Z-PINCH FUSION PROPULSION
7TH SYMPOSIUM ON REALISTIC ADVANCED SCIENTIFIC SPACE MISSIONS
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Z-Machine at Sandia Lab
FUSION PROPULSION

- Fusion-based nuclear propulsion has the potential to enable fast interplanetary transportation.
- Shorter trips are better for humans in the harmful radiation environment of deep space.
- Nuclear propulsion and power plants can enable high $I_{sp}$ and payload mass fractions because they require less fuel mass.
- Fusion energy research has characterized the Z-Pinch dense plasma focus method.
  - Lightning is form of pinched plasma electrical discharge phenomena.
  - Wire array Z-Pinch experiments are commonly studied and nuclear power plant configurations have been proposed.
  - Used in the field of Nuclear Weapons Effects (NWE) testing in the defense industry, nuclear weapon x-rays are simulated through Z-Pinch phenomena.
DM2 modules made up the Z-Machine at Sandia National Laboratories, New Mexico, USA

Expected DM2 Capabilities:
• 500 ns pulse, 2 MA current
• 1 keV, $10^{25} / \text{m}^3$ plasma state
• Effective dwell time of ~100 ns
• Capable of >1 TW instantaneous power (about 6% of world's electrical power consumption)

*AEROPHYSICS LAB AT RSA

* DECADE Module II - Defense Threat Reduction Agency, circa 1995
## Previous Fusion Propulsion Studies

<table>
<thead>
<tr>
<th>Concept</th>
<th>(\alpha) (kW/kg)</th>
<th>(n) (#/m(^3))</th>
<th>Freq. (Hz)</th>
<th>Mass (mT)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steady State</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quiet Electric Discharge (QED)</td>
<td>12</td>
<td>n/a</td>
<td>n/a</td>
<td>500</td>
<td>(Bussard and Jameson 1994)</td>
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<tr>
<td>Inertial Electrostatic Confinement (IEC)</td>
<td>0.02</td>
<td>n/a</td>
<td>n/a</td>
<td>300</td>
<td>(Miley, Satsangi et al. 1994)</td>
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<tr>
<td>Gas Dynamic Mirror (GDM)</td>
<td>10</td>
<td>1.0\times10^{22}</td>
<td>n/a</td>
<td>1225</td>
<td>(Emrich 2003)</td>
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<tr>
<td>Tandem Mirror (SOAR)</td>
<td>1.2</td>
<td>5.0\times10^{19}</td>
<td>n/a</td>
<td>1220</td>
<td>(J.F. Santarius 1998)</td>
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<tr>
<td>Spheromak</td>
<td>5.75</td>
<td>8.0\times10^{20}</td>
<td>n/a</td>
<td>1050</td>
<td>(Borowski 1994)</td>
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<tr>
<td>Field Reversed Configuration (FRC)</td>
<td>1</td>
<td>1.0\times10^{21}</td>
<td>n/a</td>
<td>1100</td>
<td>(H. Nakashima 1994)</td>
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<tr>
<td>Colliding Beam FRC</td>
<td>1.5</td>
<td>5.0\times10^{20}</td>
<td>n/a</td>
<td>33</td>
<td>(Cheung, Binderbauer et al. 2004)</td>
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<tr>
<td>Dipole</td>
<td>1</td>
<td>1.0\times10^{19}</td>
<td>n/a</td>
<td>1300</td>
<td>(Teller, Glass et al. 1992)</td>
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<tr>
<td>Spherical Torus</td>
<td>8.7</td>
<td>5.0\times10^{20}</td>
<td>n/a</td>
<td>1630</td>
<td>(Williams, Dudzinski et al. 2001)</td>
</tr>
<tr>
<td><strong>Pulsed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertial Fusion Rocket (IFR)</td>
<td>70</td>
<td>1.0\times10^{25}</td>
<td>100</td>
<td>760</td>
<td>(Borowski 1994)</td>
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<tr>
<td>Inertial Confinement Fusion (ICF)</td>
<td>3.4</td>
<td>1.0\times10^{25}</td>
<td>30</td>
<td>5800</td>
<td>(Orth and al. 1987)</td>
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<tr>
<td>Magnetized Target Fusion (MTF)</td>
<td>1.12</td>
<td>1.0\times10^{26}</td>
<td>20</td>
<td>890</td>
<td>(Thio, Freeze et al. 1999; G. Statham 2003)</td>
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<tr>
<td>Magneto-Kinetic Expansion (MKE)</td>
<td>2.2</td>
<td>1.0\times10^{24}</td>
<td>10</td>
<td>67</td>
<td>(Slough 2001)</td>
</tr>
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</table>
Z-PINCH FUSION PROPULSION

Z-Pinch is a Magneto-Inertial Fusion (MIF) approach.

To design a propulsion system, a concept mission and vehicle was designed.

- Reference mission: to transport crew and cargo to Mars and back.
- A vehicle from a previous nuclear fusion propulsion study* was used to provide a mass and many parameters in the design of a Z-Pinch propulsion system.
- This study concentrated only on Z-Pinch propulsion concept and design.

* Magnetized Target Fusion (MTF) for the Human Outer Planet Exploration (HOPE) vehicle concept
### MISSION ANALYSIS

- Z-Pinch has milli-g thrust.
- $I_{sp}$ is very high.
- Propellant mass reported doesn’t include escaping a planet’s gravity field.
- Simple orbit-to-orbit was modeled. Specific ephemeris data wasn’t used, except as noted on next page.

<table>
<thead>
<tr>
<th>552 mT burn-out mass</th>
<th>Mars 90</th>
<th>Mars 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outbound Trip Time (days)</td>
<td>90.2</td>
<td>39.5</td>
</tr>
<tr>
<td>Return Trip Time (days)</td>
<td>87.4</td>
<td>33.1</td>
</tr>
<tr>
<td>Total Burn Time (days)</td>
<td>5.0</td>
<td>20.2</td>
</tr>
<tr>
<td>Propellant Burned (mT)</td>
<td>86.3</td>
<td>350.4</td>
</tr>
<tr>
<td>Equivalent $\Delta V$ (km/s)</td>
<td>27.5</td>
<td>93.2</td>
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</table>
Outbound and return trajectories for a 90 day trip to Mars with a 1.5 day departure burn.

An optimal 90-day outbound trajectory to Mars departing Earth August 1, 2035. In all trajectories, the burn time is so small compared to the coast time that these burns are not visible on the full trajectory plots.
MISSION DELTA V

Z-Pinch Mars Round Trip (30 days 1-way)
Z-Pinch Jupiter Round Trip
Z-Pinch Mars Round Trip (90 days 1-way)
Chemical Mars 1-way trip 180 days
Z-pinch Mars 1-way trip 90 days
What is Z-Pinch Magneto-Inertial Fusion?

- A high current is sent through a column of gas.
- Cathode is along the Z-axis of column of gas.
- The magnetic field generated compresses the plasma to thermonuclear fusion conditions.
- There must be an anode or return path for electrons.
- Lots of energy is released as Z-pinch plasma expands via nuclear fusion reactions.
STAGES OF Z-PINCH FORMATION

1) Gas Injection & Preionization
   - Gas Cylinder
   - Cathode
   - Anode
   - Evacuated Chamber
   - Hypersonic nozzle

2) Initial Implosion
   - B, Magnetic Flux
   - Ion Motion
   - X-rays

3) Implosion/stagnation
   - Z
Z-Pinch Pulsed Propulsion

A high current (Megampere scale) is pulsed into a column of Deuterium/Tritium (D-T) fuel injected along the Z-axis of a parabolic nozzle.

The magnetic field generated by the high current compresses the plasma to thermonuclear fusion conditions.

Simultaneously, Lithium$^6$ (Li$^6$) is injected through an annular nozzle.

- D-T and Li$^6$ injection is focused in a conical manner so the mixture meets and the Li$^6$ liner can serve as a return path or anode to complete the circuit.
- Li$^6$ is a secondary fuel and radiation shield/neutron-getter.

Secondary Reactions:
- Li$^6$D Release 22.4 MeV
- Li$^6$-n, 4.8 MeV

Primary Reactions:
- DT Release 17.6 MeV
- DD Release 4.0 MeV
PRIMARY REACTIONS

\[
D + T \rightarrow He^4 (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \\
D + D \rightarrow T (1.01 \text{ MeV}) + p (3.02 \text{ MeV}) \\
D + D \rightarrow He^3 (0.82 \text{ MeV}) + n (2.45 \text{ MeV}) \\
D + He^3 \rightarrow He^4 (3.6 \text{ MeV}) + p (14.7 \text{ MeV}) \\
T + T \rightarrow He^4 + 2n + 11.3 \text{ MeV}
\]
Z-Pinch Pulsed Propulsion (cont.)

The Z-Pinch reaction occurs within a parabolic magnetic nozzle composed of current-carrying coils with a superconductor that generates a magnetic field.

a) The highly conductive expanding plasma compresses the nozzle magnetic field, increasing its field strength.

b) Increasing magnetic pressure slows the plasma expansion transforming kinetic into potential energy.

c) Plasma is expelled, parallel to the nozzle axis, with useful thrust applied to the vehicle.

Magnetic field pressure prevents contact between high temperature ionic plasma and the nozzle coils/material, but still imparts a force/thrust to the structure.
Z-Pinch Pulsed Propulsion (cont.)

- Nozzle thrust coils also have a second conducting ring that supports the electrical current induced during plasma expansion.
- This current is used to recharge giant capacitor banks to enable delivery of the next current pulse.
- To create the conditions necessary for fusion, each capacitor discharge is applied to the fuel bolus in about 100 nanoseconds.
- Capacitors must have very low capacitance, for very rapid discharge at incredibly high voltage.
- Pulse process is repeated over small timescales (10 Hz).
Z-PINCH DM2 ASSEMBLY CONCEPT

Single DM2 Capacitor Module

Four DM2 Modules

50 ft. (15.2 m) Overall Height

32 DM2 Modules
Charge transmission lines not shown
OTTO CYCLE – MODELING ASSUMPTIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Frequency</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Driver Energy Density</td>
<td>10 kJ/kg</td>
</tr>
<tr>
<td>Compression Ratio ($R_1/R_2$)</td>
<td>10</td>
</tr>
<tr>
<td>Initial DT Fuel Mass</td>
<td>100 mg</td>
</tr>
<tr>
<td>Lithium Liner</td>
<td>$200 \times m_{DT}$ (20 g)</td>
</tr>
<tr>
<td>Ignition Temperature</td>
<td>20 keV</td>
</tr>
</tbody>
</table>
Pulse mass: $200 \times m_{DT}$ or .02 kg
Initial Kinetic energy: 1 GJ
Useful impulse/pulse: 3812 N-sec
$I_{sp}$: 19436 sec
## PARAMETER ASSUMPTIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Frequency</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Driver Energy Density</td>
<td>10 kJ/kg</td>
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<tr>
<td>Compression Ratio</td>
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<tr>
<td>Initial DT Fuel Mass</td>
<td>100 mg</td>
</tr>
<tr>
<td>Ignition Temperature</td>
<td>20 keV</td>
</tr>
</tbody>
</table>
Z-PINCH FUSION MAGNETIC NOZZLE

The design of a magnetic nozzle to contain and direct the energy pulses of the fusion reaction is key.

- A simplified Z-Pinch fusion thermodynamic model developed parameters to characterize the propulsion system.

- The nozzle must withstand repeated high energy fusion reactions, extreme temperature and radiation.

- Magnetic nozzle design development has already begun with VASIMR*.
  - VASIMR engine is magnetically shielded and does not come into direct contact with plasma. Powerful superconducting electromagnets, employed to contain hot plasma, generate tesla-range magnetic fields.

* Variable Specific Impulse Magnetoplasma Rocket
Transforms a spherical explosion to a paraboloid expansion.

Captures useful impulse late in the expansion.

Flux compression and magnetic pressure are at a maximum.

Assume the parabolic focus/fusion point is 2 m from the apex of the nozzle.

The expanding plasma has a total mass of 0.02 kg and its initial kinetic energy is assumed to be 1 GJ (1 × 10^9 Joules).

The resulting plasma trajectories defined the dimensions and the loads subjected to the magnetic nozzle.
NOZZLE DESIGN – PLASMA TRAJECTORIES

Plasma Segment Trajectories

Focus of Parabola/Fusion Point

8 Magnetic Coils

Nozzle Ring Parabola

Initial Plasma Shell Parabola

Focus of Parabola/Fusion Point
The Performance Nozzle Model determined the required magnetic field(s) to handle fusion pulses.

Eight rings were required to provide a continuous parabolic-shaped magnetic nozzle.

Each coil must have two separate conducting rings.

A superconducting ring generates the initial seed magnetic field.

The second conventional conducting ring supports the electrical current that is induced during plasma expansion.

This current recharges the capacitor banks to enable delivery of the next current pulse.

In addition to the two conductors there are cooling channels, structure, and neutron-protection features that must be incorporated in the design.
Diagram intended to illustrate a cross-section of the structure and shielding around an actively-cooled thrust coil assembly. Eight of these coils, spaced at equal radial angles from the focal point of fusion, are supported within the C-C parabolic nozzle. Dimensions and aspect ratio to be determined after detailed structural analysis.
NOZZLE COILS
## DATA TO BUILD FEM MODEL

<table>
<thead>
<tr>
<th>Ring No.</th>
<th>Z (m) from parabolic origin</th>
<th>Ring Major Radius (m)</th>
<th>2πr (m)</th>
<th># Nodes in 1/8 Model</th>
<th># Nodes on ring</th>
<th>Max. Axial Force acting on ring (N)</th>
<th>Max. Radial Force/Linear Pressure acting on ring (N/m)</th>
<th>Axial Force N/node</th>
<th>Radial Force N/node</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>9.64E-03</td>
<td>2.78E-01</td>
<td>1.747</td>
<td>7</td>
<td>48</td>
<td>8.39E+07</td>
<td>2.74E+06</td>
<td>1.75E+06</td>
<td>9.97E+04</td>
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<td>2</td>
<td>8.90E-02</td>
<td>8.44E-01</td>
<td>5.303</td>
<td>19</td>
<td>144</td>
<td>5.49E+08</td>
<td>2.20E+07</td>
<td>3.81E+06</td>
<td>8.10E+05</td>
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<td>2.61E-01</td>
<td>1.44E+00</td>
<td>9.048</td>
<td>25</td>
<td>192</td>
<td>1.38E+09</td>
<td>5.57E+07</td>
<td>7.19E+06</td>
<td>2.62E+06</td>
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<td>2.11E+00</td>
<td>13.258</td>
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<td>288</td>
<td>1.93E+09</td>
<td>7.78E+07</td>
<td>6.70E+06</td>
<td>3.58E+06</td>
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<td>5</td>
<td>1.04E+00</td>
<td>2.88E+00</td>
<td>18.096</td>
<td>49</td>
<td>384</td>
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<td>4.48E+06</td>
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<td>6</td>
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<td>3.82E+00</td>
<td>24.002</td>
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<td>480</td>
<td>1.03E+09</td>
<td>4.16E+07</td>
<td>2.15E+06</td>
<td>2.08E+06</td>
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<td>7</td>
<td>3.19E+00</td>
<td>5.05E+00</td>
<td>31.730</td>
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<td>720</td>
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<td>5.63E+05</td>
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<td>8</td>
<td>5.79E+00</td>
<td>6.81E+00</td>
<td>42.789</td>
<td>109</td>
<td>864</td>
<td>1.02E+08</td>
<td>4.20E+06</td>
<td>1.18E+05</td>
<td>2.08E+05</td>
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</table>
FEM MODEL ANALYSIS

1/8\textsuperscript{th} of nozzle

Ti Stress Limits
• Thick-walled tubing was modeled to simulate fluid passages for coolant/FLiBe.

• Coils are embedded in 8 splines and supporting structural rings.

• Carbon Composite (C/C), (graphite epoxy, IM7/8552, >95% carbon) 3D high strength material.

• Struts extended to the vehicle truss structure to transfer the fusion pulse forces.
The Li⁶ fuel will absorb and carry away some neutrons and will slow down many more.

A 3-layer neutron shield, 25 cm, will cap the magnetic nozzle.

Lithium Hydride (LiH) slows/gets neutrons 50% better by mass than water MP 960 °K.

Boron carbide (B₄C) captures thermal neutrons.

A thin layer of Tungsten (W) is needed to reduce the gamma rays.

Beryllium shields behind the capacitor banks will also deflect gamma rays.

Radiation Shielding Thickness (cm) and Attenuation:
- Blue = 14.1 MeV neutrons.
- Red = Thermal neutrons.
- Green = Gamma rays.
## MASS ESTIMATE

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>Payload – crew hab, lander, consumables, small transport, thermal, radiation protection and ECLS equipment for crew quarters.</td>
<td>150,000</td>
</tr>
<tr>
<td>Structures – Main truss, main propulsion tanks, secondary structure</td>
<td>36,500</td>
</tr>
<tr>
<td>Main Propulsion – MIF nozzle, coils, neutron/gamma shielding, FLiBe/LN2 coolant, capacitor/Marx generator recharge system</td>
<td>111,300</td>
</tr>
<tr>
<td>Main propulsion propellent – for 90-day Mars Round trip</td>
<td>83,000</td>
</tr>
<tr>
<td>Reaction Control System- tanks and propellent</td>
<td>3,500</td>
</tr>
<tr>
<td>Thermal Management – radiators, pumps, tanks, cryo coolers, thermal fluids</td>
<td>77,000</td>
</tr>
<tr>
<td>Power – fission reactor, radiation shield, and cooling loops</td>
<td>16,500</td>
</tr>
<tr>
<td>Avionics – control boxes, sensors.</td>
<td>1,700</td>
</tr>
<tr>
<td>Total Mass</td>
<td>479,500</td>
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<tr>
<td>30% Mass Growth Allowance</td>
<td>143,850</td>
</tr>
<tr>
<td><strong>Total Mass (Best Estimate)</strong></td>
<td><strong>623,350</strong></td>
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<td>Key Technology</td>
<td>TRL</td>
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<td>---------------------------</td>
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<td>High Temperature Z-Pinch</td>
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<td>Intense Electrical Pulse Power</td>
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<td>Magneto-Hydrodynamic Electricity</td>
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<td>Thermonuclear Equations of State</td>
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<td>Dynamic Plasma Radiation Shielding</td>
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<td>Advanced Structures</td>
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<td>Reaction Containment</td>
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* Technology Readiness level
ACKNOWLEDGEMENTS

Z-Pinch Study Team:
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William Emrich, MSFC, for radiation shielding tool
MSFC Advanced Concepts Office
Jacobs ESTS Group

* Co-authors of this paper.