Modular Aneutronic Fusion Engine for an Alpha-Centauri Mission

Michael Paluszek, Samantha Hurley, Dr. Gary Pajer, Joseph Mueller, Stephanie Thomas
Princeton Satellite Systems

Dr. Samuel Cohen
Princeton Plasma Physics Laboratory

Dr. Dale Welch
Voss Scientific
Introduction

- Aneutronic Fusion
- Fusion Engine Concepts
- Mission Plan
- The Modular Aneutronic Fusion Engine
- Starship Design
- Summary and Conclusions
Aneutronic Fusion

• Fusion reactions that produce few neutrons
  - \( \text{D} + \text{^3He} \rightarrow \text{^4He} \) (3.6 MeV) + p (14.7 MeV)
    • Plus significant side reactions
      - \( \text{D} + \text{D} \rightarrow \text{^2T} \) (1.01 MeV) + H (3.02 MeV)
      - \( \text{D} + \text{D} \rightarrow \text{^3He} \) (0.82 MeV) + n (2.45 MeV)
  - \( \text{p} + \text{^{11}B} \rightarrow 3 \text{^4He} + 8.6 \text{ MeV} \)

• Fusion products can be exhausted directly through a magnetic nozzle to produce thrust
  - Jet exhaust is somewhat more complicated with spherical or toroidal geometries

• These reactions require much higher plasma temperatures than D-T
D−³He Side Reactions

D−He3 Reaction

Temperature (KeV)

Percentage

D−He3
D−Dp
D−Dn
Fuel Sources

- **Boron-proton**
  - Boron is readily available

- **Deuterium-Helium 3**
  - $^3$He is very rare
  - Volcanoes
  - Bombardment of lithium produces tritium which decays
  - Lunar mining
The Fusion Energy Balance

- p+^{11}B reaction in this case
- Bremsstrahlung due to electron braking – worse at high temperatures
- Synchrotron is RF – worse at high temperatures and high magnetic fields
- Can recycle some of the losses via a heat engine
- Ideal D-He3 reaction
  - Cold electrons
  - Hot $^3$He
  - D in the middle
Fusion Engine Concepts

- Many engine concepts have been investigated
  - Levitated dipole
  - Spherical tokamak with poloidal divertor
  - Gas dynamic mirror
  - Magnetic target fusion with plasma beams
  - Pulsed high density fusion rocket
  - Spherical tokamak with ripple effects for thrust extraction
  - Colliding beam FRC
  - RF heated FRC (our concept)
  - Many others

- Many of these are candidates for terrestrial power generation
**Fusion Engine 1/4**

- **Key Elements: FRC, RF heating and magnetic nozzle**
  - Makes a small, 5 – 10 MW fusion reactor feasible
  - Cigar shaped reactor – elongation improves stability and produces more power

- **Fuel**
  - D-³He maintain pressure by having a ratio of 1 D to 2 ³He while reducing D-D side reactions

- **Field Reversed Configuration**
  - Elongated plasma ellipsoid in which an azimuthal current reverses the field
  - Ratio of magnetic pressure to plasma pressure nearly 1 – only levitated dipole is better
  - Can use passive flux conservers – strips of high temperature superconducting film eliminates the need for active superconductors for confinement

- **Radio Frequency Heating**
  - Odd parity rotating magnetic field – heats electrons
  - Electrons transfer power to ions
  - Get explosive heating of ions
  - Physics of RF interaction with dense plasmas not well understood
Fusion Engine 2/4

- O₂
- APU
- Boron
- H₂
- Injectors
- Power Management
- Coil Power
- RF Power
- Coil Cooling
- Radiator
- 6x6 Array of Fusion Modules

RF Antenna and Direct Power Conversion
Superconducting Coil
Magnetic Nozzle Coil

Thermal Power Conversion and Shielding

FRC
Fusion Engine 3/4

D–He3 Reactor

- Fusion
- Bremsstrahlung
- Synchrotron

Power (MW/m³) vs. \( T_e \) (keV/10)
## Fusion Engine 4/4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>1.0 D³He</td>
</tr>
<tr>
<td>First Wall Thermal Power (MW/m²)</td>
<td>0.3</td>
</tr>
<tr>
<td>Aspect Ratio (L/R)</td>
<td>15.00</td>
</tr>
<tr>
<td>Plasma Radius (m)</td>
<td>0.36</td>
</tr>
<tr>
<td>Plasma Volume (m³)</td>
<td>2.18</td>
</tr>
<tr>
<td>RMS Plasma Pressure (Pa)</td>
<td>5.2e+06</td>
</tr>
<tr>
<td>Central Plasma Pressure (Pa)</td>
<td>1.0e+07</td>
</tr>
<tr>
<td>Average Magnetic Field at Coil (T)</td>
<td>3.6</td>
</tr>
<tr>
<td>Shield EM Attenuation</td>
<td>1.00e-07</td>
</tr>
<tr>
<td>Magnet Mass (kg)</td>
<td>7.29e+01</td>
</tr>
<tr>
<td>Shield Mass (kg)</td>
<td>4.19e+03</td>
</tr>
<tr>
<td>Power Conversion Mass (kg)</td>
<td>8.21e+03</td>
</tr>
<tr>
<td>Radiator Mass (kg)</td>
<td>2.04e+03</td>
</tr>
<tr>
<td>Total Mass (kg)</td>
<td>1.45e+04</td>
</tr>
<tr>
<td>Specific Mass (kW/kg)</td>
<td>0.69</td>
</tr>
<tr>
<td>Central Temperature (keV)</td>
<td>100</td>
</tr>
<tr>
<td>Deuterium Density (10²⁰ m³)</td>
<td>1.3</td>
</tr>
<tr>
<td>Helium-3 Density (10²⁰/m³)</td>
<td>1.3</td>
</tr>
<tr>
<td>Electron Density (10²⁰/m³)</td>
<td>3.9</td>
</tr>
<tr>
<td>Synchrotron (MW/m³)</td>
<td>0.10</td>
</tr>
<tr>
<td>Bremsstrahlung (MW/m³)</td>
<td>1.89</td>
</tr>
<tr>
<td>Confined Gyro Radii</td>
<td>46.4</td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td>14.3</td>
</tr>
<tr>
<td>Net Power (MW)</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Ongoing Research at PPPL

• Magnetic nozzle experiment (MNX)
  - Studying recombination and phase transition

• FRC
  - Investigating non-ideal MHD effects
  - FRC stability properties
  - Complete understanding of FRC stability is lacking
  - RF heating for dense plasmas
• Orbiting crewed assembly station in polar orbit
• Starship assembled and tested
  - 16 launches of Falcon 9 Heavy
  - Fewer with NASA HLV
• Departure using a liquid booster stage
• 14 N constant thrust
  - Not necessarily optimal thrust
• Exhaust ½ maximum from D–3He
  - Not necessarily the optimal exhaust velocity
• Assumes 10 kW/kg
  - Our work shows 670 W/kg!
• Arrives at Alpha-Centauri in 500 years
• Goes into 1 AU orbit around A or B
• Then goes into polar orbit around planet
From Earth

Thrust Normal to Orbital Plane

$\alpha = 17$ deg

$V_{FP}$

Alpha-Centauri Orbital Plane

Mission Design 2/3
Mission Design 3/3

Orbit Lowering Maneuver

Final Orbit, 1 AU

Distance at Orbit Plane Insertion
• Nine 10 MW engines
• 16 m antenna
• 0.5 m aperture telescope for navigation and science
• Communications 1 kpbs
• Pointing control differential thrust and CMGs
Starship Conceptual Design 2/2

Shows Falcon 9 Heavy shroud and Hubble Space telescope
Lifetime

- 500 years to reach Alpha-Centauri
- Neutron bombardment the major limitation to engine life
  - Boron proton 1000 times lower neutron flux than deuterium helium-3
  - Reduce neutron flux by choice of temperature and using less D in the reactor
- Longest lived satellites are Voyager 1 and 2 – 34 years
- Comsats routinely reach 15 years – fuel is the major life limiting factor
Summary and Conclusions

- Fusion propulsion enables interstellar missions
- A mission to Alpha-Centauri is feasible assuming that a fusion engine can be built
- Improvement of specific power critical
  - Magnetized target fusion claims 400 kW/kg!
- Neutron damage a major issue for the engines
  - Boron proton reaction would reduce this drastically
- Significant science and engineering required
  - Liquid rockets were demonstrated by Goddard in 1923
  - Fusion breakeven has not yet been demonstrated
- Modular Fusion Engine permits Robert Goddard like program because of its size
  - Build a test model then build another – huge budgets not required
Future Work

• Continue development of the RF heated FRC
  - Successful reactor would also help solve terrestrial energy problems

• Development of engine optimization tools
  - Find the optimal densities and temperatures
  - Heat engine optimization
  - 3D plasma models

• Trajectory optimization
  - Variable thrust and exhaust velocity
  - Star system arrival guidance
Contact Information

Michael Paluszek
map@psatellite.com
Sam Cohen
scohen@pppl.gov

Princeton Satellite Systems
6 Market St. Suite 926
Plainsboro, NJ 08536
(609) 275-9606
http://www.psatellite.com