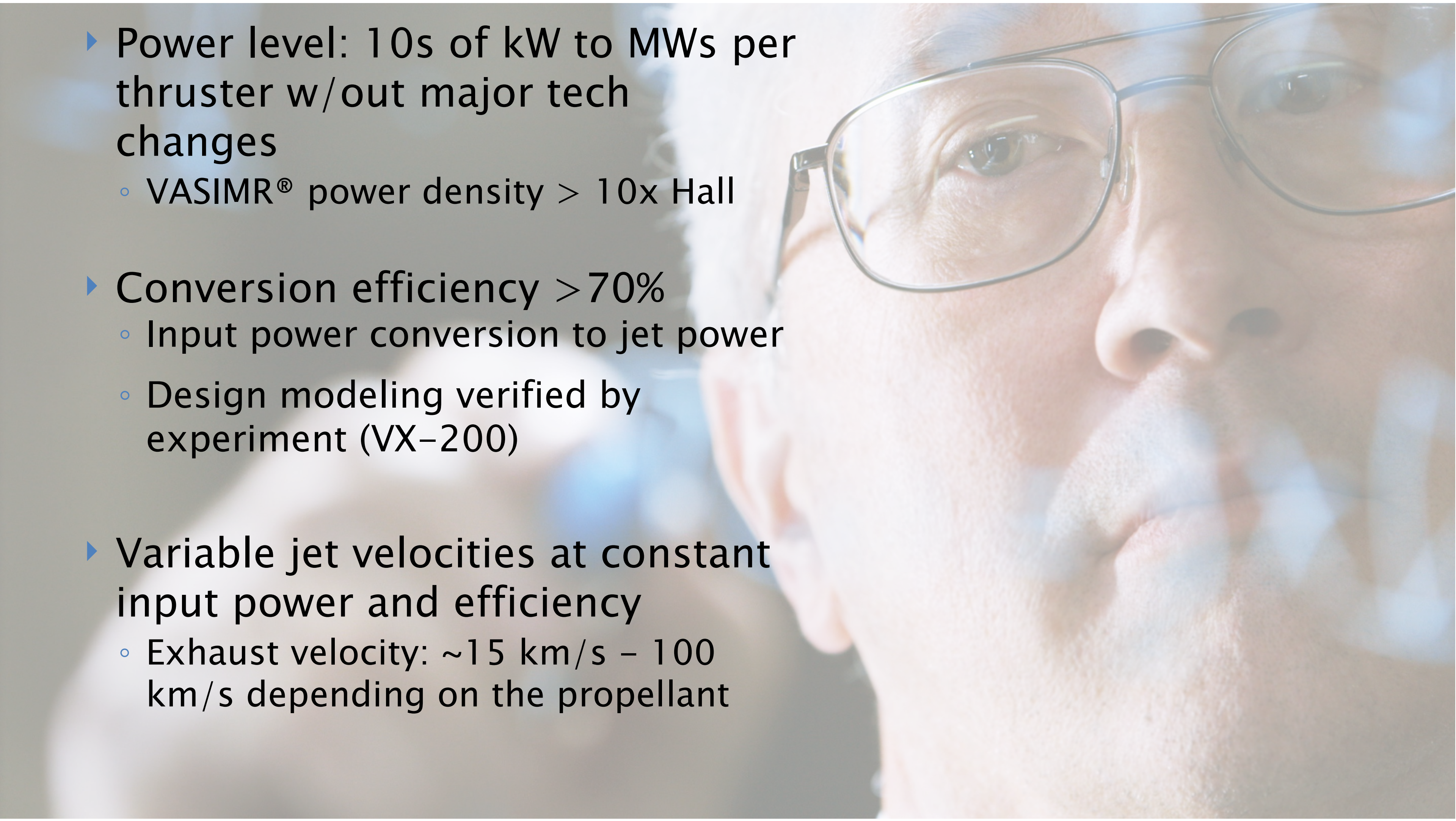
High-Power Electric Propulsion with VASIMR® Technology

Ad Astra Rocket Company™

Variable Specific Impulse Magnetoplasma Rocket (VASIMR®)

- VASIMR® engine: steady-state electric propulsion
  - Receives power from solar or nuclear source
  - Directed plasma jet generates thrust
  - Propellant options: H, He, Ne, Ar, Kr, Xe…
  - Uses RF waves to couple power
  - Does <u>not</u> use DC bias
    - Different from Hall or ion engines

VASIMR® engines are scalable and flexible

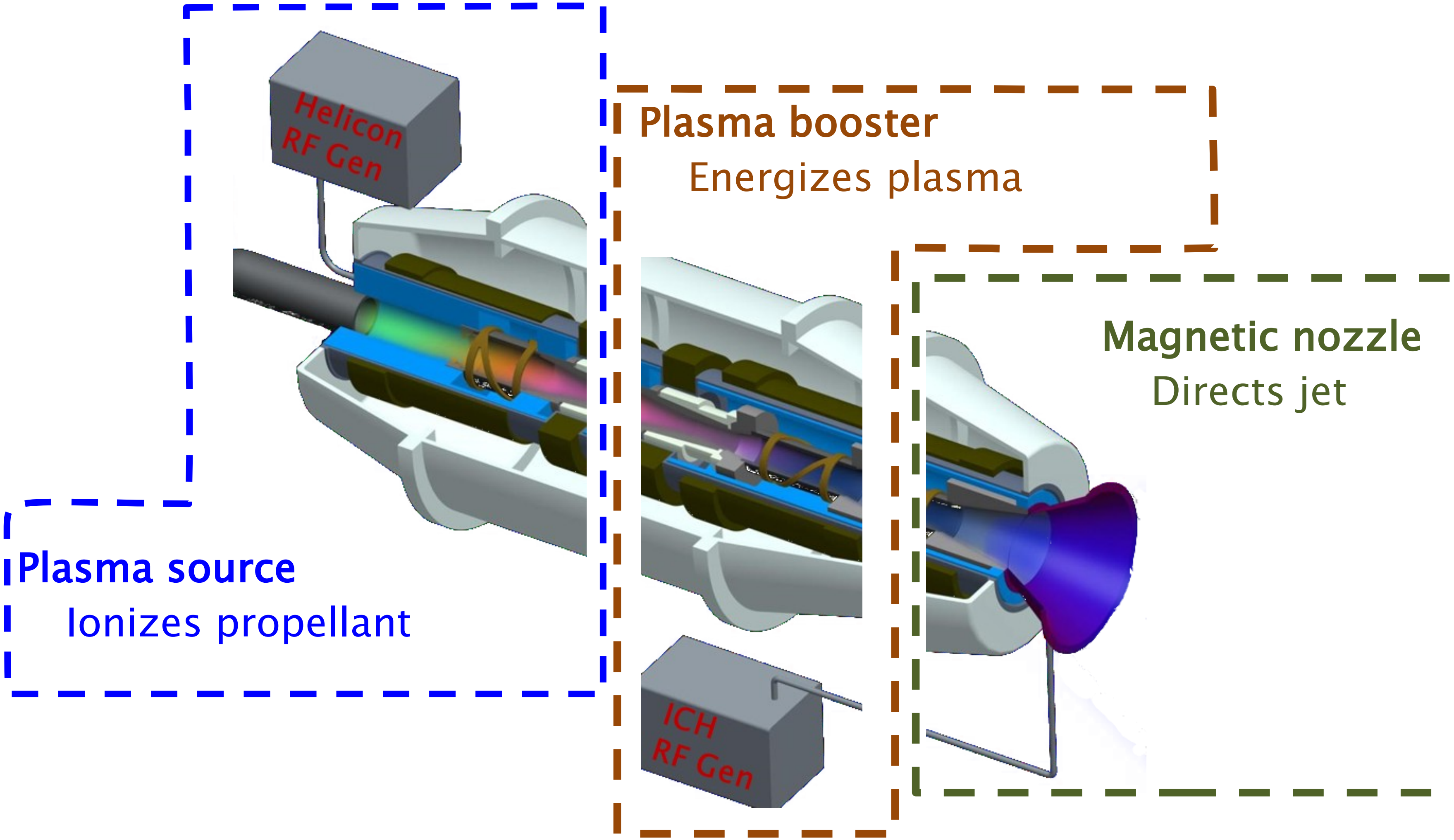


- Power level: 10s of kW to MWs per thruster w/out major tech changes
  - VASIMR® power density > 10x Hall
- Conversion efficiency >70%
  - Input power conversion to jet power
  - Design modeling verified by experiment (VX-200)
- Variable jet velocities at constant input power and efficiency
  - Exhaust velocity: ~15 km/s – 100 km/s depending on the propellant

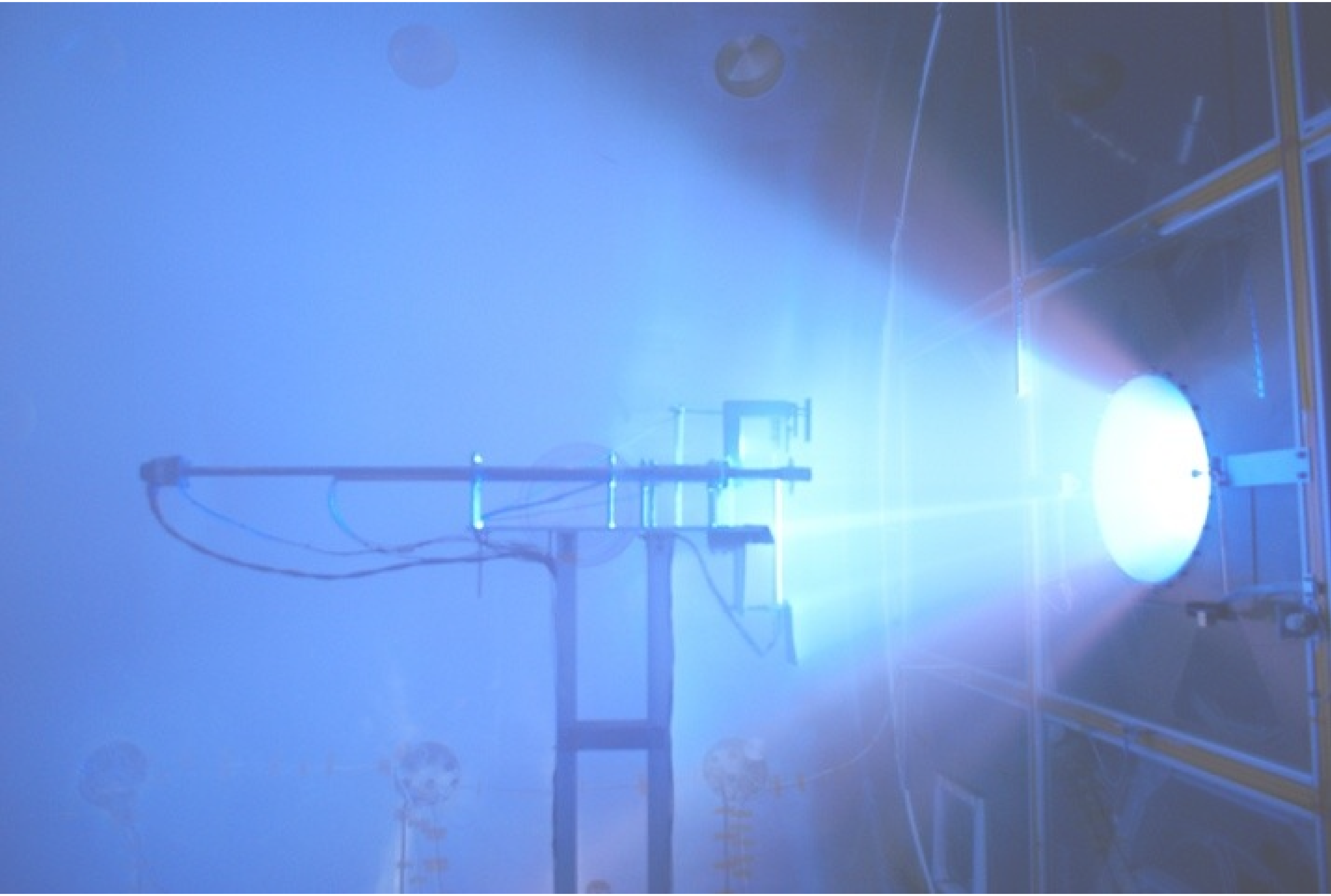
VASIMR® technology collaboration history

- Development (1979–present)
- Academia
  - (MIT, Princeton, UMD, UTexas, UMich)
- USA National laboratories
  - (ORNL, LANL)
- International labs
  - (Alfven, ANU, Japan), NASA
- Private industry

Major VASIMR® Elements

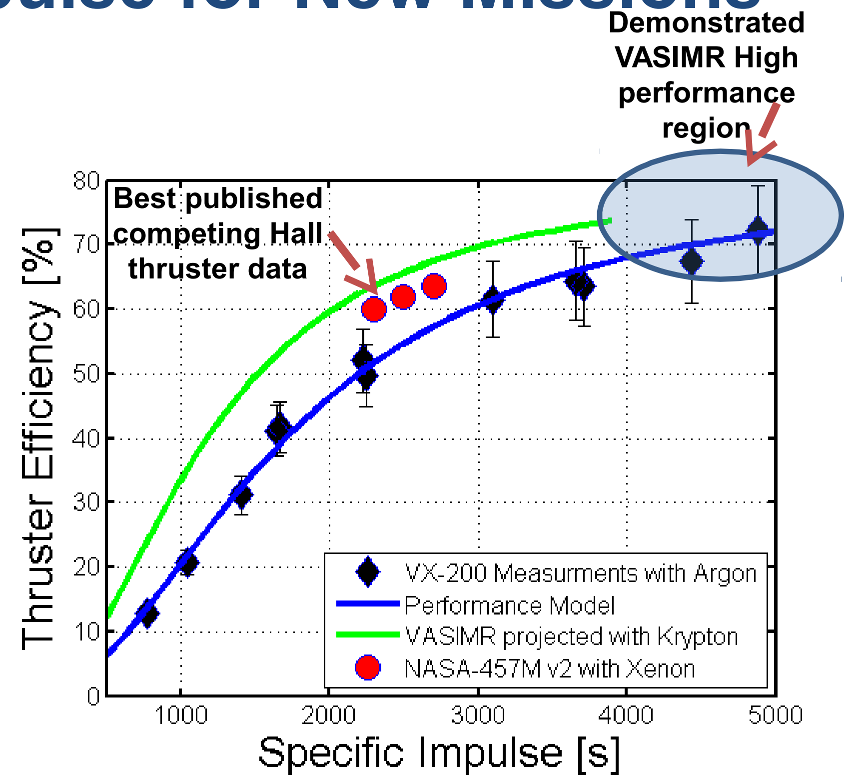


- Plus thermal control for all systems



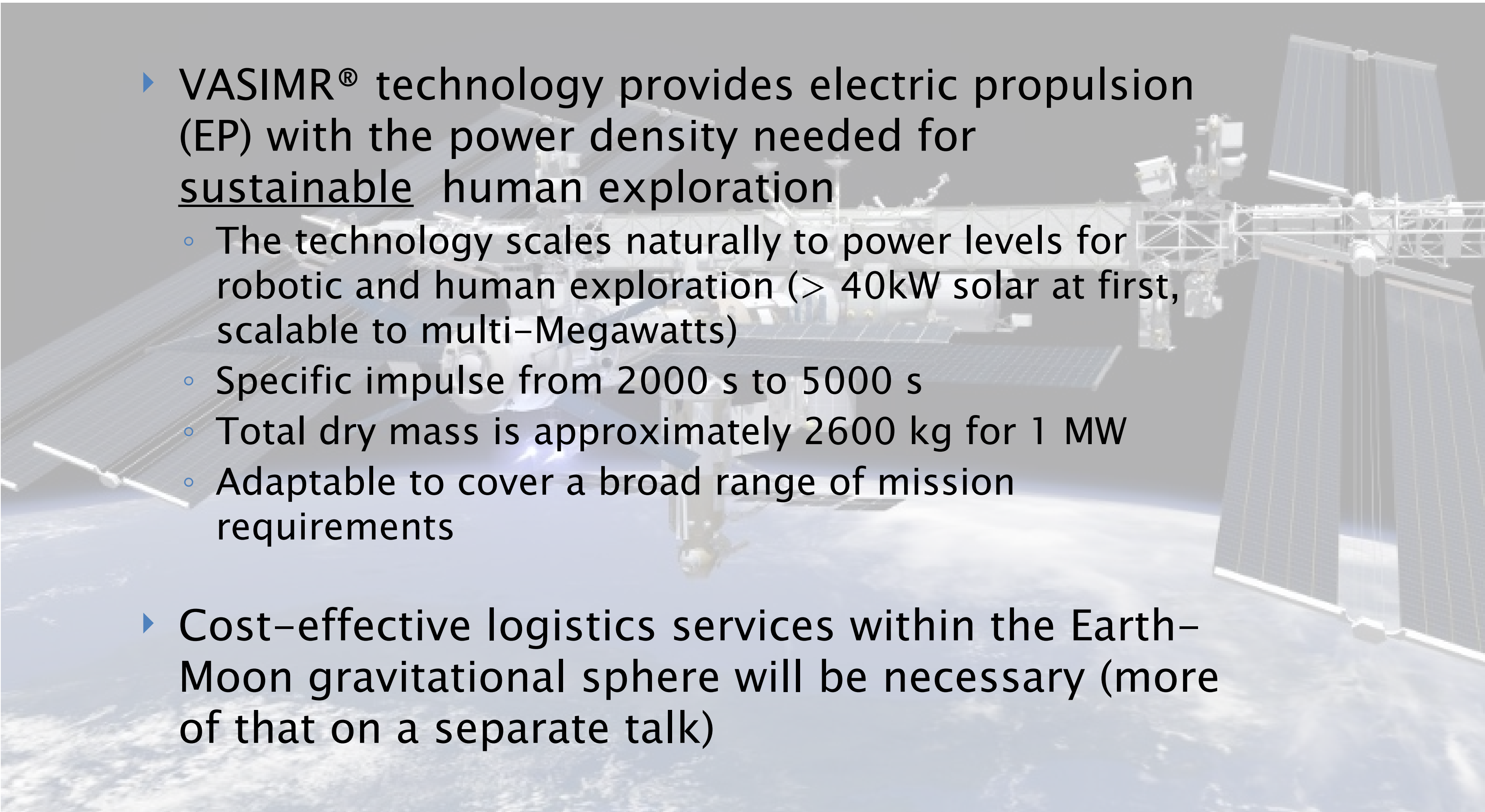
Measured VASIMR® Performance Offers a Wide Range of High Specific Impulse for New Missions

- No electrodes
  - High reliability and long life
- Variable specific impulse
  - Constant power throttling
  - Adapts to mission/ops requirements
- Measured performance in VX-200
  - 200 kW, 5000 s Isp, 72% efficiency
  - VX-200 has completed >10,000 high power firings



VX-200 laboratory testing

Human Exploration

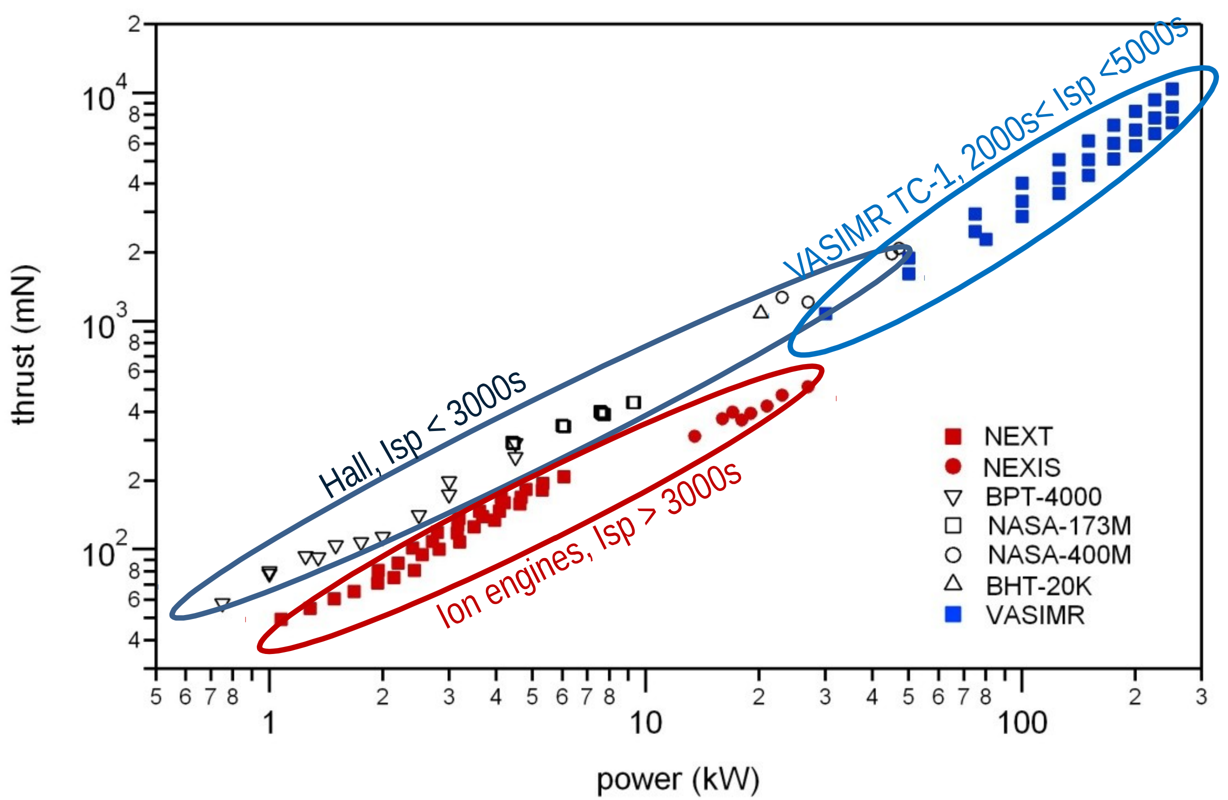


- VASIMR® technology provides electric propulsion (EP) with the power density needed for sustainable human exploration
  - The technology scales naturally to power levels for robotic and human exploration (> 40kW solar at first, scalable to multi-Megawatts)
  - Specific impulse from 2000 s to 5000 s
  - Total dry mass is approximately 2600 kg for 1 MW
  - Adaptable to cover a broad range of mission requirements

- Cost-effective logistics services within the Earth-Moon gravitational sphere will be necessary (more of that on a separate talk)

VASIMR® occupies the high power niche needed for sustained human exploration

- Scalable to multi MW power levels
- High power density (6 MW/m^2)
- Solar electric (near term and cargo)
- Nuclear electric (future)

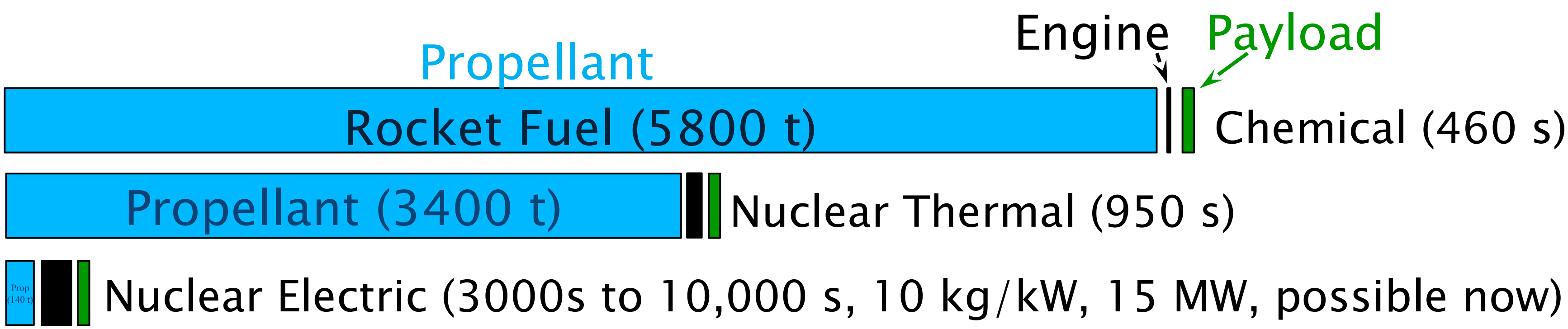


Sustainable 1 Year Human Round Trips to Mars

DRA 5.0 is a good start for basic requirements

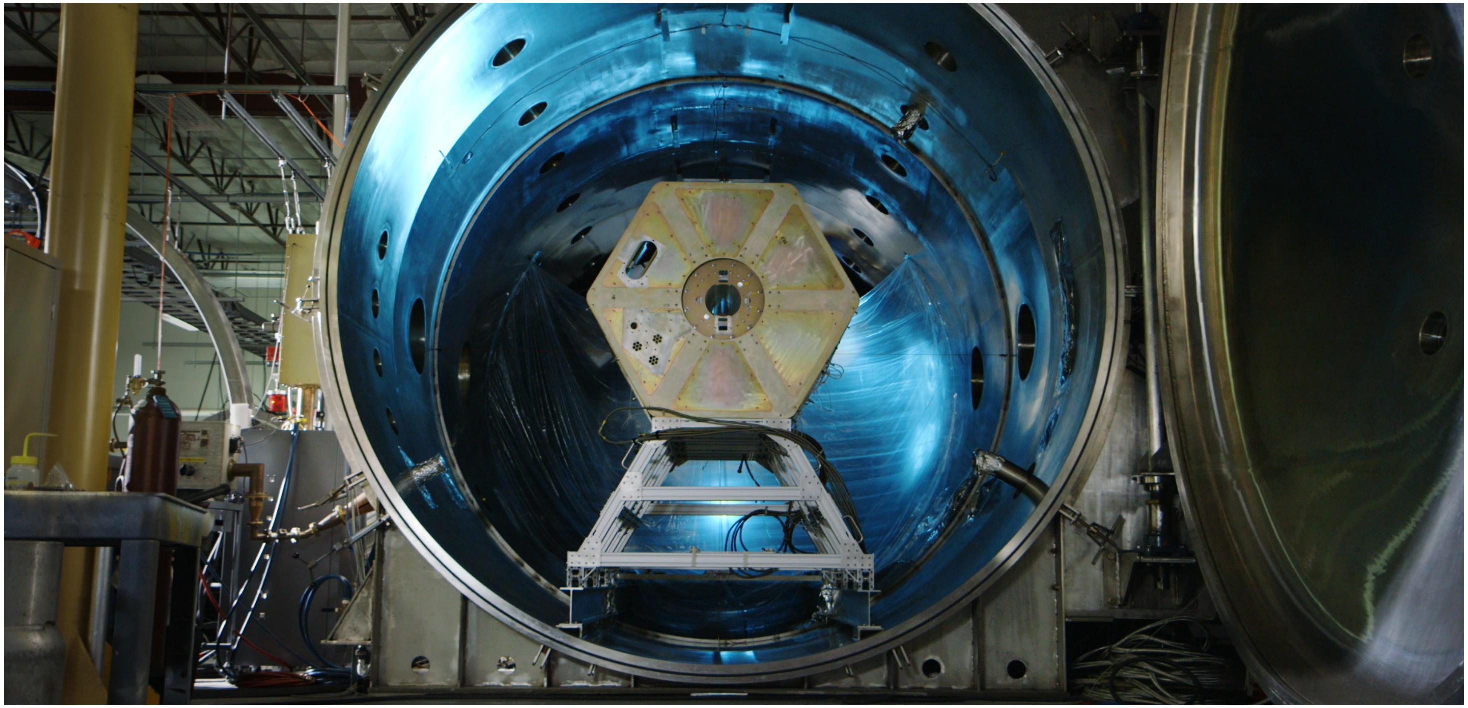
- The human habitat must allow good health and strength for surface work on arrival: 62,000 kg per DRA 5.0
- Add the capability to return the crew to Earth within 1 year
- Helio transfers must be fast enough to allow at least 30 days on the surface

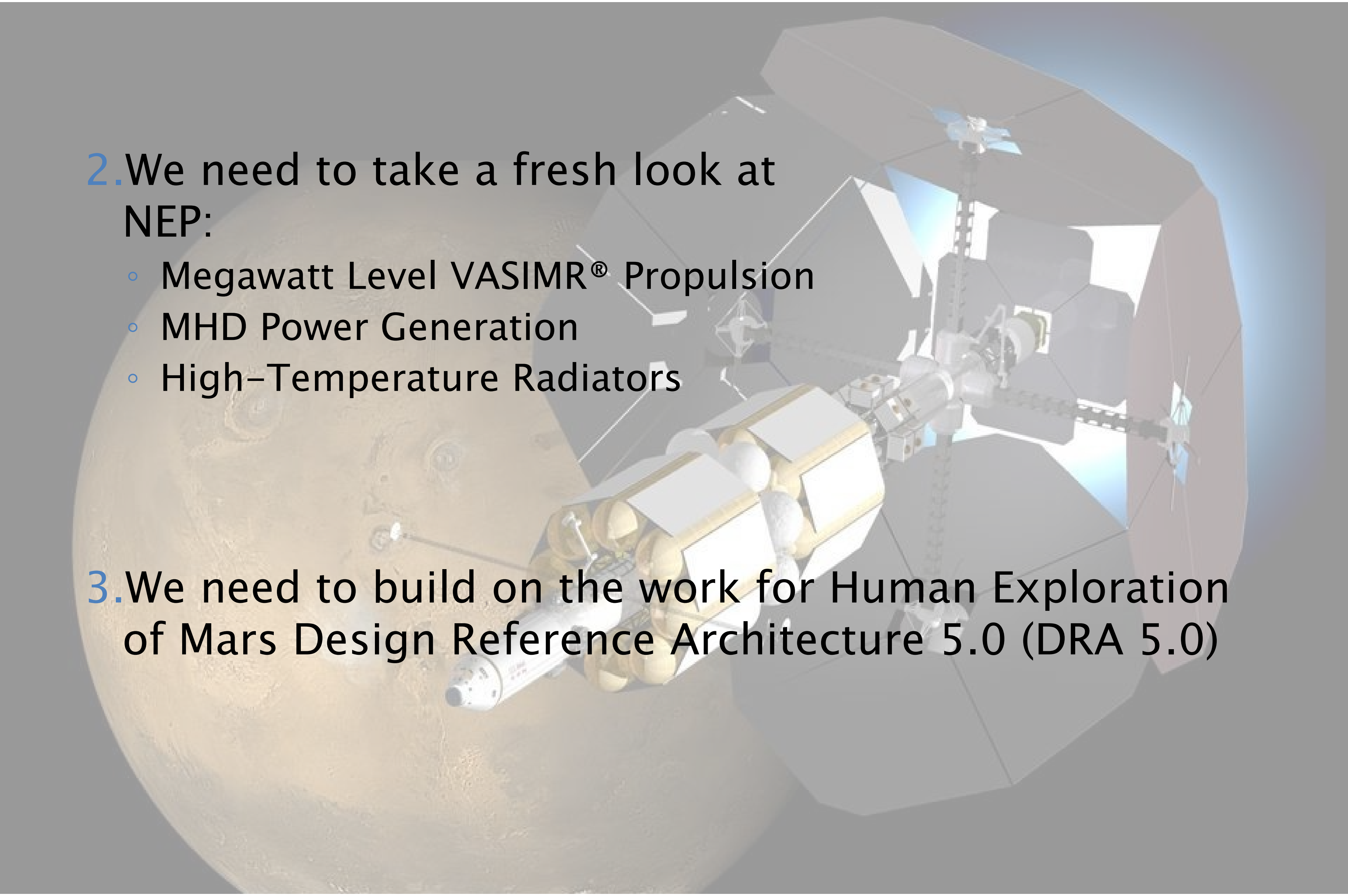
Propellant requirements practically eliminate all options except for nuclear electric



Recently Developed Technologies Enable Exciting New Mission Scenarios to Mars

1. Technology advances outside traditional aerospace
   - High Temperature Superconducting (HTS) cryogen-free magnets with light-weight Stirling cryo-coolers
   - Efficient High-power Electronic Devices
   - High Performance Ceramic Manufacturing



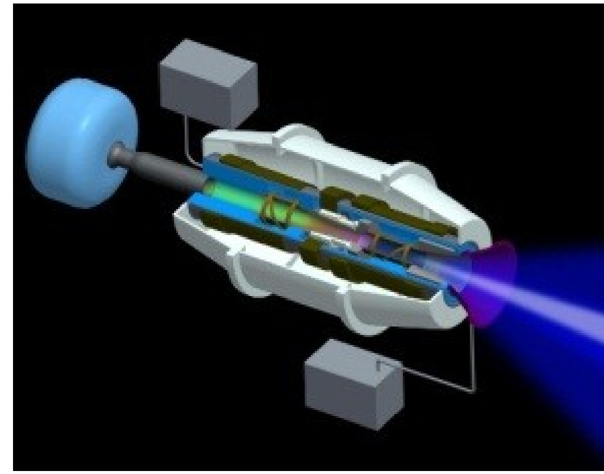


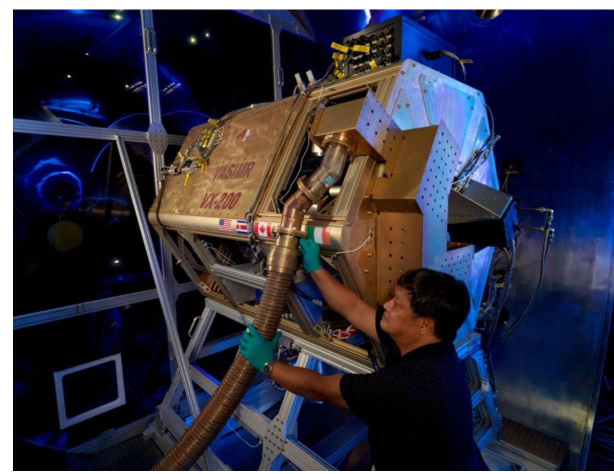
2. We need to take a fresh look at NEP:
   - Megawatt Level VASIMR® Propulsion
   - MHD Power Generation
   - High-Temperature Radiators

3. We need to build on the work for Human Exploration of Mars Design Reference Architecture 5.0 (DRA 5.0)

4. NEP allows a dramatic reduction of risk and cost:

- Launch windows: months instead of days
- Fault tolerance to loss of power or loss of propellant
- Reduced dose from exposure to Galactic Cosmic Radiation (GCR) and solar storms with faster transit
- Enables a short-stay option with 1 year round trip in addition to a long-stay with 2.5 year round trip





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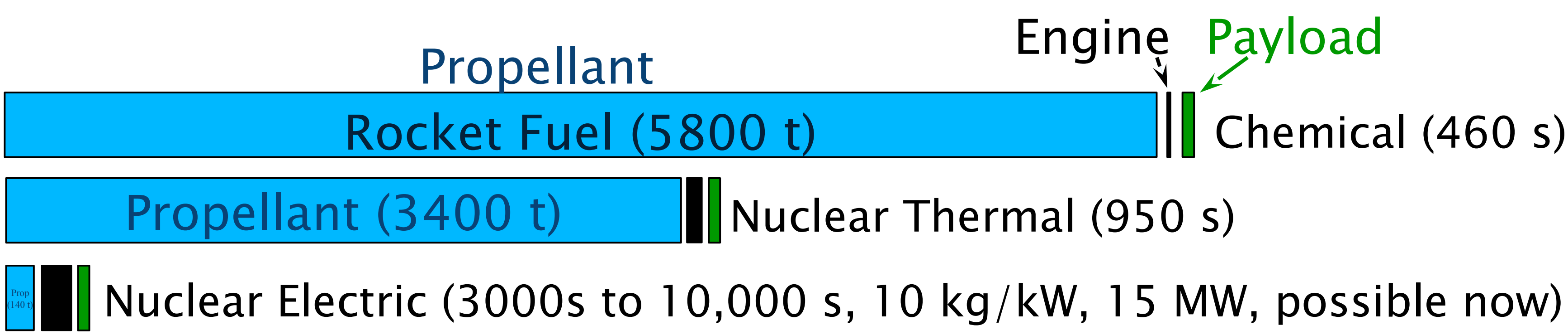


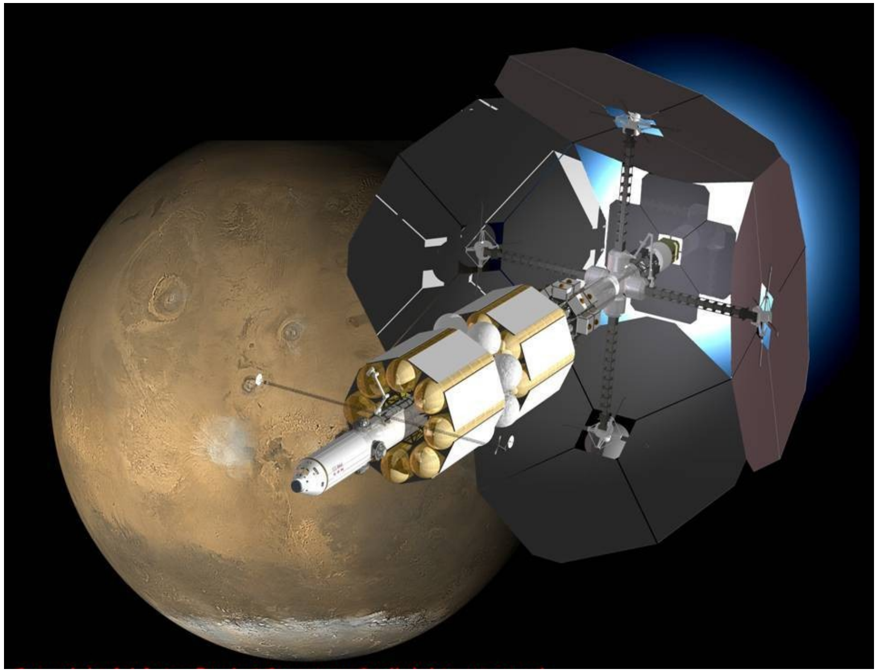
New Human Mission Scenarios from LEO to Mars

- Mission Requirements (DRA 5.0):
  - Departure: LEO (407 km)
  - IMLEO = 356.4 t
  - Payload 62 t

- NTR Mission (DRA 5.0, long stay):
  - Total mission: 914 days
  - In-flight time: 375 days (174+201)

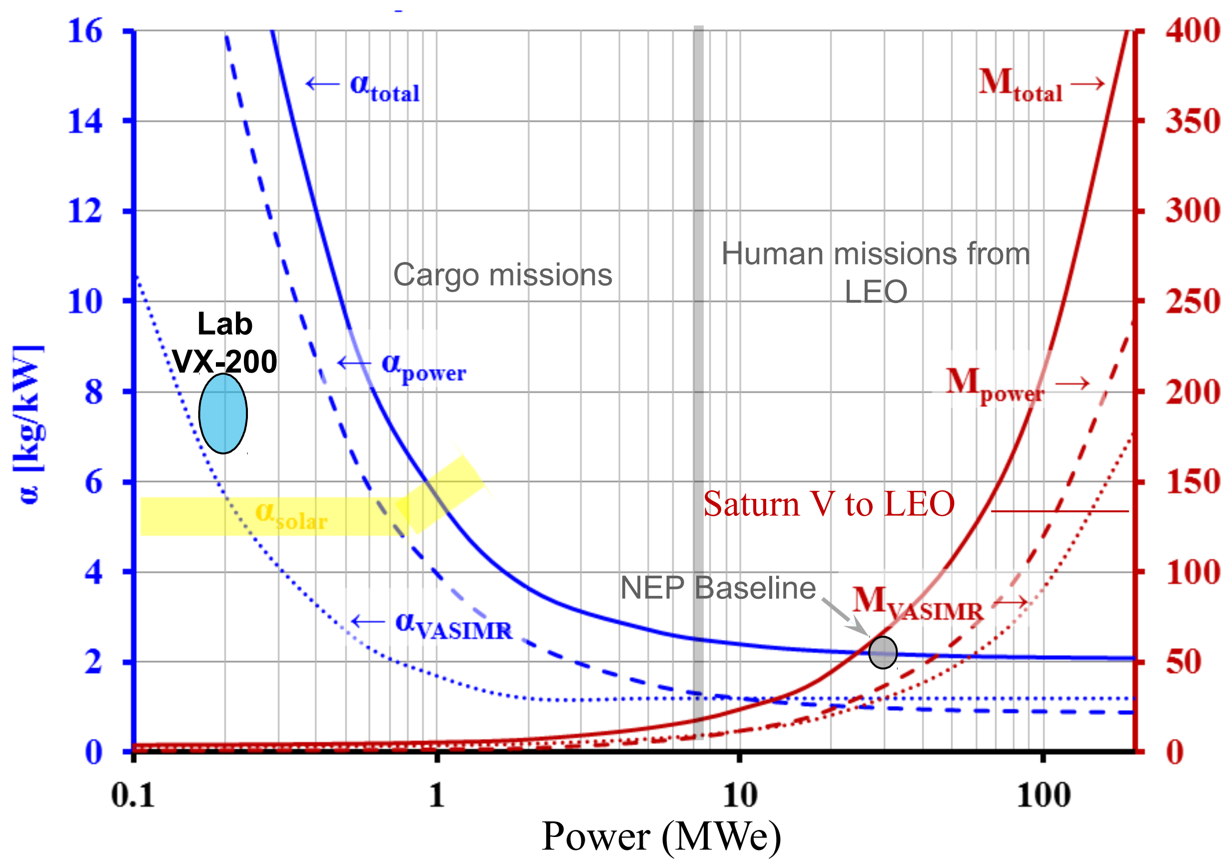
- NEP + VASIMR® (30 MW, 2 kg/kW):
  - Total mission: 867 days
  - In-flight: 149 days (76+73)

- NEP + VASIMR® short stay option:
  - Total mission: 365 days
  - In-flight: 306 days (85+221)

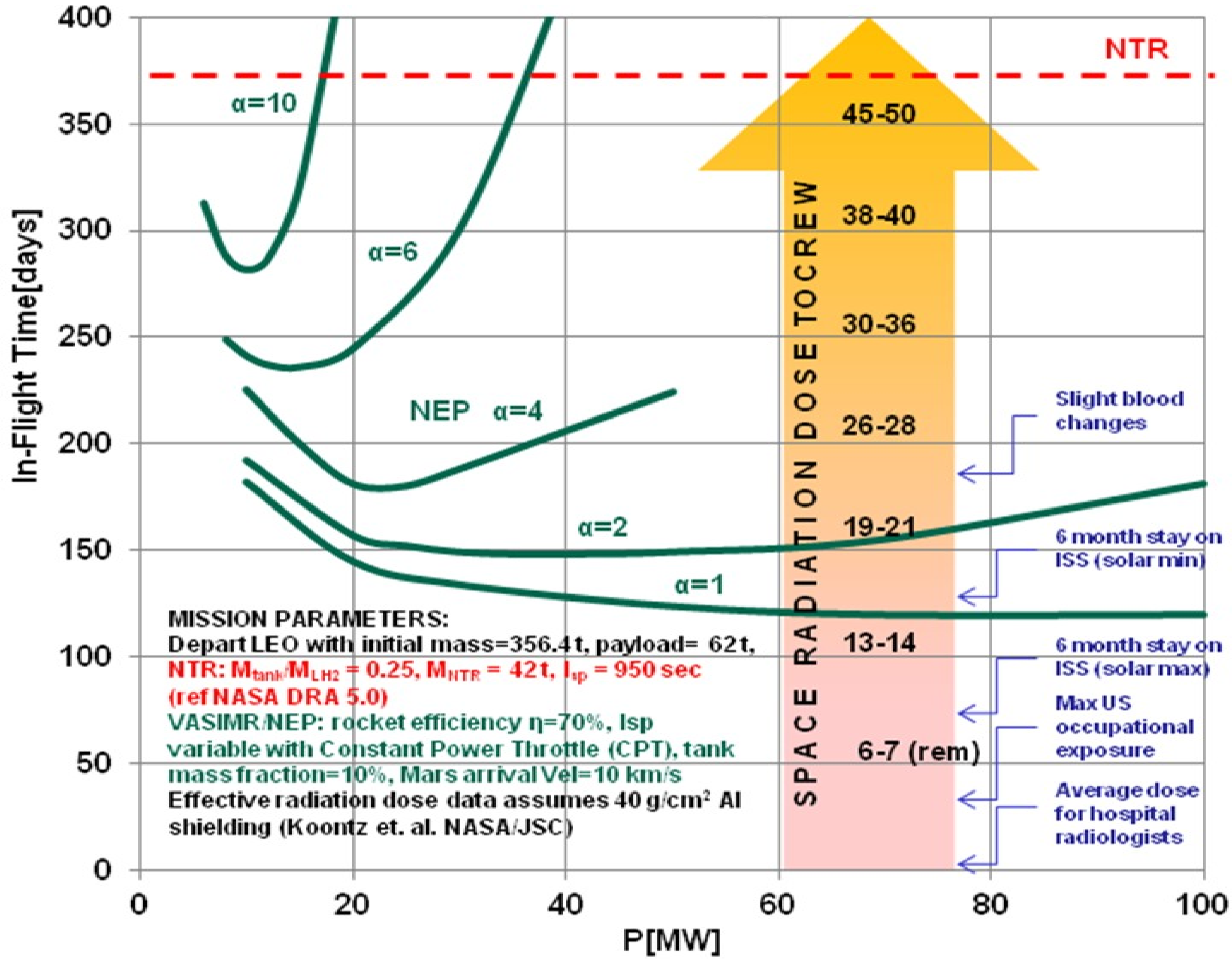


NEP + VASIMR® Specific Mass Scaling

- Human missions: 5 to 10 MWe is the minimum power needed for flight times < 1 year starting from LEO
- Specific mass and power were also studied over a wide range away from baseline

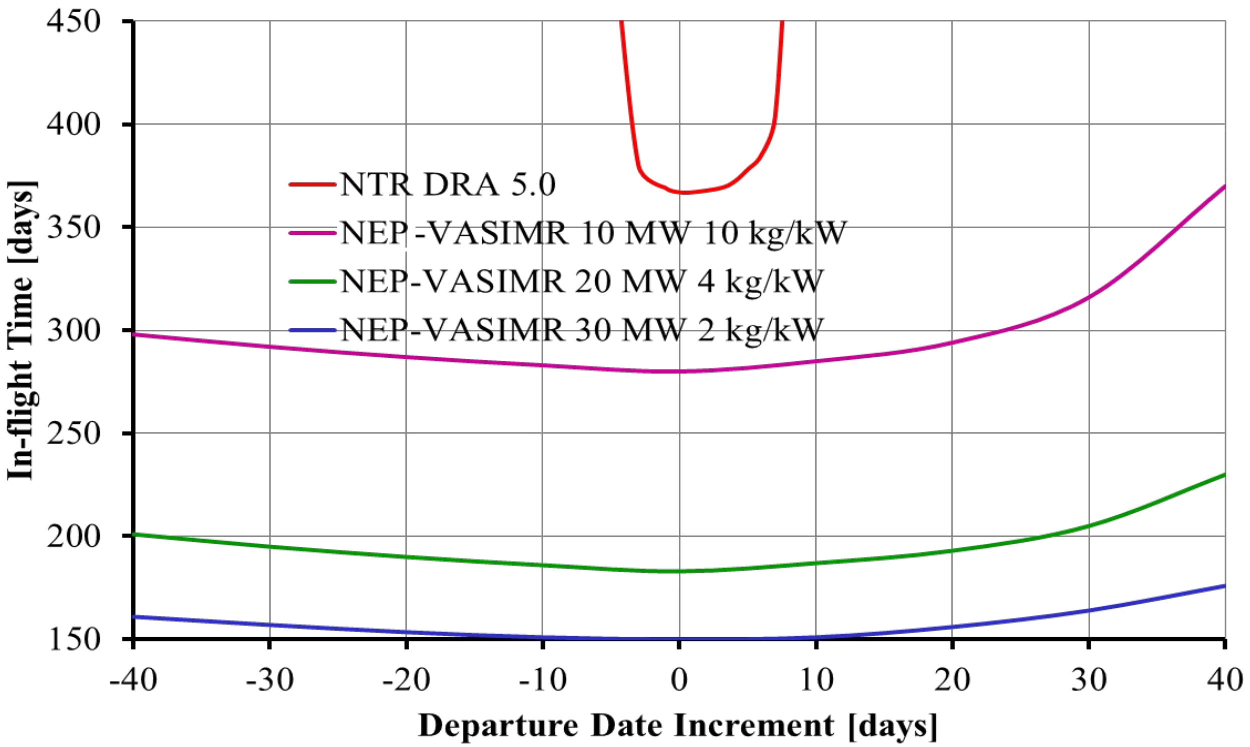


Radiation Dose is Significantly Reduced using NEP + VASIMR® instead of NTR



NEP + VASIMR® Technology Provides a Wide and Robust Departure Window

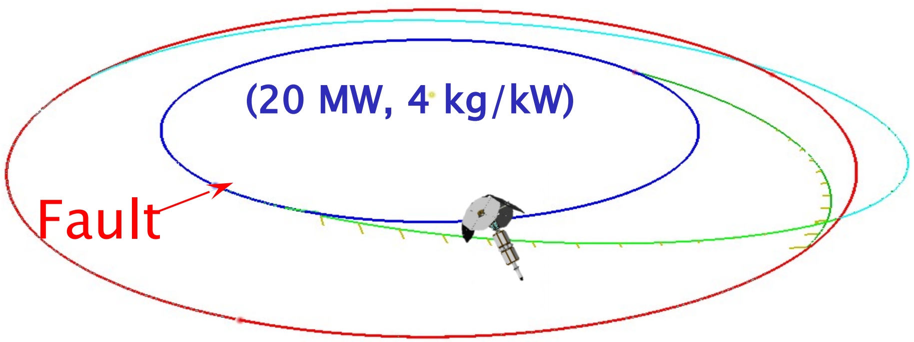
- Missing the launch window requires waiting more than 2 years
- NEP + VASIMR® missions have long launch windows of several months.
- Logistics are greatly simplified!



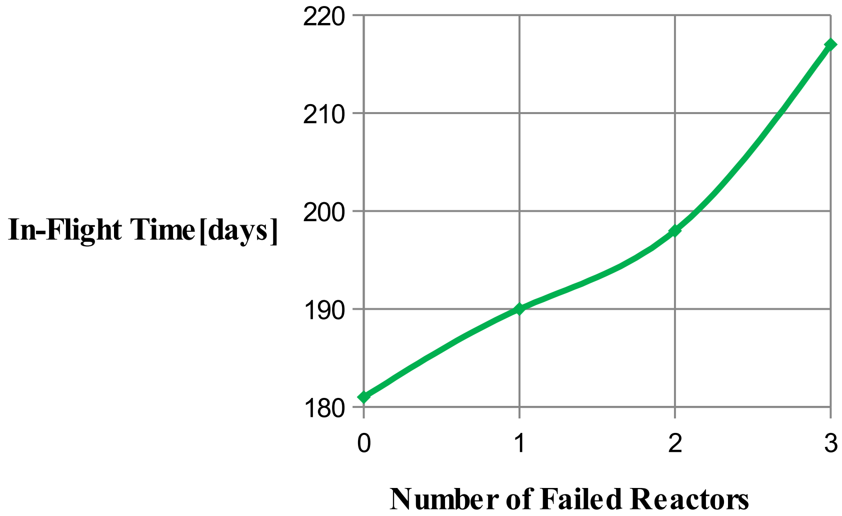
The DRA 5.0 mission launch window is less than 2 weeks!

NEP + VASIMR® is fault tolerant because of Variable Specific Impulse

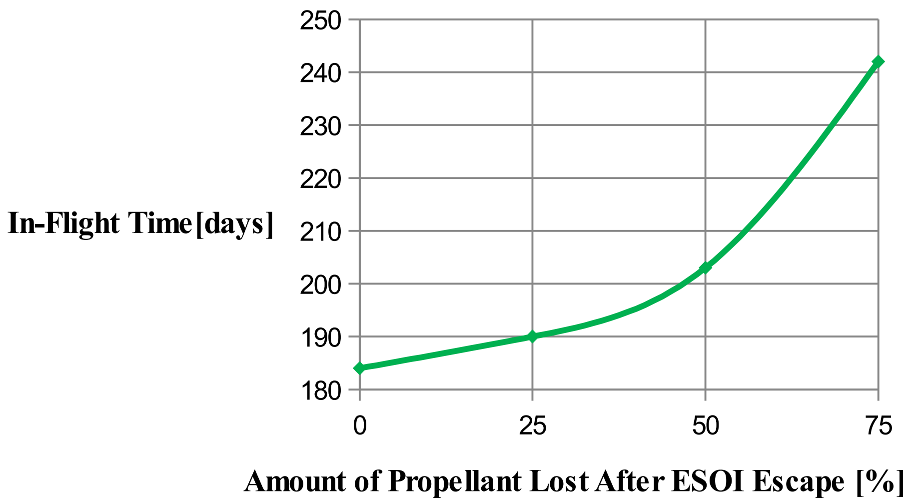
- NEP missions can continue with up to 75% power failure after ESOI escape
- NEP mission can continue after a loss of up to 75% of propellant after ESOI escape



Power Failure and ejection of 3 (out of 4) reactors at ESOI



Propellant loss at ESOI



Jose Antonio Castro-Nieto, PhD.

Chief Scientist

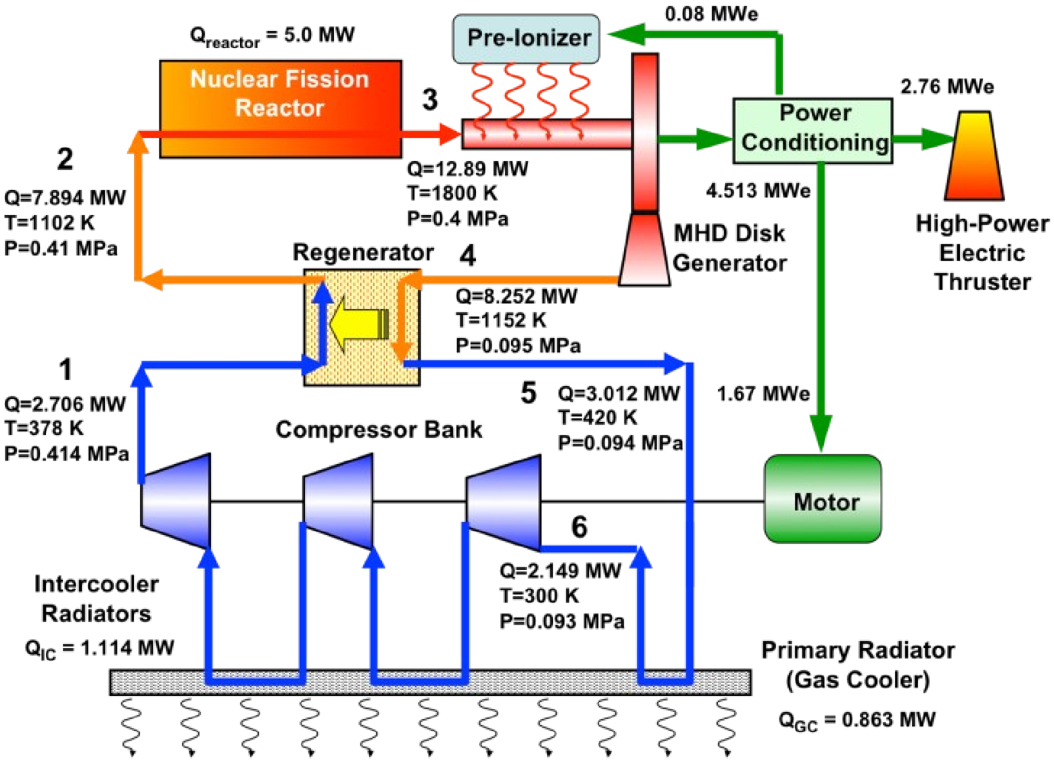
jose.castronieto@adastrarocket.com

Ad Astra Rocket Company™

More Information

Thermodynamic Considerations for Mass Scaling are Included in Mission Scenarios

MHD Thermodynamics and Mass Scaling:



High Temperature Radiators Reject Waste Heat for both VASIMR® and MHD

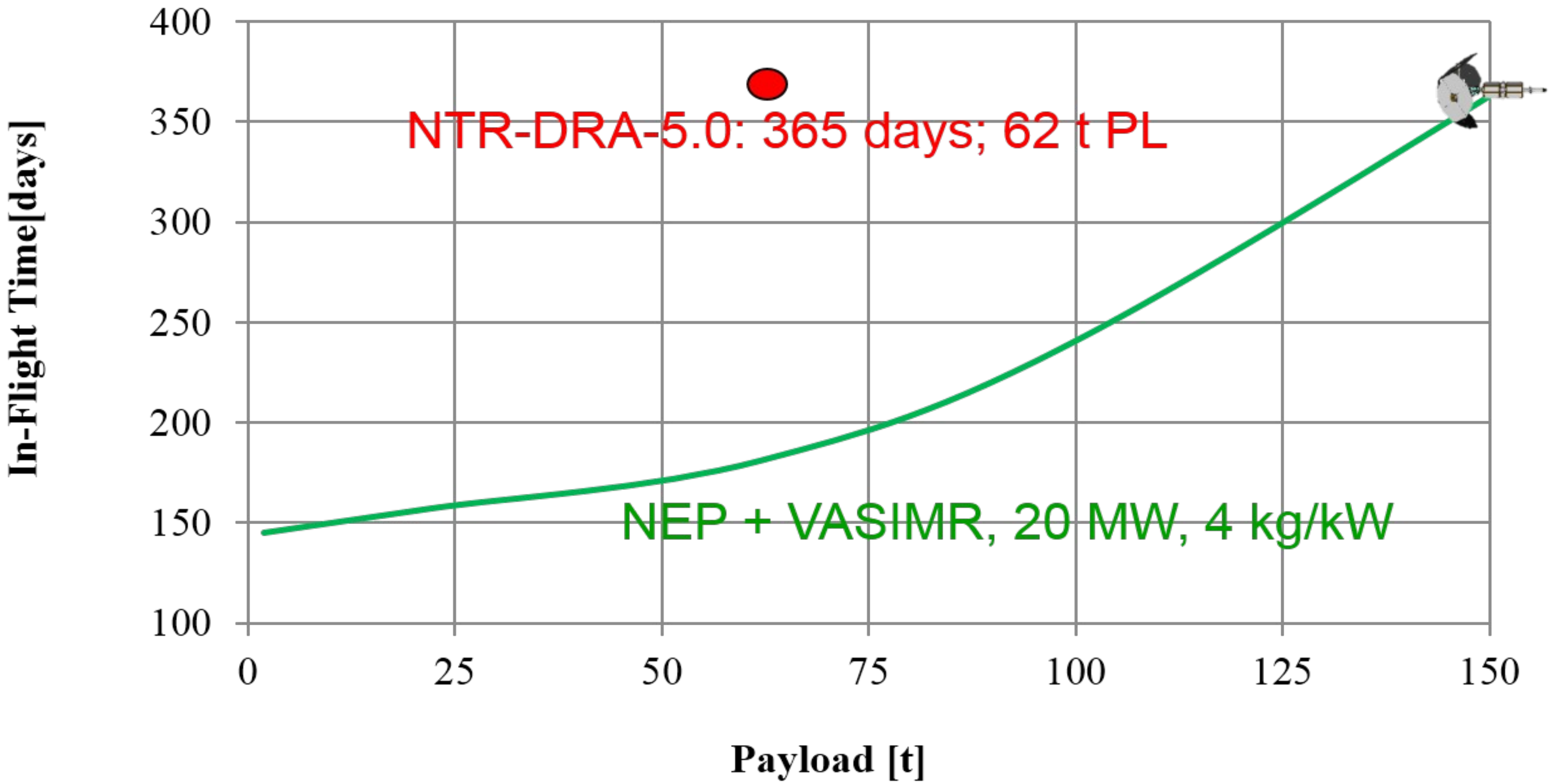
- Radiator mass reduction for space drives the design to high temperatures (Stefan-Boltzmann law)
- High thermodynamic efficiency requires large ΔT
- Materials limit the maximum temperature
- Surface density can approach 1 kg/m2 and specific mass below 0.2 kg/kW at 300 C

“Multi-MW Closed Cycle MHD Nuclear Space Power Via Nonequilibrium He/Xe Working Plasma” by Ron J. Litchford and Nobuhiro Harada (NETS-2011)

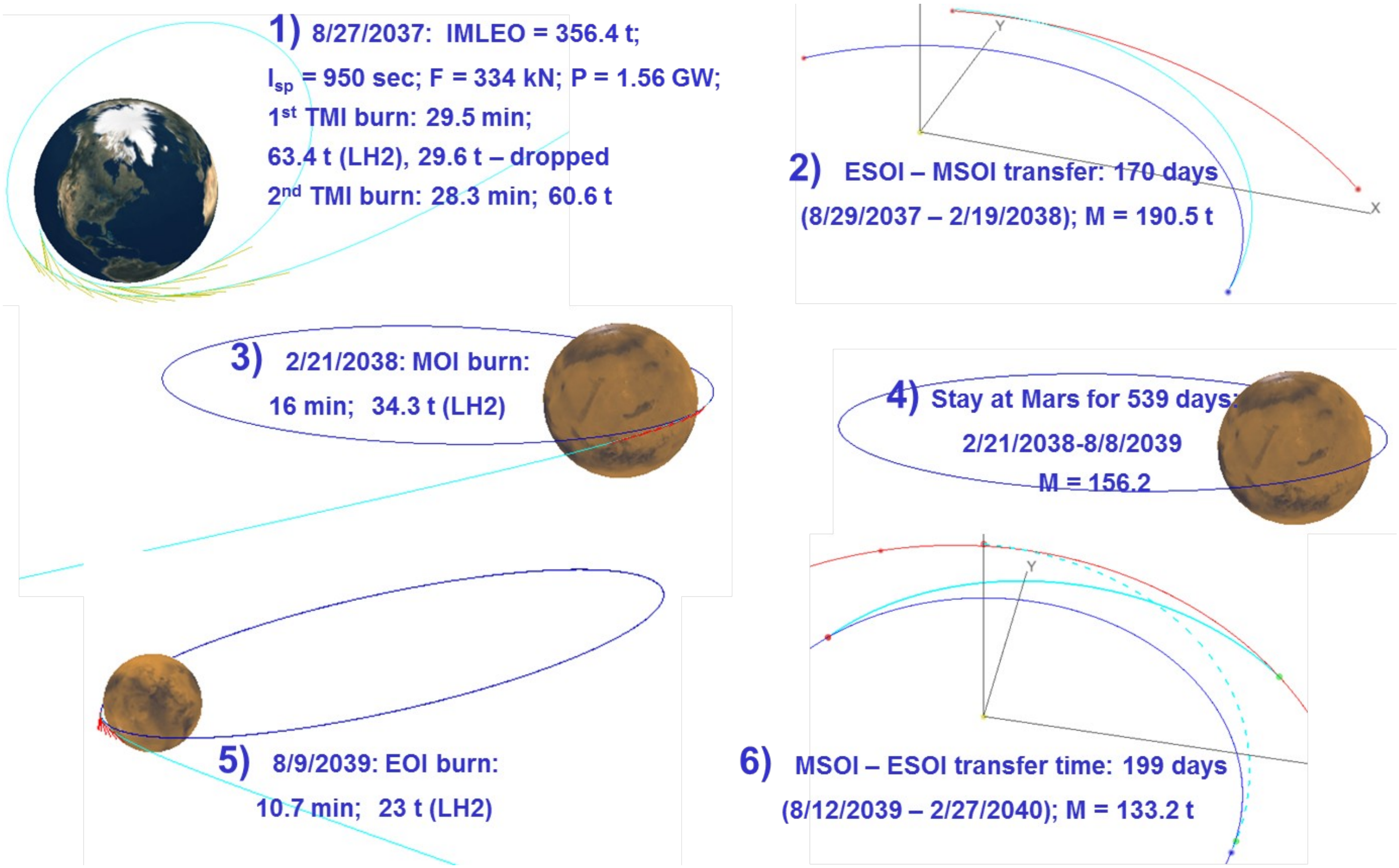
Cargo Support is Critical for Mars Exploration

The NEP + VASIMR® architecture can deliver more shielding for human missions and/or more cargo than the NTR-DRA-5.0 mission

- Twice the payload to Mars per launch greatly reduces the cost
- Simplified logistics with wide launch window reduce risk and cost



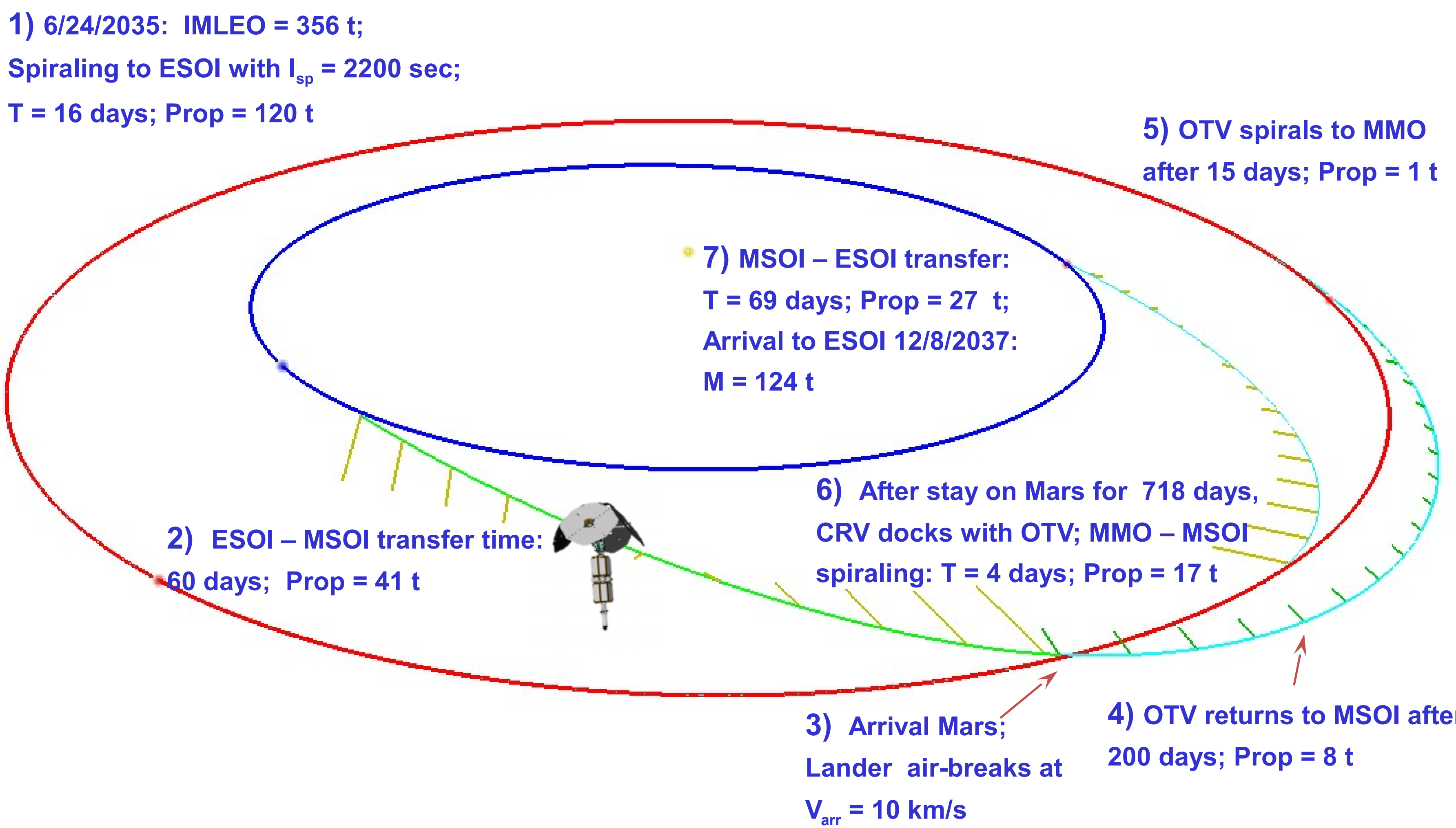
NTR LEO-Mars Human Mission per DRA 5.0



In-flight time: 369 days

Stay on Mars: 539 days

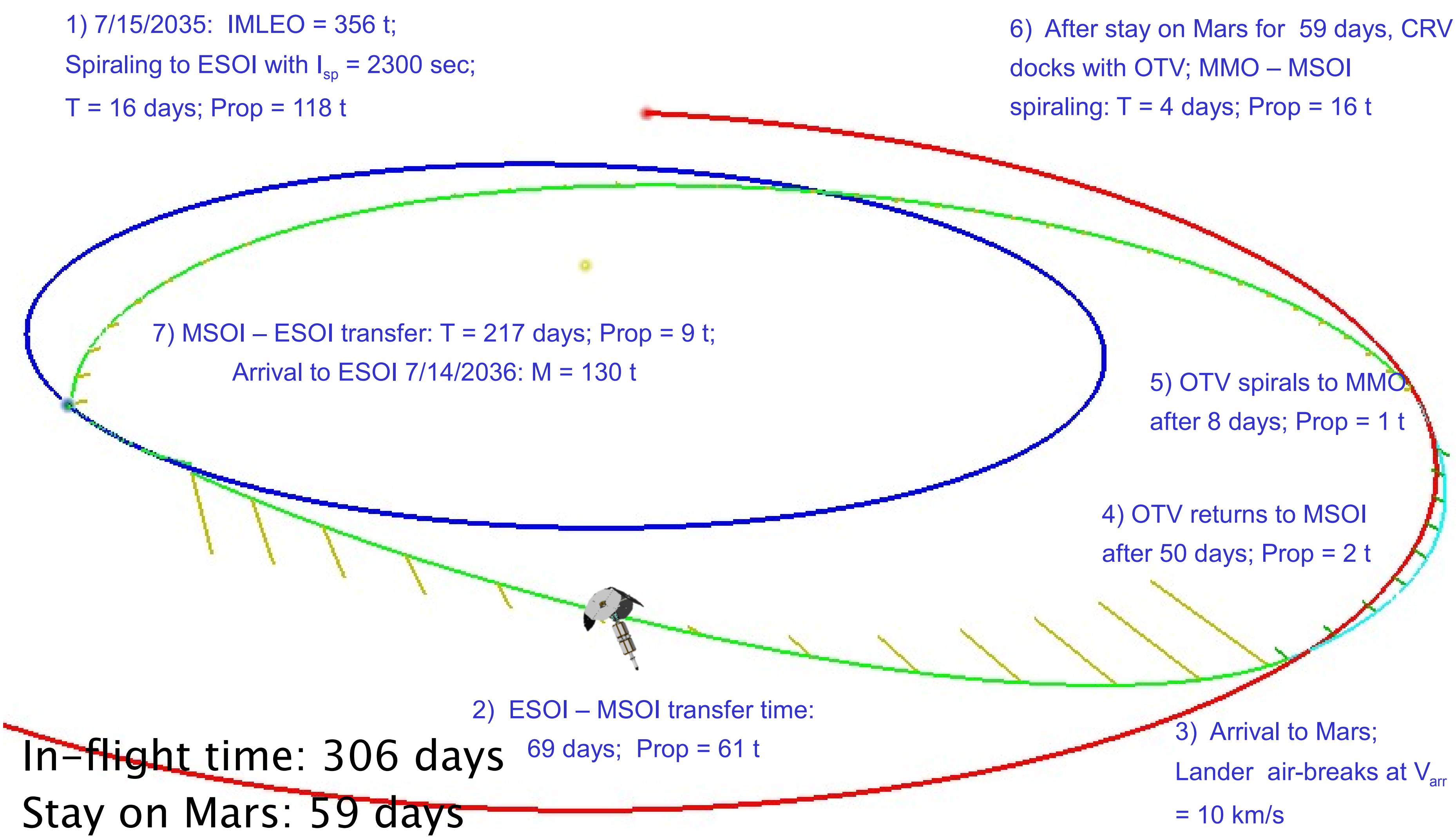
VASIMR® LEO-Mars Human Mission



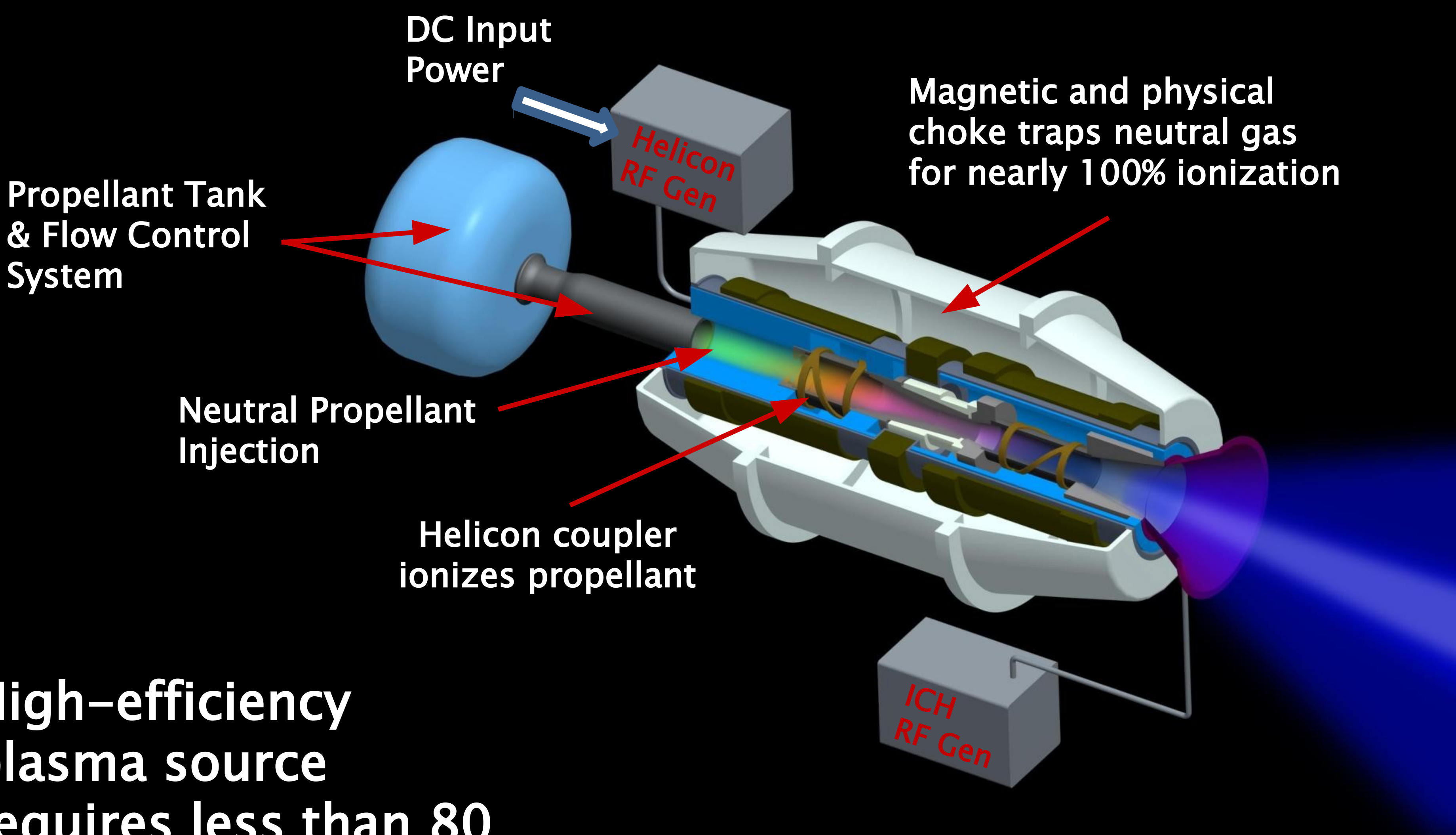
In-flight time: 145 days

Stay on Mars: 718 days

VASIMR® LEO-Mars Human Mission (short stay)

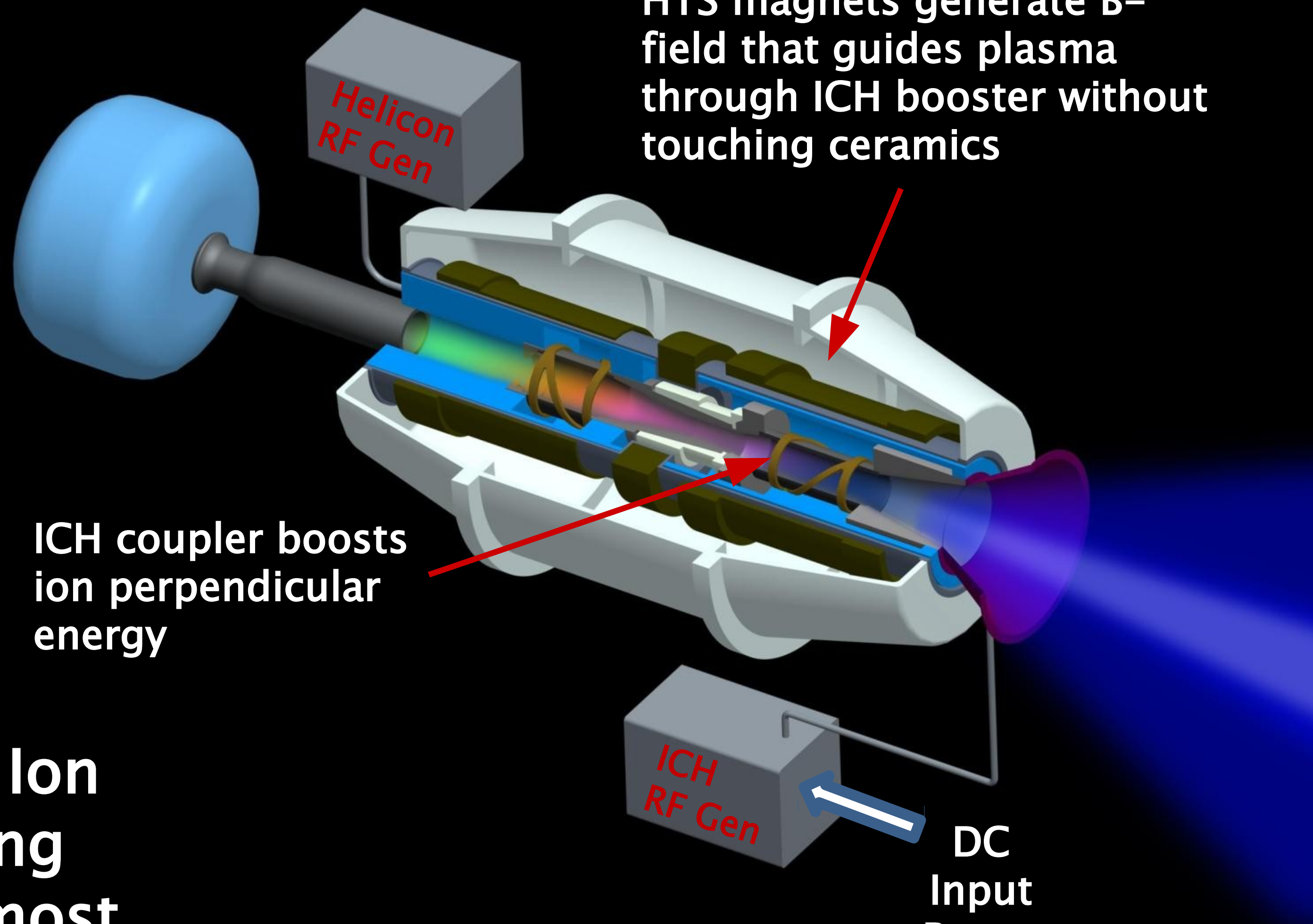


VASIMR® Plasma Source



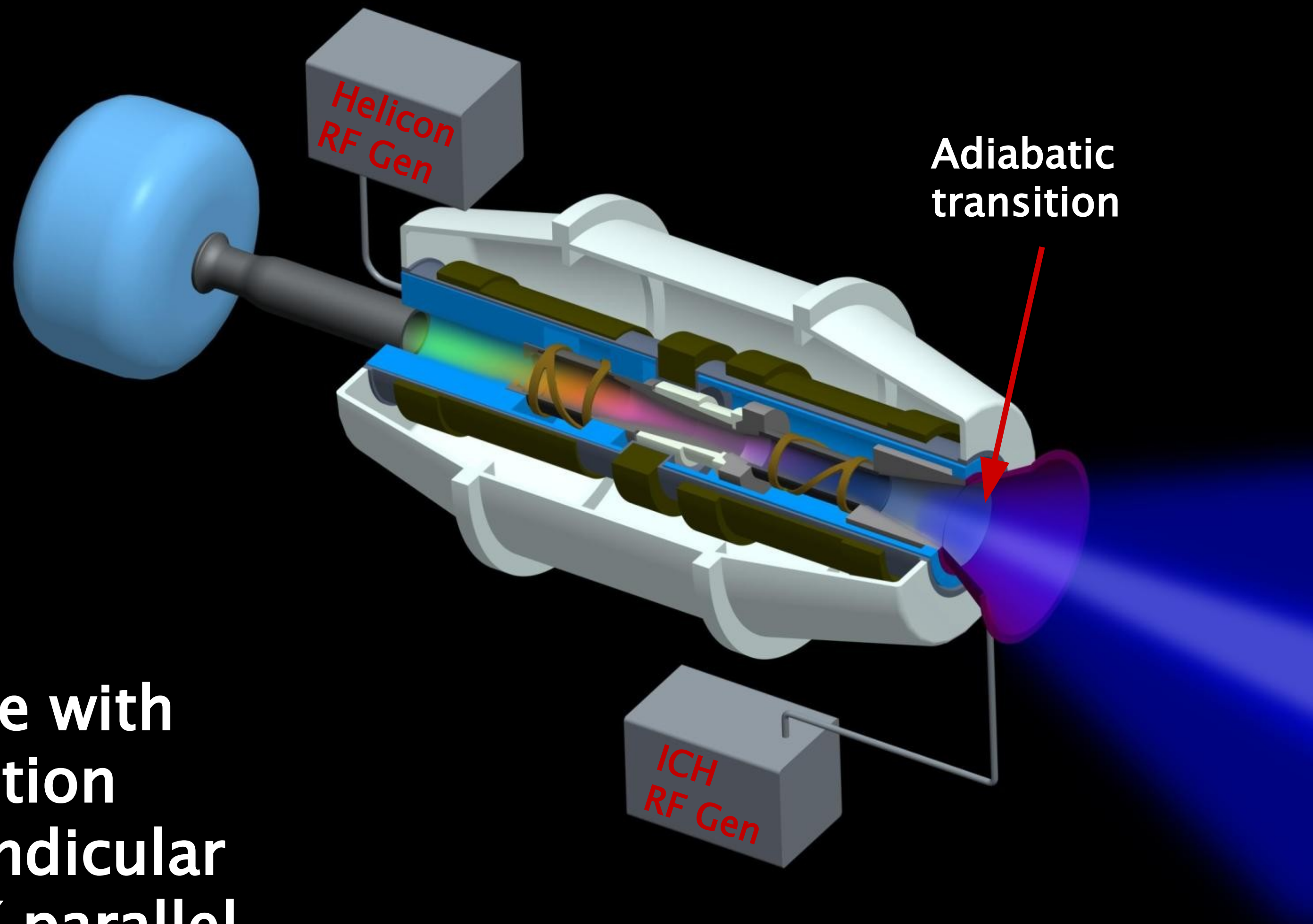
High-efficiency plasma source requires less than 80 eV per ion extracted

VASIMR® Plasma Booster



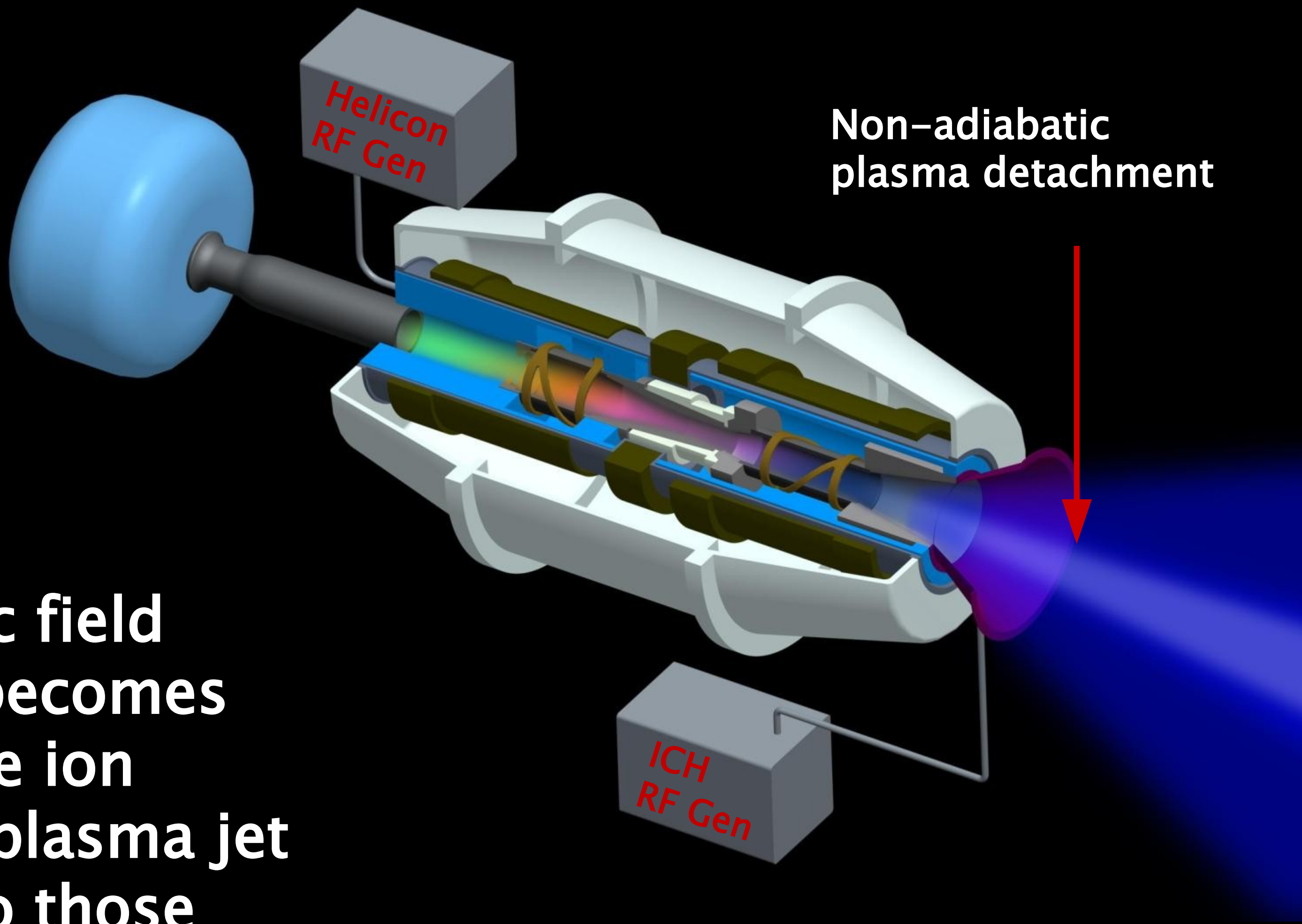
High-efficiency Ion Cyclotron Heating (ICH) provides most of the jet power

VASIMR® Magnetic Nozzle



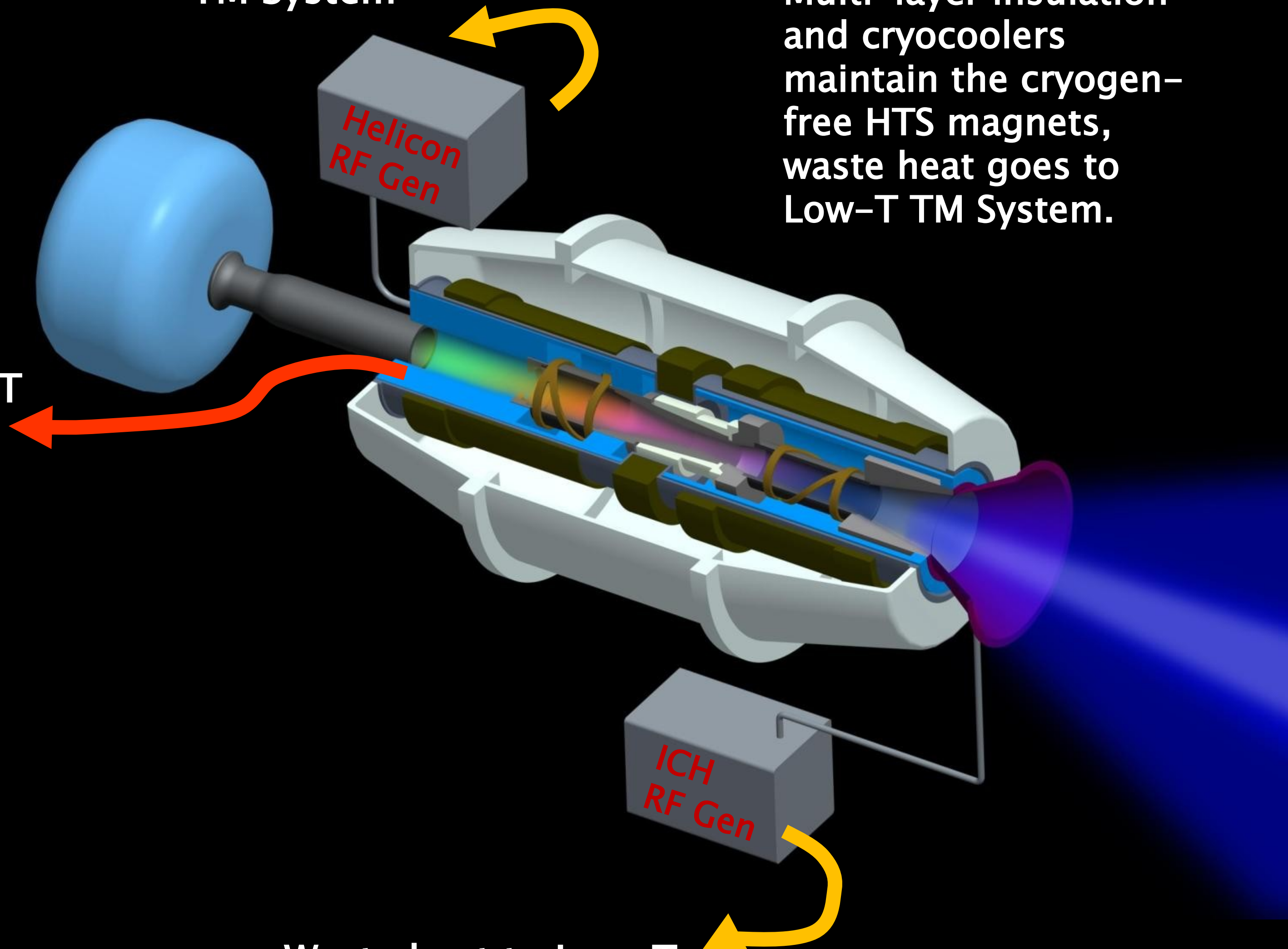
Magnetic nozzle with adiabatic transition converts perpendicular energy to ~90% parallel flowing plasma jet

VASIMR® Plasma Detachment



Where magnetic field line curvature becomes smaller than the ion gyro-radius, a plasma jet forms similar to those observed in astrophysics

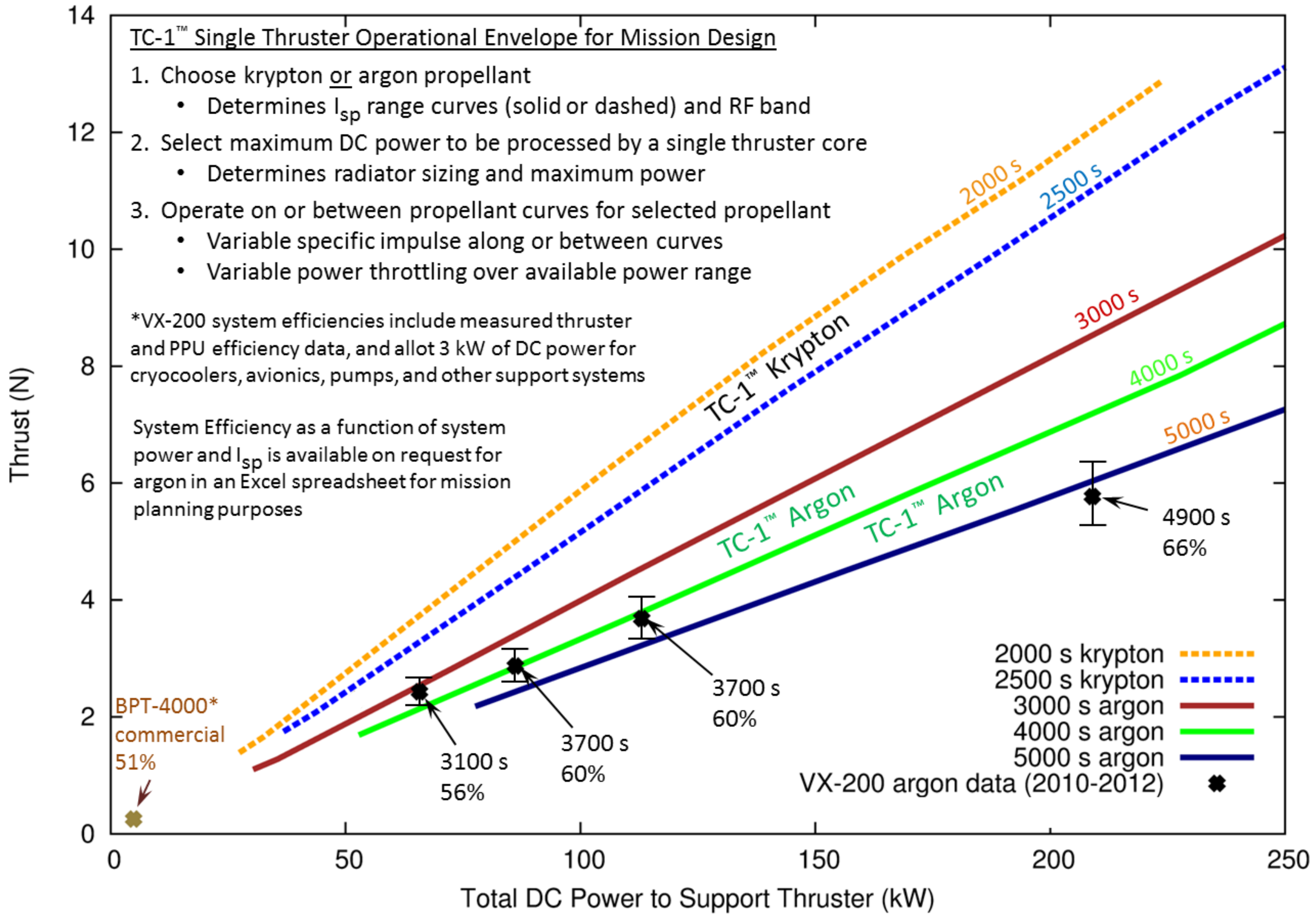
VASIMR® Thermal Control



Active thermal management rejects waste heat (~20% of input power)

*Thermal Management (TM)

VASIMR® TC-1™ Single Thruster Core Ops Envelope



Unique features of VASIMR® technology

- ***Very high power density*** (~6 MW/m^2) compared with DC discharges by coupling RF power through ceramic windows to excite naturally occurring plasma waves
- ***No DC bias is applied***, no cathodes or anodes are needed!
- ***Plasma facing materials are well insulated by strong magnetic fields*** with field strength of a few tesla
- ***Specific impulse can be varied at constant power*** by adjusting the balance between the plasma source and the ion cyclotron heating (ICH) booster sections
- ***Wide range of operating power*** supported without loss of efficiency
- ***Very efficient conversion of input power to jet power*** (75% thruster efficiency, >65% system efficiency) allows more thrust and less propellant usage than Hall thrusters for a given solar electric power plant
- ***Wide range of propellant choices*** including xenon, krypton, argon, and neon. May also be adaptable to solids or liquids (ammonia, iodine, potassium, rubidium, etc.) if condensates do not pose a risk to the spacecraft.

VASIMR® and Hall power technologies are very different

Subsystem	VASIMR®	Hall
Solar Power Processing	• Simple MOSFET radio* • Isolated resonant LC circuits	• Complex DC-to-DC • Large fluctuations
Power Coupling	• Natural RF plasma waves • **NO** DC BIAS so **NO** NEUTRALIZATION REQUIRED • Active RF components isolated from the plasma †	• DC biased electrodes • NEUTRALIZATION **IS** REQUIRED • Active cathode and anode cannot be isolated from plasma
Plasma source	• Independent "FM" radio	• Coupled DC bias
Plasma acceleration	• Independent "AM" radio	

*Up to megawatts of power for VASIMR® alread available due to commercial broadcast market and chip manufacturing advances.

† Vacuum isolation of active components allows much higher exhaust pressures to be tolerated during high power testing when compared with Hall thrusters.

VASIMR® subsystem coupling is simpler than Hall

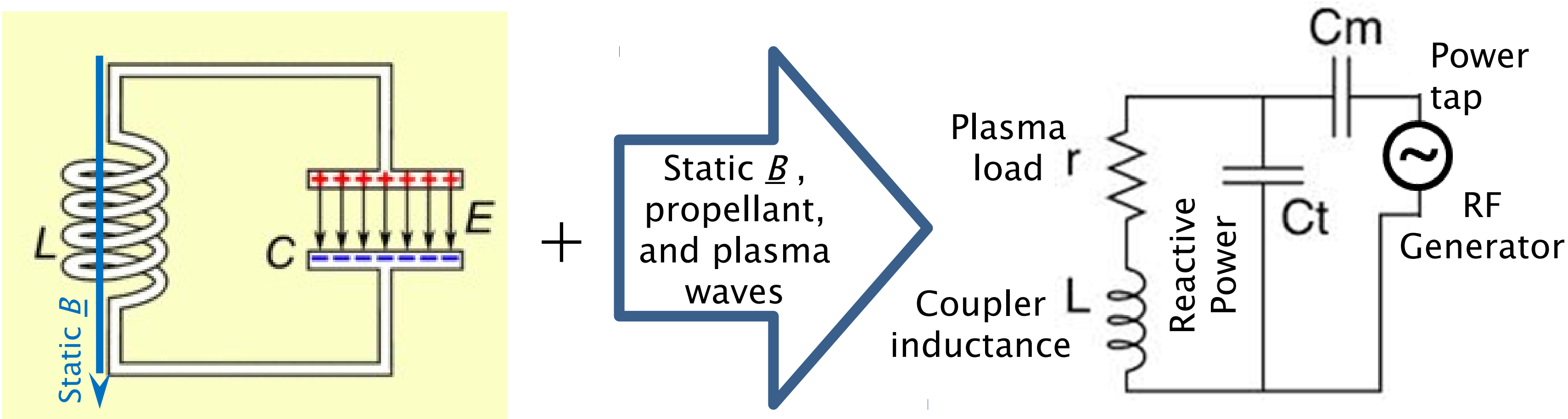
Subsystem	VASIMR®	Hall
Gas Injection	• Single port injection • Simple flow control	• Separate injection for anode and cathode • Complex feedback required for flow control
Magnets	• Superconducting for high field with minimal power • Well isolated from plasma • Alignment with flow inherently provides surface protection	• Conventional, limits field • Close proximity to plasma • Alignment perpendicular to flow requires compromise for surface protection
Thermal Management	• Low- temperature fluid loop for power and avionics • High-temperature fluid loop to manage thruster heat rejection	• Low-temperature fluid loop for power and avionics • Very high-temperature to reject thruster waste heat by direct radiation

VASIMR® subsystems are **nearly independent** and **weakly coupled** while Hall subsystems are **highly interdependent** and **nonlinearly coupled.**

Drilling a little deeper into how VASIMR® technologies work

RF power is coupled to natural modes of magnetized plasma in the rocket core

- Natural plasma waves provide the primary resistive load for a resonant LC circuit



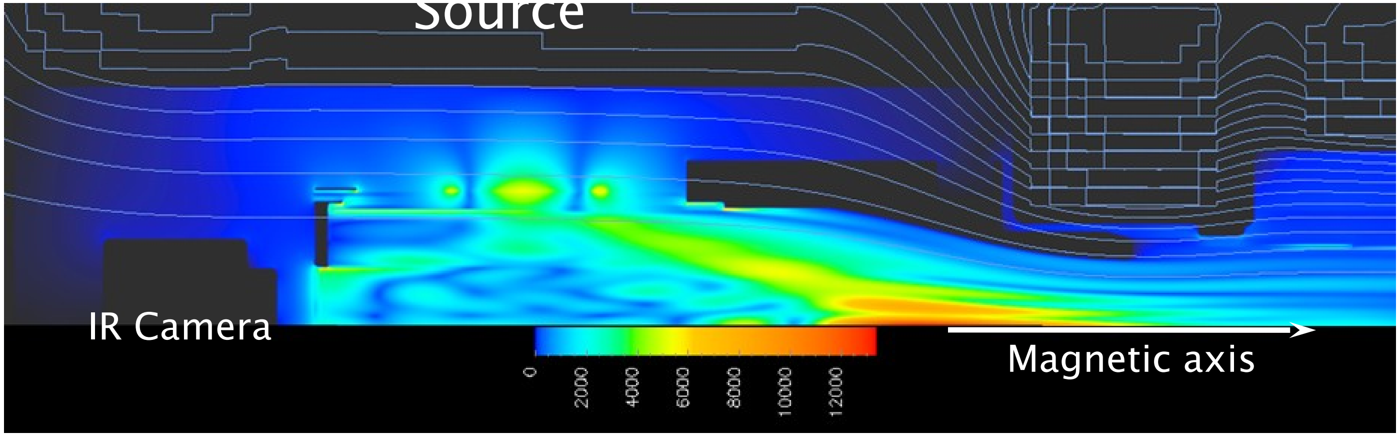
Reactive power in a simple resonant LC circuit

Real power from the RF generator is matched to the plasma load

Similar circuit topology for both the plasma source and booster

VASIMR® plasma source robust and decoupled from the booster

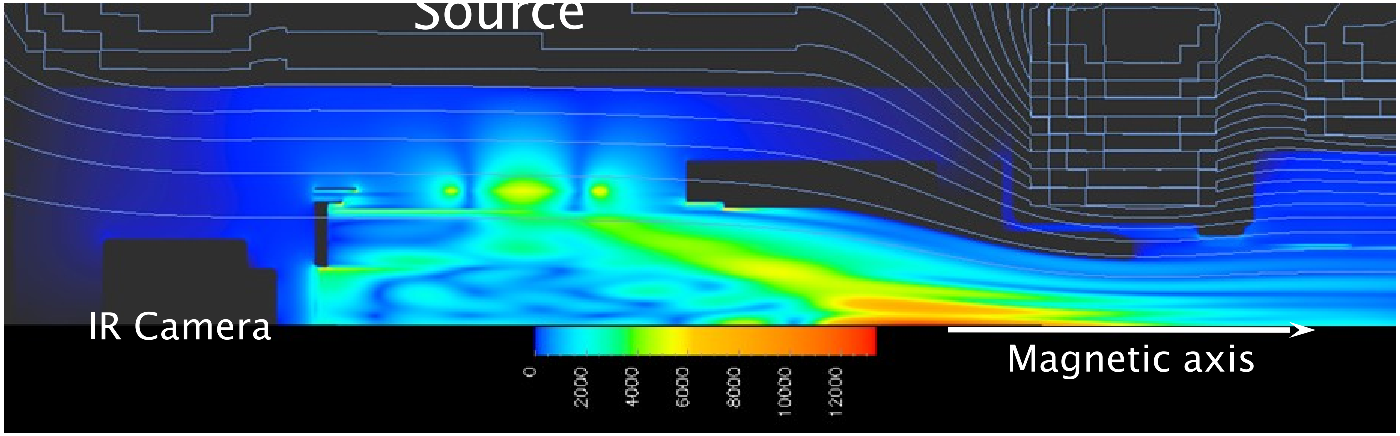
- Natural RF modes drive plasma **<u>instead</u>** of forced DC bias
  - "Helicon" or "high-harmonic fast" wave
  - Heats electrons over a wide range of plasma parameters
  - Reactive power in LC circuit stabilizes fluctuations at generator
  - Quiet, quasi-linear operation decoupled from plasma acceleration
  - Plasma remains quasi-neutral in a direct current sense



Helicon modeling for VX-100 circa 2007

VASIMR® plasma source robust and decoupled from the booster

- Synergistic physical/magnetic choke provides "gas trap"
  - ~100% ionized plasma to the booster section
- Predictive physics-based models used for all designs
  - First experimentally benchmarked in 2007

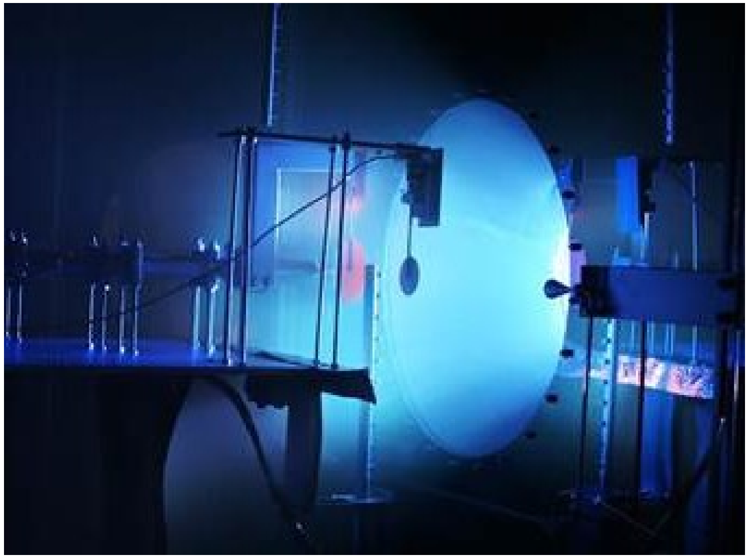


Helicon modeling for VX-100 circa 2007

About 85% of plasma thrust generated in booster section

- Natural plasma mode heats ions in the booster section
  - Called the "ion cyclotron" wave
  - Ion Cyclotron Heating (ICH) uses resonance between wave and ion gyro-motion
  - Resonance near the aft end of the booster
  - Magnetic field fully shields ceramic parts
  - Acceleration from ICH enhances the source

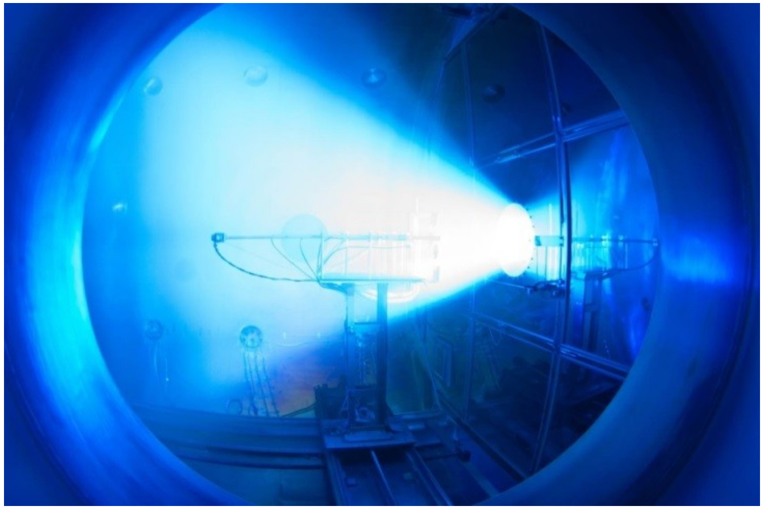
Magnetic nozzle directs plasma jet onto thrust targets
VX-200 circa 2010 [Reference 1]



About 85% of plasma thrust generated in booster section

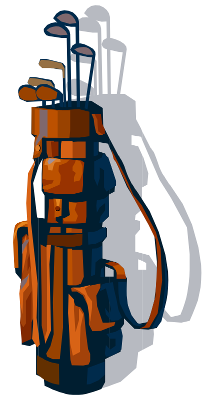
- Heated ions enter an adiabatic "nozzle" in the static magnetic field
  - Directs ~90% of the ion energy into an axial plasma jet for thrust

Click here for pictures and video of VX-200 operation



RF PPU ready for flight development

- Steady-state RF PPU
  - Compact
  - Highly efficient
  - Operated with both plasma stages
  - TRL 5-6 (individual boards in vacuum)



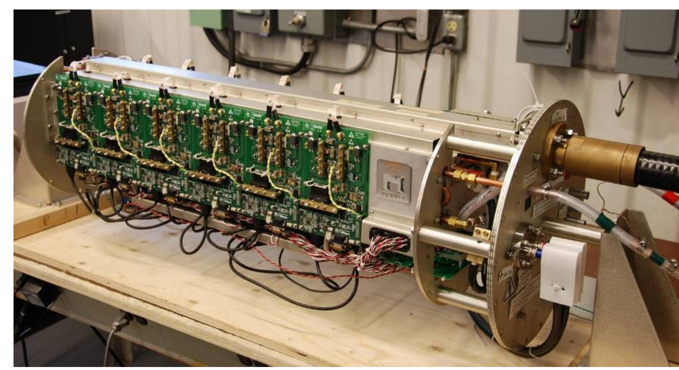
Helicon

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

- CSi tech has come to market since, improved performance <u>**is**</u> possible.



Gas Injection is simple

- No cathode, no anode, and **no** DC bias ever!!!
  - Only one gas delivery point per thruster
- Gas flow feedback control **is not** necessary
  - Gas dynamics stabilize in approximately 10 ms
- Plasma source has wide range of tolerance for gas parameters (limited effect on ionization efficiency)
- Any fluctuations are heavily filtered by the LC circuit

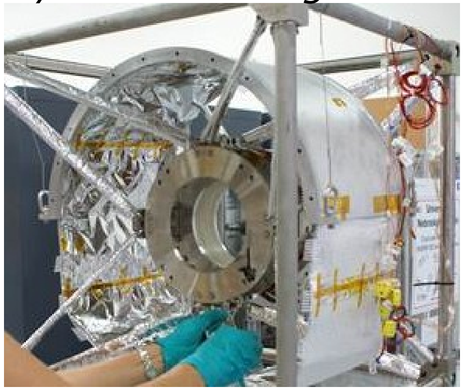
Commercial programmable feed for two thrusters (mass 1.2 kg) with two-fault tolerance and up to ~150 mg/s delivery of argon, krypton or xenon with 1% accuracy

The magnet subsystem is superconducting

- Experiments from 2009-2012 used a low-temperature superconducting magnet
  - 6 K
  - No coupling to plasma operation…
- "Set and forget"…
  - Negligible current maintenance for steady magnetic field
- High-temperature superconducting (HTS) magnet coil prototype developed and tested in 2007 (Creare, Tai Yang)
  - Preliminary design of proto-flight coils and manufacturing test with 2nd generation HTS (SuperPower Inc.) in 2008
  - Performance improving with Moore's law
- Sunpower GT cryocooler baselined in 2013 preliminary design (200,000+ ho[urs] time to failure)

Niobium-Titanium superconducting magnet used for all VX-200 experiments (2009-2012)

Creare/Tai Yang magnet configured for Sunpower cryocooler testing

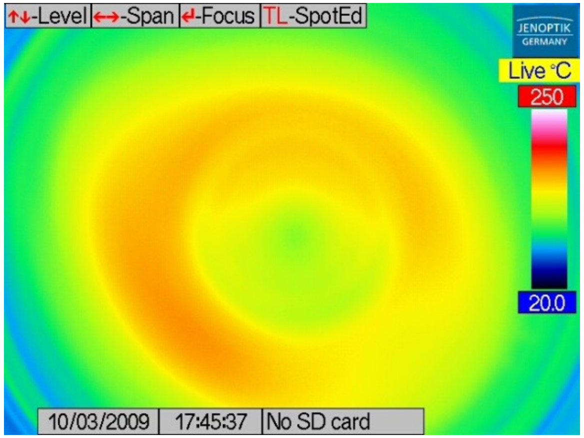


SunPower GT commercial cryocooler

Thermal control systems for steady state operation

- "Low temperature" system is pretty conventional
  - Avionics, controllers, and cryocoolers with max temp ~35 °C
  - RF generators with CSi modules can tolerate max temp up to ~85 °C to reduce radiator size
- "High temperature" system for rocket core
  - Heat flux measured during VX-200 operation
  - Rocket core has Integrated Cooling and Electrical (ICE) jackets
  - Combination cooling function with the RF power couplers
  - As high as 280 °C

An infrared camera and thermocouples measured the temperature evolution inside the VX-200 plasma source during operation with no cooling. Transient analysis was used to identify heat flux and hot spots [Reference 3].



Background on VASIMR® technology

- VASIMR® technology provides electric propulsion (EP) with the power density needed for <u>sustainable</u> robotic space operations and human exploration [Reference 2,4]
  - The technology scales naturally to power levels supported by the National Research Council for robotic and human exploration (> 40kW solar at first, scalable to multi-Megawatts)
- VASIMR® technology differs from traditional Hall thrusters and ion engines in that it relies on natural wave propagation in magnetized plasma to reach high power density.
  - Waves include whistler or high-harmonic fast waves (HHFW) and ion cyclotron waves
  - Relaxes Child-Langmuir and Debye shielding constraints encountered in DC discharges
- The technology has a long history of development (1979-present) with collaboration of academia (MIT, Princeton, UMD, UTexas, UMich, etc.), national laboratories (ORNL, LANL), international labs (Alfven, ANU, Japan), NASA and private industry.
  - All of the physics to support VASIMR as an advanced propulsion technology are well understood and have been demonstrated in the appropriate laboratory environment
  - Experimental results have been presented and published in multiple peer reviewed journals over several years
  - VASIMR® technology has been developed almost entirely with private funding (~$30M) and has been patented, but a great deal of misinformation circulates about its status
- VASIMR is now fully enabled by modern technology developments, particularly high-power solid state transistors and high-temperature superconducting (i.e. YBCO) tape.
- It is time to do the engineering development necessary to test VASIMR® engines extensively on the ground and in space

Unique features of VASIMR® technology

- ***Very high power density*** (~6 MW/m^2) compared with DC discharges by coupling RF power through ceramic windows to excite naturally occurring plasma waves
  - See for example the graduate level textbooks by T.H. Stix, *Waves in Plasmas*, AIP (1992) or M. Brambilla, *Kinetic Theory of Plasma Waves*, Clarendon Press Oxford 1998
  - Scales from moderate (~ 20kW) to very high power (>200kW) without changing the magnet
- ***No DC bias is applied***, no cathodes or anodes are needed!
- ***Plasma facing materials are well insulated by strong magnetic fields*** with field strength of a few tesla
- ***Specific impulse can be varied at constant power*** by adjusting the balance between the plasma source and the ion cyclotron heating (ICH) booster sections
- ***Wide range of operating power*** supported without loss of efficiency
  - The PPU is already TRL 5+ based on commercial broadcast radio (Nautel)
- ***Very efficient conversion of input power to jet power*** (75% thruster efficiency, >65% system efficiency) allows more thrust and less propellant usage than Hall thrusters for a given solar electric power plant
- ***Wide range of propellant choices*** including xenon, krypton, argon, and neon. May also be adaptable to solids or liquids (ammonia, iodine, potassium, rubidium, etc.) if condensates do not pose a risk to the spacecraft.
- ***Low cost ground testing*** because a natural seal between the high pressure plasma discharge region and the electromagnetic coupling circuits can be exploited

A few recent references

1. *Improved Efficiency and Throttling Range of the VX-200 Magnetoplasma Thruster*, B.W. Longmier, et.al., J. of Propulsion and Power, Vol. 30, No. 1, 2014, p 123
2. *Low Thrust Trajectory Analysis (A Survey of Missions using VASIMR® for Flexible Space Exploration - Part 2),* A.V. Ilin, 2012, Johnson Space Center Technical Report JSC-66428
3. *Inverse estimate of heat flux on a plasma discharge tube to steady-state conditions using thermocouple data and a radiation boundary condition*, D. de Faoite, D.J. Browne, J.I. Del Valle Gamboa, K.T. Stanton, International Journal of Heat and Mass Transfer 77 (2014) 564-576
4. *VASIMR® Spaceflight Engine System Mass Study and Scaling with Power*, J.P. Squire, et.al., 33rd International Electric Propulsion Conference, Washington DC (2013) IEPC-2013-149