Progress on the Pulsed Fission-Fusion Propulsion System Concept

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PuFF Concept
Introduction to PuFF

- Magnetic nozzle coils
- Magnetic field lines
- Lithium liner and radiation shield
- UF6 fuel
- D-T fuel
- Cathode
Operation of a Z Pinch

Vaporized Wire Array

Evacuated Chamber

Plasma Cylinder

B, Magnetic Flux

Anode

Cathode
Heating Mechanisms Included in Model

- Bremmstrahlung and Cyclotron Radiation
- Axial and Radial Thermal conduction
- Fissionable liner
- Magnetic Field Lines
- DT FRC Target Plasma
- Neutron induced Fast fission reactions
- Fusion heating power
- Fission heating power
Fusion Power Balance

- Parameter space for ignition
- Greatly broadened with embedded magnetic field
- Marginally improved with $^6$Li and thorium liners
- Significantly enhanced with uranium liners ($^{235}$U and $^{238}$U)
Parameters within net Power Increase

◆ Choose $\rho R = 10^{-5}$ at 15 keV.
◆ Let $R = 1$ mm, thickness of uranium liner is 5 mm, length of target is 2 cm
◆ Density of DT target is 0.1 kg/m$^3$
◆ Total energy in DT target is only $\sim$5 kJ, 1% of Charger 1 stored energy
Our Approach: Solve Maxwell's Equations Coupled to Multifluid (Ions, Electrons, Neutrals) Equations of Motion

Maxwell’s Equations

- Solve with Smooth Particle Electromagnetic Variant of Finite-Difference Time Domain (FDTD) method
- FDTD well documented, highly accurate grid-based method for analyzing the time evolution of electric and magnetic fields, utilized in PIC codes
- Can interpolate charged fluid particles to grid to model conductivity or charge and current density

Multifluid Equations of Motions

- Solve with Smooth Particle Hydrodynamics (SPH)
- Gridless Lagrangian technique
- Vacuum/plasma boundary well defined
- Leverage same engine as Maxwell Equation Solver

Both methods yield to ‘vectorized’ coding, making multiprocessor (parallel) computing easy
What is SPH?

- Numerical method for approximating probability densities over a domain of particles.
- Currently used mostly in hydrodynamic modeling and CG effects in film and video games.
How does SPH work?

Integral interpolant:

\[ A_I(r) = \int A(r')W(r - r', h)dr' \]

- \( A \) – quantity measured (density, temperature, etc.)
- \( W \) – differentiable kernel function
- \( dr' \) – volume differential
- \( h \) – smoothing length.

Summation over mass elements:

\[ A_S(r) = \sum_b m_b A_b \frac{\rho_b}{\rho} W(r - r_b, h) \]

Similar to density probability calculations. How quantities are accurately calculated with a small particle domain.
Equations of motion (completed)

\[ \frac{\partial}{\partial t} n_e + \nabla \cdot \mathbf{u}_e = 0 \]
\[ \frac{\partial}{\partial t} n_i + \nabla \cdot \mathbf{u}_i = 0 \]

\[ n_e m_e \frac{\partial}{\partial t} \mathbf{u}_e + \nabla p_e + e n_e (\mathbf{E} + \mathbf{u}_e \times \mathbf{B}) = \cdots \]

\[ n_i m_i \frac{\partial}{\partial t} \mathbf{u}_i + \nabla p_i - Z e n_i (\mathbf{E} + \mathbf{u}_i \times \mathbf{B}) = \cdots \]

\[ \frac{3}{2} n_e k T_e + p_e \nabla \cdot \mathbf{u}_e = -\pi_e : \nabla \mathbf{u}_e - \nabla h_e - (\mathbf{u}_e - \mathbf{u}_i) \cdot \mathbf{R}_e - Q_i \]

\[ \frac{3}{2} n_i k T_i + p_i \nabla \cdot \mathbf{u}_i = -\pi_i : \nabla \mathbf{u}_i - \nabla h_i - Q_i \]

Transport effects, which can be based on nonequilibrium distribution functions (kappa and power law)

\[ R_a \equiv \int m_\alpha \mathbf{w} \sum_{\beta} C_{\alpha \beta} d\mathbf{w} \]
\[ R_a \approx -\sum_{\beta} m_\alpha n_\alpha (\mathbf{V}_\alpha - \mathbf{V}_\beta) \langle \mathbf{V}_{\alpha \beta} \rangle \]

\[ p_\alpha \equiv \frac{1}{3} m_\alpha n_\alpha \langle \mathbf{w}^2 \rangle \]
\[ \pi_i \equiv n_\alpha m_\alpha \langle \mathbf{w} \mathbf{w} \rangle - p_\alpha \mathbf{I} \]
\[ h_\alpha \equiv \frac{1}{2} n_\alpha m_\alpha \langle \mathbf{w}^2 \mathbf{w} \rangle \]
\[ Q_a \equiv \int \frac{1}{2} m_\alpha w_\alpha^2 \sum_{\beta} C_{\alpha \beta} d\mathbf{w} \]
Initial Pulsed Nozzle Model

- Test thermal expansion of gas nozzle with various initial conditions
  - Nozzle geometry
  - Gas
    - Temperature
    - Density
    - Radius
    - Length
    - Composition
- Lays ground work and expectations for magnetic nozzle
Preliminary results
Preliminary results
Preliminary results
Preliminary results
Preliminary results
NIAC Phase I Goals
Crewed Mars Mission Concept

- Deuterium-Tritium Tank (2.4 m dia. - 4 pcs)
- SP-100 Reactor
- Lithium 6 Tank (4.8 m long x 2.6 m dia. - 4 pcs)
- Two-Sided Crew/Avonics Radiators (176 m² total area)
- Two-Sided Med. Temp. Radiators (608 m² total area)
- Two-Sided High Temp. Radiators (1910 m² total area)
- ISRU
- Transhab
- Lander
- Surface Habitat

- Stacked Capacitor Module (2) (10 m long x 3.6 m x 7.2 m - 8 pcs)
- Z-Plunge Nozzle
- Lithium Hydride Radiation Shield (25 m thick)
- SMES Envelope (1.8 m x 1.8 m x 2.4 m)
- 4-Pod RCS 700 lbf MR 80 B 3 Hydrazine Thrusters, RCS Tank (85 m dia.) and RCS Helium Pressurant Tank (64 m dia.) (6 pcs - 4 Aft and 4 Forward)
### Mission Concepts

<table>
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<tr>
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<th>Mars 90</th>
<th>Mars 30</th>
<th>Jupiter</th>
<th>550 AU</th>
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<tbody>
<tr>
<td><strong>Outbound Trip Time (days)</strong></td>
<td>90.2</td>
<td>39.5</td>
<td>456.8</td>
<td>12936</td>
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<tr>
<td><strong>Return Trip Time (days)</strong></td>
<td>87.4</td>
<td>33.1</td>
<td>521.8</td>
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<tr>
<td><strong>Total Burn Time (days)</strong></td>
<td>5.0</td>
<td>20.2</td>
<td>6.7</td>
<td>11.2</td>
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<tr>
<td><strong>Propellant Burned (mT)</strong></td>
<td>86.3</td>
<td>350.4</td>
<td>115.7</td>
<td>194.4</td>
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<tr>
<td><strong>Equivalent DV (km/s)</strong></td>
<td>27.5</td>
<td>93.2</td>
<td>36.1</td>
<td>57.2</td>
</tr>
</tbody>
</table>

*Figure 3 Mars 90 Day Transfer Trajectories*

- **Engine**
  - $Isp = 19,400$ sec
  - $T = 38$ kN
  - 10 Hz pulse freq.

- **Vehicle**
  - $M_{dry} = 552$ mT
  - $M_{pay} = 150$ mT
  - 30% MGA

*Polsgrove, T. et al. Design of Z-Pinch and Dense Plasma Focus Powered Vehicles, 2010 AIAA Aerospace Sciences Meeting*
Mating SPFMaX and MCNP

◆ SPFMax gives
  • Ability to model 3d effects
  • Can propagate magnetic fields in vacuum
  • Easily editable

◆ MCNP
  • Track neutron life, fission reactions
  • Flexible geometries

◆ Second half of NIAC is to run codes concurrently
  • synchronize neutron population vs. time
  • Optimize energy output
    - As function of geometry
    - As function of composition
      – Mix of UF6, D-T
      – Lithium liner thicknesses
Single turn Magnetic Nozzle

- Gasdynamic nozzle performance to be compared with magnetic nozzle to assess loss mechanisms in magnetic nozzles, e.g.
  - Field/plasma instabilities
  - Plasma detachment

Direction of current
NIAC Phase II Experimental Options
A test facility for high power and thermonuclear fusion propulsion concepts, astrophysics modeling, radiation physics

Located in the UAH Aerophysics Lab at Redstone

The highest instantaneous pulsed power facility in academia – 572 kJ (1 TW at 100 ns)
**Methodology**

- Incremental improvements in experimental capability
- Benchmark model with experimental data
- Can also run any experiments below with lower power systems
- Looking for comments and suggestions here!

![Diagram showing the experimental roadpath process](image)

- **Li wire**
- **Deuterated Polyethylene**
- **D-D slush**
- **Implosion**
- **Neutron flux**
- **Plasma stability**
- **Solid U\textsubscript{238}**
  - D-T slush
- **Solid U\textsubscript{238}**
  - D-Li solid
Long Range Plans

◆ Charger II

• Construct breadboard PuFF system capable of 10-20 Hz operation
  - Upgrade to flight weight hardware – NASA
  - Optimize pulse for maximum power output – DOE
  - Astrodynamics, radiation protection, other research goals - Various