - 30 days in Mars orbit
  - 50 km/s and 310 days roundtrip
- 130 MT max for SLS Extended launch

<table>
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<tr>
<th>Type of Trajectory</th>
<th>Low Thrust Spiral</th>
<th>High Thrust Hohmann Transfer</th>
<th>Continuous Thrust</th>
<th>Lambert Solution (Ideal, not attainable)</th>
<th>Modified Fixed Burn Lambert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundtrip ΔV (km/s)</td>
<td>11.2</td>
<td>10.8</td>
<td>106.7</td>
<td>47.8</td>
<td>49.10</td>
</tr>
<tr>
<td>Total Trip Time</td>
<td>12 years</td>
<td>975 days</td>
<td>277.5 days</td>
<td>210 days</td>
<td>310 days</td>
</tr>
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</table>
Conclusions
Conclusions

- DFD has the potential to enable many missions
  - Human Mars exploration with shorter flight durations, lower mass and abort capability
  - Game-changing power and capability for outer planet missions including asteroid deflection
  - Military applications for high-power Earth orbit missions
- Demonstration of a burning plasma possible in 10-12 years with enough funding, ~$50M
- Flight by 2032 possible
- Fusion may be closer than you think!
See you on Mars!
For More Information

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References

Papers/Conferences

• G. Pajer, Y. Razin, M. Paluszek, A. H. Glasser, S. Cohn, Modular Aneutronic Fusion Engine, *Space Propulsion 2012*, May 2012

Patents

Challenges of Direct Fusion Drive

- Need to demonstrate a burning plasma
  - PFRC-4
- Need to get Helium-3
  - Not that much needed, terrestrial sources have enough to support Mars exploration
  - Moon and gas giants are future sources
- Must minimize engine mass
  - Need high power per unit mass
- Need ways to startup the reactor in space
  - Recent provisional patent using a chemical rocket engine: Paluszek, Cohen, Ham
- Long duration cryogenic fuel storage in space
  - NASA has R&D in this area
- Need all the supporting hardware to be low mass and have high reliability
  - Ideally last for multiple missions
- Radiation shielding
  - Neutrons (but not too many)
  - Bremsstrahlung – x-rays
  - Synchrotron
DFD-Based Space Transportation Network

- DFD-powered space station
- $^3\text{He}$ mined on Moon, transported to station by DFD powered electromagnetic launchers
- Supports robotic missions, such as asteroid deflection and outer planet exploration
- Human missions to Mars, Asteroid Belt, and the Inner Planets