VASIMR® Propulsion Development - Ready for the Next Level

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Outline

- Summary of technology development status
- VASIMR® Technology Basics and Key Elements
  - Measured performance
- TC–1 and TC–1m, flight model VASIMR® engine elements.
- Major technological element descriptions
  - Rocket Core
  - RF Power Processing (PPUs)
  - High Temperature Superconductor (HTS) Magnet
  - Thermal Management
  - Propellant Management, and Command and Date Handling (C&DH)
- Spaceflight model performance
- Next level: thermal steady-state, VX–200SS
- SEP Applications
- Conclusions
Progress in Technology development

✓ Plasma production performance
✓ Plasma acceleration performance
✓ Integrated system performance
✓ RF power processing technology
✓ Superconducting technology
✓ Mass assessment
➢ Thermal steady-state demonstration
➢ Spaceflight system version TRL 6
➢ Independent testing
Major VASIMR® Elements

- Plasma source
  - Ionizes propellant
- Superconducting Magnet
- Helicon RF Gen
- Plasma booster
  - Energizes plasma
- Magnetic nozzle
  - Directs jet

Plus thermal control for all systems
1. **Helicon Coupler** ionizes propellant gas, forming cold plasma.
   - *No further contact between plasma and hardware.*
2. ICH coupler boosts ion perpendicular energy.
3. Magnetic Nozzle converts perpendicular energy to parallel flow.
4. Detachment of plasma from the vehicle.
Three PHPK TM-1200i nude cryopanels (58,000 l/s Ar) were used for the duration of the campaign to maintain ~10^{-8} torr base pressure and minimize charge-exchange.

Chamber divider wall to maintain high vacuum (~10^{-6} torr) in the Rocket region during the firing.

Exit plane

VX-200 in the 150 m³ Vacuum Chamber, top view

VX-200 firing at 200 kW, argon propellant. 2010
**Measured Thruster Efficiency**

- Performance using argon propellant in VX-200.
- Size the system for the $I_{sp}$ range of high efficiency, 3000 to 5000 s, argon propellant.
- ICH to Helicon power ratio together with gas input controls the specific impulse and sets the size of the RF generators.

- Up to 200 kW RF power operation is repeatable
- Thermal measurements taken during operations
- Krypton helicon efficient operation demonstrated
- Details of these data are peer reviewed:

**Range for mass scaling**

- Krypton propellant would extend efficient operation down to $I_{sp} \approx 2000$ s
VX–200 plume detaches from magnetic field

- Within 2m of the VX–200 rocket core exit, the ion flux is measured flowing independently from the magnetic field.
- Classical resistivity, comparable with natural reconnection physics, seems to dominate detachment ($\nabla \cdot J = 0$) although some fluctuations in the anomalous region are observed.
Six Basic Subsystems of a Spaceflight VASIMR® TC-1 and TC-1m

- A **TC-1** is a complete VASIMR® single-core spaceflight engine, VX-200 sized.
- A **TC-1m** a “mini” version, about half the size and power.
- Power of **TC-1**: 50 to 250 kW and **TC-1m**: 25 to 150 kW.
- Variable specific impulse capable at a chosen constant total power, $I_{sp}$ range of **3000 to 5000 s** with argon propellant, krypton capable.
- A **VF-200™** is a specific clustering of two TC-1s or TC-1ms.

1. Rocket Core
2. RF PPUs
3. HTS Magnet
4. Thermal Management
   a) Spacecraft (35 °C)
   b) High-T (250 °C)
5. Propellant Management (PM)
6. Command & Data Handling (C&DH)
System Mass Scales with Processed Power

- Simple scaling: \( \alpha_{VF} = A_{sys} + \frac{B_F}{P_e} \)
- 100 kW\(_e\) example, \( I_{sp} = 3000\) s argon

\[
\begin{align*}
P_e &= 100\ kW_e \\
HEL RF PPU & \rightarrow 31\ kW_{HEL} \\
ICH RF PPU & \rightarrow 63\ kW_{ICH} \\
RF System & 98\ kW_e, 94\ kW_{RF} \\
Variable & 4\ kW_t \\
Fixed & 2\ kW_t \\
Spacecraft Thermal & 18\ kW_t, 3\ kW_t \\
High-T Thermal & 3\ kW_t \rightarrow P_{jet} \approx 58\ kW
\end{align*}
\]

- Frozen in flow
- Energy distribution
- Divergence
We have developed a highly detailed design of a flight-relevant, TC-1, steady-state core for testing in VX-200SS.

Pro-Engineer CAD model calculates a precise mass.

Include fluid and MLI to protect the magnet.

\[ \text{TC-1: } B_{RC} = 82 \pm 4 \text{ kg and TC-1m = 42 kg} \]
PPU is ready for flight development

- Steady-state compact and highly efficient RF PPU s operated with both plasma stages. **TRL 5–6** (individual boards in vacuum)

**Helicon**

- **Power rated:** 48 kW
- **Efficiency:** 91% (expect to increase to 95%)
- **Size:** 40 cm x 40 cm x 120 cm
- **Weight:** 40.1 kg; α = 0.9 kg/kW

- Silicon Carbide technology has come to market since these first generation RF generators, so improved performance is possible.

**ICH**

- **Power rated:** 180 kW (24 hr ss burn in)
- **Efficiency:** 98% now
- **Size:** 40 cm x 40 cm x 120 cm
- **Weight:** 87.1 kg; α = 0.5 kg/kW
High Temperature Superconductor (HTS) technology has made tremendous gains in the last decade, e.g. SuperPower® YBCO tape.

Higher temperature enables the use of high efficiency cryocoolers, such as the Sunpower® GT models.

Detailed electromagnetic analysis coupled with the Rocket Core

Mechanical analysis under Falcon 9 launch loads.

\( TC-1: B_M = 199 \pm 20 \text{ kg} \) and \( TC1-m: B_M = 124 \pm 20 \text{ kg} \)
We baseline a two temperature thermal rejection system using pumped loops to create a parametric model for the mass scaling.

- Spacecraft thermal, \( \sim 35 \, ^\circ\text{C} \)
- High-T, \( \sim 250 \, ^\circ\text{C} \)

\[
M_{plj} = M_{fj} + \left[ \alpha_{pl} + \frac{m_R}{N_s \eta_{Rj} \sigma T_{Rj}^4} \right] Q_{Rj}
\]

- Pumped loop
  - \( M_f = 25 \, \text{kg} \)
  - \( \alpha_{pl} = 0.26 \, \text{kg/kW} \)
- 2-sided radiators
  - \( N_s = 2 \)
  - \( \eta_R = 0.75 \)
  - \( m_R = 4 \, \text{kg/m}^2 \)

- \( A_{TM} = 0.4 \, \text{kg/kW} \) and \( B_{TM} = 61 \, \text{kg} \)

**Diagram:**
- RF PPU waste heat to \( Q_{RF} \)
- Rocket Core waste heat to \( Q_{RC} \)
- \( T_R = 35 \, ^\circ\text{C} \) for Spacecraft Thermal
- \( T_R = 250 \, ^\circ\text{C} \) for High-T Thermal
- HTS Magnet and avionics
Propellant Management and C&DH, TRL 7+

- Propellant management, $B_{PM} = 19.7$ kg
  - Based on VACCO XFCM
  - Valves, fittings and tubing
  - Control electronics
  - Plus cabling

- C&DH: $B_{C&DH} = 20$ kg
  - COTS control products
  - Plus cabling

Aitech E900 and E950
TC–1 has a very wide power range for operation with argon or krypton

- Benchmark physics-base performance model.
- Based on VX–200 (argon data shown) with modeling to optimize performance.
- Plasma source operation was experimentally verified with krypton propellant.
- Same curves apply for TC–1m, limited to 150 kW.

Thrust (N)

Total DC Power to Support Thruster (kW)

TC–1™ Single Thruster Operational Envelope for Mission Design

*VX–200 system efficiencies include measured thruster and PPU efficiency data, and allot 3 kW of DC power for cryocoolers, avionics, pumps, and other support systems.
VASIMR® TC–1m mass advantage above 60 kWe, complementary to HET technology

- HET mass model (Hofer) plus 0.5 kg/kW active PPU cooling, $\eta$ for 457M v2.
- TC–1m mass model with a gimbal added.
VASIMR® TC–1m clusters favor one active thrusters with spare, while HET favors more than five

- Mass comparison for a single–string fault tolerant 150 kW system
Funding to develop both Hall Effect Thruster (HET) and VASIMR® (and others) technologies is important!

Above single-string power levels of about 50 kWe, VASIMR® technology shows competitive advantage.

Solar power, electric bus and operational technologies are in common.

VASIMR® technology is favorable for missions requiring system jet power levels above 80 kW.

- Higher and flexible I<sub>sp</sub>
- Lighter
- Higher efficiency
- Simple PPU

The mass of solar panels, assumed to be 7 kg/kW, is important. The effect of efficiency on propellant savings is a bigger effect assuming 5000 kg of propellant per 40 kW of input power.
Challenges to build and test a VX-200SS

- Plans for upgrading with active cooling for thermal steady-state testing, more than 100 hours at high power.
  - The VX-200 rocket core
  - RF Power Processing systems
  - Superconducting Magnet servicing
  - Significant chamber setup to perform duration testing at over 100 kW.
Preparations for Steady-State, VX-200SS

VX-200SS setup in the 150 m³ Vacuum Chamber, top view

Rocket Region

Plume Region

Translating stage

Chamber divider wall, enables high vacuum (~10⁻⁶ Torr) in Rocket Region during firing.

Performance data

Argon

Four PHPK TM-1200i nude cryopanels (58,000 l/s Ar), with room for additional 8 panels.

Plasma Dump

VX-200 firing at 200 kW
Exhaust Plasma Diagnostics will need Modifications

- Force Impact Target #1
- RPA
- Horizontal mid-plane
- Force Impact Target #2
- 3-axis Magnetometer
- Swept Langmuir Probe
- Ion Flux Probe Array #1
- Ion Flux Probe Array #2
Mounting interest for L1 as staging point near Moon for deep space missions
- Support of this outpost needs to be (economically) sustainable
- Chemical propulsion not cost effective (low payload capability = high cost)
- IMLEO is limited by foreseeable launch capability (~50 t to LEO)
- Study assumes 400 kW VASIMR solar electric propulsion
- Ad Astra is conducting a mission study based on potential outpost mass
- This same tug has application to support human exploration of Mars

### Table: VASIMR 400 kW Solar Electric Space Tug for Cargo Delivery from LEO to L1, or beyond

<table>
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<th>Isp [sec]</th>
<th>IMLEO</th>
<th>Prop(LEO-L1)</th>
<th>PayLoad</th>
<th>IML1</th>
<th>Prop(L1-LEO)</th>
<th>FMLEO</th>
<th>Time [days]</th>
<th>mdot [kg/sec]</th>
<th>DelV[m/sec]</th>
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<td>N/A</td>
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Asteroid Redirect Alternate

- Assume 1300 ton asteroid (ref. Keck Institute for Space Studies)
- Time value of money is important factor

<table>
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<tr>
<th>Type</th>
<th>Fuel Type</th>
<th>Fuel Cost</th>
<th>Years</th>
<th>2012 Cost</th>
<th>Final Cost</th>
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<tr>
<td>VASIMR® VF–200</td>
<td>Argon</td>
<td>$5 per kg</td>
<td>2.0</td>
<td>$3.3B</td>
<td>$5 B</td>
</tr>
<tr>
<td>Hall Thruster 40kW</td>
<td>Xenon</td>
<td>$1000 per kg</td>
<td>10.1</td>
<td>$2.6B</td>
<td>$20 B</td>
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</table>

Concept of a 200 kW VASIMR® engine adapted to KISS study NEA retrieval module
Orbital Debris Removal

Example: Initial Mass in Low Earth Orbit (IMLEO) and mission time required to remove 19, 8.3 ton “Zenit” SL-16 rocket upper stages in 19 different high inclination orbits.

<table>
<thead>
<tr>
<th></th>
<th>Technology</th>
<th>Propellant</th>
<th>$I_{sp}$</th>
<th>Mission time</th>
<th>IMLEO</th>
<th>Cost</th>
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<tr>
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<td>10.5 y</td>
<td>80 t</td>
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<tr>
<td>2</td>
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<td>7500</td>
<td>10 y</td>
<td>20 t</td>
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Primary propulsion for a growing market of deep space planetary missions carrying exploratory robots. Payload capacity is bound by launch capability and cost.

Ad Astra’s fast payload delivery approach utilizes a VASIMR® solar electric space tug using a solar power boost trajectory. The tug is ultimately recovered for multiple uses.

Example: a 22 t solar–electric, VASIMR® driven spacecraft, starting at the Earth Sphere of Influence, delivers a 4,000 Kg payload to Jupiter in about 2.8 years (for comparison: NASA’s 3,625 kg Juno spacecraft will take over 5 years to reach Jupiter).
Asteroid Deflection

Deflecting a 7 million ton, 150 m asteroid on a collision course with Earth

Chelyabinsk meteor, 15th February 2013
Conclusions

- VASIMR® system technology has made significant progress toward SEP spaceflight ready application.
- The VX–200™ program has proven and published plasma and power performance data.
- TC–1m, “mini”, version with 25 to 150 kWe runs with argon or krypton propellant. \( I_{sp} = 2000 \text{ to } 5000 \text{ s} \) and system efficiency of 70% is possible.
- VASIMR® technology is complementary to HET with a specific mass advantage transition at about 50 kWe.
- The next level of development is thermal steady-state durations testing at 100 kW.
- There are many exciting SEP applications for a 100 kWe class VASIMR® propelled spacecraft.