Advances in Duration Testing of the VASIMR® VX-200SS System

EP-23. Advanced EP Concepts, AIAA-2016-4950

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Presented by Mark Carter

Two parts:

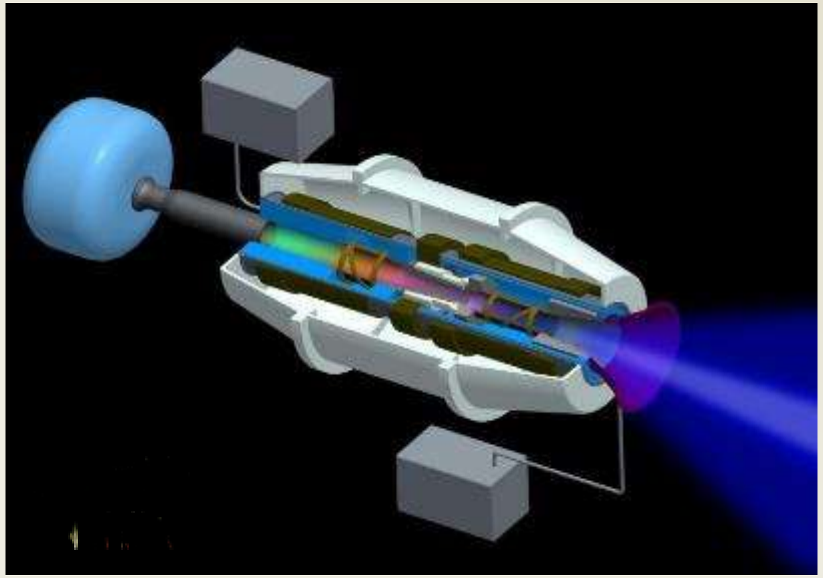
1. A review of VASIMR® physics

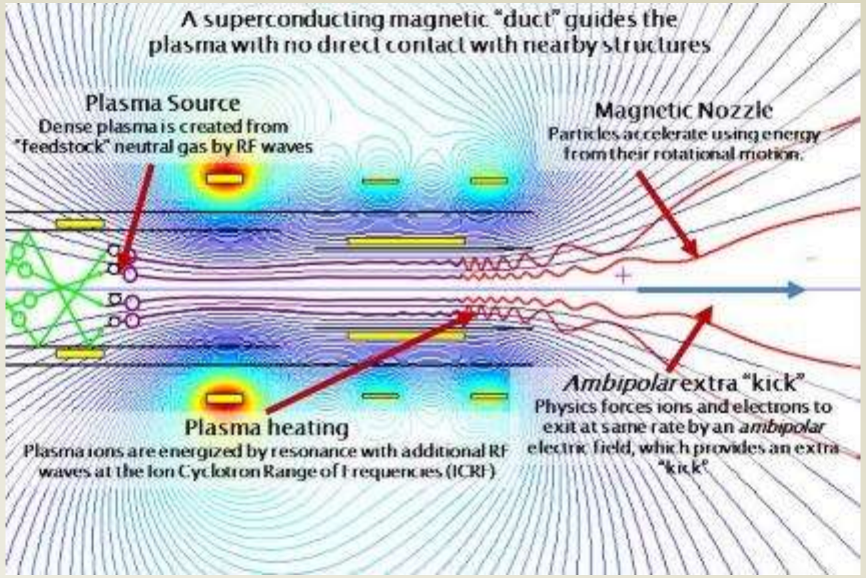
2. Status of Ad Astra's NextSTEP program with NASA for a TRL-5 test of a VASIMR® engine operating at 100 kW continuously for 100 hours

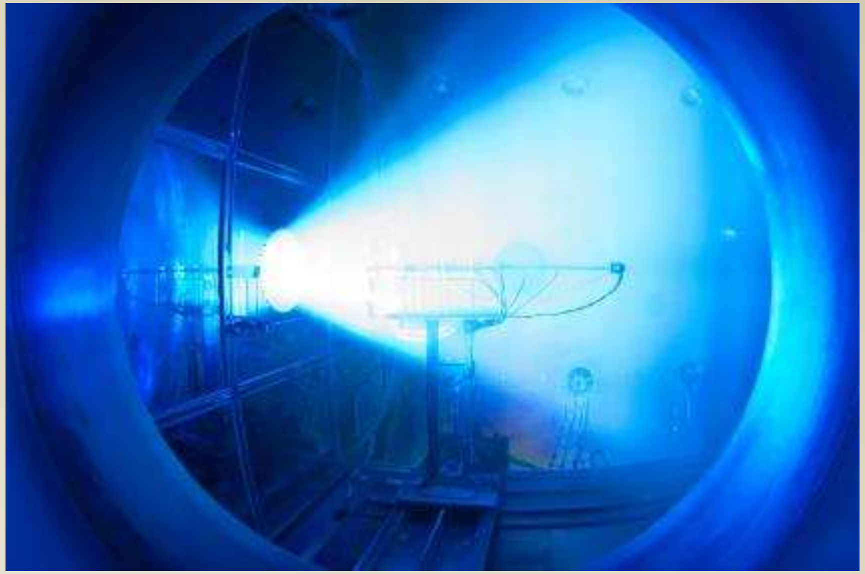
Rocket Company™
AD ASTRA

What is a VASIMR® engine?

- A high power density electric rocket, scalable (less than 50 kW to multi-MW)
- Electrodeless design implies long component life with no DC bias
- Steady-state operation with multiple, low cost and abundant propellants
- Variable thrust, specific impulse, and power throttling adapts to the mission
- Privately funded by Ad Astra from TRL 2-4, Current NASA funding to TRL-5

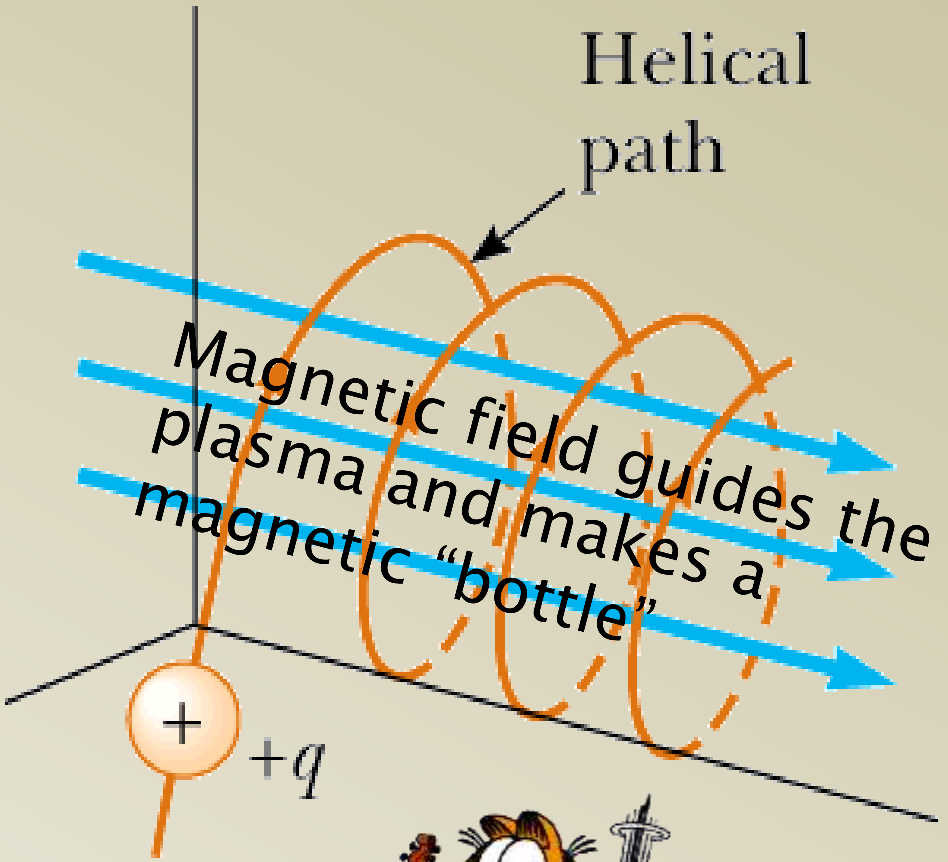






Strongly magnetized plasmas have natural waves not found in weakly magnetized plasma

- Ions and electrons spiral in the magnetic field
- A rich set of new natural modes and waves appear because of the helical motion
- The plasma “cooperates” with these waves when resonantly driven
- A VASIMR® engine <u>is designed </u>to take advantage of these natural modes



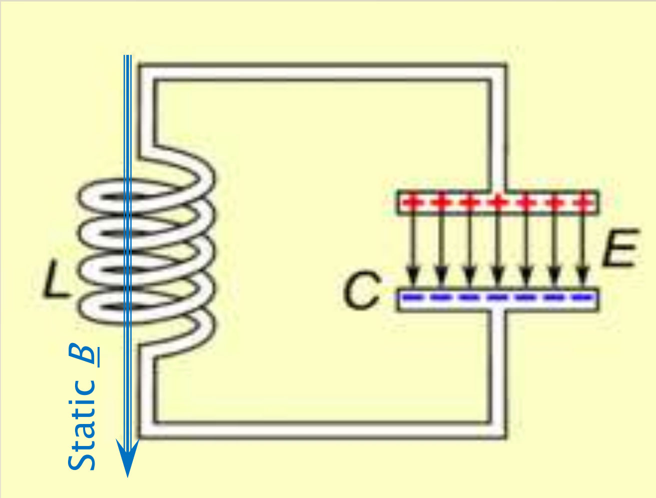
Plasma physicist

Clipartpanda

Historical note: These waves have been studied extensively since the 1950s. A good graduate level text is T.H. Stix, *Waves in Plasmas*, 1992 2nd Ed. ($92 on Amazon)

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

Electromagnetic power coupling is analogous to resonantly pushing a swing



Reactive power in a simple resonant LC circuit

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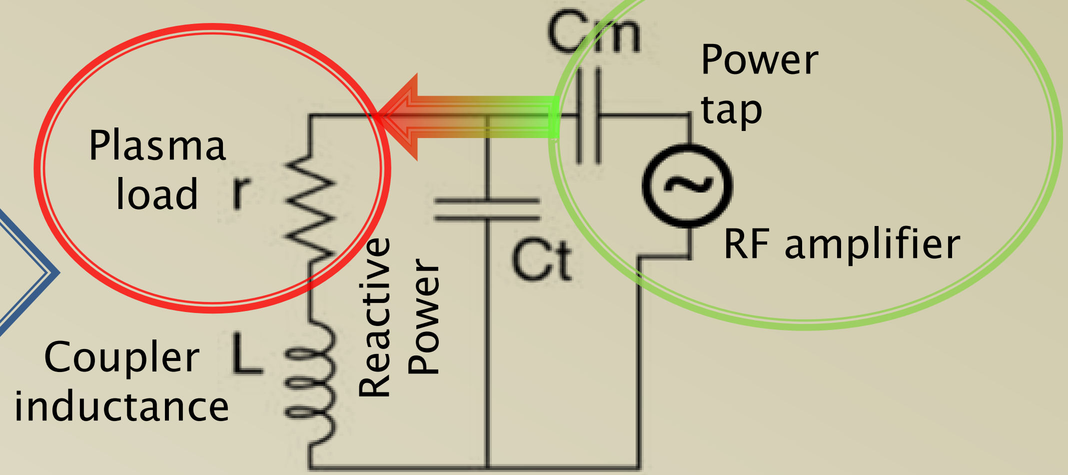
Static $\underline{B}$, propellant, and plasma waves

Power from the RF amplifier is matched to the plasma

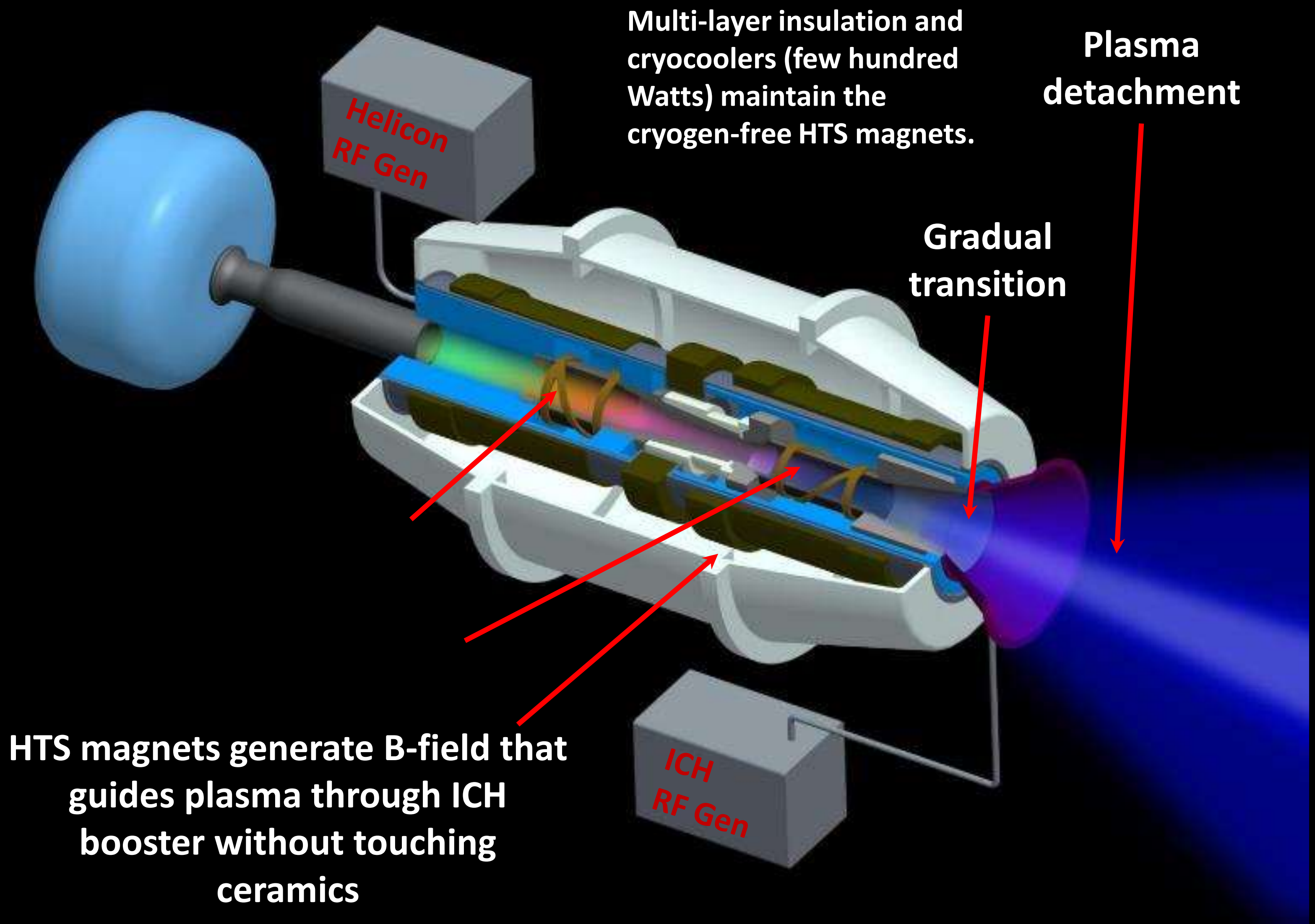


This is a commonly used RF matching circuit

Similar circuit topology for both the plasma source and booster

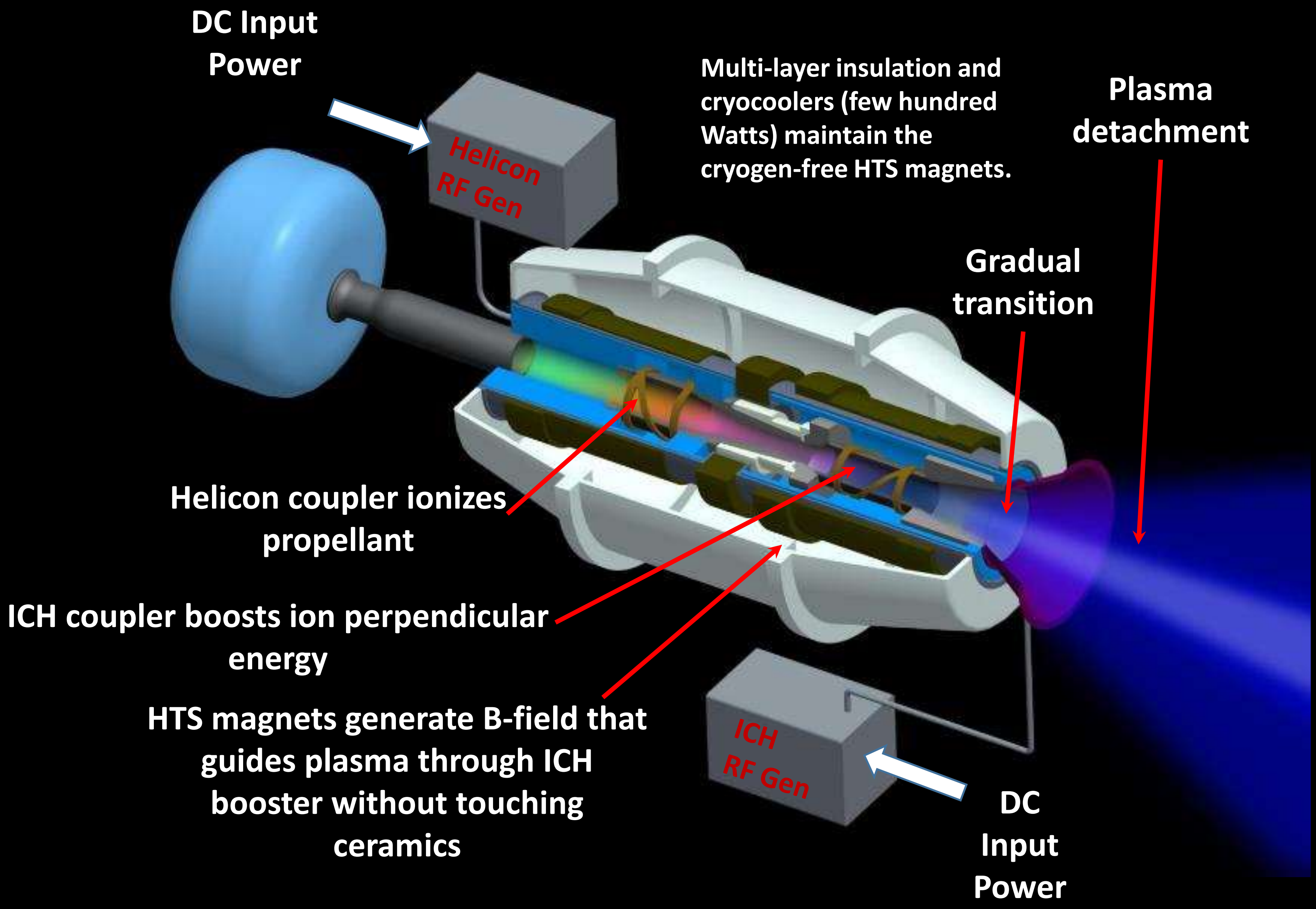
A VASIMR® Engine has five basic parts

1. **Magnet: High-temperature superconductors produce fields ~2 Tesla using only a few hundred watts of refrigerator power. The static field sets resonant modes, protects material surfaces and guides plasma to form a jet for thrust.**



A VASIMR® Engine has five basic parts

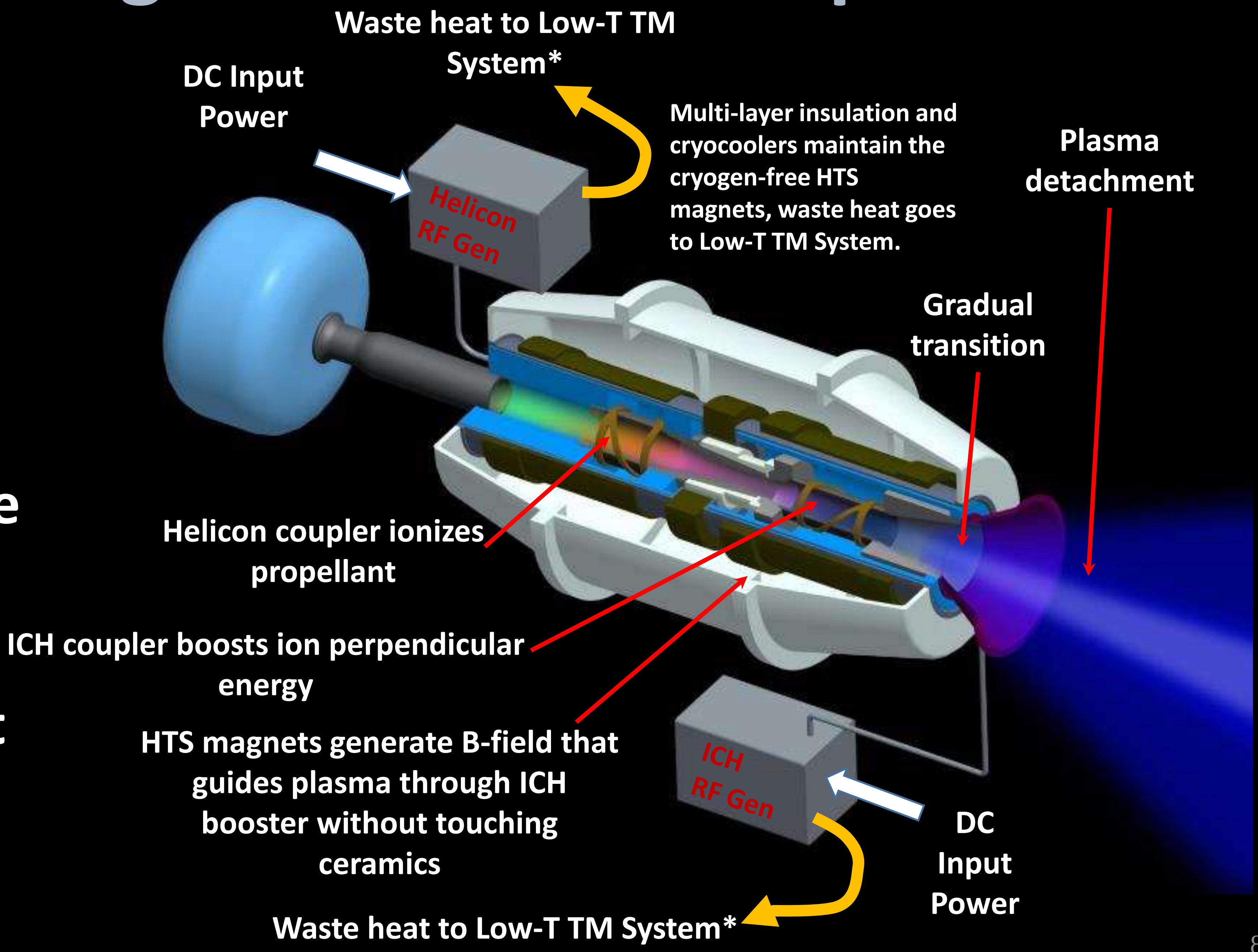
1. Magnet
2. Rocket core: RF power is coupled in two stages, one to ionize propellant and the other to heat the plasma. Neutral gas flow is controlled by surfaces tangentially aligned with the magnetic field.



*Thermal Management (TM)

A VASIMR® Engine has five basic parts

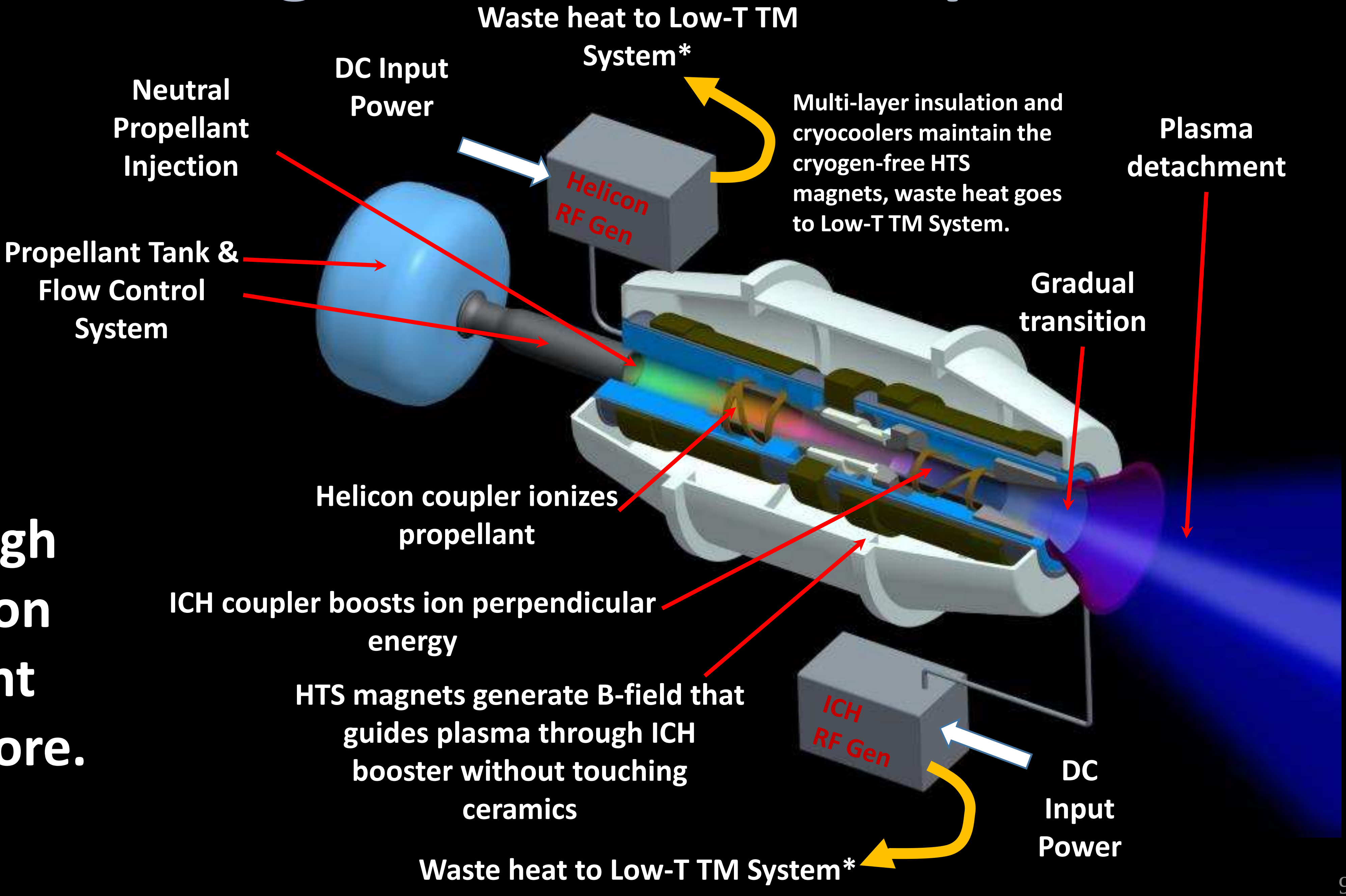
1. Magnet
2. Rocket core
3. RF amplifiers (PPUs): More than 95% of solar DC power is converted to RF power at precisely the frequencies needed by the rocket core. The PPUs are tolerant of DC variations and well isolated.



*Thermal Management (TM)

A VASIMR® Engine has five basic parts

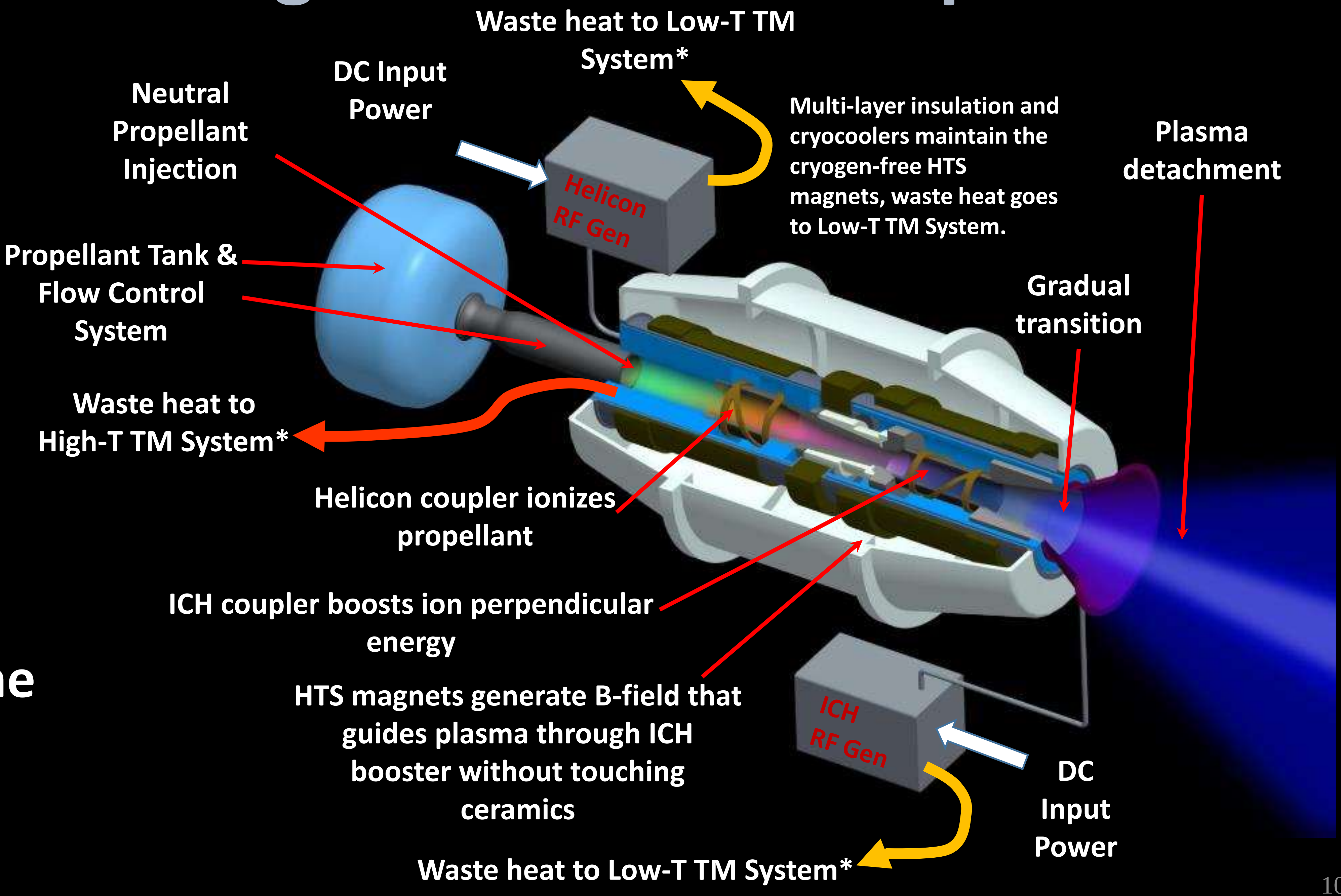
1. Magnet
2. Rocket core
3. RF amplifiers (PPUs)
4. Propellant injection: Propellant is supplied through a single injection port in the front of the rocket core.



*Thermal Management (TM)

A VASIMR® Engine has five basic parts

1. Magnet
2. Rocket core
3. RF amplifiers (PPUs)
4. Propellant injection
5. Thermal management: Fluid loops at ~200 °C cool the rocket core.



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A VASIMR® Engine has five basic parts

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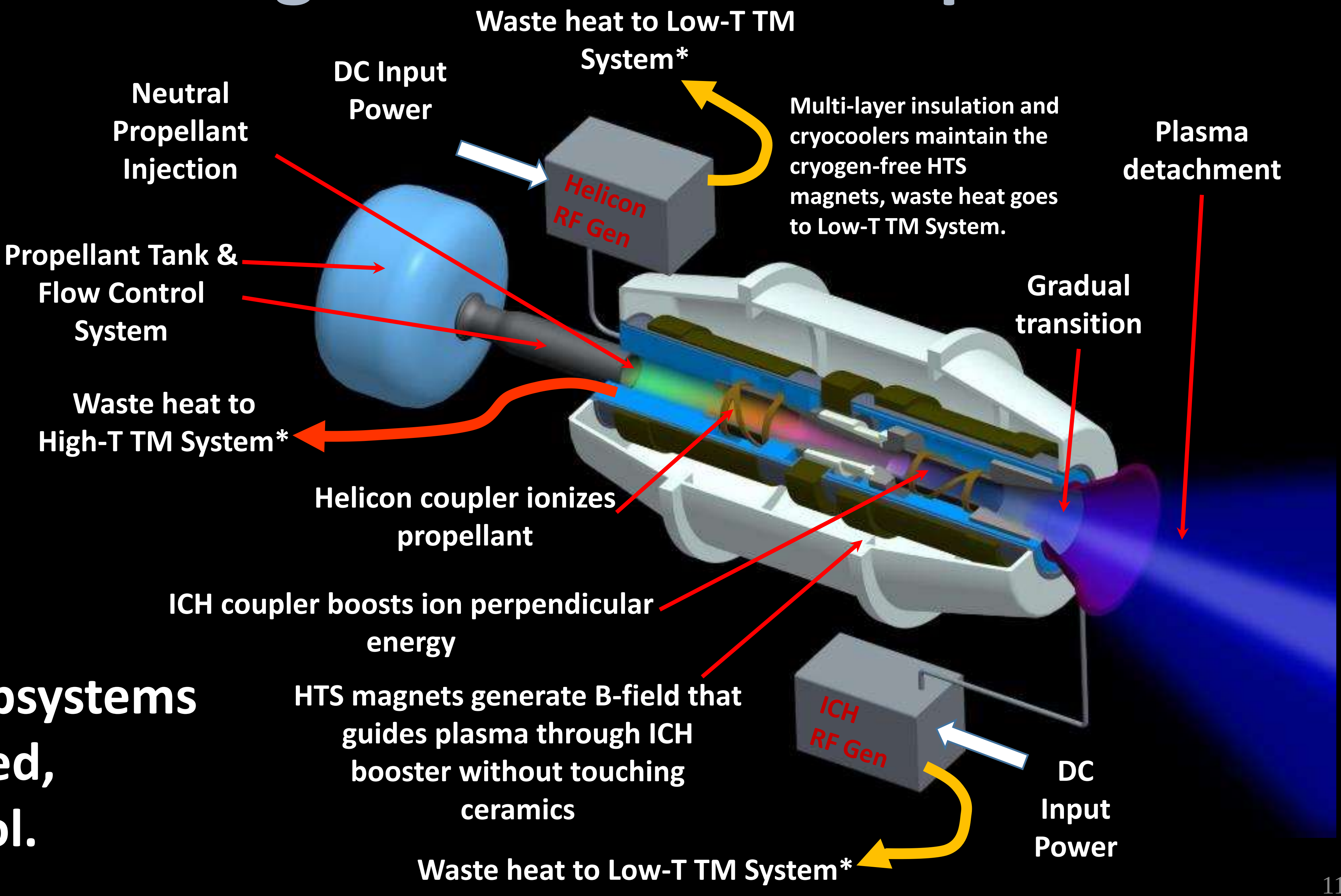
5. Thermal management

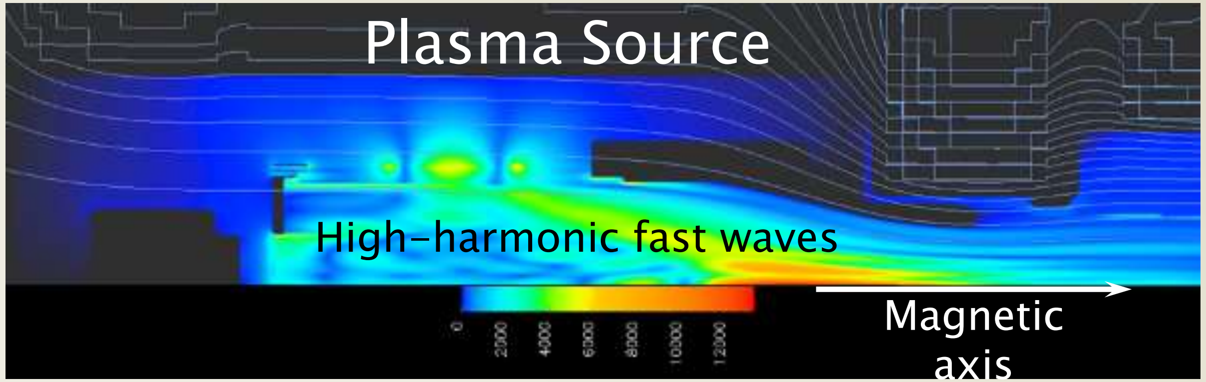


The combined subsystems are weakly coupled, simplifying control.

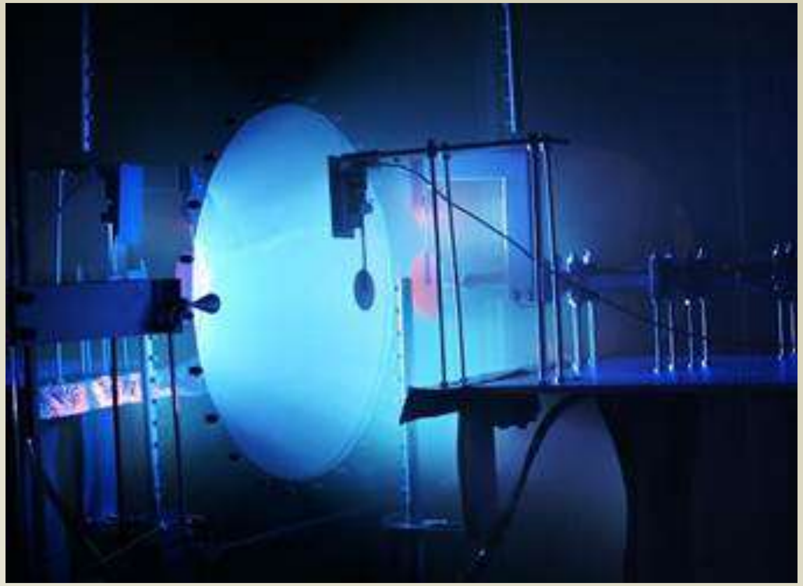
*Thermal Management (TM)

Component availability and computational models determine VASIMR® engine designs

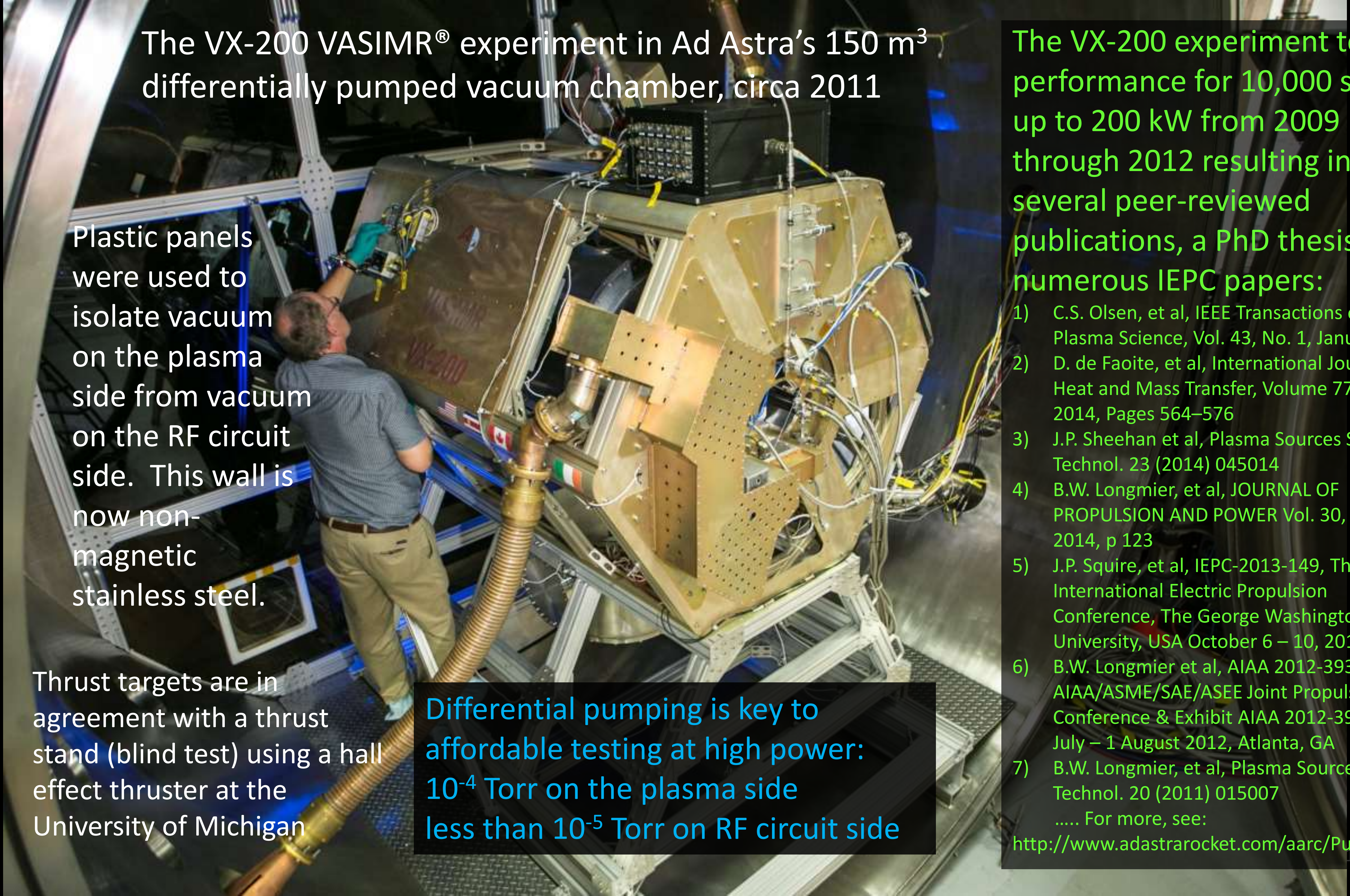
- Resonant waves and modes are chosen <u>by design</u> to take advantage of readily-available commercial technologies
  - Highly efficient light-weight radio frequency amplifiers with hundreds of kW
  - Superconducting magnets, similar to MRI solenoids except conduction cooled
- Ad Astra has been using physics-based predictive computational models for self-consistency in its designs since 2006



Helicon modeling for VX-100 circa 2007



VASIMR® Exhaust from superconducting VX-200 circa 2012



The VX-200 VASIMR® experiment in Ad Astra's 150 m^3 differentially pumped vacuum chamber, circa 2011

Plastic panels were used to isolate vacuum on the plasma side from vacuum on the RF circuit side. This wall is now non-magnetic stainless steel.

Thrust targets are in agreement with a thrust stand (blind test) using a hall effect thruster at the University of Michigan

Differential pumping is key to affordable testing at high power:
10^{-4} Torr on the plasma side
less than 10^{-5} Torr on RF circuit side

The VX-200 experiment tested performance for 10,000 shots up to 200 kW from 2009 through 2012 resulting in several peer-reviewed publications, a PhD thesis, and numerous IEPC papers:

1) C.S. Olsen, et al, IEEE Transactions on Plasma Science, Vol. 43, No. 1, January 2015
2) D. de Faoite, et al, International Journal of Heat and Mass Transfer, Volume 77, October 2014, Pages 564–576
3) J.P. Sheehan et al, Plasma Sources Sci. Technol. 23 (2014) 045014
4) B.W. Longmier, et al, JOURNAL OF PROPULSION AND POWER Vol. 30, No. 1, Jan 2014, p 123
5) J.P. Squire, et al, IEPC-2013-149, The 33st International Electric Propulsion Conference, The George Washington University, USA October 6 – 10, 2013
6) B.W. Longmier et al, AIAA 2012-3930, 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit AIAA 2012-3930, 29 July – 1 August 2012, Atlanta, GA
7) B.W. Longmier, et al, Plasma Sources Sci. Technol. 20 (2011) 015007

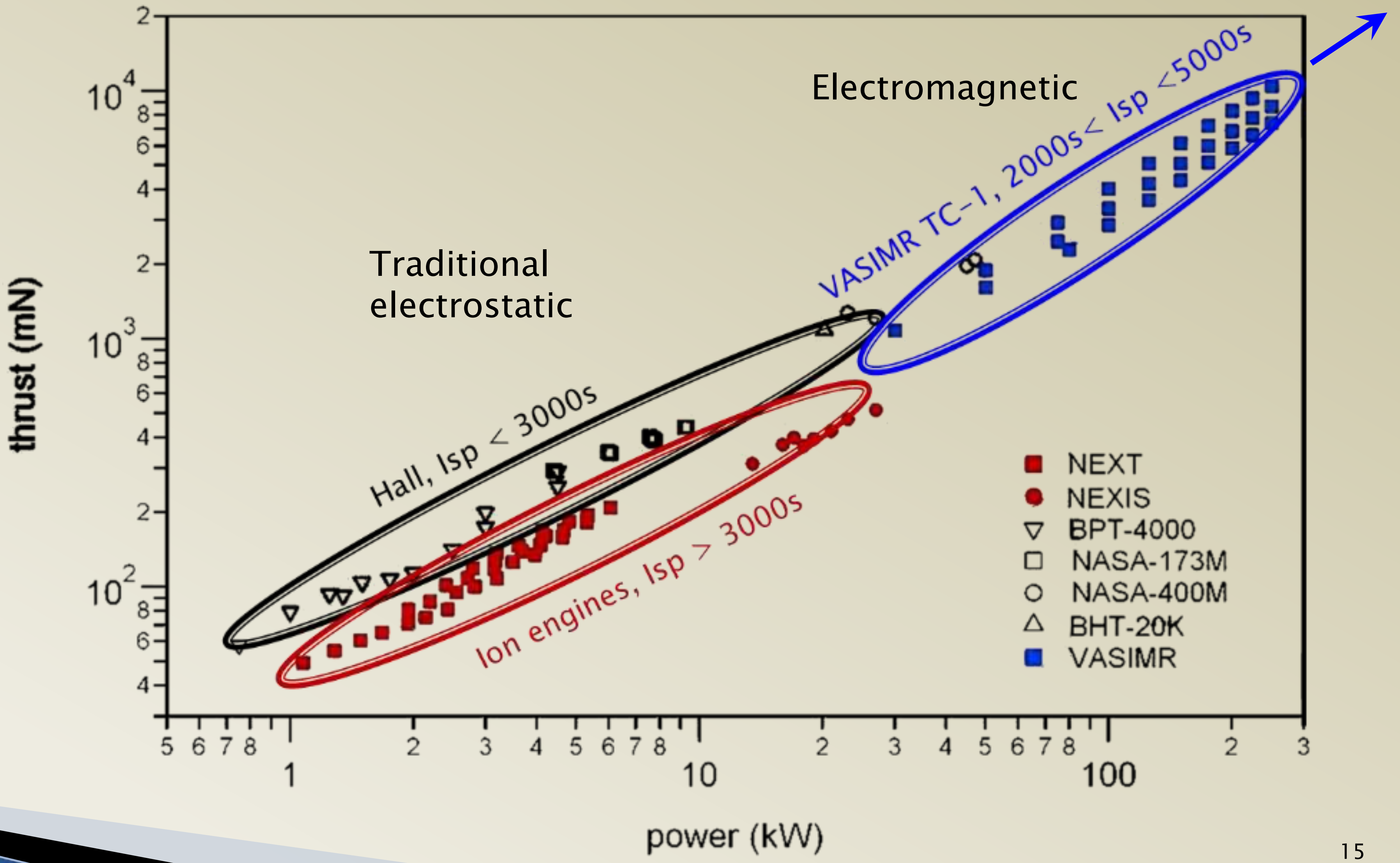
..... For more, see: http://www.adastrarocket.com/aarc/Publications

Unique features of VASIMR® technology

Subsystem	VASIMR®
Electromagnetic Power Coupling	• Natural RF plasma waves allow >10X the power of traditional EP • Eliminates the need for neutralization (no DC bias) • Active RF components do not touch the plasma
Simple Solar Power Processing	• Very efficient (>95%) and light-weight MOSFET radio amplifiers • Insensitive to solar power output voltages and fluctuations • Well isolated from any plasma fluctuations by resonant LC circuits
Plasma Source	• Low MHz band (commercial radio) with no plasma density limit
Plasma Acceleration	• High kHz band (commercial radio) scales to high power
Gas Injection	• Single port injection (no cathode or anode) • Simple flow control (fast feedback not required)
Magnets	• Light-weight high temperature (~77 °K) superconducting technology allows high field with minimal mass and power (less than 500 W) • Thermally well isolated from plasma with active and passive barriers • Alignment protects plasma-facing surfaces from erosion
Thermal Management	• Overall heat rejection is low because of high efficiency components • High-temperature (~200 °C) fluid loop for rocket core heat rejection

VASIMR® engines occupy the high-power niche for electric propulsion

- Offer "high-power" advantages in mass, specific impulse, and efficiency
- Complement other technologies for power levels above approximately 30 kW
- The magnet requires a minimum mass investment, but it can process a lot of power



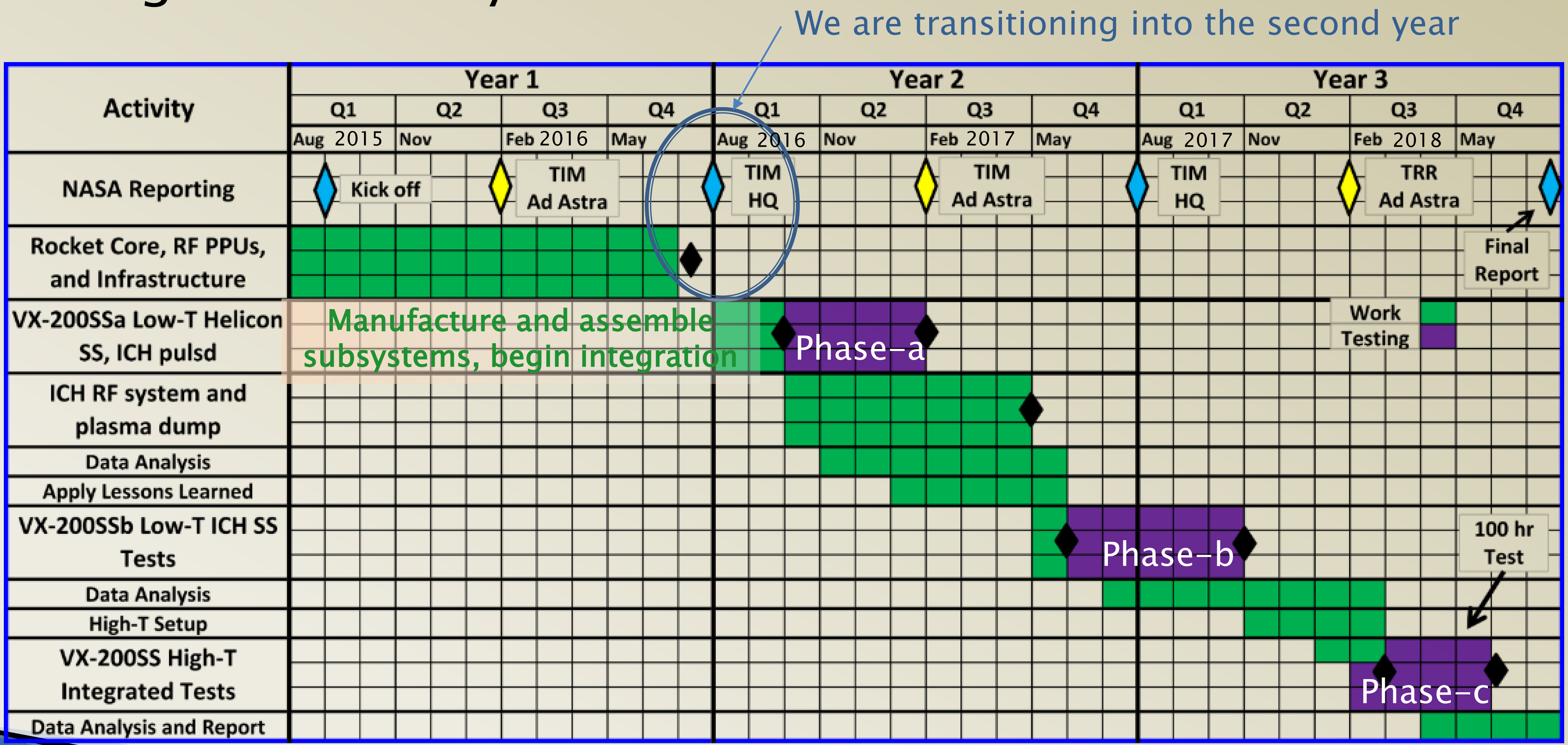
NASA NextSTEP program for testing a VASIMR® engine at TRL-5 at 100 kW continuously for 100 hours

Project goals and objectives

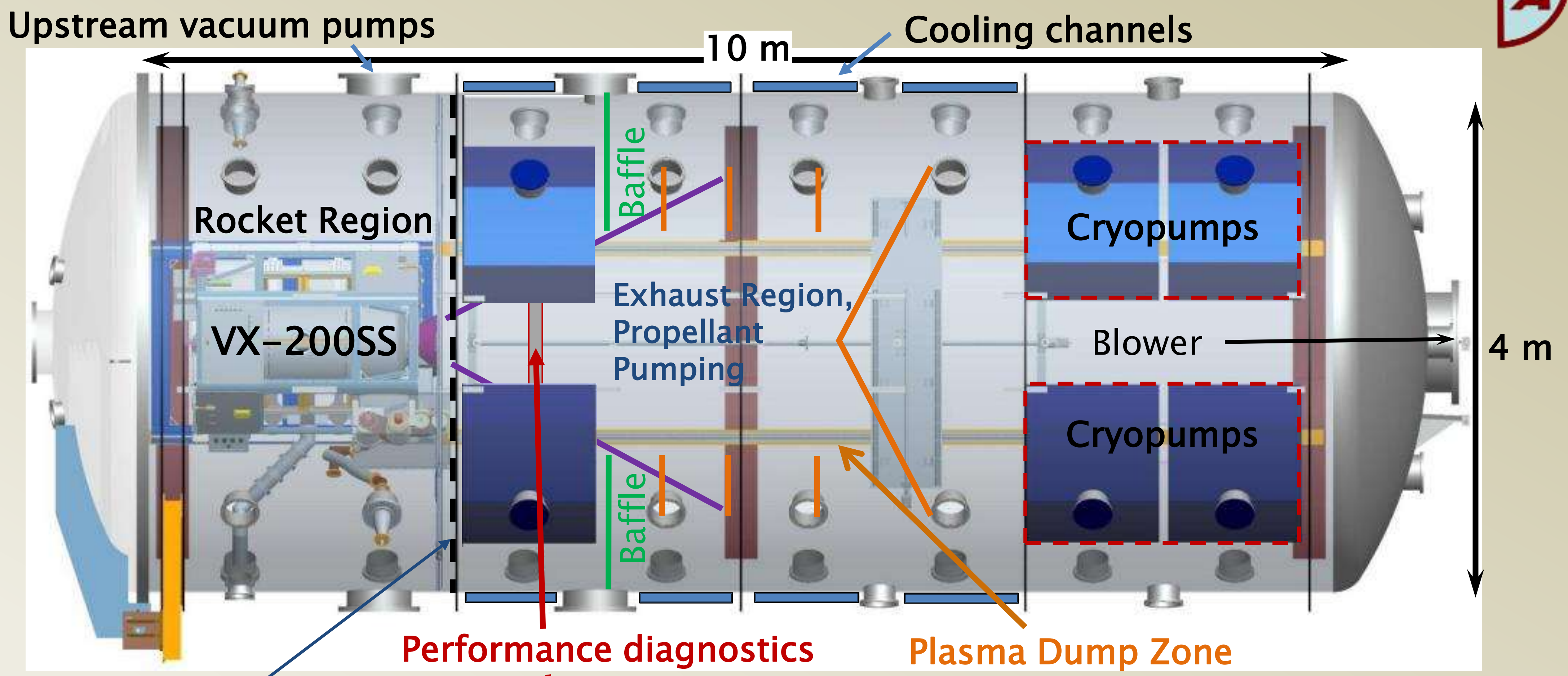
- The goal of this work is to demonstrate a VASIMR® engine in thermal steady-state by operating it continuously for 100 hours at a power level of 100 kW
- Objectives
  - Achieve the goal over the course of 3 years in 3 phases
  - *Phase a*: Shake-out basic systems, pulses of minutes, uncooled booster section, accumulate 1 hour, inspect
  - *Phase b*: Add cooling to booster section, accumulate 100 hours, inspect
  - *Phase c*: Upgrade rocket core cooling for heat rejection at ≈ 200 °C, shake out high temperature cooling systems, install PPUs in vacuum, execute a 100 hour continuous test, inspect

Three phases of plasma operation

- Nearing the end of year 1 in contract schedule



VX-200SS setup in the 150 m³ vacuum chamber, top view



Chamber divider wall, enables high vacuum ($<10^{-5}$ Torr) in Rocket Region during firing.

Six PHPK TM-1200i nude cryopanels (58,000 l/s Ar) installed

- Two top near divider wall
- Four in top-rear behind dump
- Room for additional 4 panels.

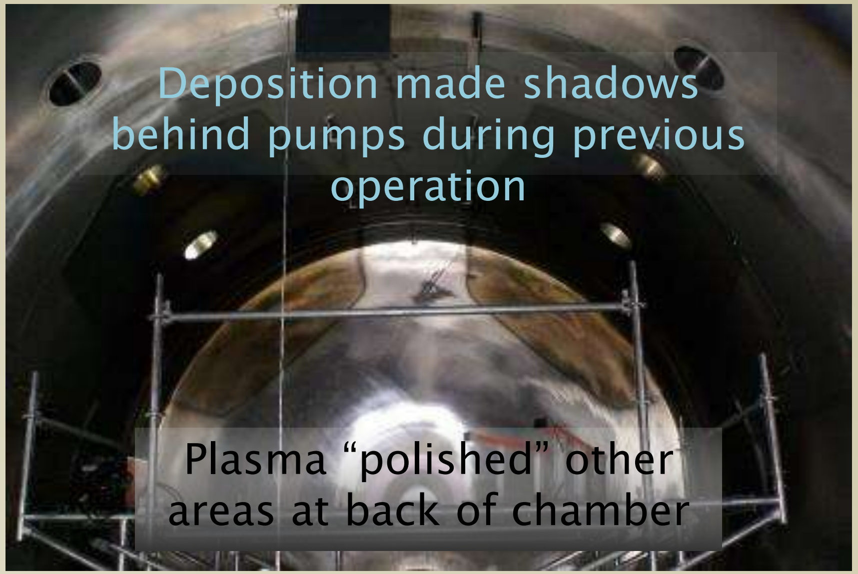
As year 1 ends all subsystems are ready for integration, on or ahead of schedule

- **Vacuum chamber** modifications:
  - Divider wall installed and tested to allow long pulse differential pumping
  - Facility water systems reconfigured to handle phase-a and phase-b ops
  - Six cryo-pumps installed (4 refurbished and 2 new) for phase-a
  - Plasma dump ready for phase-a integration and testing
  - Chamber cooling mods are ahead of schedule to avoid conflict in second year
- Refurbished and tested our **PPUs** (>200 kW capability)
  - PPUs are now integrated outside vacuum chamber with dummy loads for testing
- Conduction-cooled **superconducting magnet** restored to full operation
  - Thermal bus repair was verified with full field testing
  - Magnet is now integrated in the engine bus with better-than-new (2009) thermal margin
  - Field line mapping to integrate the rocket core is ready to begin
- **Rocket core** ready for final coatings, assembly and test
  - All parts manufactured, dry-assembled and leak-checked
  - First steps toward integration are underway
- **Command and control** using National Instruments cRIO® architecture
  - Facility command is ready for vacuum pump operation compatible with phase-a
  - Rocket command computer integrated ahead of schedule with software porting underway
- **Performance diagnostics** are being modified for long-pulse ops and testing
  - Diagnostics and translation table are restored, integrated with command computer

Project began by clearing chamber in August 2015

Port covers and pumps removed for inner surface prep

Removed equipment used for VX200 tests (2012)



Deposition made shadows behind pumps during previous operation

Plasma “polished” other areas at back of chamber

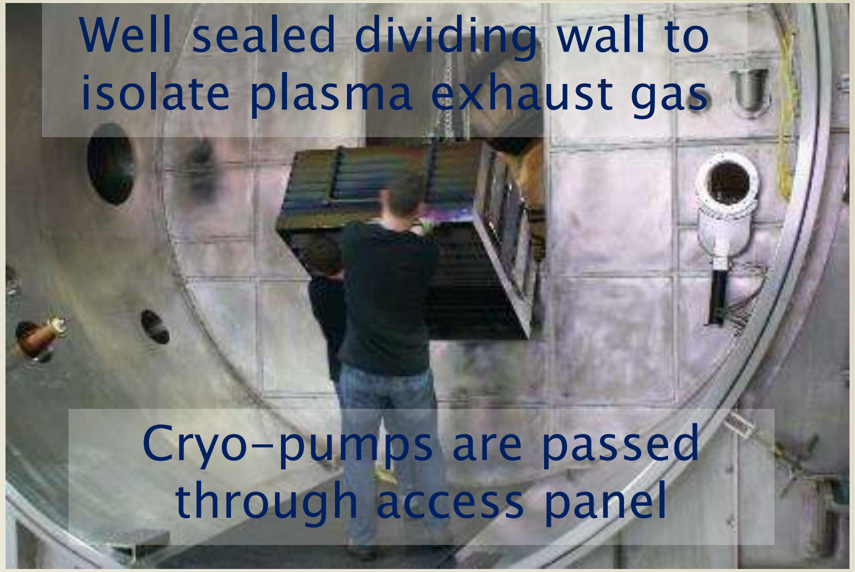
Space cleared for cryo-pump compressors and PPUs

Initiated pump servicing and vacuum chamber update

Plasma damage and deposition on cryo-pumps

Four original pumps needed service

Installed pumps and external cooling for phases a and b



Commission divider wall for differential pumping
Installed new and refurbished pumps

Prepared chamber to handle continuous heat loads to chamber walls

Chamber is now ready to begin integration of the test article for phase-a

- Facility control computer operational
- Facility water available for all heat loads
- Dry fit for outer chamber cooling
- Differential pumping divider wall fully tested
- PPUs tested into dummy loads with command and control system

All milestones accepted for year 1

On schedule with NASA ATP for year 2

Plans going forward

- Rocket core integration with magnet (Aug 2016)
  - Field line mapping and rocket core alignment
  - Instrumentation and electrical testing
- Integration of VX-200SSa test article in chamber (Sept 2016)
  - Cooling line hookups and leak checking
  - RF matching circuit connections and tuning
  - Command, control and data acquisition verification
- Initial high-power firing with plasma in Phase-a (Oct 2016)
  - Phase-a will have pulse lengths on the order of minutes
  - Measure rocket performance
  - Evaluate aspects of the chamber and plasma dump
- Install final components for VX-200SSb (May 2017)
  - Fully cooled with operation times on the order of hours
- Hot steady-state operation with VX-200SS (Feb 2018)
  - Ready for 100 hours of continuous operation at 100 kW
  - New PPUs installed inside the vacuum chamber