Propagating Magnetic Wave Accelerator (PMWAC) for Manned Deep Space Missions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First Stage</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>System length</td>
<td>5 m</td>
<td>25 m</td>
</tr>
<tr>
<td>Plasma mass (m_p) :</td>
<td>0.2 mg D(_2)</td>
<td>(same)</td>
</tr>
<tr>
<td>Final plasma velocity:</td>
<td>(3 \times 10^5) m/sec (I(_{sp}) = 30,000 s)</td>
<td>(1 \times 10^6) m/s</td>
</tr>
<tr>
<td>Acceleration (Force):</td>
<td>(2 \times 10^{10}) m/s (4 kN)</td>
<td>(same)</td>
</tr>
<tr>
<td>Thrust Power (0.2 kHz rep)</td>
<td>2 MW</td>
<td>20 MW</td>
</tr>
</tbody>
</table>
Propulsion Requirements for Deep Space Missions

• High Specific Power - $\alpha \ (\text{kW}_{\text{thrust}}/\text{kg}_{\text{spaceship}})$
  
  $\alpha > 1 \text{ kW/kg}$

• High (and variable) exhaust velocities $v_{ex}$
  
  $\max v_{ex} \sim 10^4 \text{ km/s} \ (I_{sp} = v_{ex}/g \sim 10^6 \text{ s})$

• Continuous power with near zero maintenance for months
Trip Time and the Specific Power Requirement

Accelerating a mass $M_{ss}$ over a time $\tau$ implies a power $P$ where:

$$P \approx \frac{M_{ss} v_c^2}{2\tau}$$

One defines a characteristic velocity $v_c$:

$$v_c = (2 \alpha \tau)^{1/2}$$

where $\alpha$ is the specific power.

The trip time $\tau_{\text{trip}}$ to go a distance $L$ is given roughly as:

$$\tau_{\text{trip}} \approx 2 \frac{L}{v_c} \quad \tau_{\text{trip}} \text{(months)} = \frac{2L(\text{astronomical units})^{2/3}}{\alpha(\text{kW} / \text{kg})^{1/3}}$$
Rapid Manned Mars Mission Power Requirement

\[
\alpha (\text{kW/kg}) = 8 \frac{[S \text{(astronomical units)}]^2}{\tau \text{(months)}^3} \approx 1
\]

for \( M_{ss} \sim 20 \text{ MT} \), \( P_{\text{thrust}} = 20 \text{ MW} \)
Velocity and Energy Requirements for Deep Space Missions

(\(\alpha = 1 \text{ kW/kg}\))

<table>
<thead>
<tr>
<th>Destination</th>
<th>(x_{\text{trip}} \sim 2 \text{ A.U. (Mars)})</th>
<th>(t_{\text{trip}} \sim 3 \text{ months})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(x_{\text{trip}} \sim 10 \text{ A.U. (Jupiter)})</td>
<td>(t_{\text{trip}} \sim 12 \text{ months})</td>
</tr>
<tr>
<td>Characteristic Velocity</td>
<td>(v_{\text{Mars}} \sim 125 \text{ km/sec})</td>
<td>(v_{\text{Jupiter}} \sim 250 \text{ km/sec})</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>(\varepsilon_{\text{Mars}} \sim 8 \times 10^9 \text{ J/kg})</td>
<td>(\varepsilon_{\text{Jupiter}} \sim 3 \times 10^{10} \text{ J/kg})</td>
</tr>
</tbody>
</table>

- **Propulsion System**
  - Chemical
  - Electric
  - FRC at RPPL
  - Thermal Fusion

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>Exhaust (km/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>5</td>
</tr>
<tr>
<td>Electric</td>
<td>30</td>
</tr>
<tr>
<td>FRC at RPPL</td>
<td>250</td>
</tr>
<tr>
<td>Thermal Fusion</td>
<td>2000</td>
</tr>
</tbody>
</table>

- **Fuel Specific Energy**
  - Chemical
  - Fission
  - Fusion

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<thead>
<tr>
<th>Fuel</th>
<th>Specific Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>(1 \times 10^7 \text{ J/kg})</td>
</tr>
<tr>
<td>Fission</td>
<td>(5 \times 10^{13} \text{ J/kg})</td>
</tr>
<tr>
<td>Fusion</td>
<td>(1 \times 10^{15} \text{ J/kg})</td>
</tr>
</tbody>
</table>

\[ \alpha = \frac{v_{\text{char}}^2}{2} \frac{1}{t_{\text{trip}}} \]
\[ \varepsilon = \frac{v_{\text{char}}^2}{2} = \alpha \ t_{\text{trip}} \]

Nuclear Power is Necessary for Deep Space Travel
Current and Planned “Breakeven” Fusion Experiments

ITER (MFE)          PHD          NIF (ICF)
Plasma Density and Energy Regimes for Different Fusion Concepts

- ICF (Inertial Confinement Fusion)
- MTF (Magnetic Tokamak Fusion)
- CT (Classical Tokamak)
- PHD (Pre-Hot Detonation)
- MFE (Magnetic Fusion Experiment)

- Mag. Force > Material Strength
- Electron Thermal Conduction

Plot showing the plasma density and energy regimes for different fusion concepts.
High Voltage Energy Storage
V~ 120 kV

Low Voltage Storage
V~ 12 V

Shiva Star Facility for MTF
~ 10 MJ

2 Auto Batteries
~ 10 MJ
Fusion reaction rate $R$:
$$R = n_D n_T <\sigma_{DT} v>$$
At $T_p = 10$ keV,
$$<\sigma_{DT} v> \approx 10^{-22} \text{ m}^3/\text{sec}$$

For space-based fusion:
G ~ 3 (thermal electrical)
$$n\tau_{\text{burn}} \sim 1 \times 10^{20} \text{ m}^{-3} \text{ sec}$$
To maintain burn: $\tau_E \sim \tau_{\text{burn}}$

Lawson Criterion:
$$n\tau_E \sim 1 \times 10^{20} \text{ m}^{-3} \text{ sec}$$

Plasma pressure < Magnet Yield Limit (2x10^4 Atm):
$$(T_p = 10 \text{ keV})$$
$$n_{\text{fus}} = 1 \times 10^{24} \text{ m}^{-3}$$
and
$$\tau_E = 100 \mu\text{sec}$$
Field Reversed Configuration (FRC) Propulsion

- Propellant (plasma) is magnetically insulated from thruster wall
- No plasma detachment problem
  - Plasma (FRC) contained separately in a magnetic envelope
- Plasma is thermally isolated from thruster walls
  - Fully ionized plasma is vacuum isolated
- Both thrust and Isp can be varied easily over a wide range
  - Change of gas fill pressure is all that is required
- Thrust and Isp are decoupled from plasma thermal energy
  - With $v_{\text{dir}} \gg v_{\text{th}}$ theoretical efficiency can approach unity
- Enables a direct, simple method to achieve fusion propulsion with minimum investment
PHD Fusion Rocket

From past FRC experiments: $\tau_E \sim \tau_N = 1.3 \times 10^{-12} x_s r_p^2 n^{1/2}$ \quad $(x_s = r_p/R_c)$

- with $n = n_{fus}$, $r_p = 1 \text{ cm} \quad (R_c = 1.3 \text{ cm})$
- with $l_p/r_p = 5$, $E_p = 50 \text{ kJ}$
- rep rate = 200 Hz, 17 MW directed thrust power

- FRC formed at low energy ($\sim 5 \text{ kJ}$) and relatively low density ($\sim 10^{21} \text{ m}^{-3}$)
- FRC accelerated and compressed by low energy propagating magnetic field ($< 0.4 \text{ T}$).
- FRC is decelerated, compressed, and heated as it enters high field burn chamber
- FRC expands and cools converting thermal and magnetic energy into directed thrust
FRC Acceleration and Heating Expts. at UW

FRC mass: 0.4 mg Deuterium

FRC terminal velocity:

\[ v_d = 2.5 \times 10^5 \text{ m/s} \]

Average FRC acceleration:

\[ (5 - 30 \mu\text{sec}) \]

\[ a_{\text{avg}} = 9 \times 10^9 \text{ m/s}^2 \]

FRC Energy (final)

15 kJ

Thermal Conversion of FRC directed Energy
FRC Acceleration Method Employed in UW Expts.

- Upper plot of flux contours taken from numerical calculations for discharge 1647 during the acceleration of an FRC at UW.

- Bottom plot illustrates phasing of the accelerator coils:
  Each coil in turn is switched on for one complete cycle.
  Phase of each coil at time of calculation is indicated by arrow.
Propagating Magnetic Wave Accelerator

For transmission line:
\[ v_p^2 = \frac{1}{LC} \quad Z^2 = \frac{L}{C} \]

For shell capacitor (per unit length):
\[ C = \frac{2 \pi R_c \varepsilon_0 \kappa \varepsilon_S}{V} \]

Inductance (per unit length):
\[ L = \mu_0 \pi R_c^2 n^2 \]

From these eqs. Solving for \( R_c \)
\[ R_c = \frac{2V \kappa \varepsilon_S}{c^2 B^2} \]

and finally for the phase velocity:
\[ v_p = \sqrt{\frac{2V}{R_c^3 \kappa \varepsilon_S}} \frac{c}{2\pi n} \]

\[ \varepsilon_S = 5 \times 10^6 \text{ V/m} \quad \kappa = 2500 \varepsilon_0 \]
\[ V = \pm 25 \text{ kV} \]

\( \text{BaTiO}_3 \)

\( 1 \text{ cm} \)

\[ v_p = 10^6 \text{ m/s} \quad B = 0.5 \text{ T} \]
for \( R_c = 5.5 \text{ cm} \quad n = 10 \text{ turns/m} \]
PMWAC SPICE Calculation for Constant Z

Vacuum load

Dissipative load (plasma)
Resistive 2D MHD Calculation of FRC with Propagating Magnetic Field (0.4 T)
PMWAC Can Also Be Employed to Provide High $I_{sp}$, High Thrust Electrical propulsion

\[
V = \pm 3.5 \text{ kV} \iff B_{\text{acc}} = 0.2 \text{ T}
\]

$M_{\text{FRC}} = 0.2 \text{ mg}$

$-a = 1.2 \times 10^9 \text{ g}$

$T (\mu\text{sec})$

$V_{\text{FRC}}$ ($10^5 \text{ m/s}$)

Time ($\mu\text{sec}$)

$0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30$

$0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5$

$R (\text{m})$

$Z (\text{m})$

$0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \quad 1.4 \quad 1.6 \quad 1.8 \quad 2 \quad 2.2 \quad 2.4 \quad 2.6 \quad 2.8 \quad 3 \quad 3.2 \quad 3.4 \quad 3.6 \quad 3.8 \quad 4 \quad 4.2 \quad 4.4 \quad 4.6 \quad 4.8 \quad 5 \quad 5.2 \quad 5.4 \quad 5.6 \quad 5.8 \quad 6 \quad 6.2 \quad 6.4 \quad 6.6 \quad 6.8 \quad 7 \quad 7.2 \quad 7.4 \quad 7.6 \quad 7.8 \quad 8 \quad 8.2 \quad 8.4 \quad 8.6 \quad 8.8 \quad 9 \quad 9.2 \quad 9.4 \quad 9.6 \quad 9.8 \quad 10 \quad 10.2 \quad 10.4 \quad 10.6 \quad 10.8 \quad 11 \quad 11.2 \quad 11.4 \quad 11.6 \quad 11.8 \quad 12 \quad 12.2 \quad 12.4 \quad 12.6 \quad 12.8 \quad 13 \quad 13.2 \quad 13.4 \quad 13.6 \quad 13.8 \quad 14 \quad 14.2 \quad 14.4 \quad 14.6 \quad 14.8 \quad 15 \quad 15.2 \quad 15.4 \quad 15.6 \quad 15.8 \quad 16 \quad 16.2 \quad 16.4 \quad 16.6 \quad 16.8 \quad 17 \quad 17.2 \quad 17.4 \quad 17.6 \quad 17.8 \quad 18 \quad 18.2 \quad 18.4 \quad 18.6 \quad 18.8 \quad 19 \quad 19.2 \quad 19.4 \quad 19.6 \quad 19.8 \quad 20 \quad 20.2 \quad 20.4 \quad 20.6 \quad 20.8 \quad 21 \quad 21.2 \quad 21.4 \quad 21.6 \quad 21.8 \quad 22 \quad 22.2 \quad 22.4 \quad 22.6 \quad 22.8 \quad 23 \quad 23.2 \quad 23.4 \quad 23.6 \quad 23.8 \quad 24 \quad 24.2 \quad 24.4 \quad 24.6 \quad 24.8 \quad 25 \quad 25.2 \quad 25.4 \quad 25.6 \quad 25.8 \quad 26 \quad 26.2 \quad 26.4 \quad 26.6 \quad 26.8 \quad 27 \quad 27.2 \quad 27.4 \quad 27.6 \quad 27.8 \quad 28 \quad 28.2 \quad 28.4 \quad 28.6 \quad 28.8 \quad 29 \quad 29.2 \quad 29.4 \quad 29.6 \quad 29.8 \quad 30
Inductive Magnetized Plasma Accelerator Source
Developed with NASA STTR funding at MSNW
PMWAC Development Program

Phase 1:

• Determine Accelerator Requirements and Parameters
• Design Proto-Accelerator for Electrical Validation
• Construct Accelerator and Measure Electrical Performance
• Develop Full Electrical Model with Plasma Interaction

Phase II:

• Design and Construct Full-scale Accelerator
• Install Accelerator and Demonstrate FRC Acceleration to Fusion Velocities (~10^6 m/s).