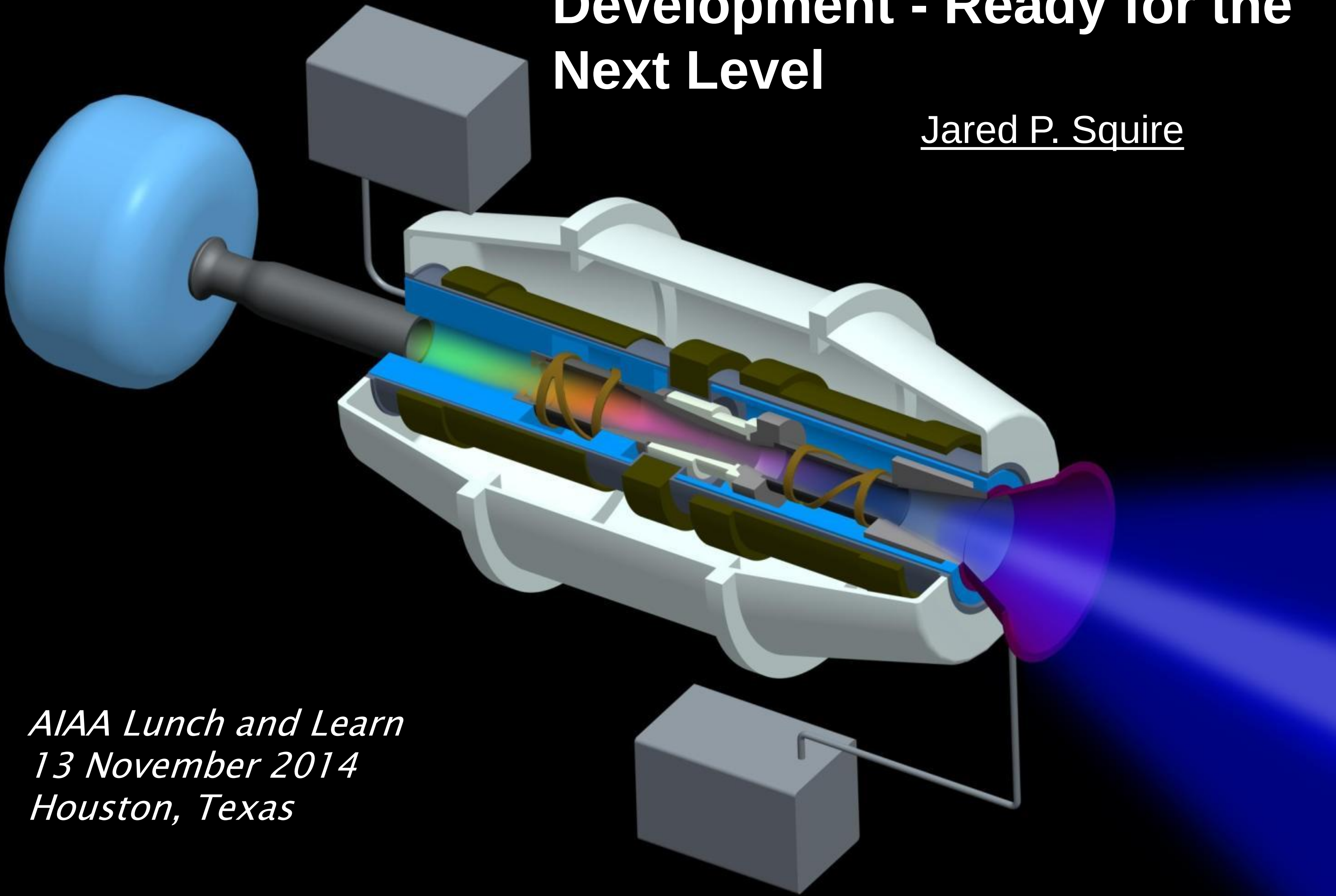
VASIMR® Propulsion Development - Ready for the Next Level

Jared P. Squire



AIAA Lunch and Learn
13 November 2014
Houston, Texas

Outline

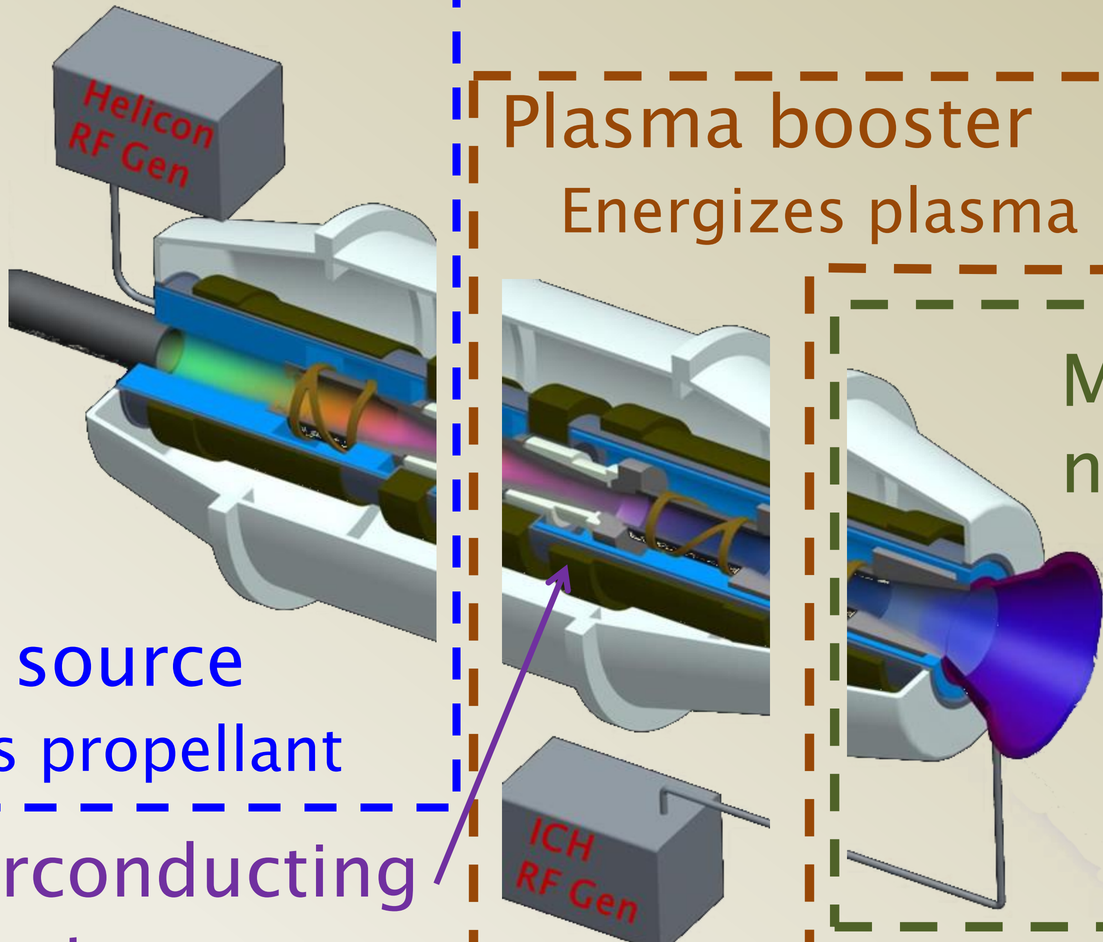
- Summary of technology development status
- VASIMR® Technology Basics and Key Elements
  - Measured performance
- TC-1 and TC-1m, flight model VASIMR® engine elements.
- Major technological element descriptions
  - Rocket Core
  - RF Power Processing (PPUs)
  - High Temperature Superconductor (HTS) 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

Ad Astra Rocket Company™

Major VASIMR® Elements



Plasma booster
Energizes plasma

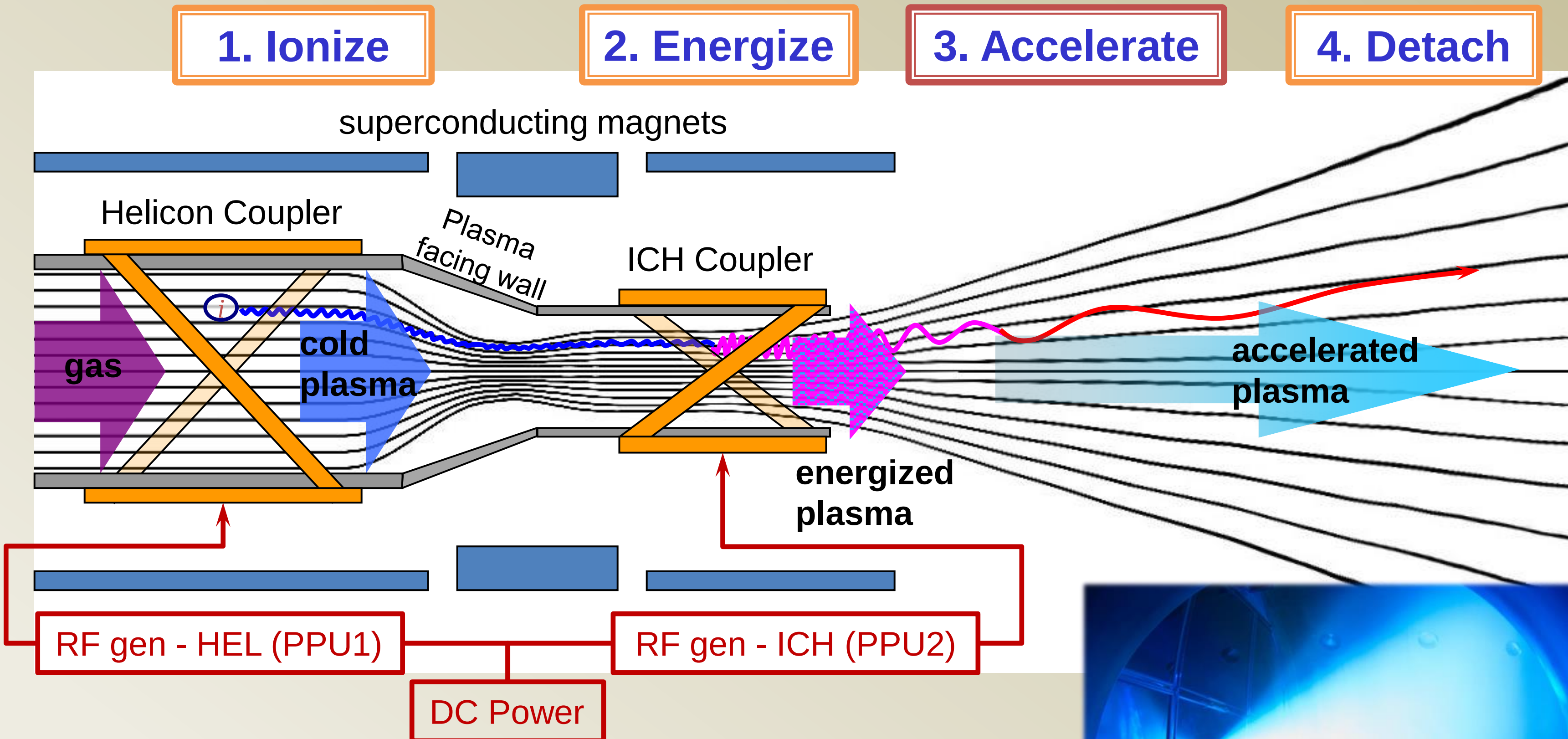
Magnetic nozzle
Directs jet

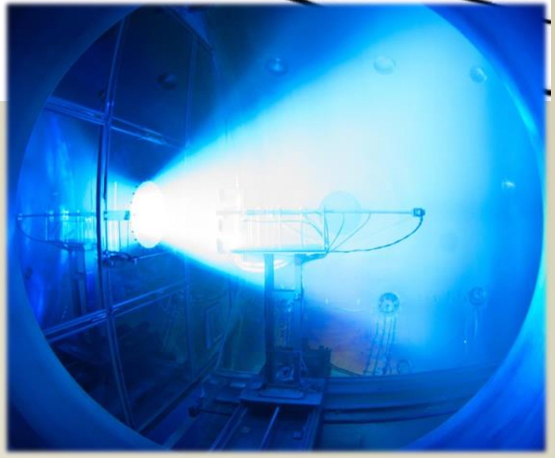
Plasma source
Ionizes propellant

Superconducting Magnet

- Plus thermal control for all systems

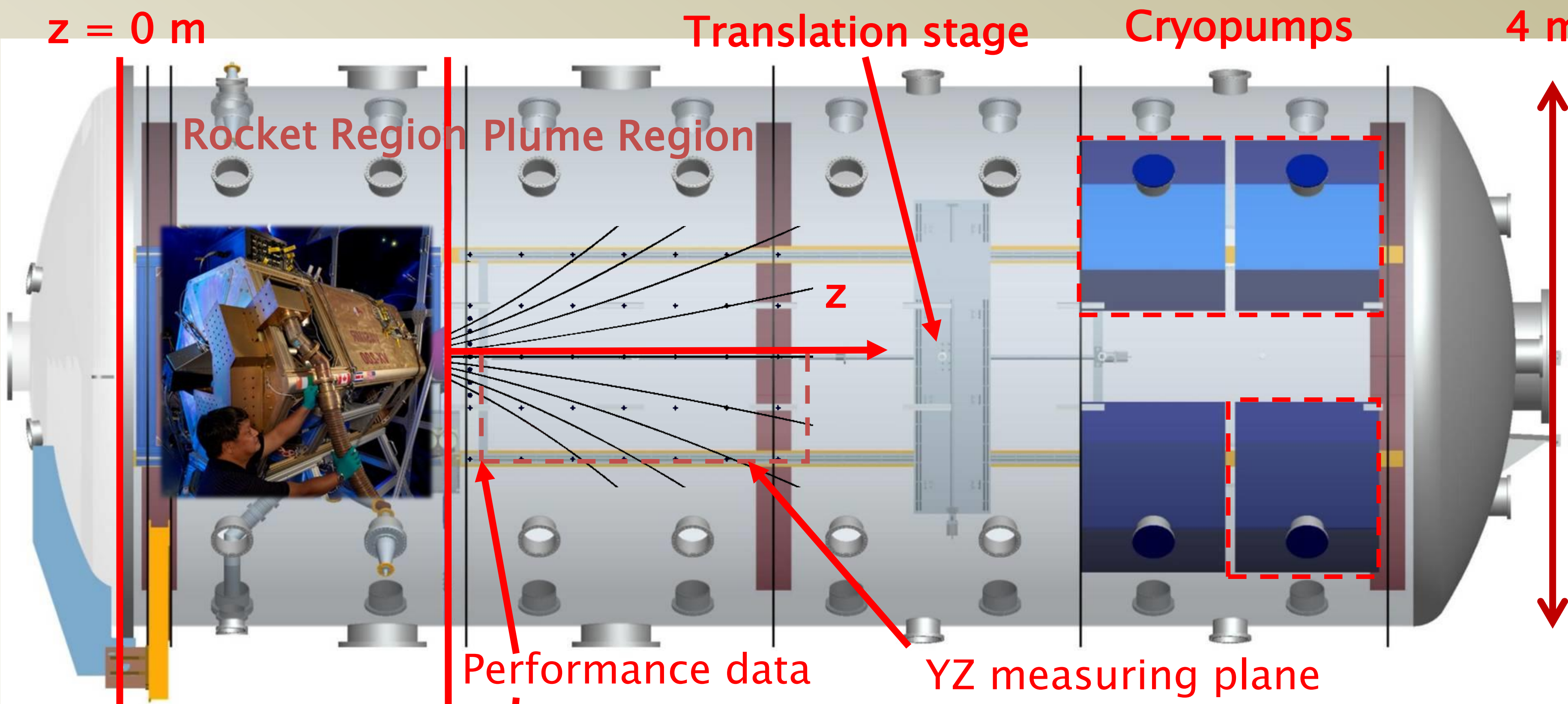
VASIMR Technology: Basic Principles





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.**

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



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

Exit plane

VX-200 firing at 200 kW, argon propellant. 2010

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.

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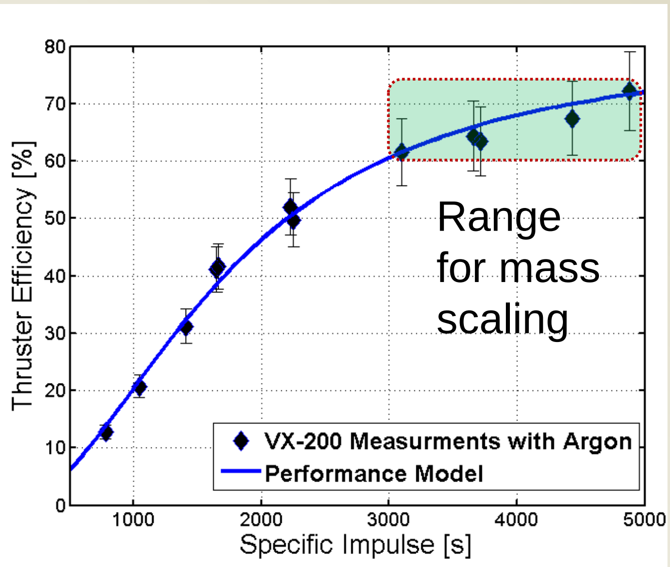
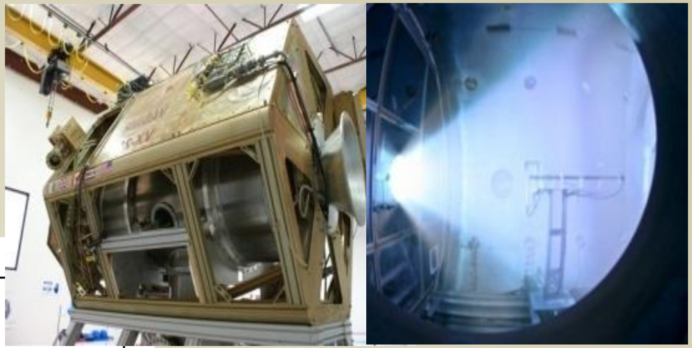
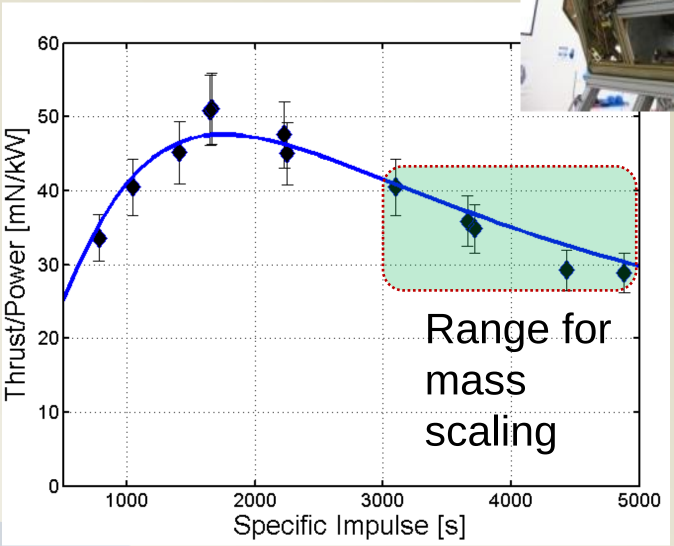
Measured Thruster Efficiency

- 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:
  - Longmier, B.W., et al., *Journal of Propulsion and Power*, **27**, July – August 2011.
  - Longmier, B.W., et al., *Journal of Propulsion and Power*, **30** January – February 2014.

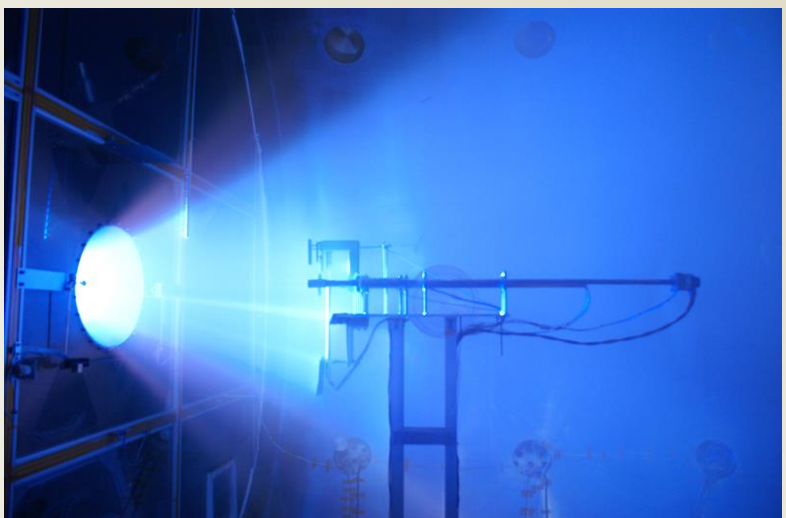


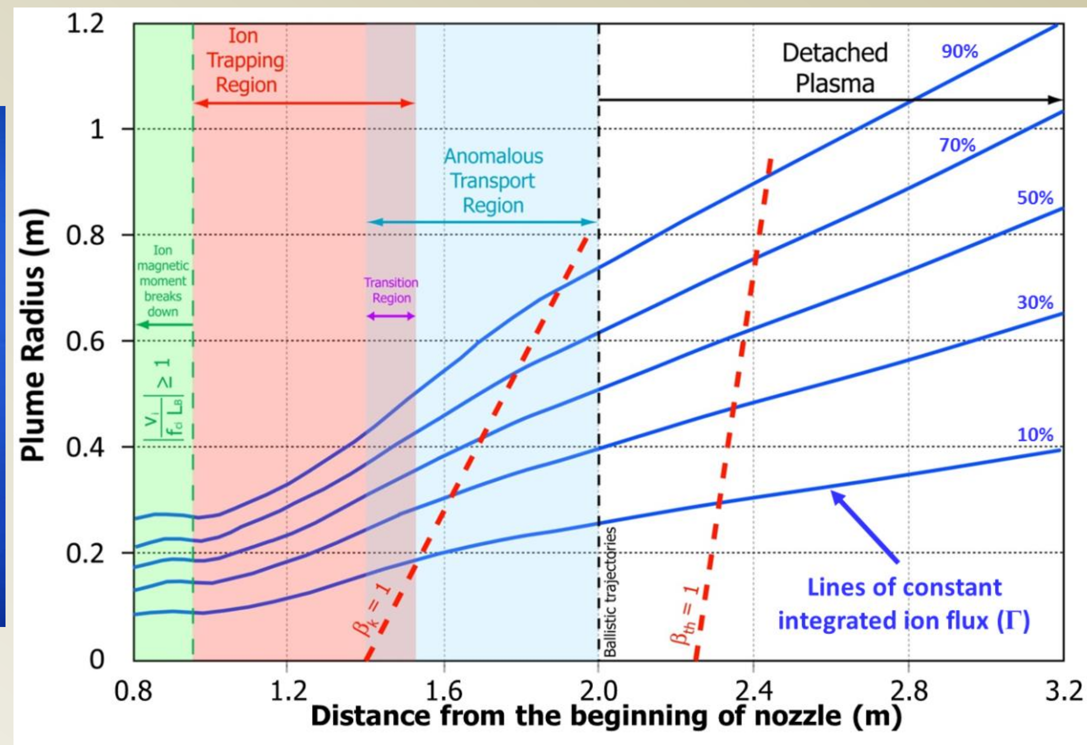


- Krypton propellant would extend efficient operation down to $I_{sp} \approx 2000$ s

VX-200 plume detaches from magnetic field

- Plasma detachment is evident per C.S. Olsen, IEEE Transactions on Plasma Science (2104) and PhD Thesis (Rice University 2013)
- 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

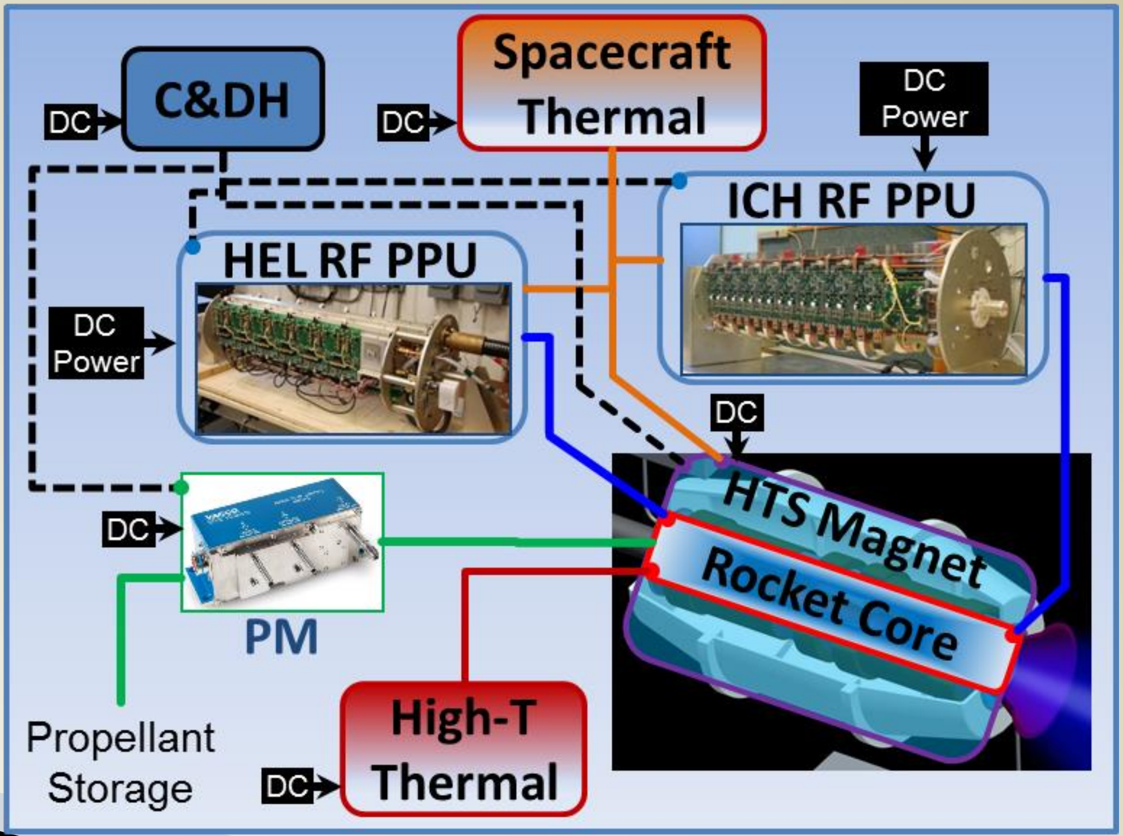




Six Basic Subsystems of a Spaceflight VASIMR® TC-1 and TC-1m

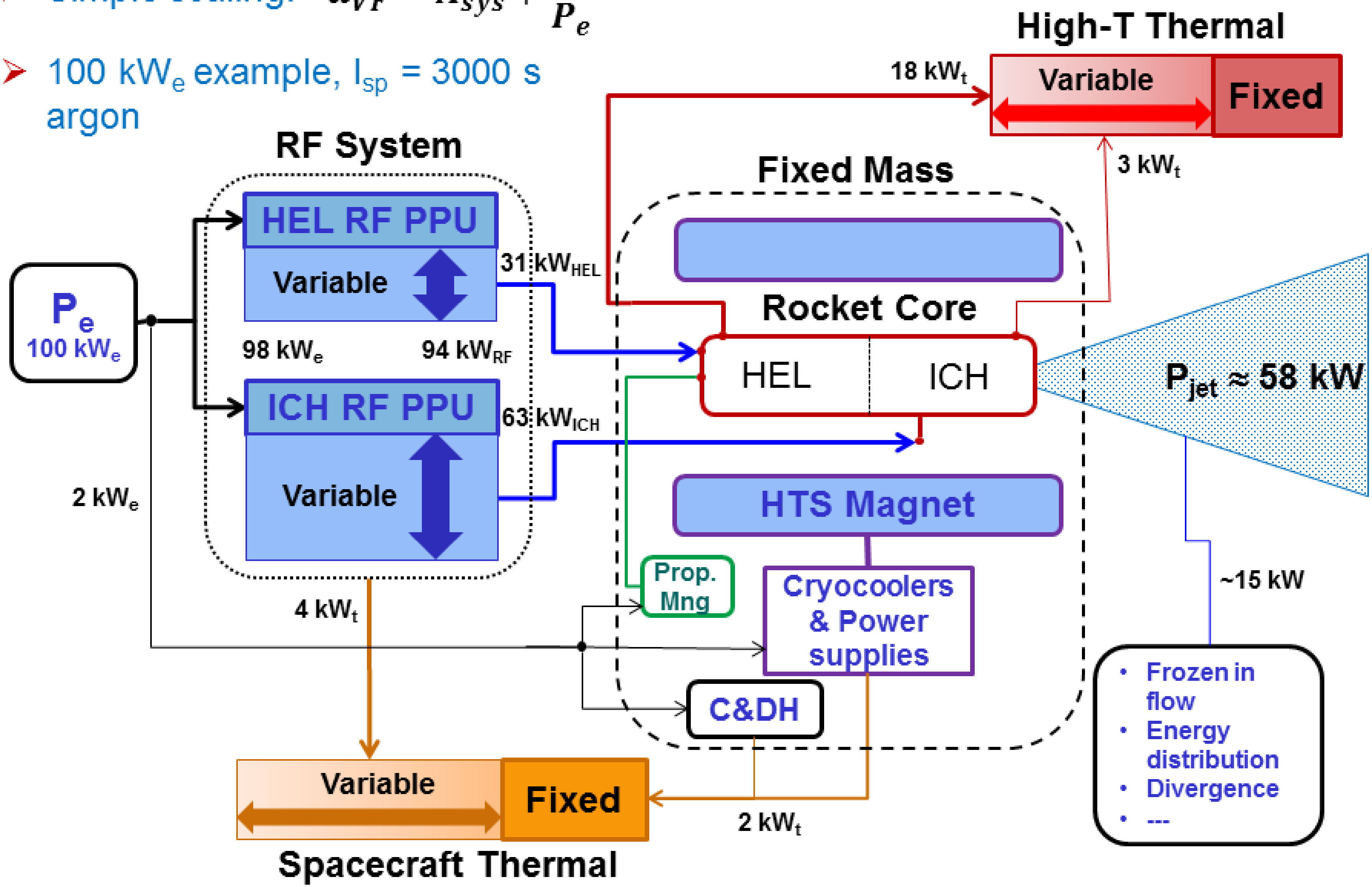
- A **TC-1** is a complete VASIMR® single-core spaceflight engine, VX-200 sized.
- A **TC-1m** a **"mini"** version, about half the size and power.
- Power of **TC-1: 50 to 250 kW** and **TC-1m: 25 to 150 kW**.
- Variable specific impulse capable at a chosen constant total power, I_{sp} range of **3000 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)



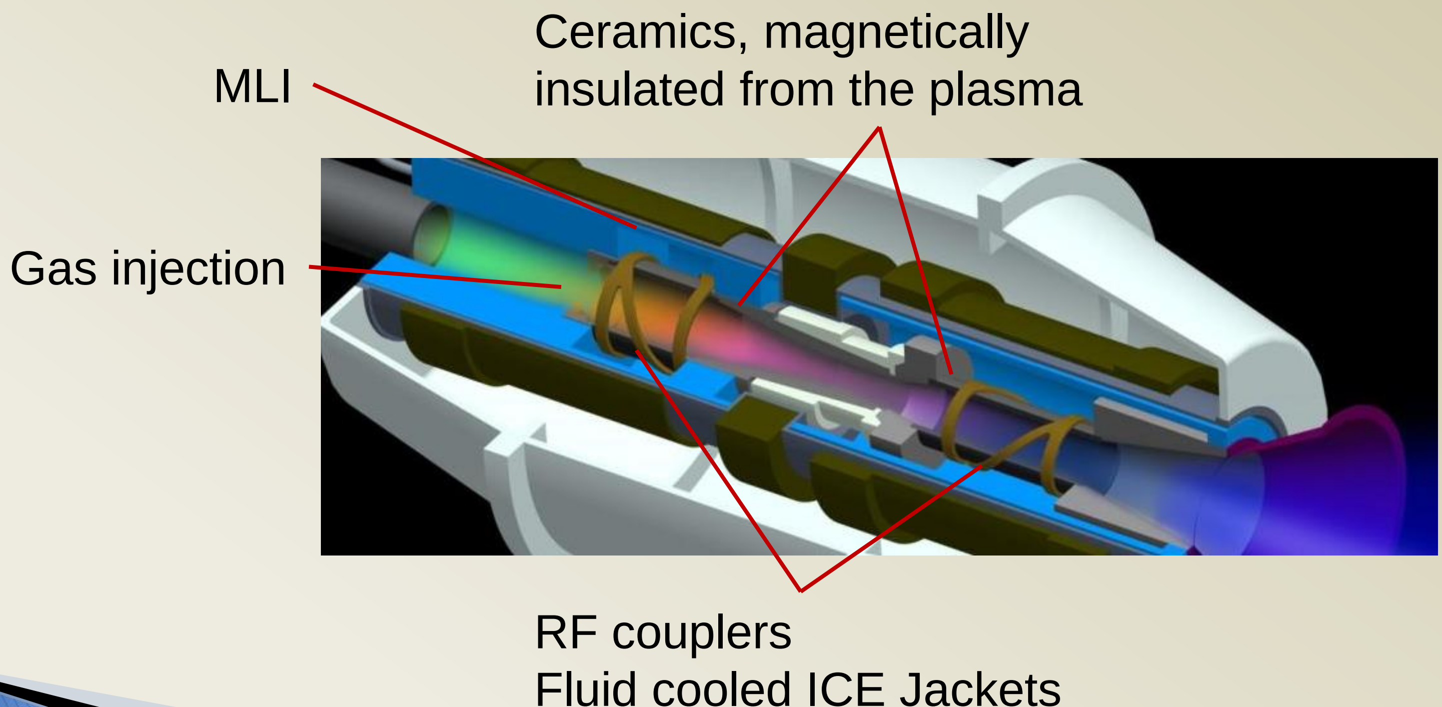
System Mass Scales with Processed Power

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



Rocket Core, Steady-state model in the building process

- 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.
- *TC-1:* B_{RC} = **82 ± 4 kg and TC-1m = 42 kg**



PPU is ready for flight development

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

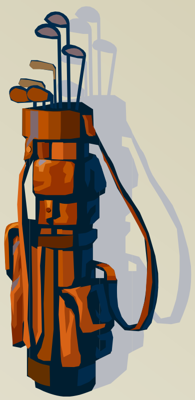
Helicon

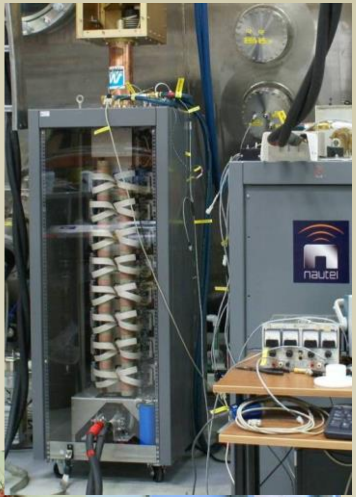
Power rated: 48 kW
Efficiency: 91% (expect to increase to 95%)
Size: 40 cm x 40 cm x 120 cm
Weight: 40.1 kg; α = 0.9 kg/kW

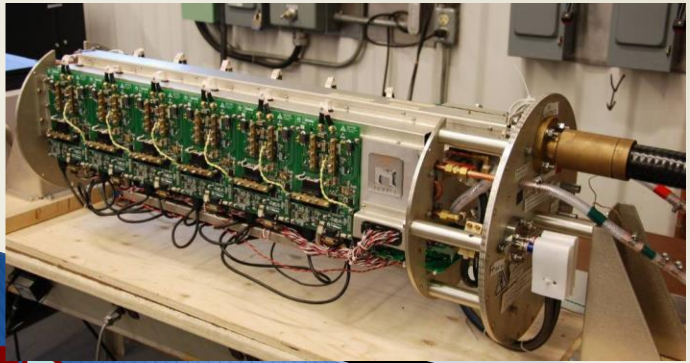
ICH

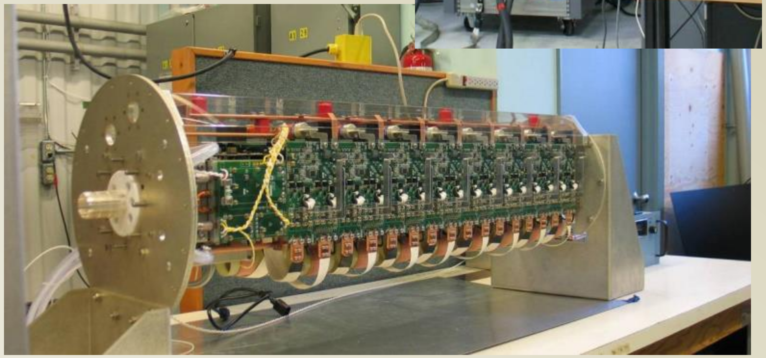
Power rated: 180 kW (24 hr ss burn in)
Efficiency: 98% now
Size: 40 cm x 40 cm x 120 cm
Weight: 87.1 kg; α = 0.5 kg/kW

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



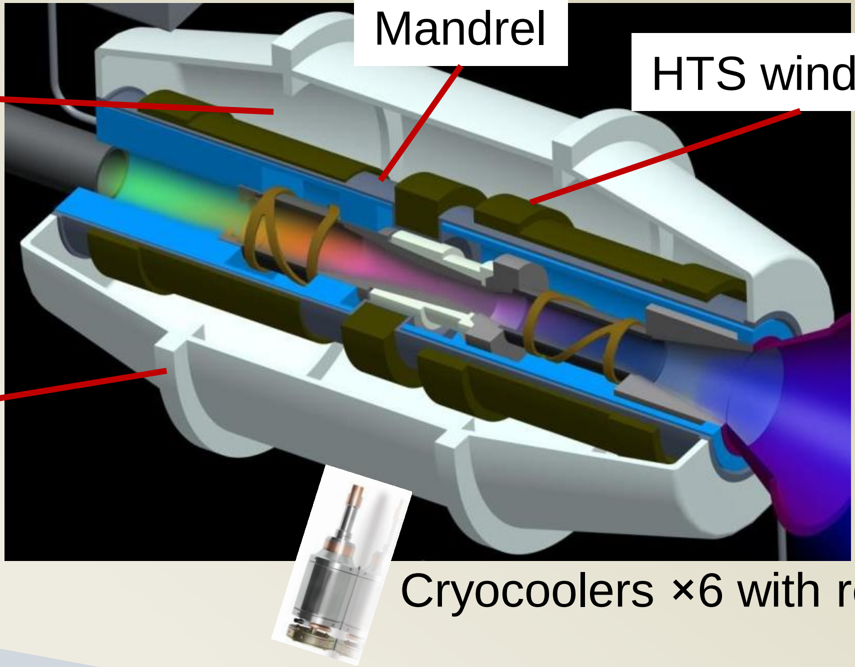






HTS Magnet Technology is ready

- 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 ± 20 kg and TC1-m: B_M = 124 ± 20 kg



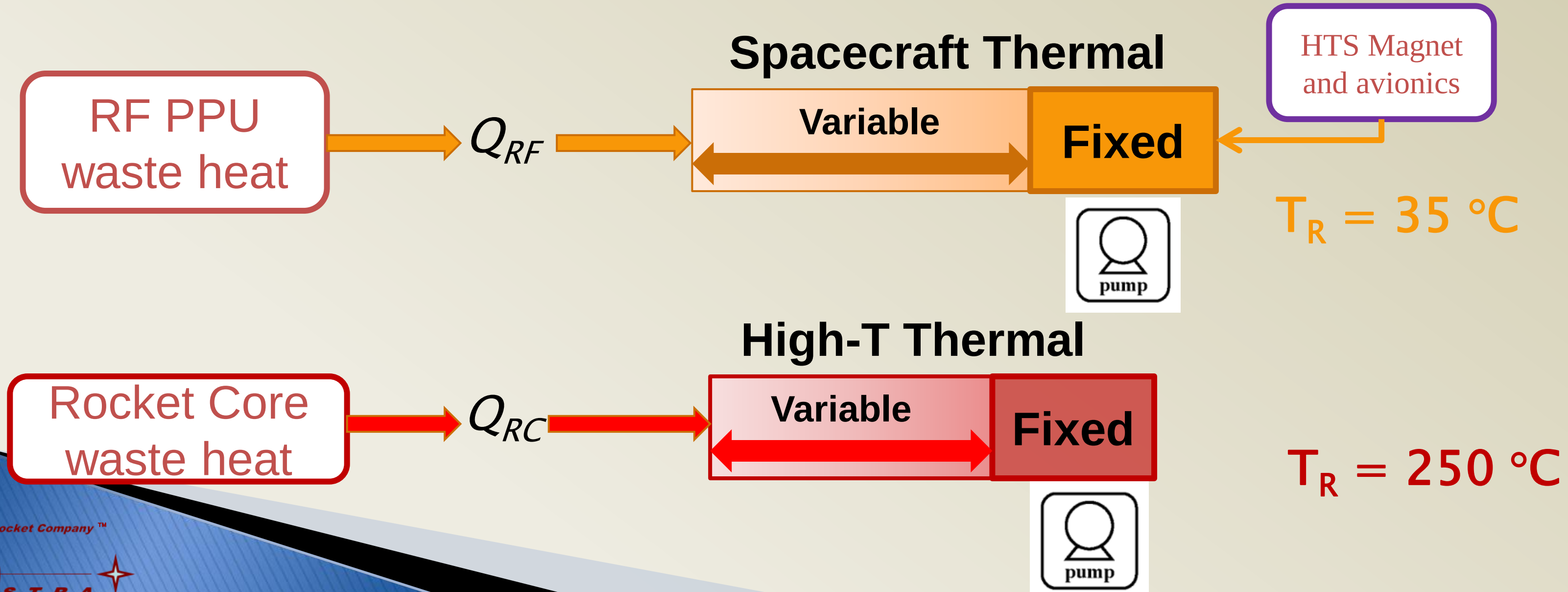
Thermal Management, parametric mass model

- We baseline a two temperature thermal rejection system using pumped loops to create a parametric model for the mass scaling.
  - Spacecraft thermal, ~ 35 °C
  - High-T, ~ 250 °C

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

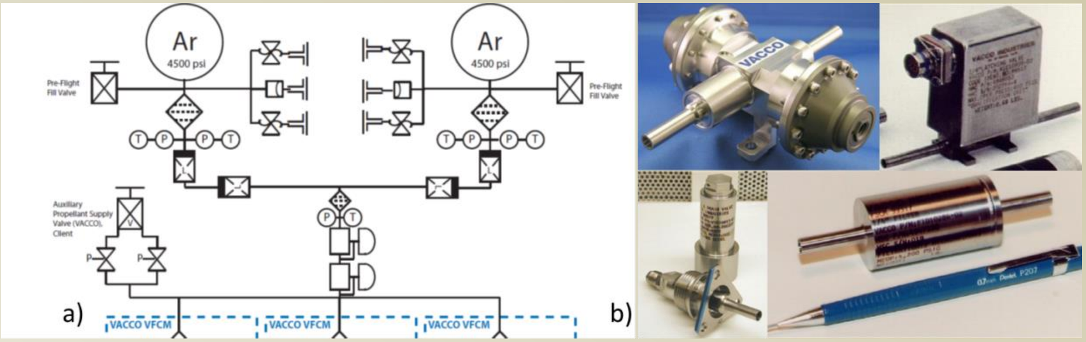
- Pumped loop
  - $M_f = 25$ kg
  - $\alpha_{pl} = 0.26$ kg/kW
- 2-sided radiators
  - $N_s = 2$
  - $\eta_R = 0.75$
  - $m_R = 4$ kg/m²

➢ ***A_{TM}* = 0.4 kg/kW** and ***B_{TM}* = 61 kg**



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

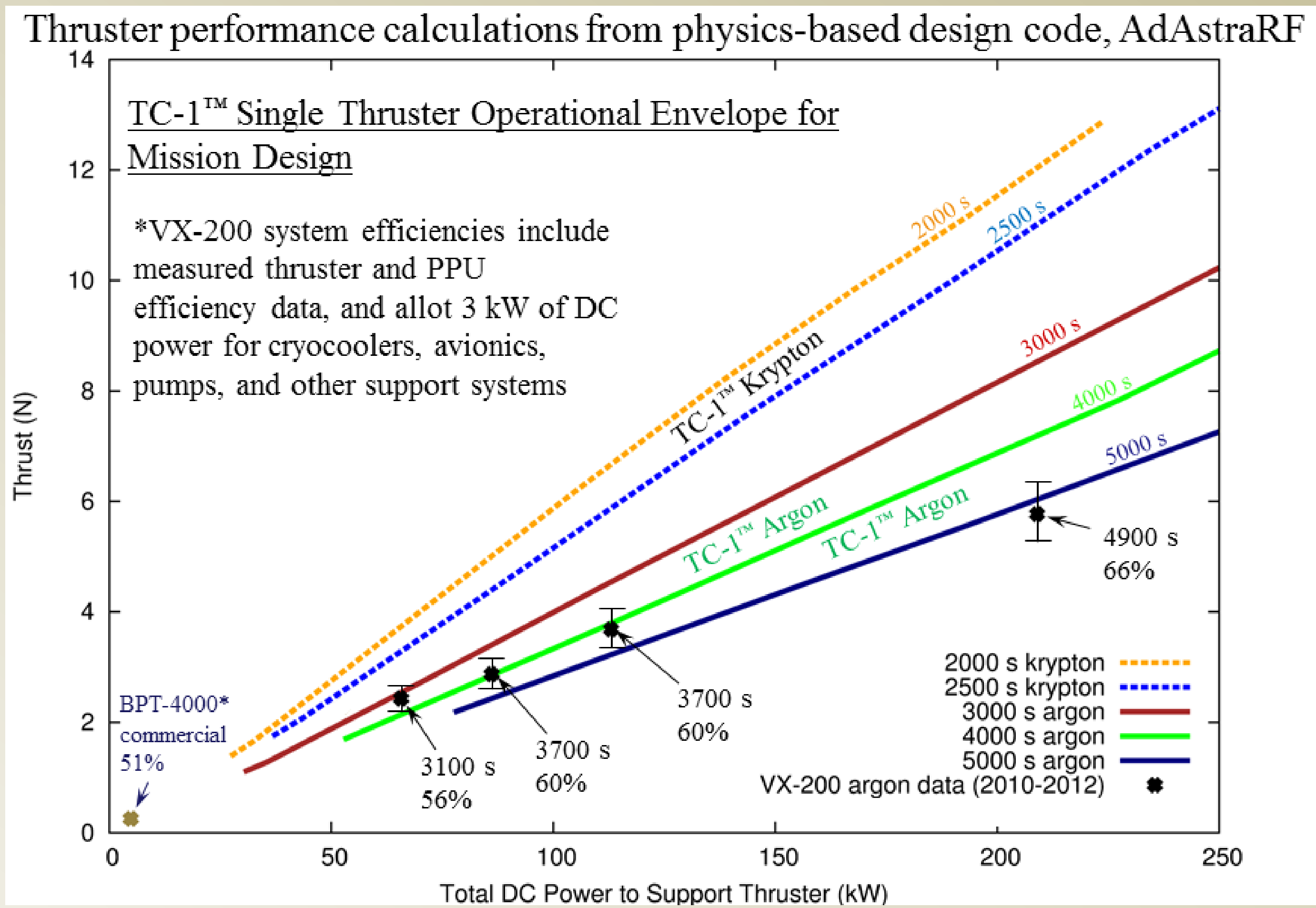


- C&DH: $B_{C\&DH} = 20$ kg
  - COTS control products
  - Plus cabling

Aitech
E900 and E950

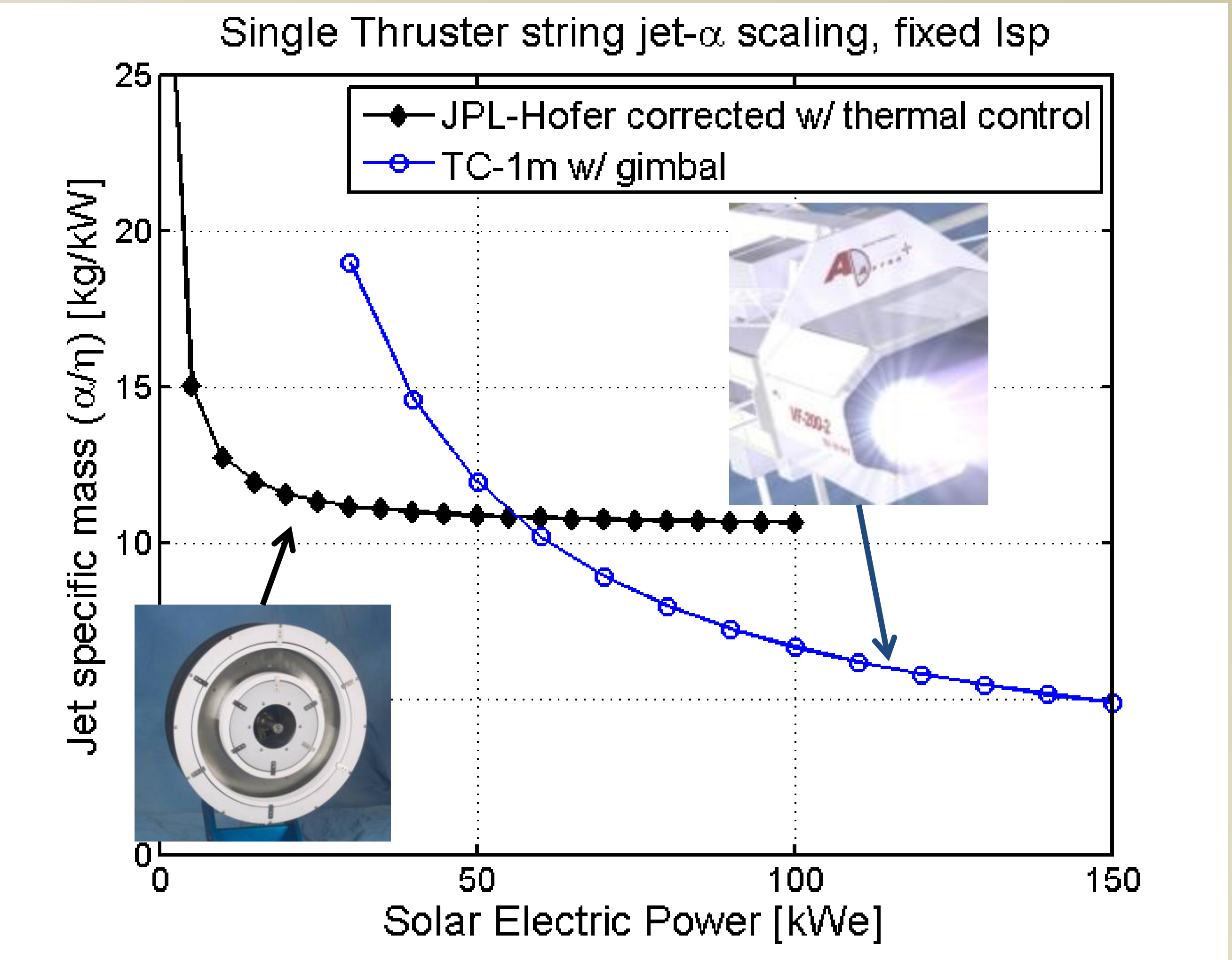
TC-1 has a very wide power range for operation with argon or krypton

- 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



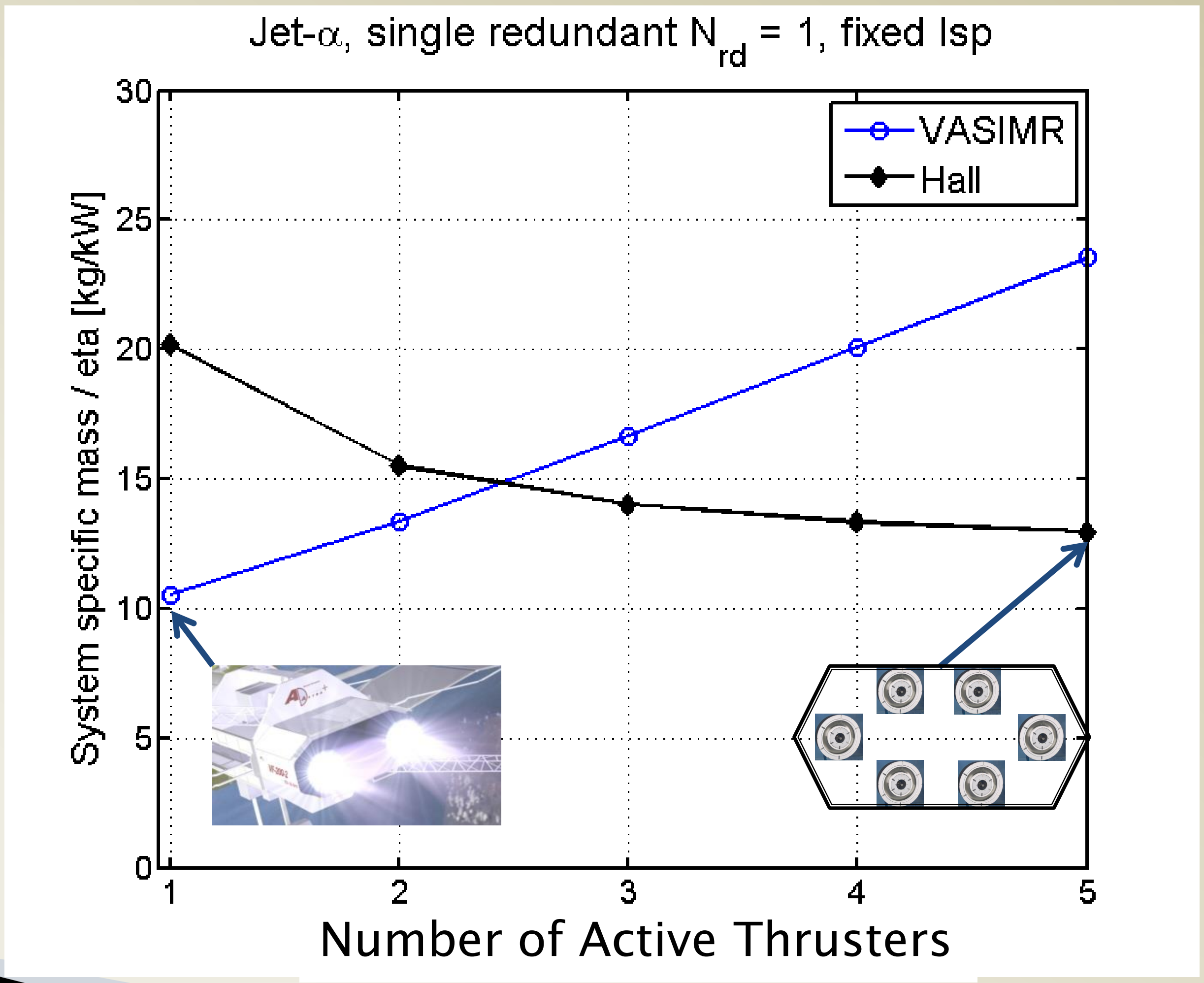
VASIMR® TC-1m mass advantage above 60 kWe, complementary to HET technology

- HET mass model (Hofer) plus 0.5 kg/kW active PPU cooling, η for 457M v2.
- TC-1m mass model with a gimbal added.



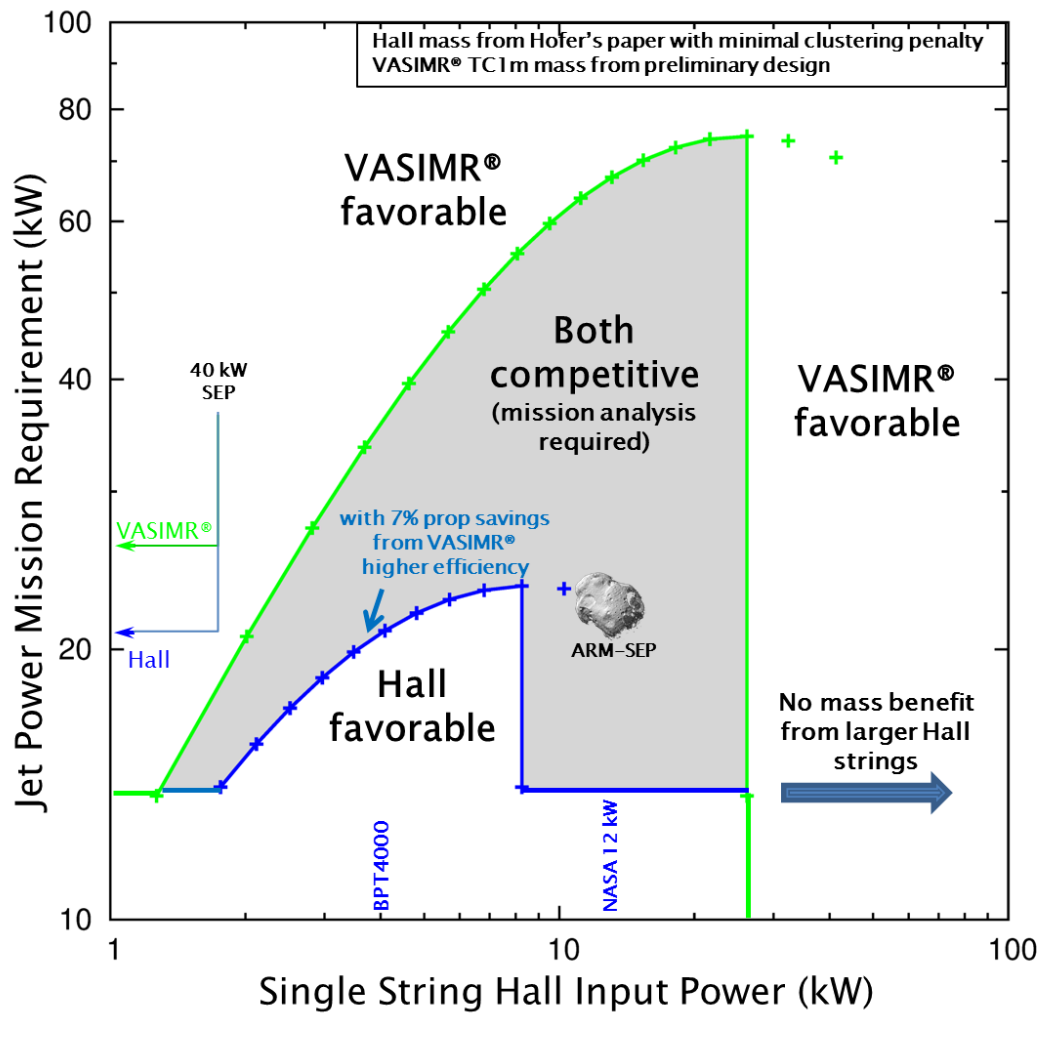
VASIMR® TC-1m clusters favor one active thrusters with spare, while HET favors more than five

- Mass comparison for a single-string fault tolerant 150 kW system



VASIMR® is complimentary to HET technology with a transition at about 50 kW

- 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_{sp}
  - Lighter
  - Higher efficiency
  - Simple PPU

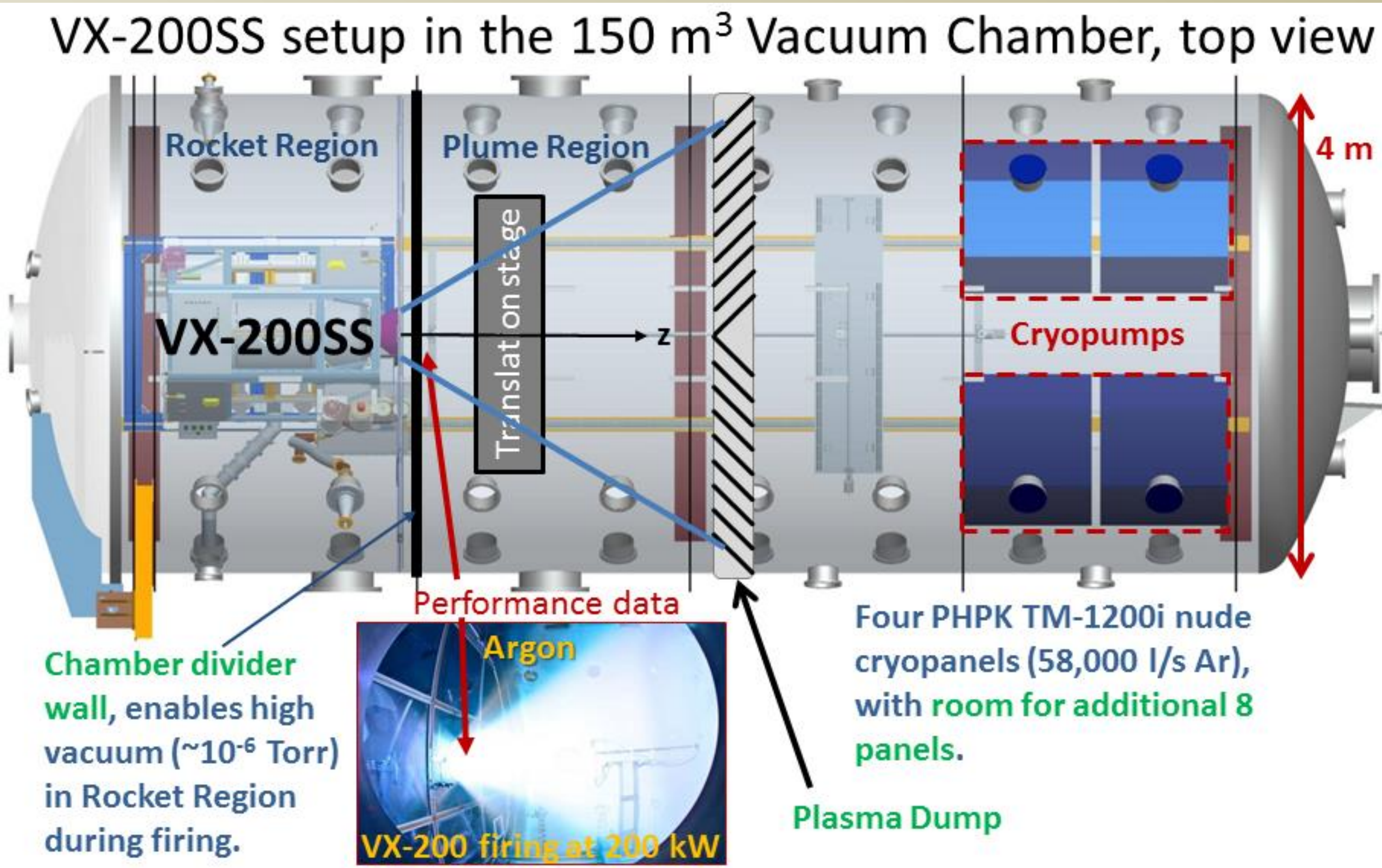


The mass of solar panels, assumed to be 7 kg/kW, is important. The effect of efficiency on propellant savings is a bigger effect assuming 5000 kg of propellant per 40 kW of input power.

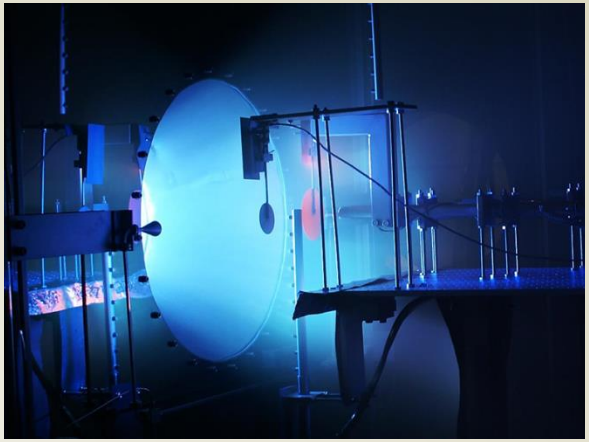
Challenges to build and test a VX-200SS

- 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



Exhaust Plasma Diagnostics will need Modifications



Force Impact Target #1

RPA

Horizontal mid-plane

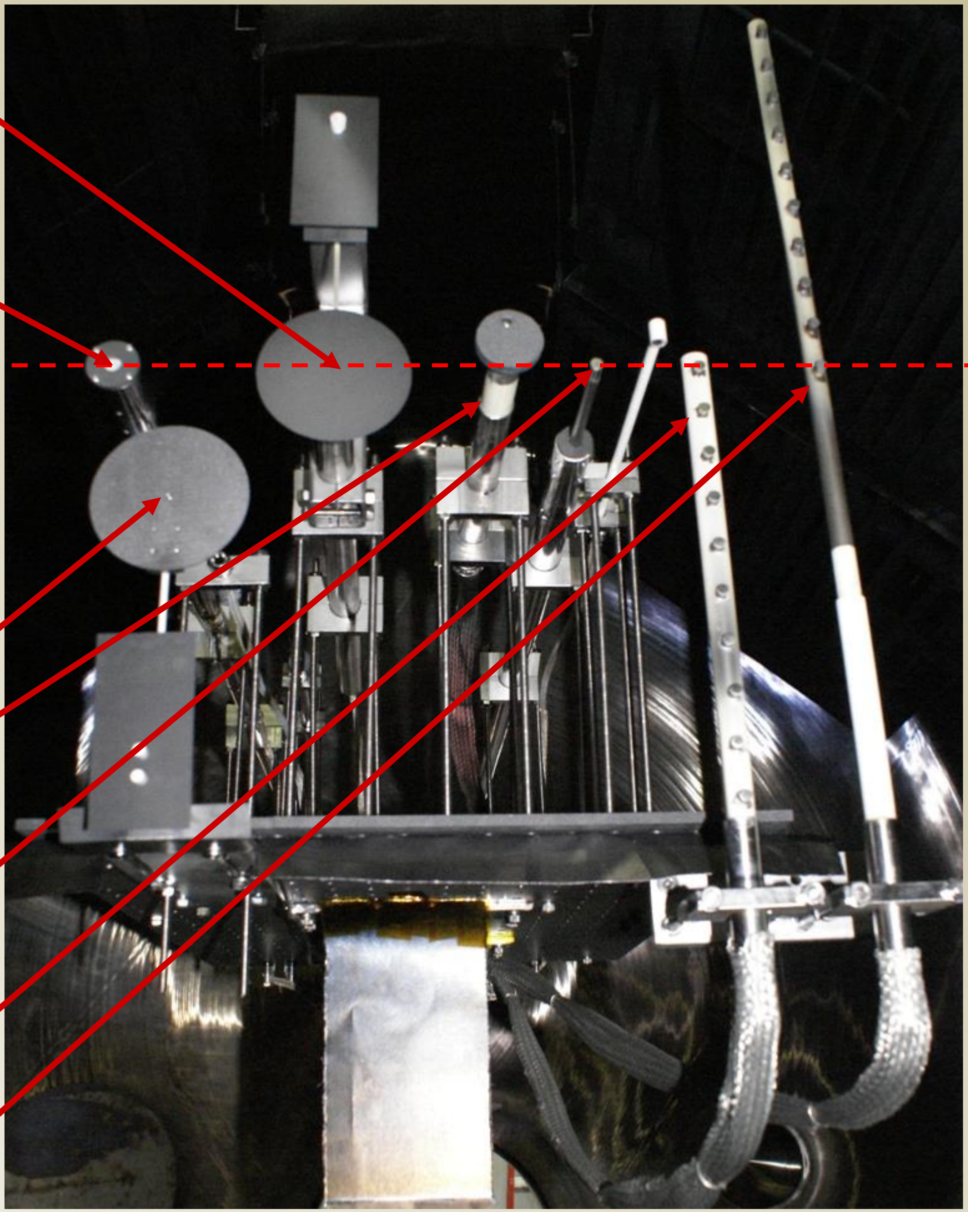
Force Impact Target #2

3-axis Magnetometer

Swept Langmuir Probe

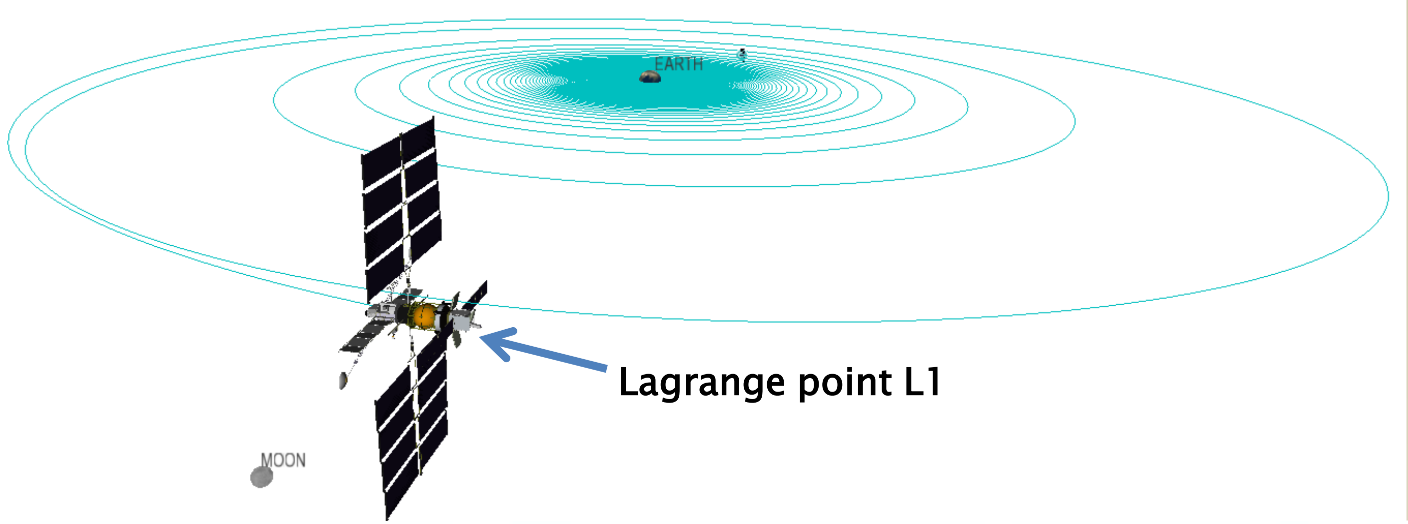
Ion Flux Probe Array #1

Ion Flux Probe Array #2



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

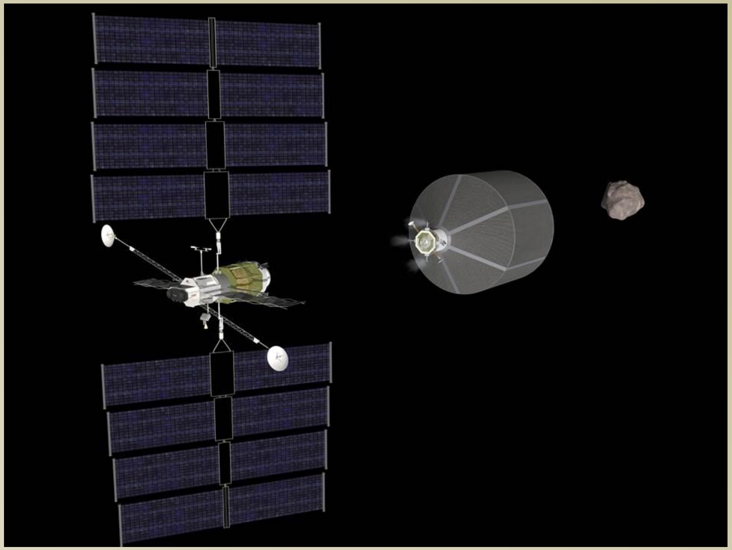
- Mounting interest for L1 as staging point near Moon for deep space missions
- Support of this outpost needs to be (economically) sustainable
- chemical propulsion not cost effective (low payload capability=high cost)
- IMLEO is limited by foreseeable launch capability (~50 t to LEO)
- Study assumes 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



Isp		Mass Budget [t]					Time [days]		mdot	DelV[m/sec]
[sec]	IMLEO	Prop(LEO-L1)	PayLoad	IML1	Prop(L1-LEO)	FMLEO	LEO-L1	L1-LEO	[kg/sec]	LEO-L1
5000	50	6.3	37.5	5.6	0.7	4.8	363	41	0.00020	6,556
2500	50	12.0	30.3	6.5	1.6	4.8	173	22	0.00080	6,652
1500	50	18.8	21.1	8.2	3.1	4.8	98	16	0.00222	6,811
450	50	29	15	6	chem one way only		4	N/A	N/A	3800
350	50	33	10	7	chem one way only		4	N/A	N/A	3800

Asteroid Redirect Alternate

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



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

Type	Fuel Type	Fuel Cost	Years	2012 Cost	Final Cost
VASIMR® VF-200	Argon	$5 per kg	2.0	$3.3B	$5 B
Hall Thruster 40kW	Xenon	$1000 per kg	10.1	$2.6B	$20 B

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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.

	Technology	Propellant	I_{sp}	Mission time	IMLEO	Cost
1	Hall Thruster	Xenon	3000	10.5 y	80 t	$800M
2	VASIMR®	Argon	5000	9 y	30 t	$300M
3	VASIMR®	NH3	7500	10 y	20 t	$200M

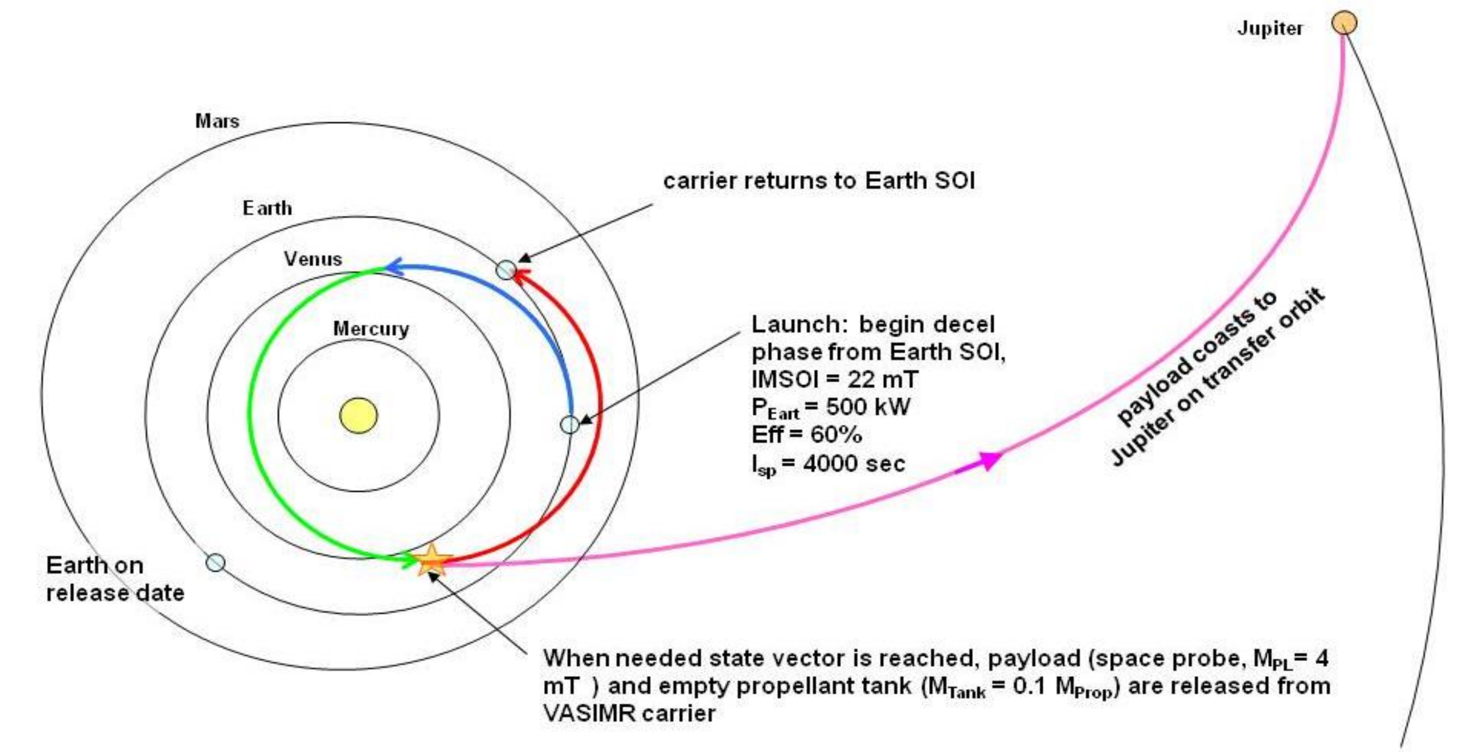
VASIMR® Deep Space Catapult for Jupiter Missions

See Paper 105-ST-3, paper by E. Bering.

Primary propulsion for a growing market of deep space planetary missions carrying exploratory robots. Payload capacity is bound by launch capability and cost.

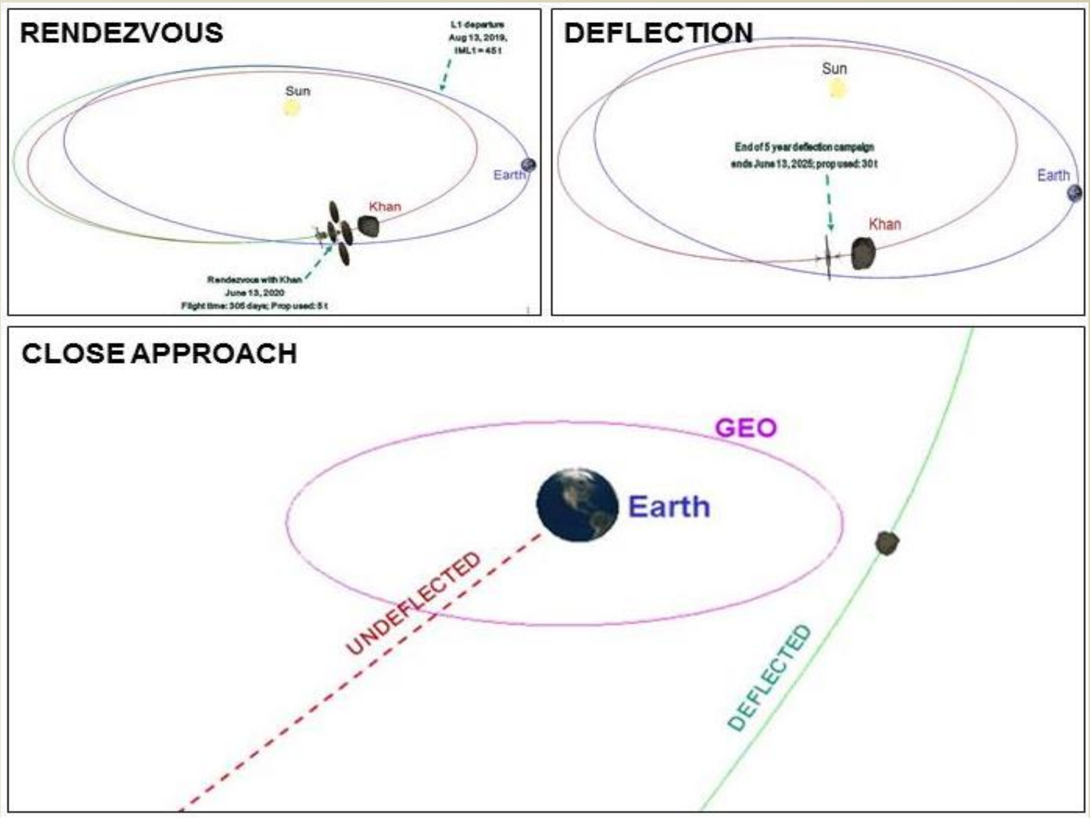
Ad Astra's fast payload delivery approach utilizes a VASIMR® solar electric space tug using a solar power boost trajectory. The tug is ultimately recovered for multiple uses.

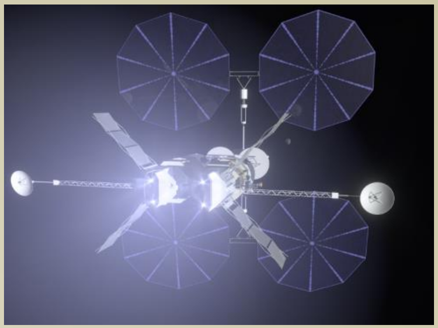
Example: a 22 t solar-electric, VASIMR® driven spacecraft, starting at the Earth Sphere of Influence, delivers a 4,000 Kg payload to Jupiter in about 2.8 years (for comparison: NASA's 3,625 kg Juno spacecraft will take over 5 years to reach Jupiter)

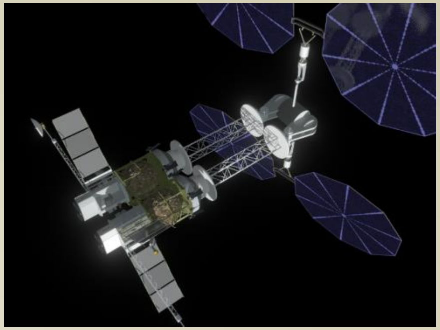


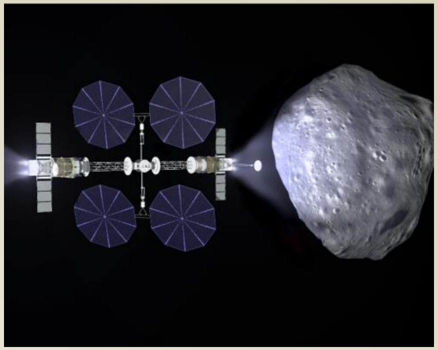
Asteroid Deflection

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. $I_{sp} = 2000$ to 5000 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.

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