VASIMR®: THE FUTURE OF HIGH POWER ELECTRIC PROPULSION

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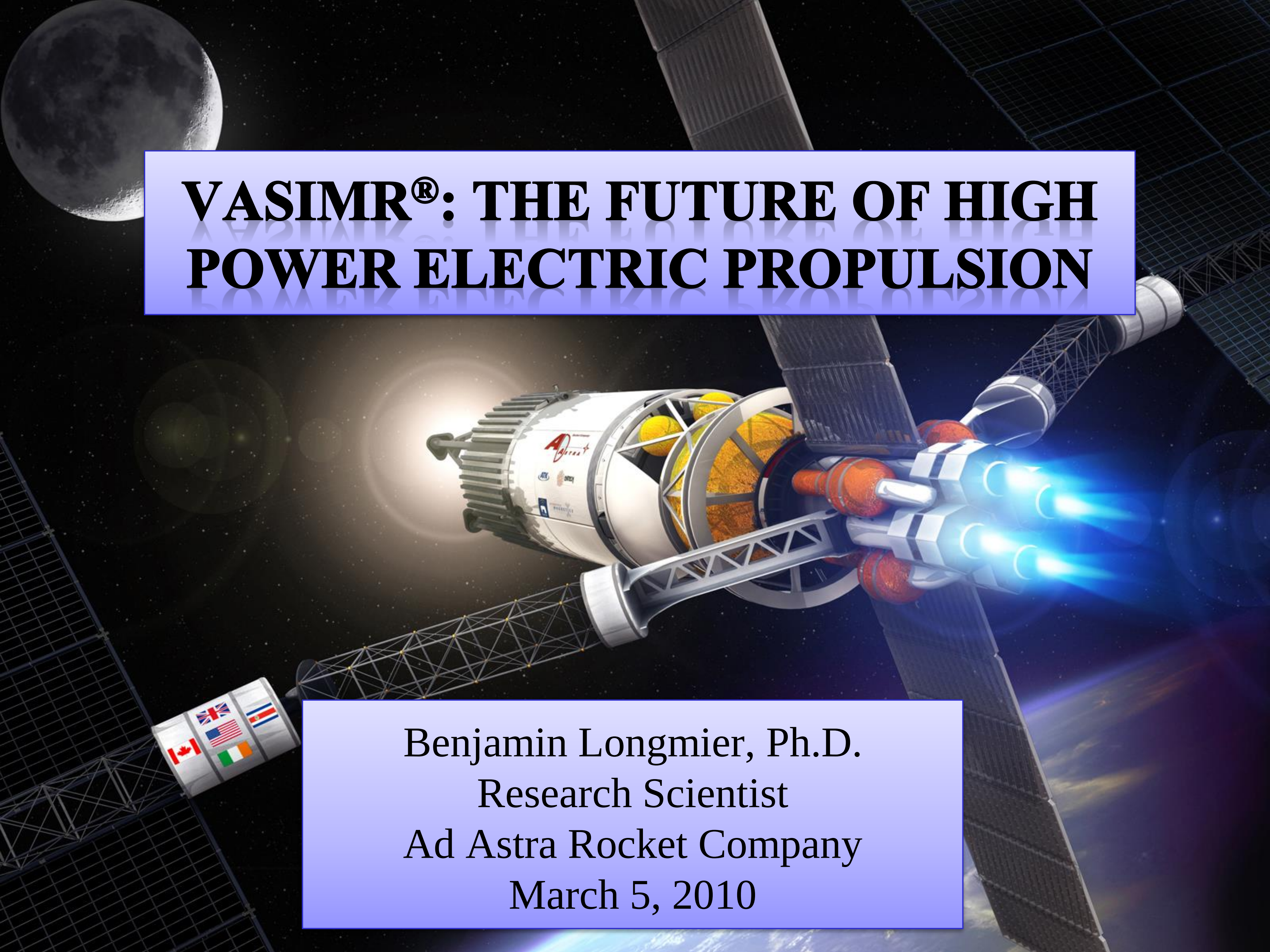
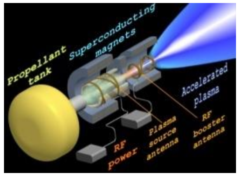
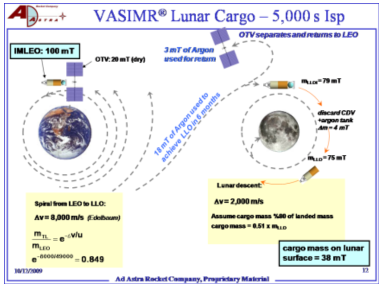
March 5, 2010

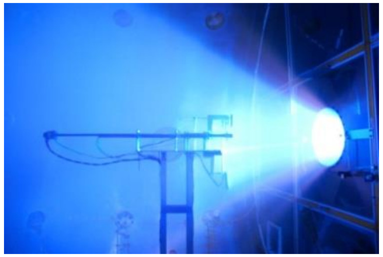


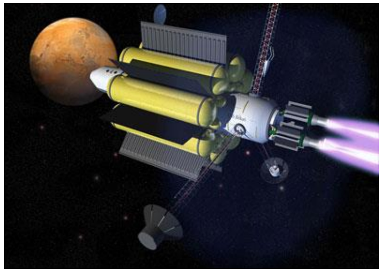
Outline

- What is VASIMR®?
- Why VASIMR®?
  - Other ion propulsion concepts
  - Missions that are enhanced by VASIMR®
- Are we testing VASIMR®?
  - Houston and Cost Rica labs
  - VX-100
  - VX-200
  - VF-200
- Where do we go from here?









Two Facilities

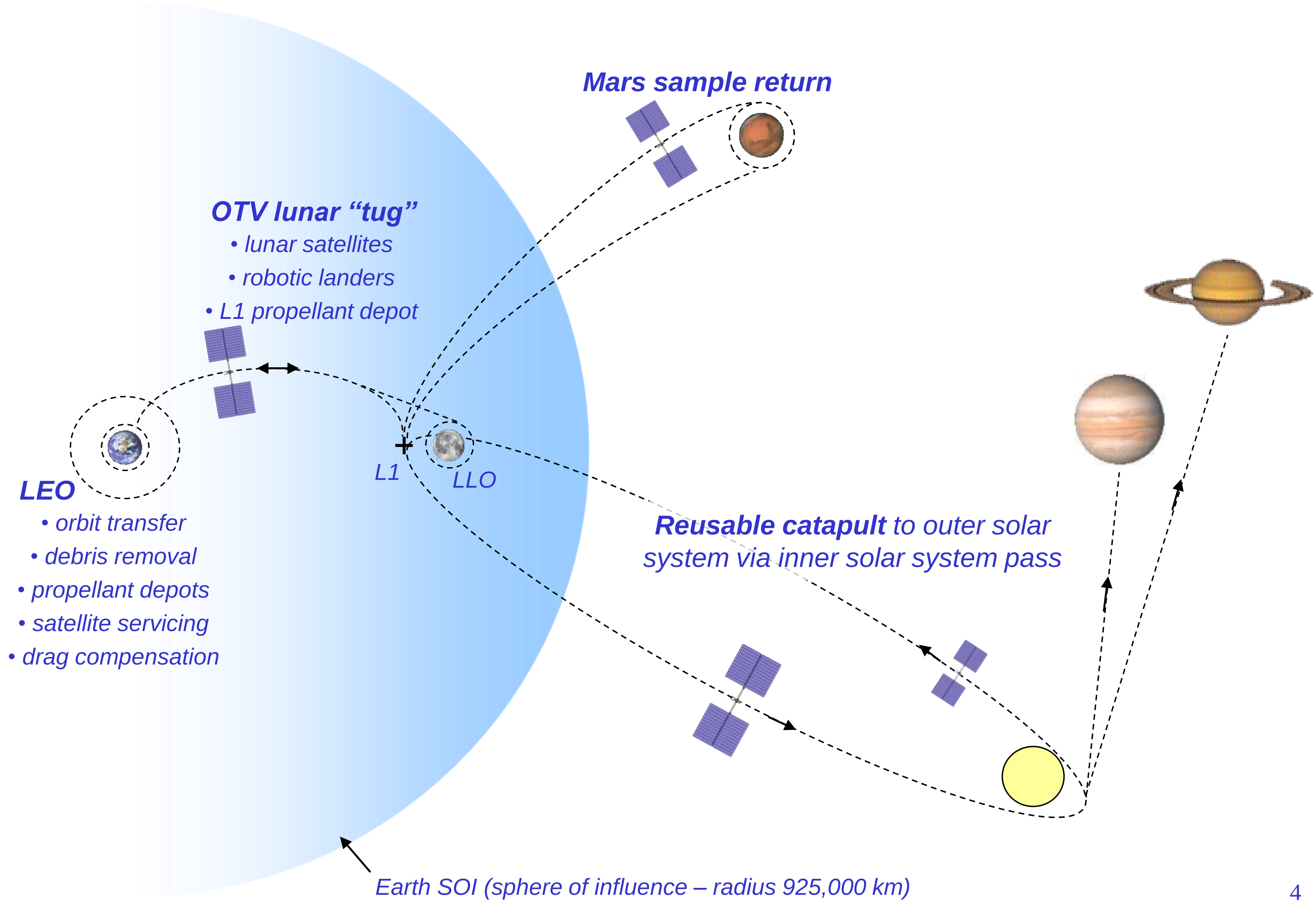
- Ad Astra Rocket Company, a Delaware Corporation, is capitalizing on more than 25 years of NASA R&D on plasma propulsion. Primary operations in USA
- Small facility in Costa Rica. Fully firewalled for export control

Primary Facility in Webster, TX

24,000 sqft, near NASA's Johnson Space Center

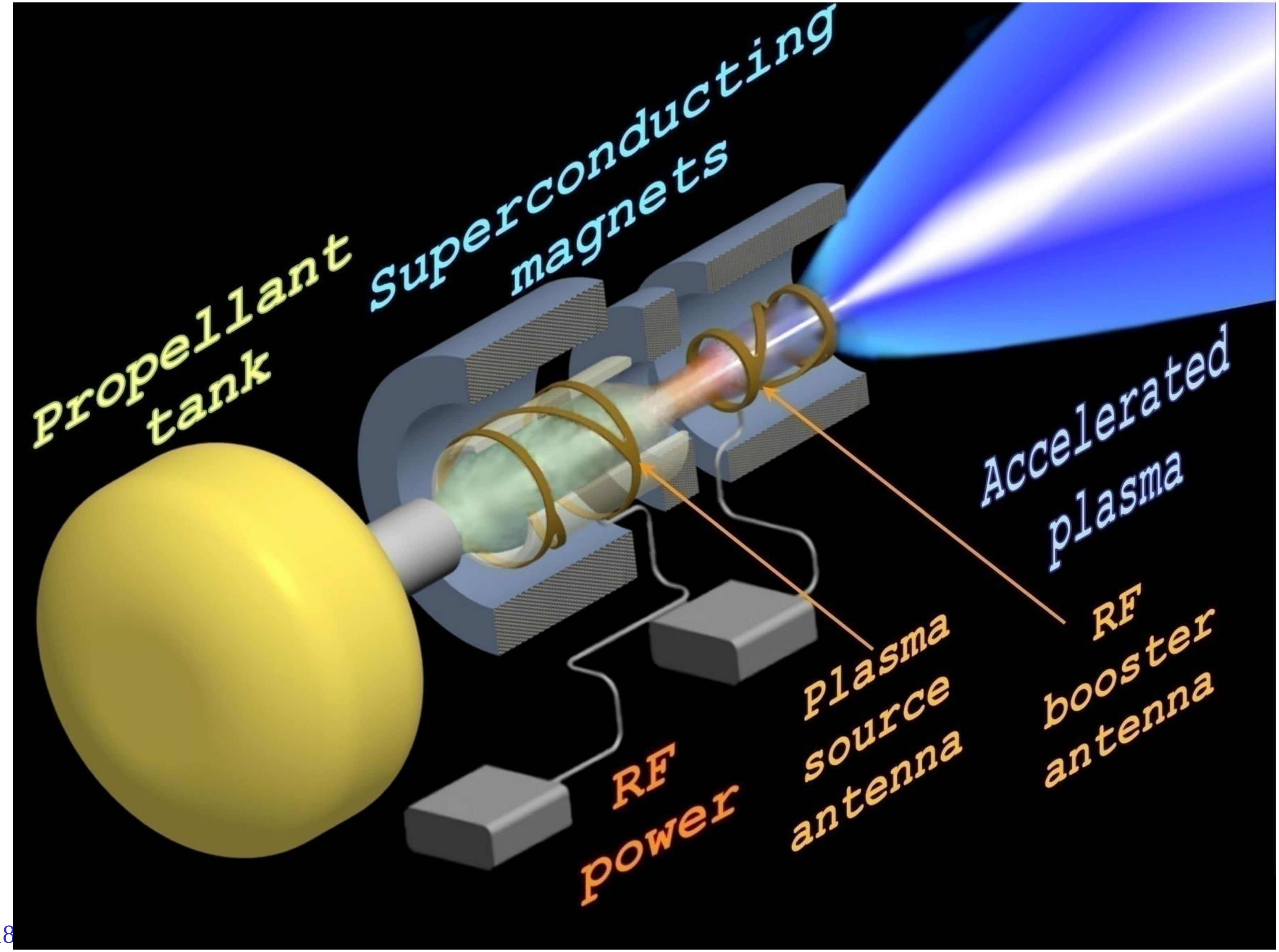
La Flor Campus, 7,000 sqft, Liberia, Costa Rica

Comprehensive Space Transport Architecture



VASIMR® Fundamental Concept

Variable Specific Impulse Magnetoplasma Rocket



Chemical Versus Electric Propulsion

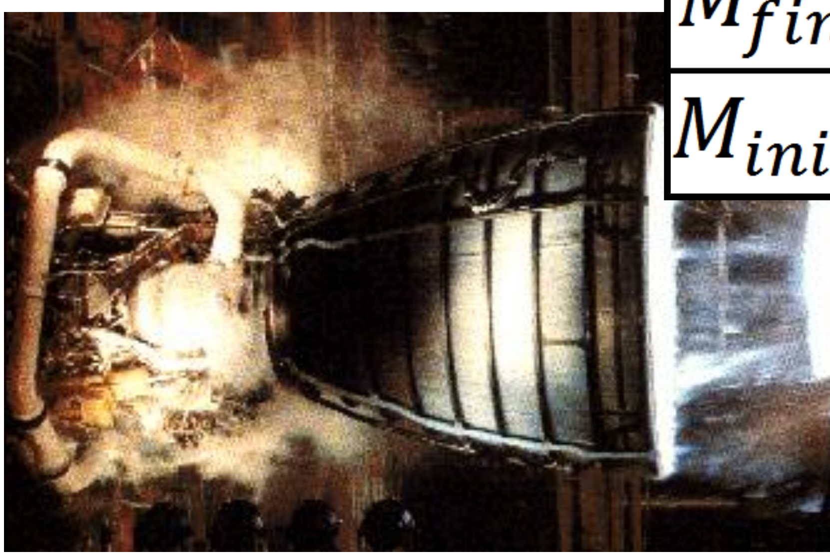
Chemical Propulsion

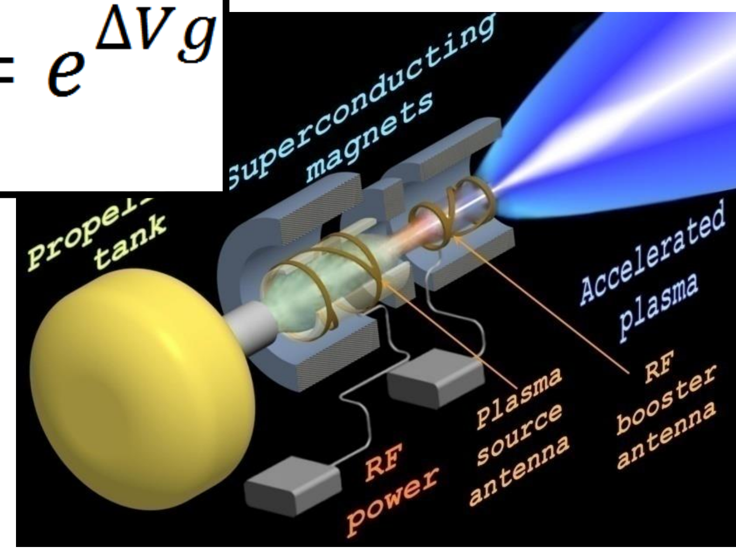
- Low Isp: < 450 s
- High thrust: $10^1 – 10^6$ N
- Short firing: < 1-10 min
- Requires fuel & oxidizer

Electric Propulsion

- High Isp: 1,000 to 40,000 s
- Low thrust: < ~10 N
- Long firing: Months -Years
- Requires electrical power
- Advantage: Saves propellant

$$\frac{M_{final}}{M_{iniial}} = e^{\frac{I_{SP}}{\Delta V g}}$$

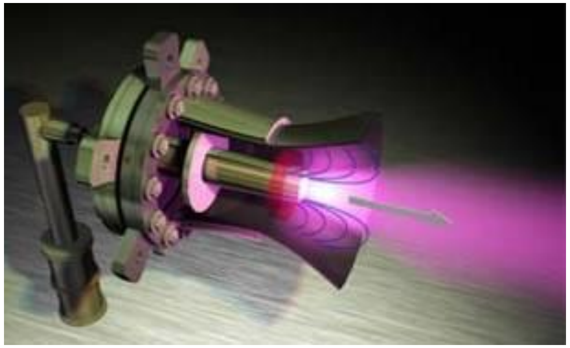




Electric Propulsion Devices

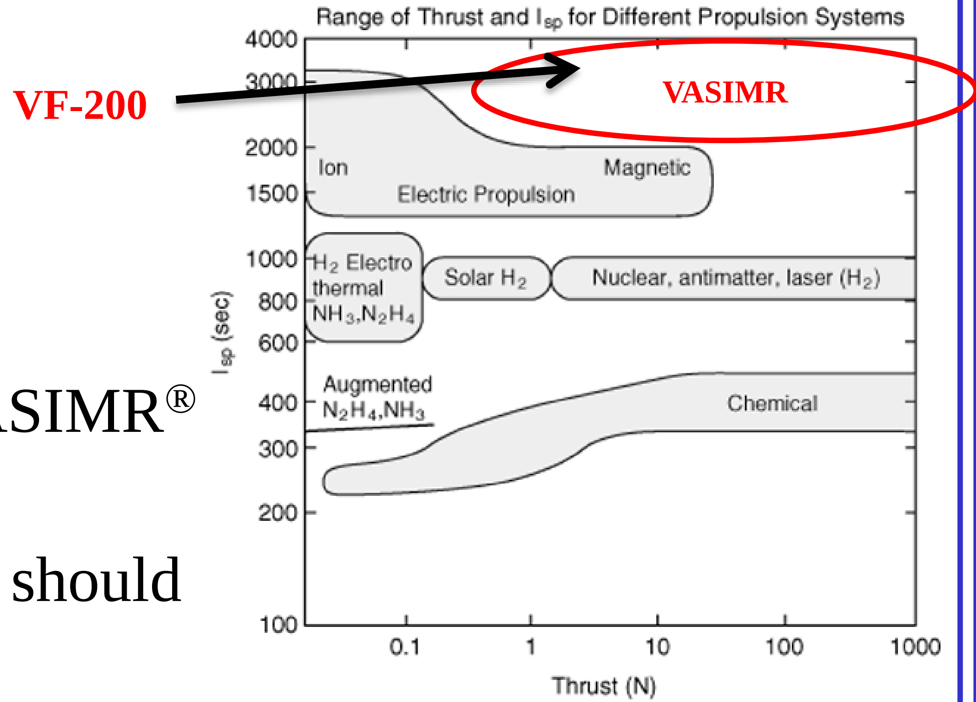
- Ion thrusters
  - Flight proven: 5 kW, ~70% to 80% efficient, > 30,000 hrs (XIPS, NSTAR)
  - Ground tested: 30 kW, 80% efficient (HiPEP, NEXIS)
- Hall thrusters
  - Flight proven/qualified: 4.5 kW, 60% efficient, 6,000 hrs (SPT)
  - Ground tested: 50 kW, 60% efficient (NASA-457M)
  - Advanced designs: 150 kW, 60% efficient (NASA-1000M)

- MPD thrusters
  - Flight test: Quasi-steady, one test flight, it worked (SFU)
  - Ground tested: Up to 500 kW, 30% - 60% efficient, 100s hours
  - Advanced designs: >250 kW, 50% efficient (α^2)



Unique VASIMR® Capabilities

- Operational parameters
  - 100s kW to 10s MW
  - >50% efficient
  - >>10,000 hours of lifetime
- Few thrusters can operate in VASIMR® power range
- VASIMR® is electrode-less and should have long lifetime
- Constant power throttling



- We believe that very soon there will be a market requiring thrusters that use 200 kW to 20 MW of power and that VASIMR® is best suited to fill that market

VASIMR® markets

All-Chemical Lunar Cargo Performance

IMLEO: 100 mT

LOX/LH2 Engine
450 s Isp throughout
masses rounded to nearest mT

LOI: lunar orbit insertion

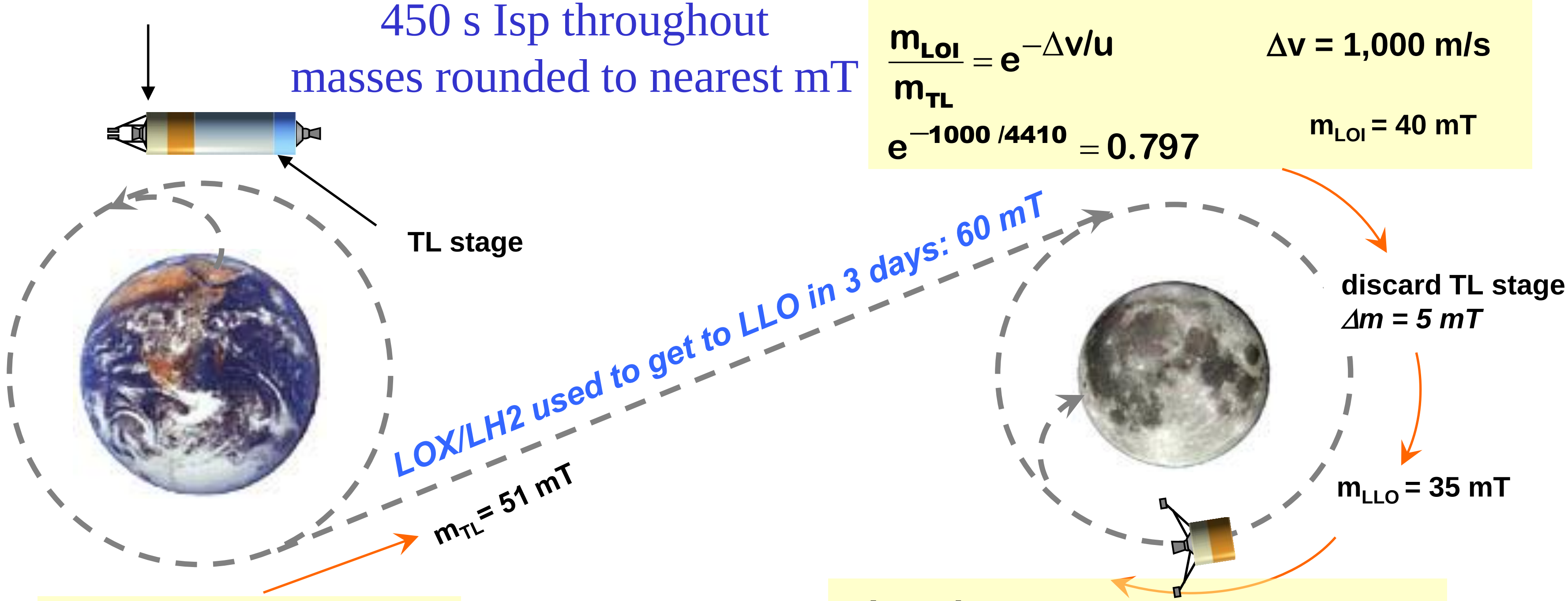
$$\frac{m_{LOI}}{m_{TL}} = e^{-\Delta v/u}$$

$$e^{-1000/4410} = 0.797$$

LOI burn:

Δv = 1,000 m/s

m_{LOI} = 40 mT



TLI: trans-lunar insertion

TLI burn:

Δv = 3,000 m/s

$$\frac{m_{TL}}{m_{LEO}} = e^{-\Delta v/u}$$

$$e^{-3000/4410} = 0.506$$

lunar descent:

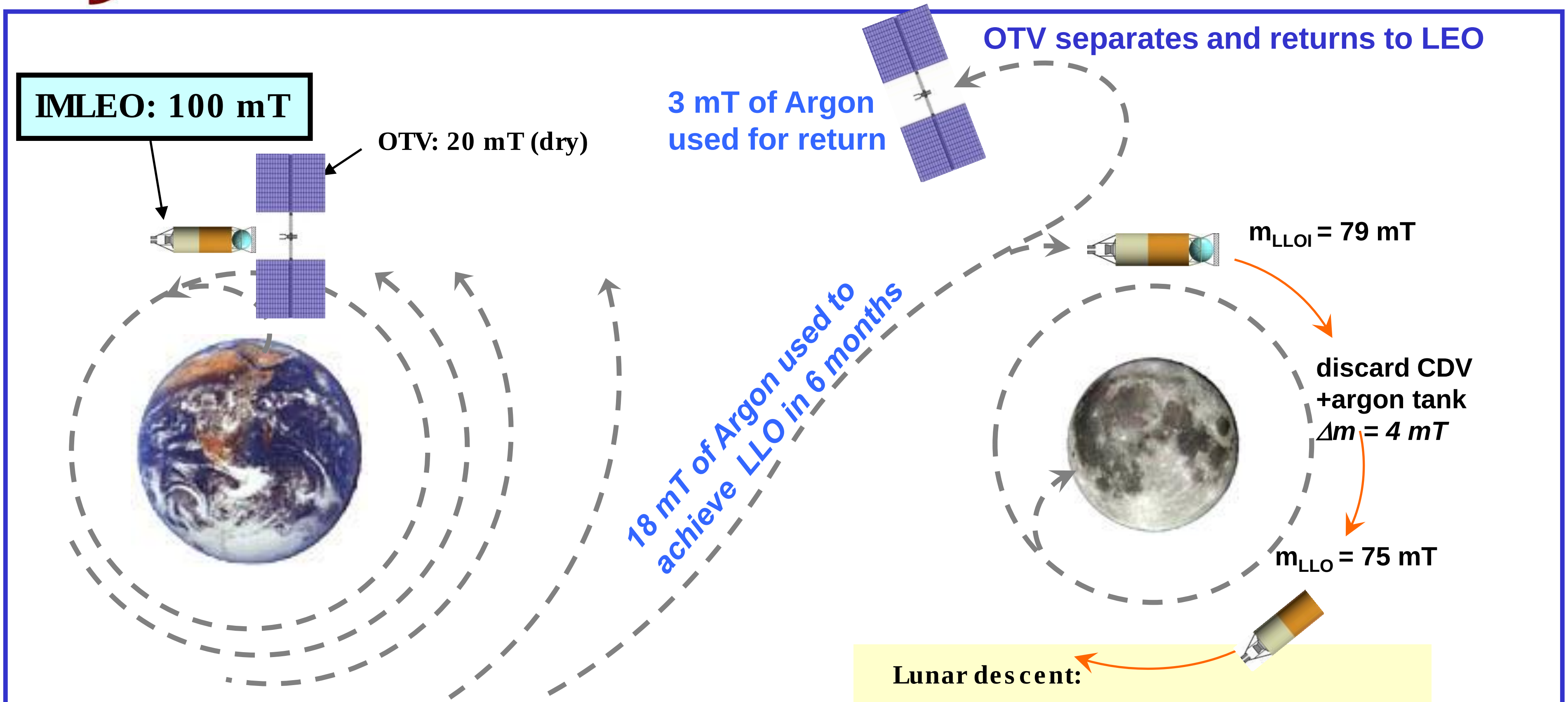
Δv = 2,000 m/s

Assume cargo mass %80 of landed mass

cargo = 0.51 x m_{LLO}

cargo mass on lunar surface = 18 mT

VASIMR® Lunar Cargo – 5,000 s Isp



Spiral from LEO to LLO:

Δv = 8,000 m/s *(Edelbaum)*

$$\frac{m_{TL}}{m_{LEO}} = e^{-\Delta v/u}$$

$$e^{-8000/49000} = 0.849$$

Lunar descent:

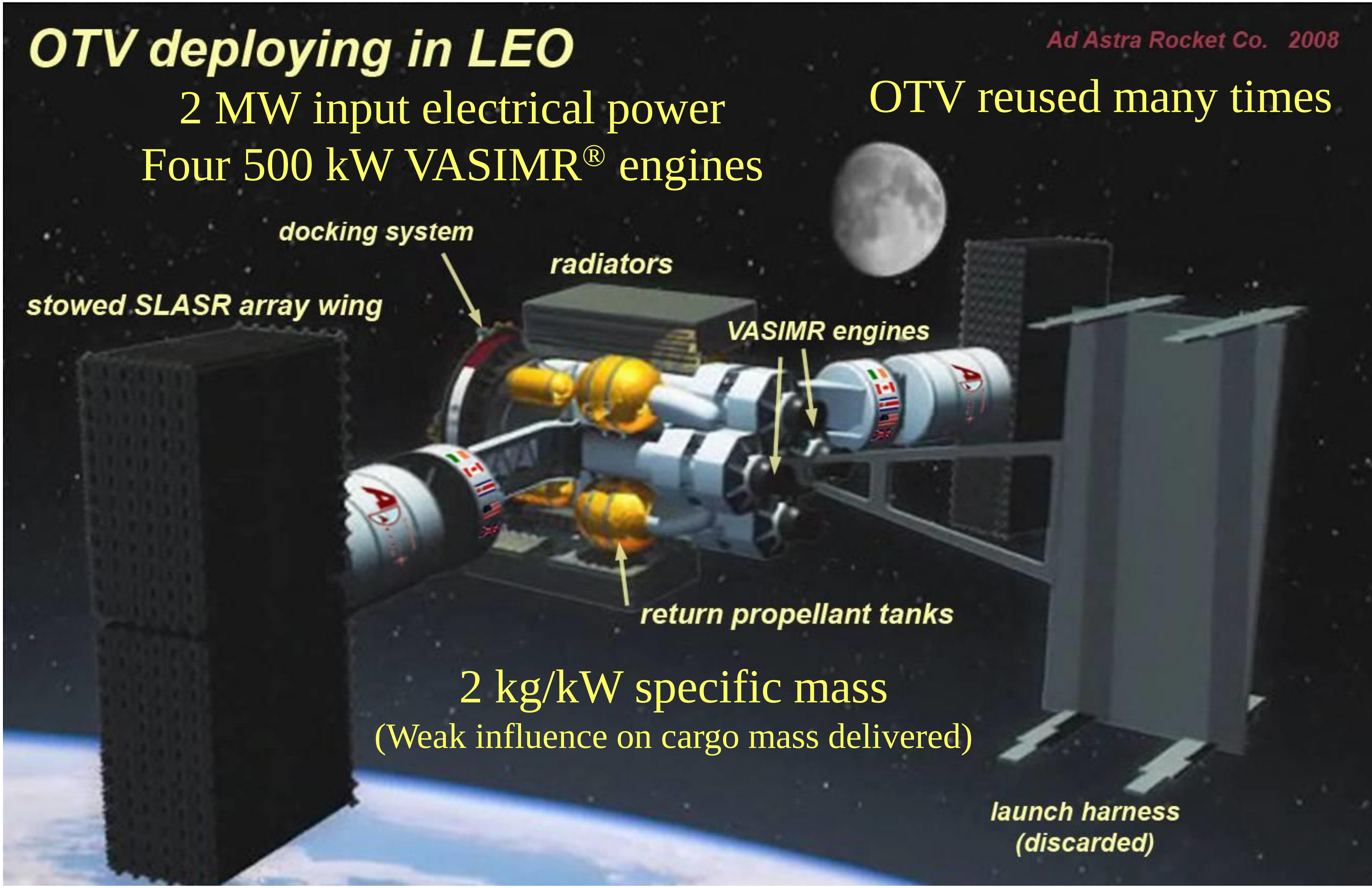
Δv = 2,000 m/s

Assume cargo mass %80 of landed mass

cargo mass = 0.51 x m_{LLO}

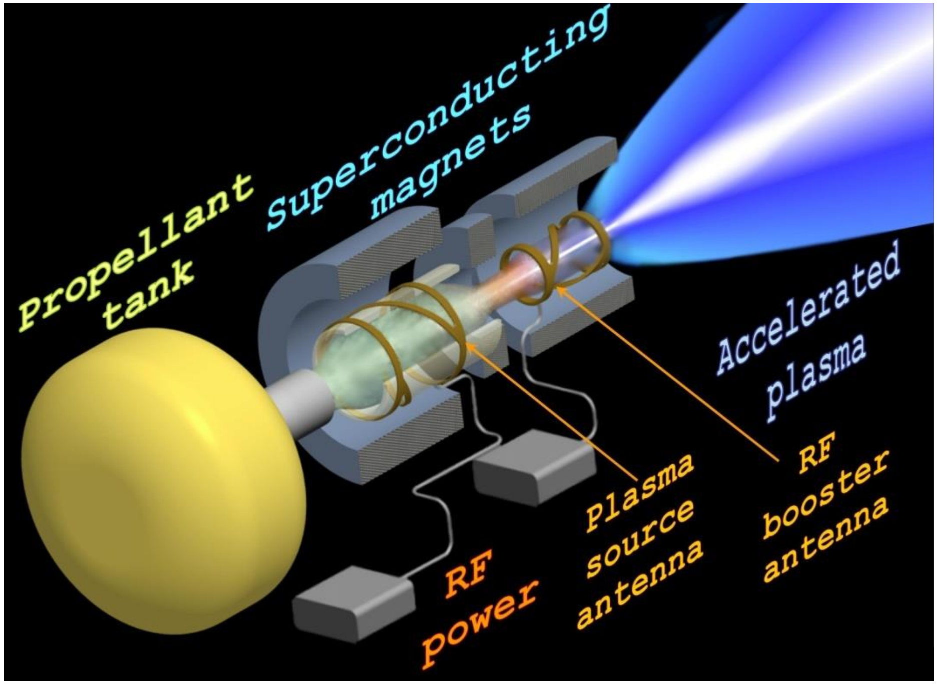
cargo mass on lunar surface = 38 mT

VASIMR® Orbital Transfer Vehicle



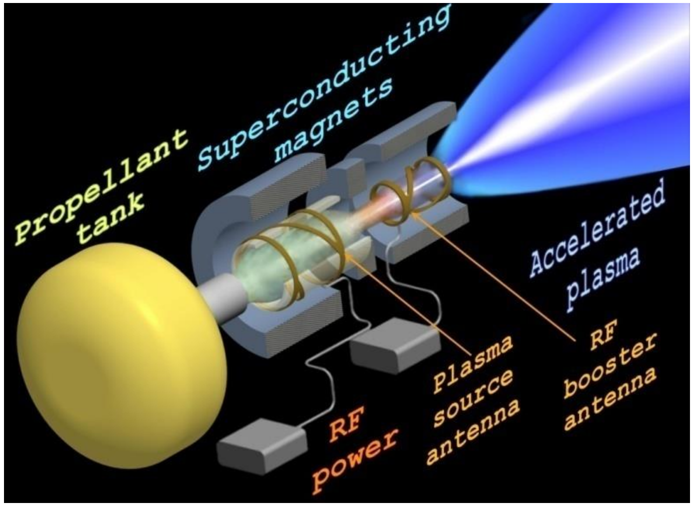
VASIMR® Design Challenges

- Waste heat management
  - With 50% efficiency, half the input power becomes waste heat
  - Heat must be extracted from within the magnet bore
  - Desire high temperature for small radiators
- RF power generation & efficient coupling to plasma
- Superconducting magnets
- Overall performance
  - >50% efficiency
  - Lifetime measurement
  - Plasma detachment



Plasma Diagnostics Challenges

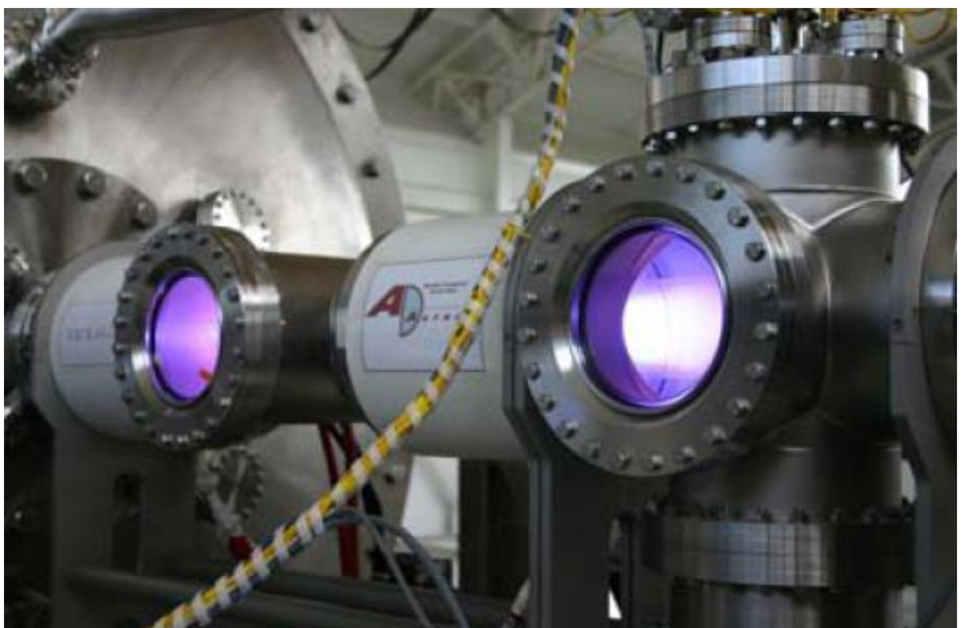
- Plasma Impact
  - >200 kW of heating!
  - Biased electrodes in a conducting medium
    - >300A available from plasma at low voltages
  - Erosion from 200 eV argon ion impact
- Large amounts of data
- RF harmonics and noise

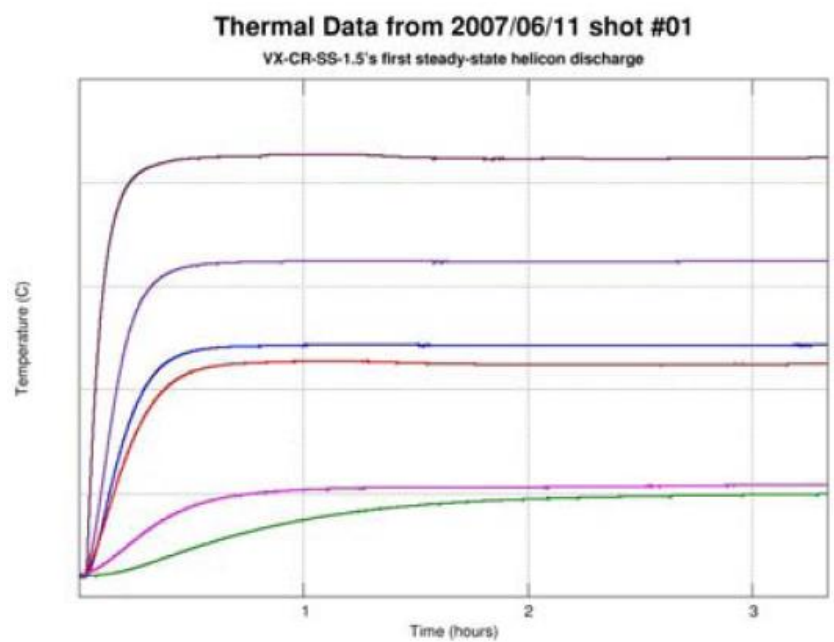


Ad Astra Costa Rica Subsidiary

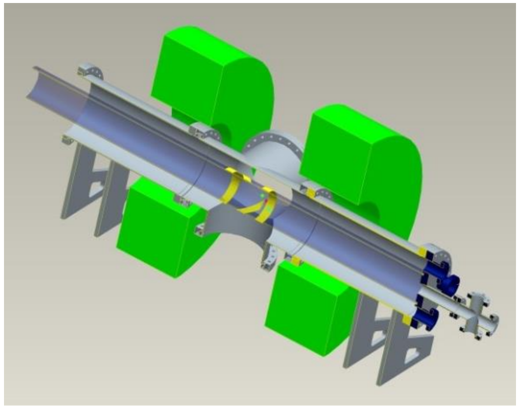
Costa Rica subsidiary

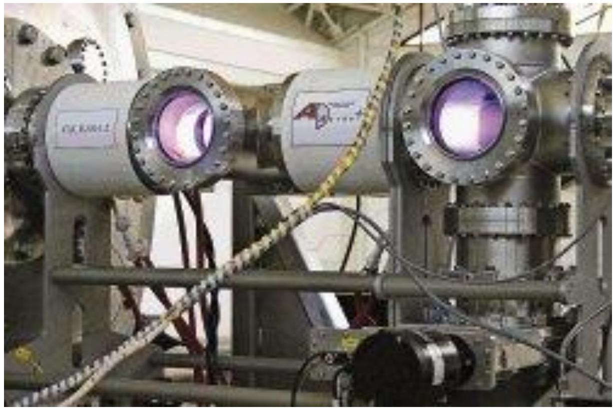
- Established Oct, 2005
- Formally incorporated Nov, 2005 to support USA operation
- Initial engineering tasks:
  - Helicon plasma source thermal management
    - Steady-state helicon operation
  - Life testing of VASIMR components
  - Engineering support of hazardous waste processing using plasma technology
- Initial 10 m^3 laboratory facility in EARTH La Flor campus



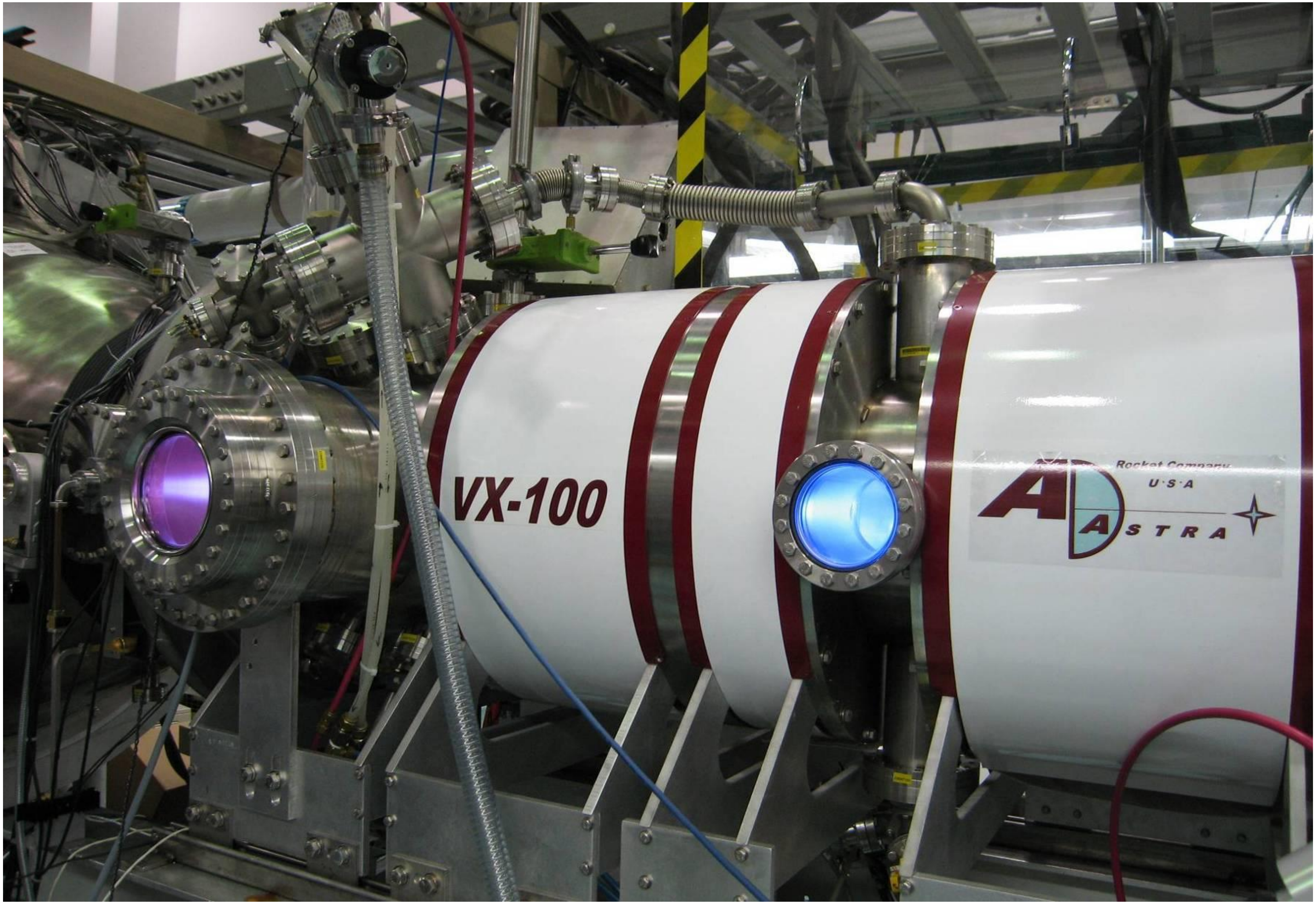


13 kW Ar Helicon Plasma Source



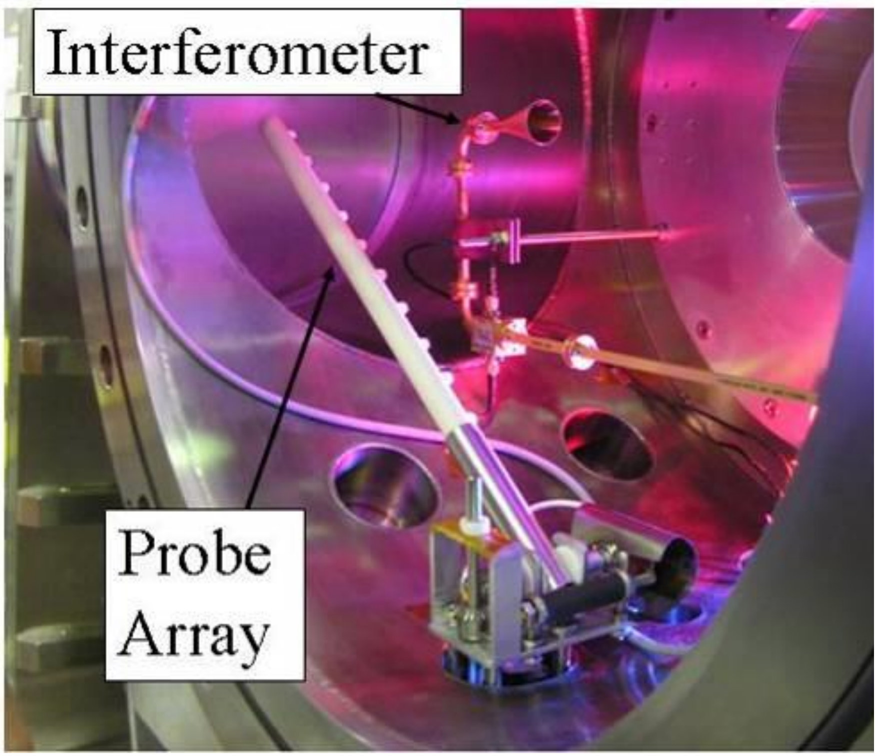


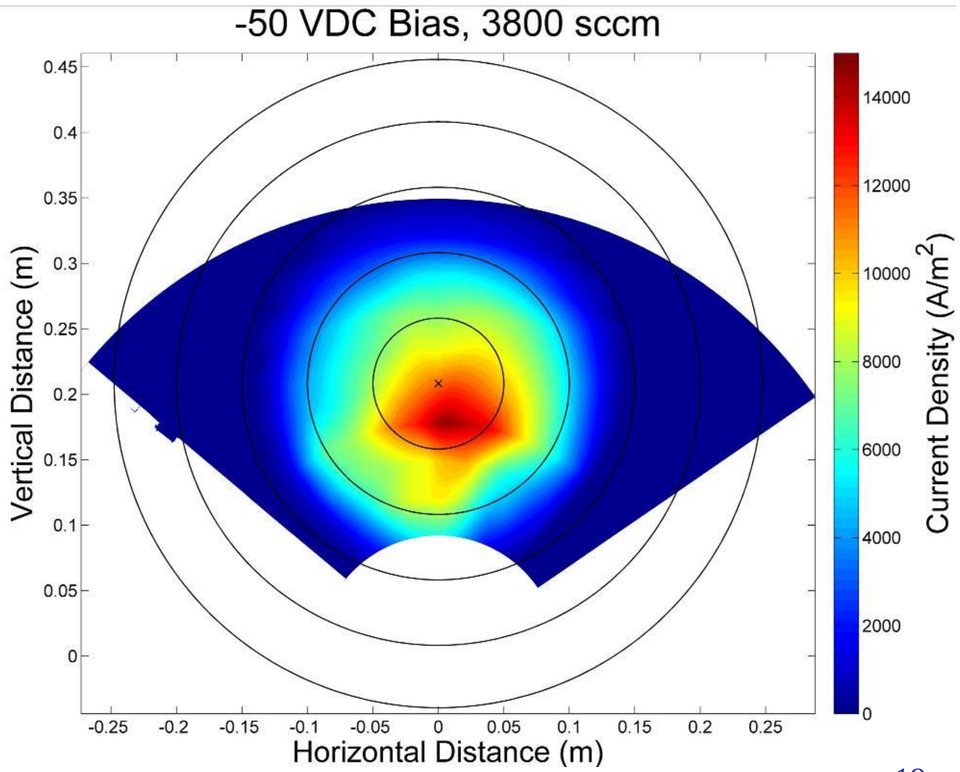
NASA-ASPL in Houston,VX-100 Operated 2007



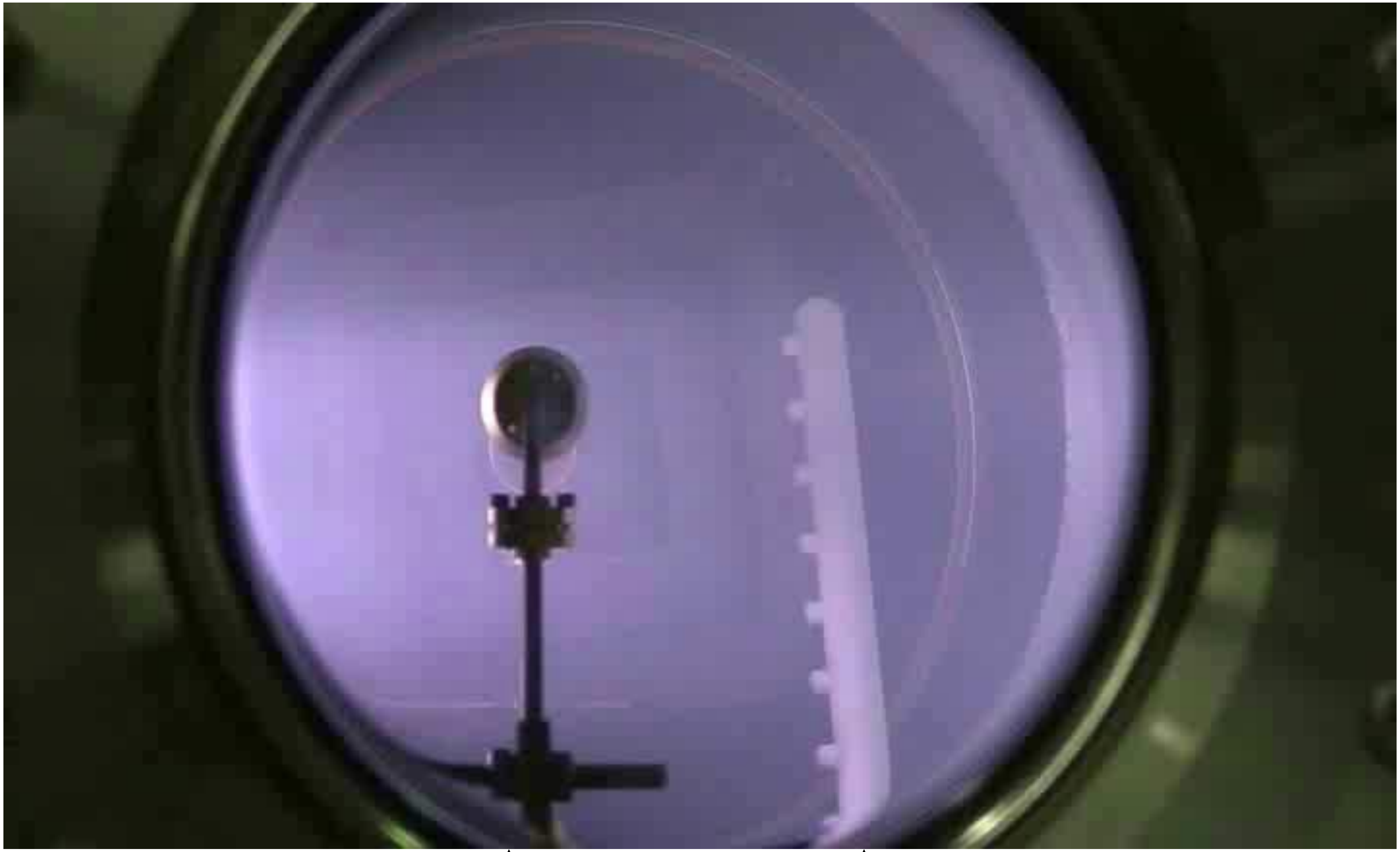
Source Performance Met Design Objective

- Two dimensional measurement of the plasma flux
  - Mechanically swinging
  - 10-collector planar Langmuir probe array
- Good agreement w/ past measurements that assumed axial symmetry.
- $1.7 \pm 0.3 \times 10^{21}$ ions/sec at 25 kW $E_I = 80$ eV, as desired





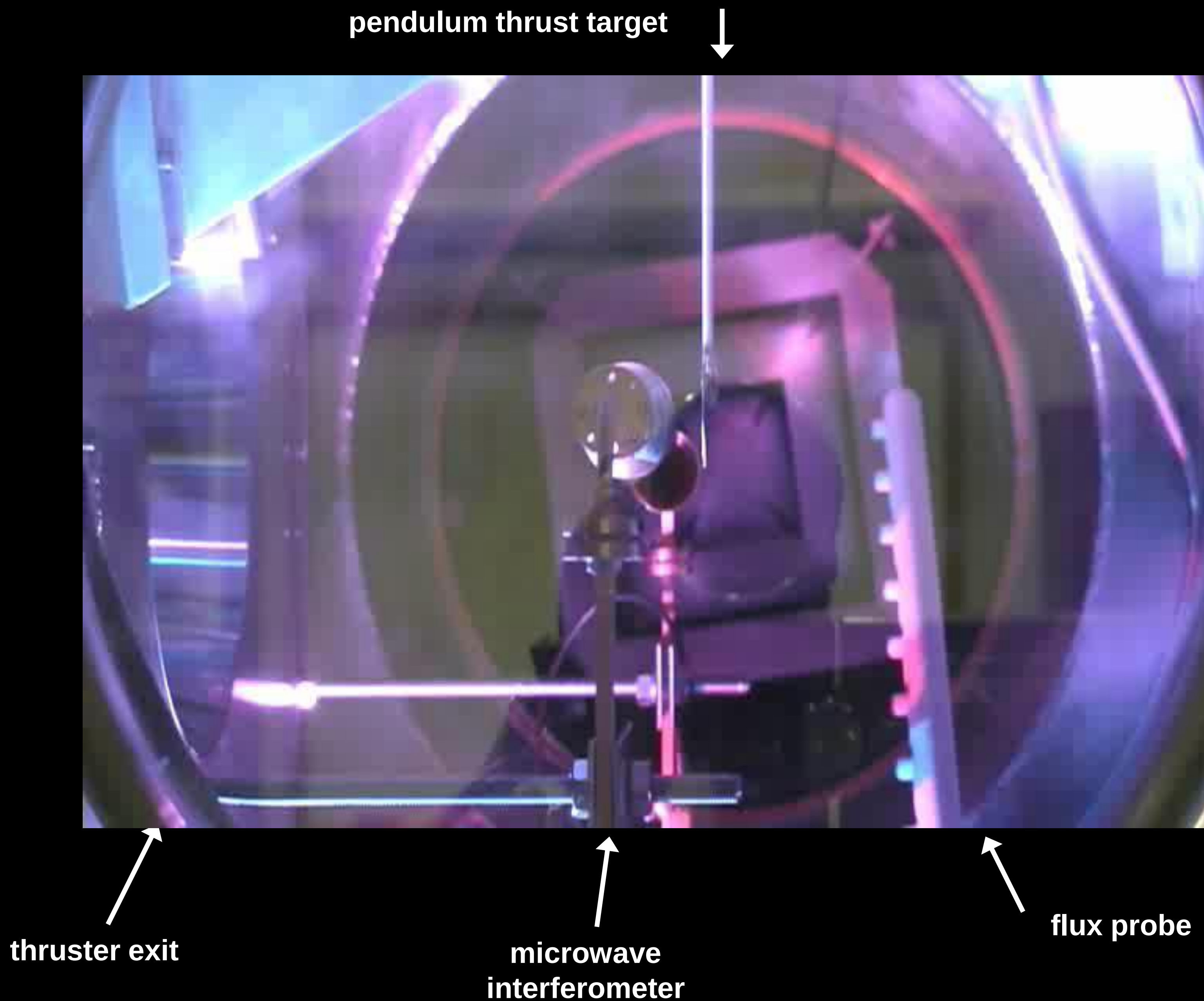
VX-100 Flux Measurement: Γ, ions/sec



$$E_I \equiv \frac{P_{helicon}}{\Gamma}$$

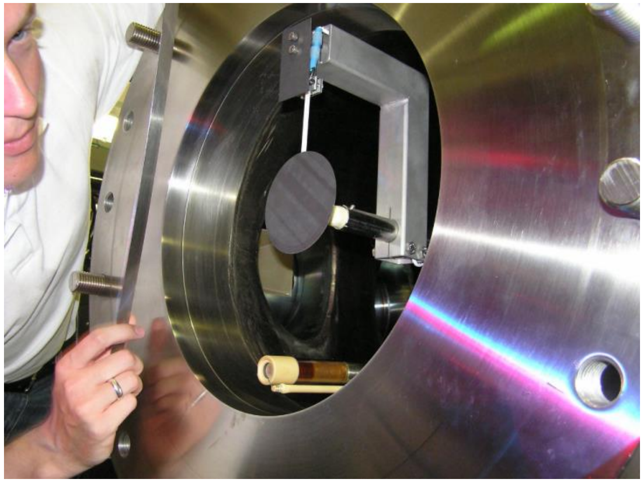
microwave interferometer

flux probe


pendulum thrust target
thruster exit
microwave interferometer
flux probe

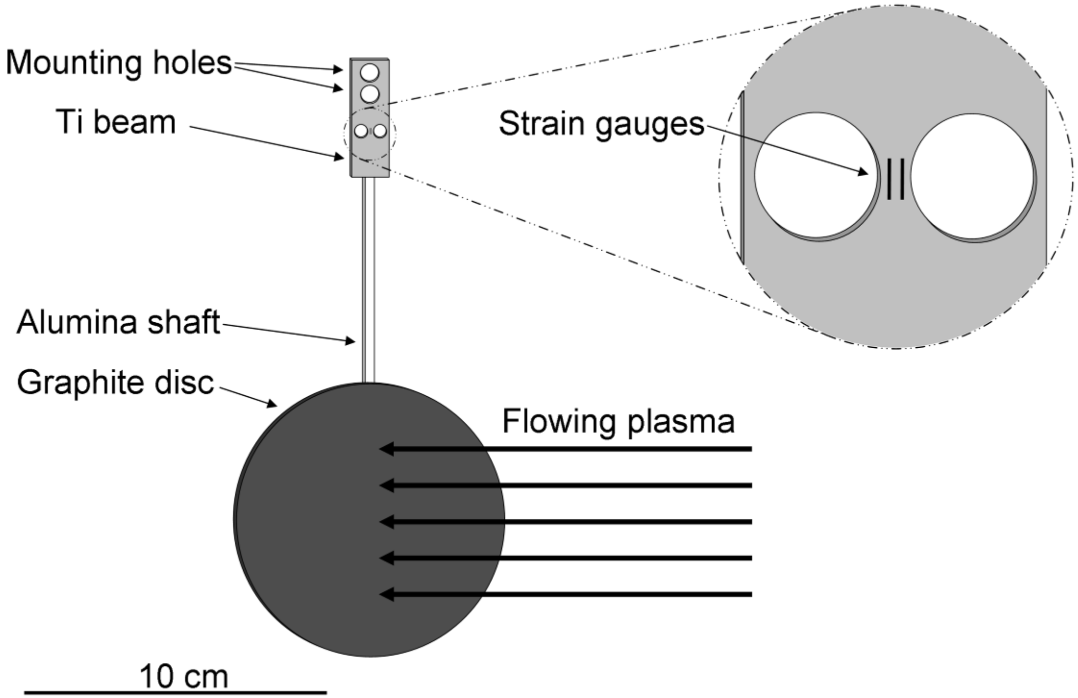
No one works in a vacuum

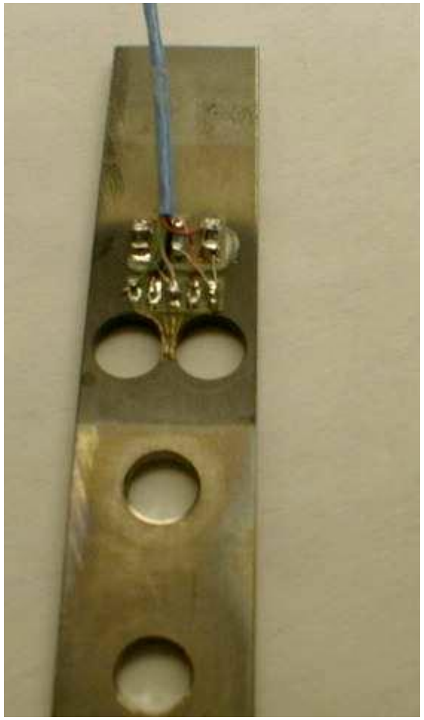
- Calibrated a force target sensor for the VX-100, VX-200 against a well studied Xe Hall Thruster
  - This technique is now used for VX-200 measurements



Force Target Design

- 9 cm graphite target is attached to a rigid alumina beam
- Alumina beam attached to strain gauge assembly (Ti beam)
  - Strain gauge assembly mounted to fixed structure on translation stage
- Use "isthmus" as a stress concentrator
  - 4 high output semiconductor strain gauges
  - Wheatstone bridge configuration
  - Bonded to Ti beam
- Strain gauge assembly based on G. Chavers design (NASA-MSFC).

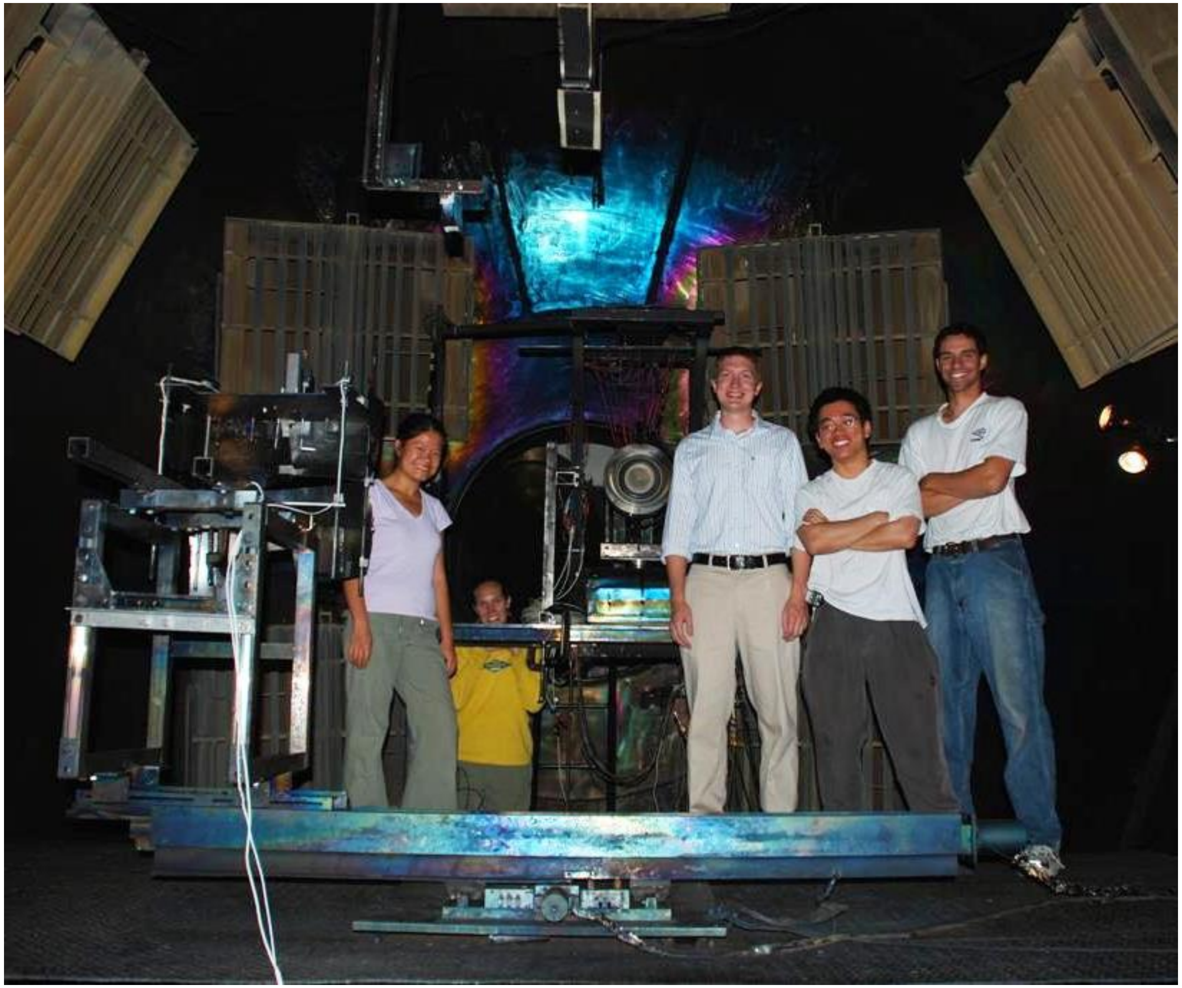


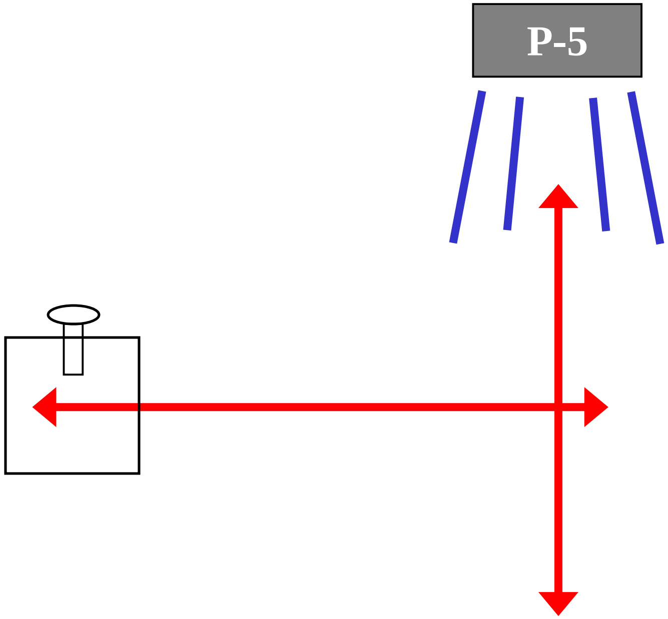


Univ. of Michigan LVTF chamber

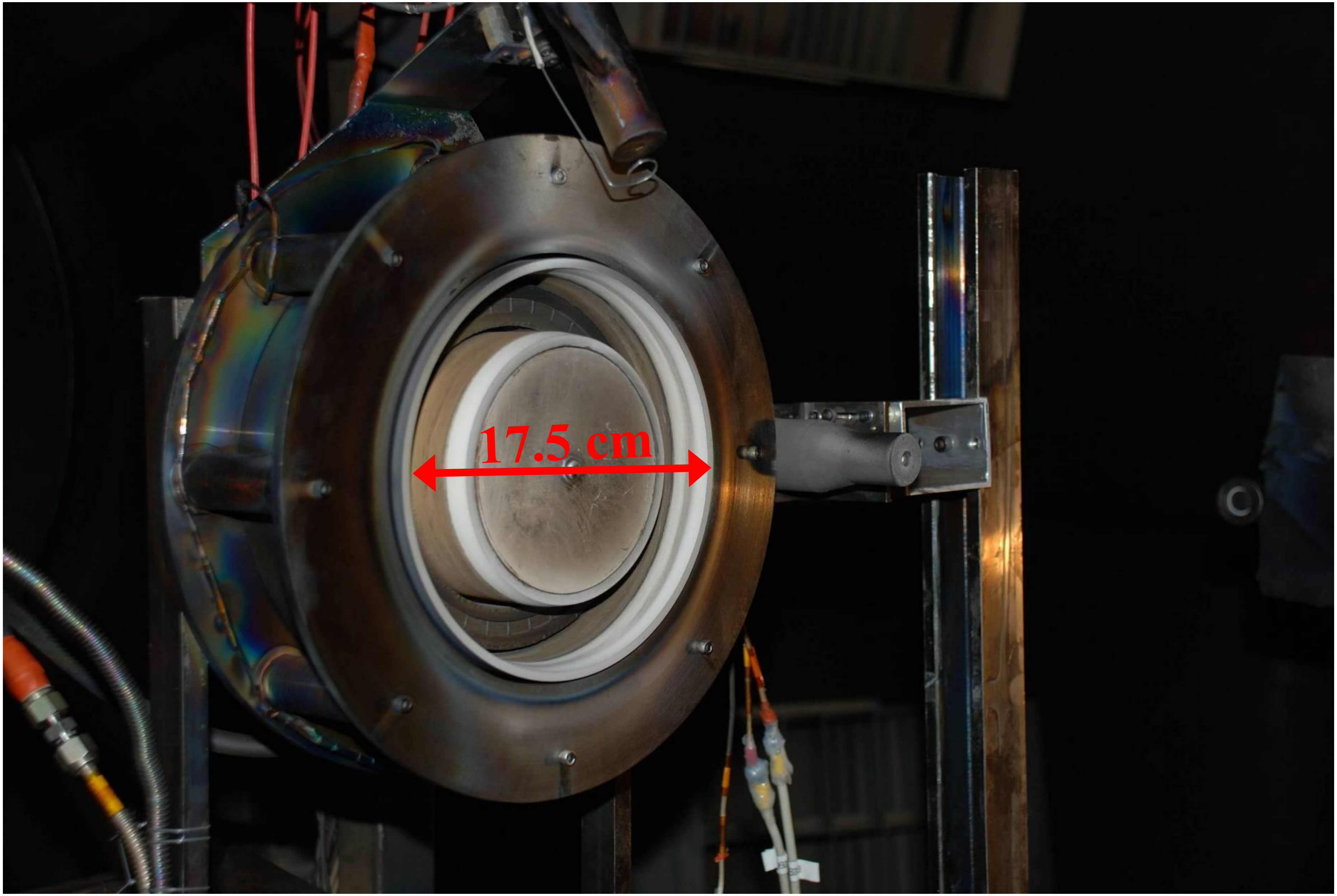
- Base pressure = 1x10^{-7} Torr
- Operating pressure (5 mg/s Xe) = 3x10-6 Torr
- Total Xe pumping speed 140,000 l/s
  - Used 4 of 7 cryopanels

- 9 m long x 6 m diameter
- Stainless steel clad chamber
  - Graphite panel beam dump
- 100 cm by 75 cm 2-axis translation stage

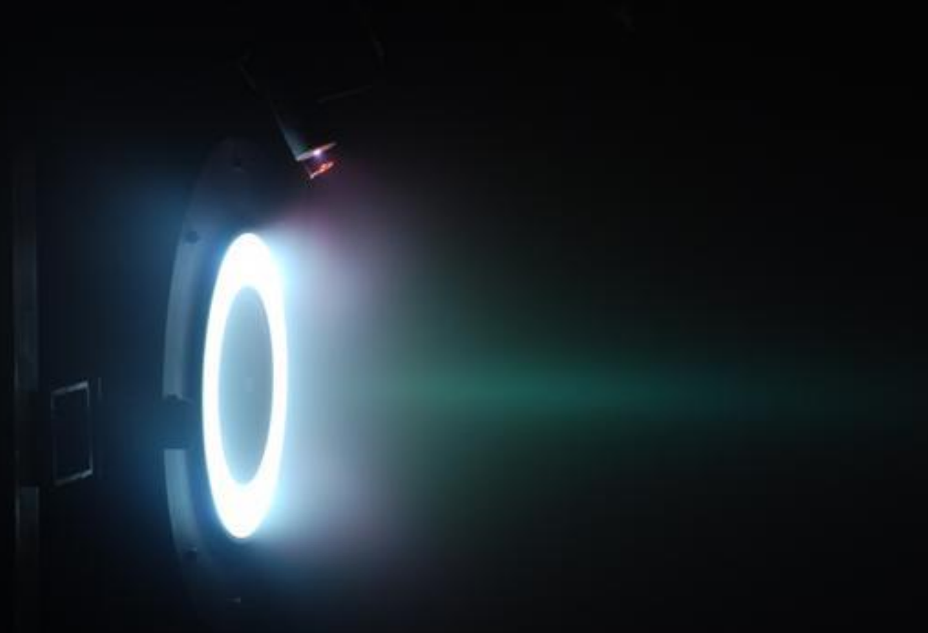




P5 Hall Thruster



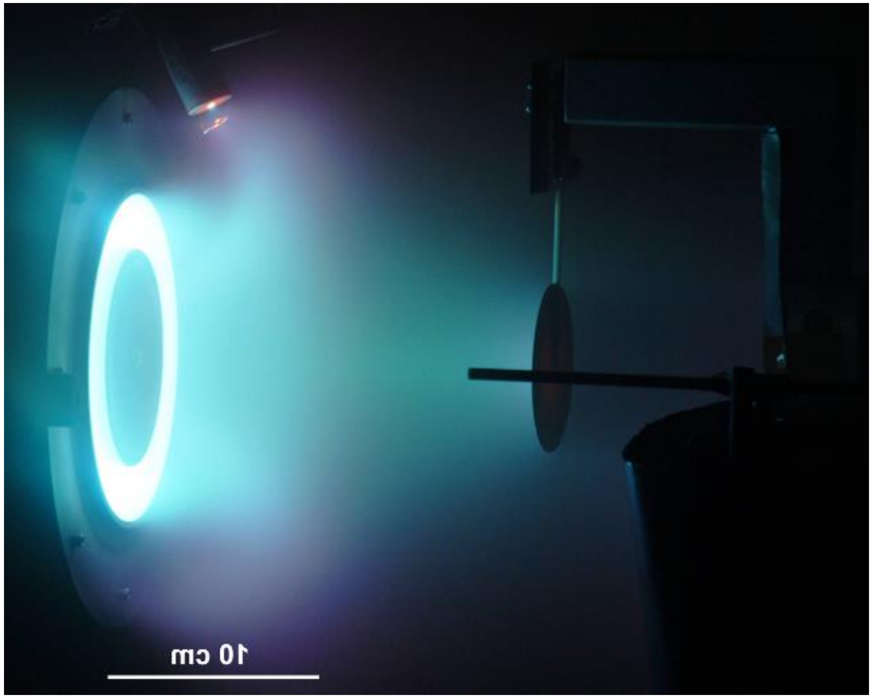
P5 Hall Thruster

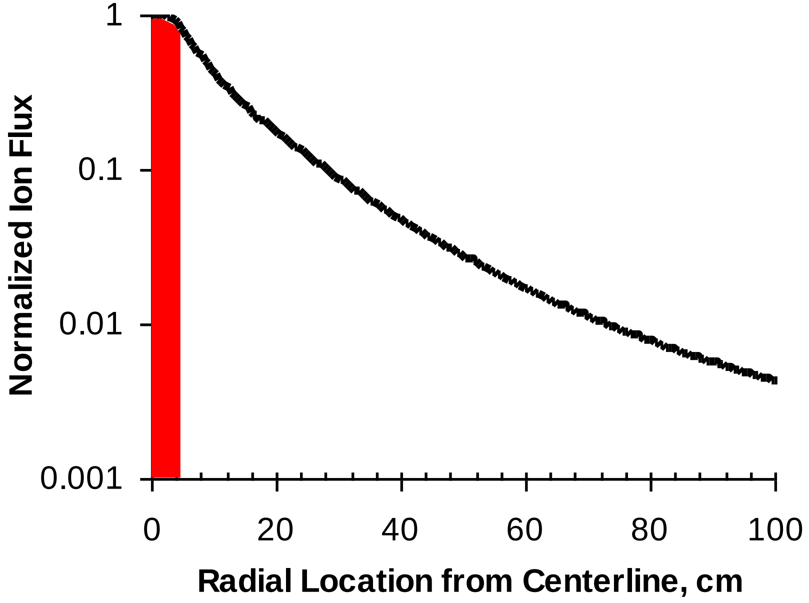


- 5 kW nominal power rating
  - ~300 V, 10 mg/s Xe
- Discharge OD: 17.5 cm
  - Channel width: 2.5 cm
- Performance comparable to commercial grade Hall thrusters
- Developed by UM and US AFRL
- Throttled P5 from 0.7 kW to 7.7 kW
  - 150 V to 500 V
  - 5 mg/s to 15 mg/s Xe
    - ~150 to 500 sccm Xe

Ion flux radial profile

- PMFS target only intercepts fraction of exhaust plume
  - Integration of the plume is computed based on a radial ion flux profile
    - Corrections made for sputtering
  - Assume azimuthal symmetry
    - Good assumption for P5

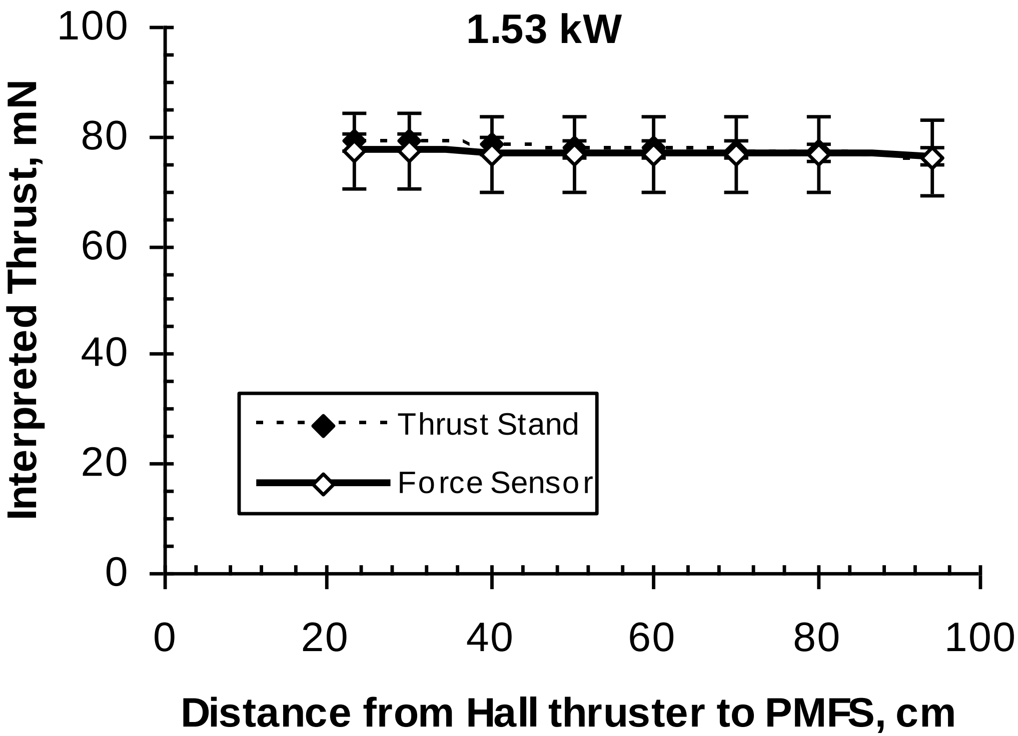




$$F_{\text{Total}} = F_{\text{Target}} \frac{\int_{r=0}^{r=100} \pi \left(r_{x+1}^2 - r_x^2\right) I\left(r_x\right)}{\int_{r=0}^{r=4.5} \pi \left(r_{x+1}^2 - r_x^2\right) I\left(r_x\right)}$$

Axial separation scan, less discrepancy than error bars

- All data points within error range of both force measurement techniques
- Typical error for thrust stand is ± 2 mN for these parameters.
- Observed increase in actual thrust as target approached Hall thruster
  - Recycling of neutrals
  - Increase in neutral pressure for close approach distance
  - Observed in similar experiments G. Chavers, NASA-MSFC



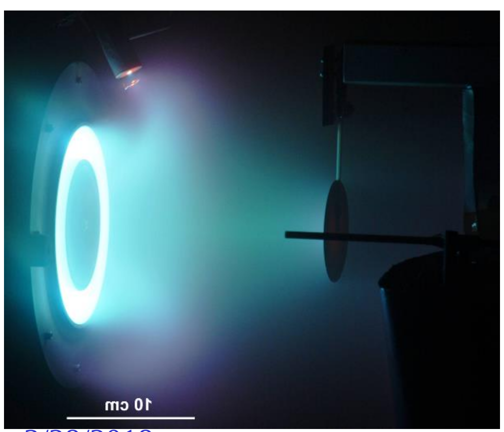
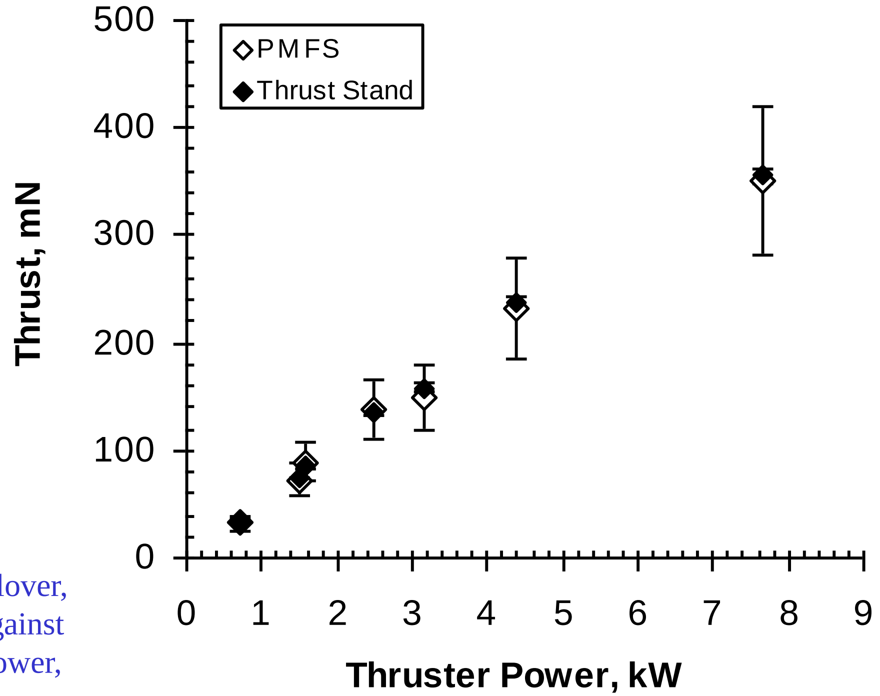


Table 1. Measured thrust versus the separation distance of the PMFS target from the Hall thruster.

Separation distance, cm	94	80	70	60	50	40	30	23
PMFS, mN	**76.1**	**76.6**	**76.8**	**76.8**	**76.9**	**76.9**	**77.1**	**77.3**
Thrust stand, mN	**76.3**	**77.1**	**77.6**	**77.9**	**77.9**	**78.4**	**79.2**	**79.2**
Difference, %	0.3	0.6	1.1	1.4	1.2	1.9	2.6	2.4
Anode Voltage, V	300	300	300	300	300	300	300	300
Xe flow rate, mg/s	5	5	5	5	5	5	5	5
Anode current, A	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1

Varying Hall thruster power level

- 50 cm separation distance between thruster and target
- Throttled P5 from 0.7 kW to 7.7 kW
  - Thruster system parameters were varied while leaving target stationary
    - 5 mg/s to 15 mg/s Xe
    - 150 V to 500 V anode bias
  - 7.7 kW operated in “pulsed” mode at high voltage (500 V)



B. Longmier, A. Gallimore, F. Chang Diaz, J. Squire, G. Chavers, T. Glover, **E. Bering III**, B. Ried, Validating a Plasma Momentum Flux Sensor Against an Inverted Pendulum Thrust Stand, AIAA Journal of Propulsion and Power, Vol. 25, No. 3, 2009, pp. 746 752.

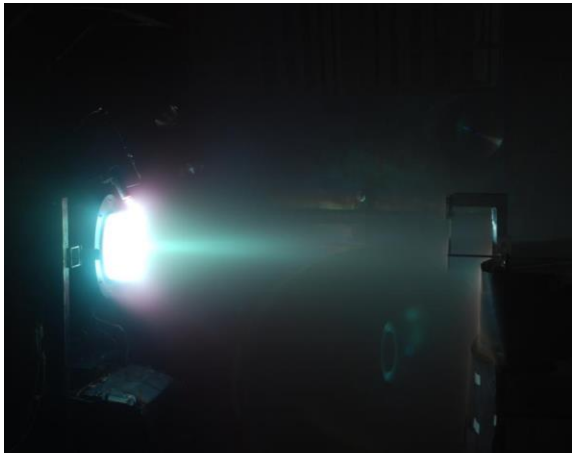
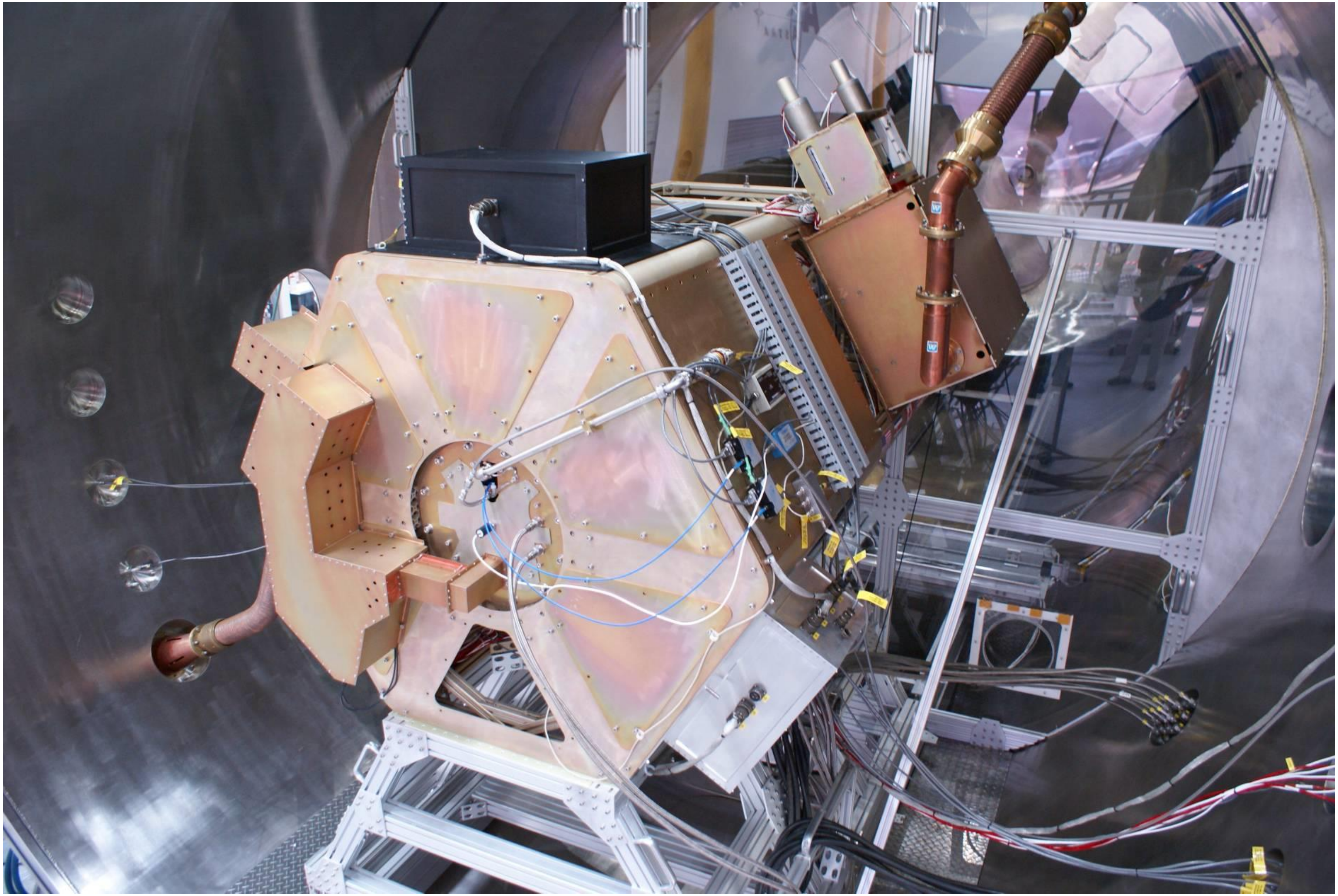


Table 3. Measured thrust for a variety of P5 Hall thruster power levels. The PMFS was located 50 cm downstream from the thruster exit plane.

Thruster power, kW	0.71	1.50	1.58	2.49	3.15	4.38	7.65
PMFS, mN	**32.6**	**72.7**	**89.2**	**138.2**	**149.7**	**231.4**	**350.7**
Thrust stand, mN	**33.9**	**73.6**	**85.9**	**136.6**	**158.8**	**237.1**	**355.8**
Difference, %	3.6	1.2	3.8	1.2	5.7	2.4	1.4
Anode Voltage, V	150	300	150	150	300	300	500
Xe flow rate, mg/s	5	5	10	15	10	15	15
Anode current, A	4.7	5.0	10.5	16.6	10.5	14.6	15.3

VX-200i – Starboard Side

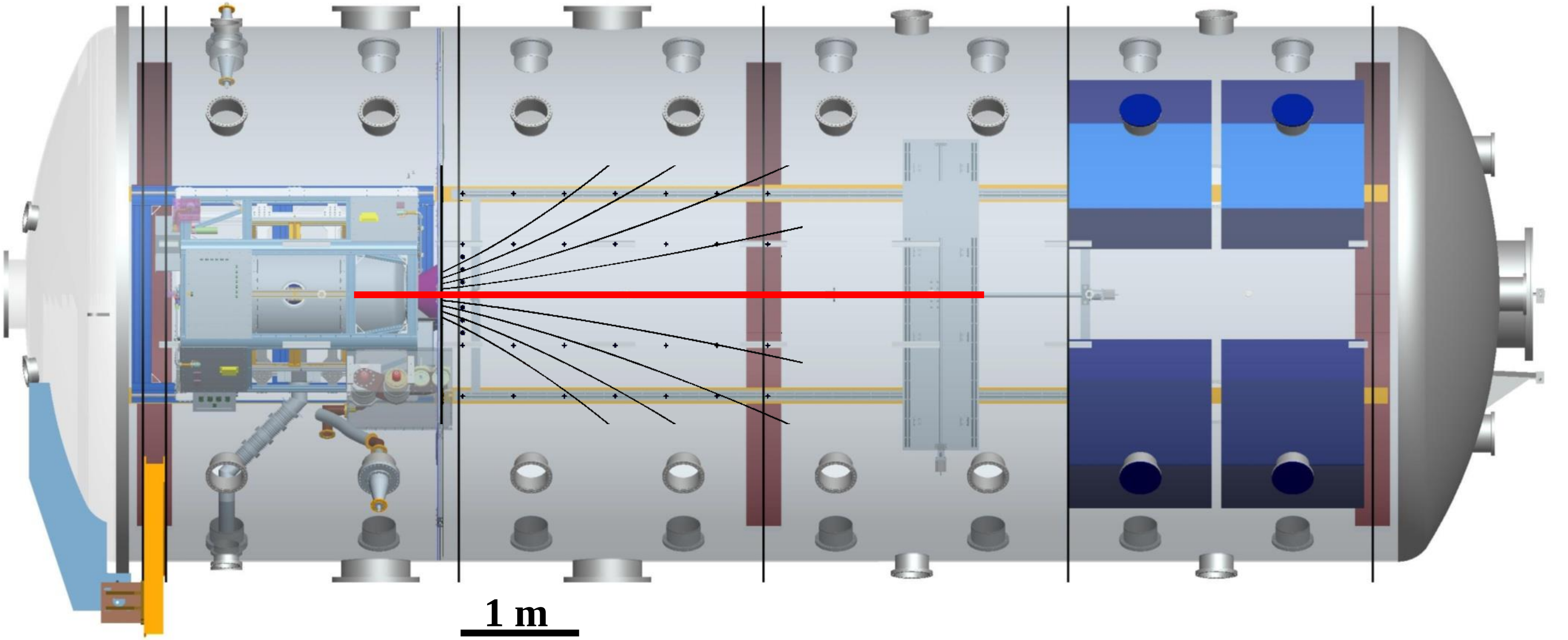
VX-200i – Port Side



New Houston Facility–150 m^3 Vacuum Chamber

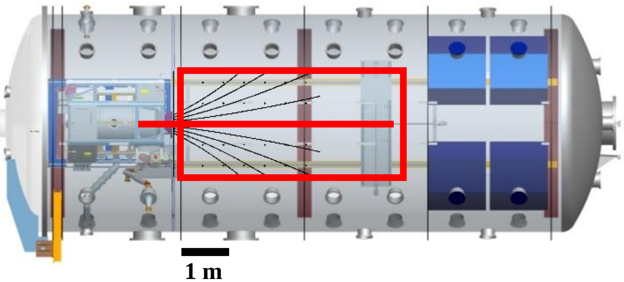
Diagnostics range and vacuum magnetic field lines

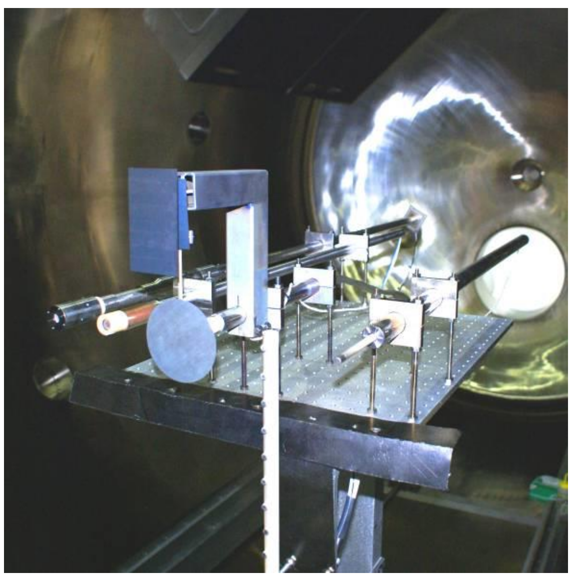
- Axial measurements were made over a 5 m range
  - 40 cm increments were used for coarse scan
  - 5 cm increments were used at interesting points
- 4x 50,000 l/s (N_2) cryo-panels
  - $2x10^{-8}$ Torr base pressure
  - $2x10^{-5}$ Torr with 25 mg/s argon propellant flow rate
- Vacuum chamber partitioned into rocket section and exhaust section
  - Used to maintain high vacuum in rocket section

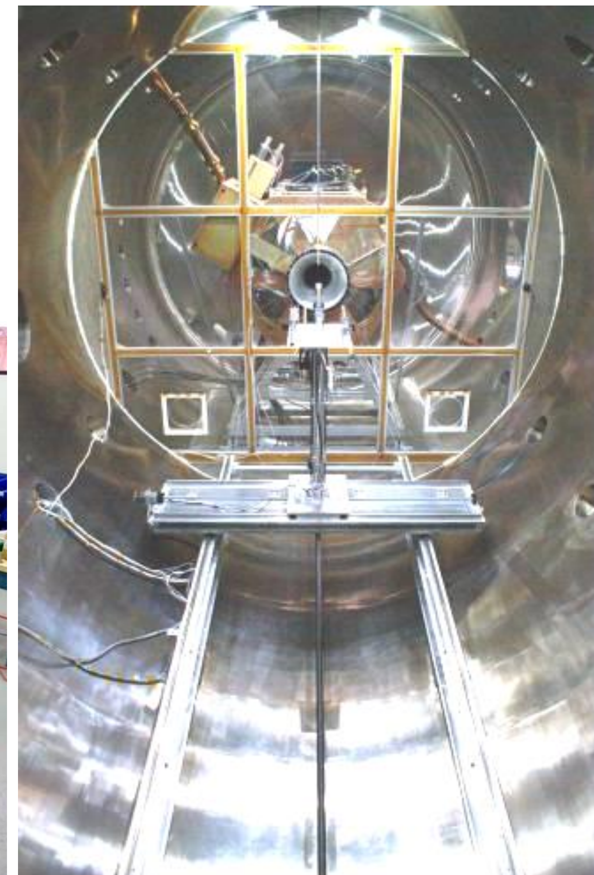


Translation stage allows full sampling of magnetic nozzle t

- 5 m by 2 m translation stage
  - 0.5 mm resolution
  - Graphoil leading edges
  - High vacuum compatible
  - Plasma diagnostics secured to mounting platform
  - Driven by ball screw via vacuum stepper motors
  - Linear guide rails
  - 200 kg capacity



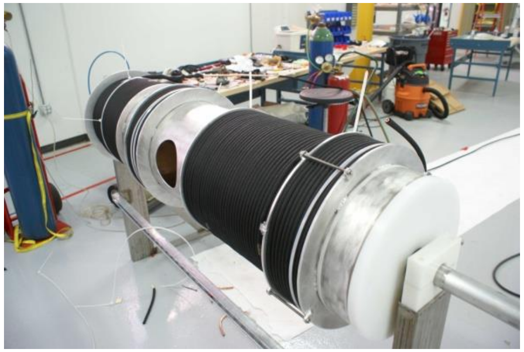




Interim magnet installation in VX-200i June,2008


Winding conductor


Alignment


Finished coil


Insertion in cryostat


Bus structure prep


Module insertion


Structure closure

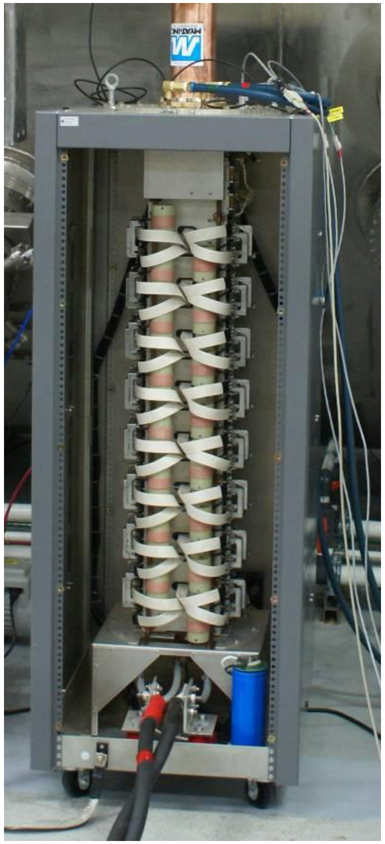

Pressure integrity prep

The "interim" magnet was developed very quickly (about 2 weeks) and involved the concentrated effort of the Costa Rica and Houston teams working closely together

RF Generator Development

- Nautel Limited designed and manufactured to our specs
  - Solid state
  - High efficiency
  - Very compact
  - Low mass
- Helicon
  - 48 kW
  - 93% efficient
- ICH:
  - 165 kW
  - 98% efficient

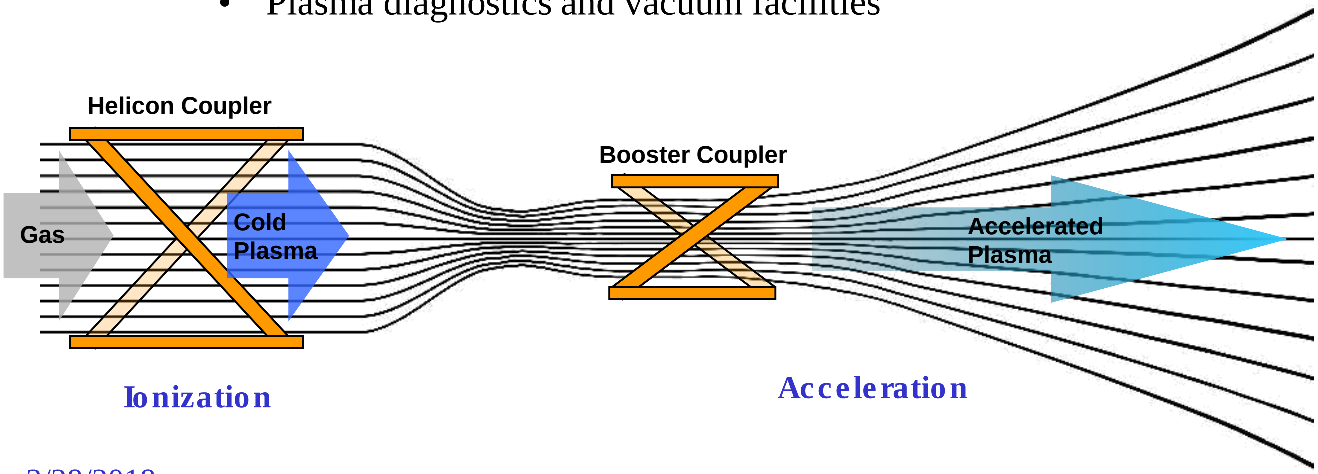
Helicon RF Generator



ICH RF Generator

VX-200i was technology test-bed, retired Apr 2009

- VX-200i prototype was a test bed for VASIMR technologies
  - 10% magnetic field strength of VX-200, but still a very interesting physics experiment
    - ~1700 gauss, water cooled copper magnets
  - Used to demonstrate:
    - Solid-state RF power generation at high power
    - High power RF transmission
    - Plasma-facing core
    - Engine bus assembly
    - In-vacuum control avionics
    - In-vacuum gas flow control
    - Plasma diagnostics and vacuum facilities



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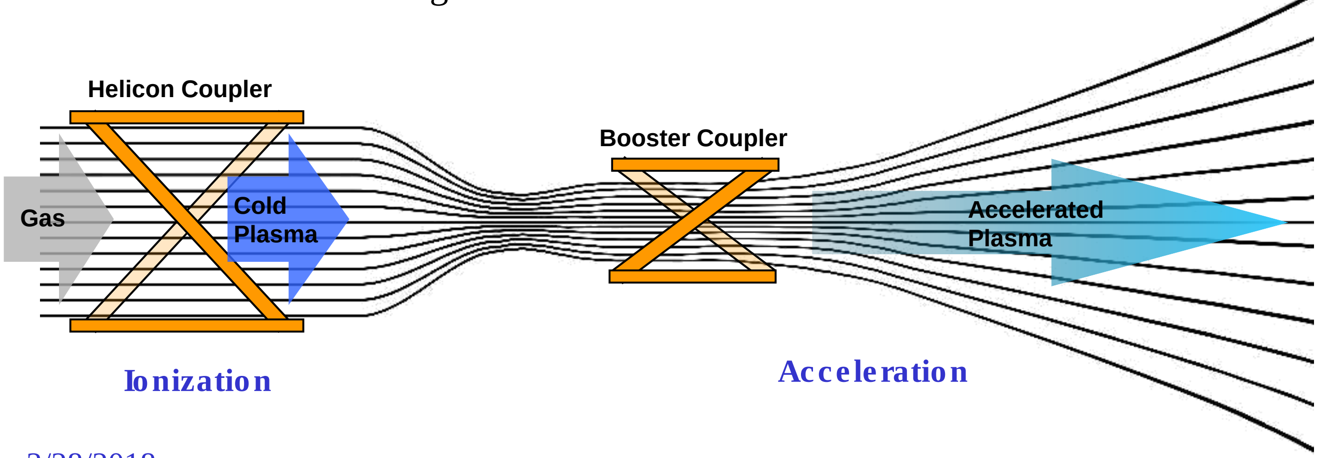
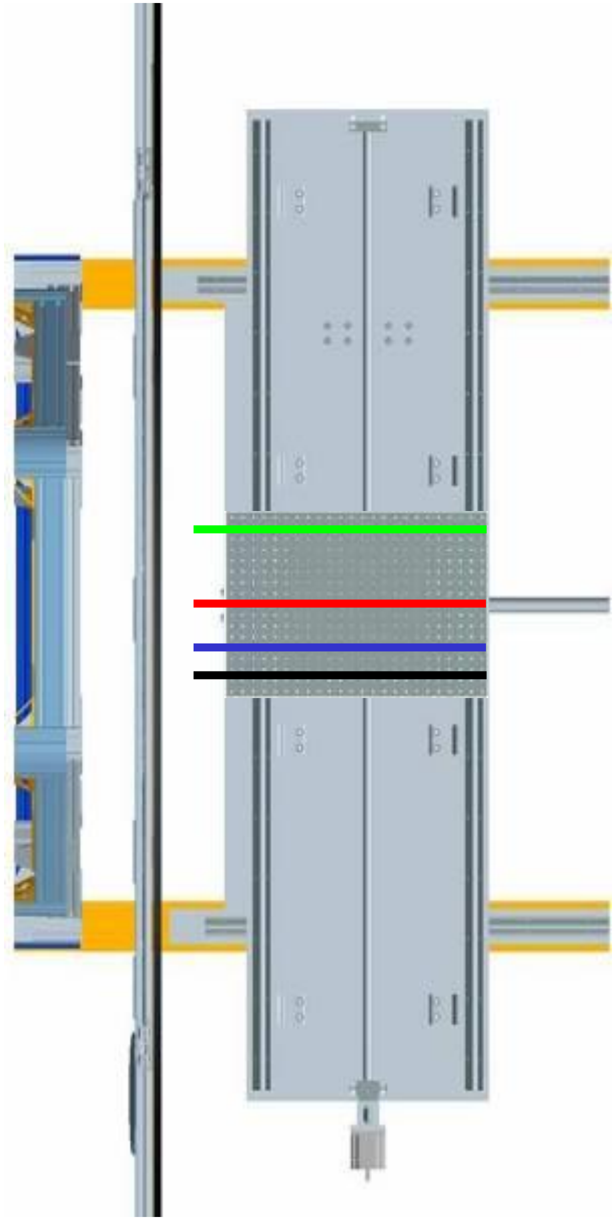
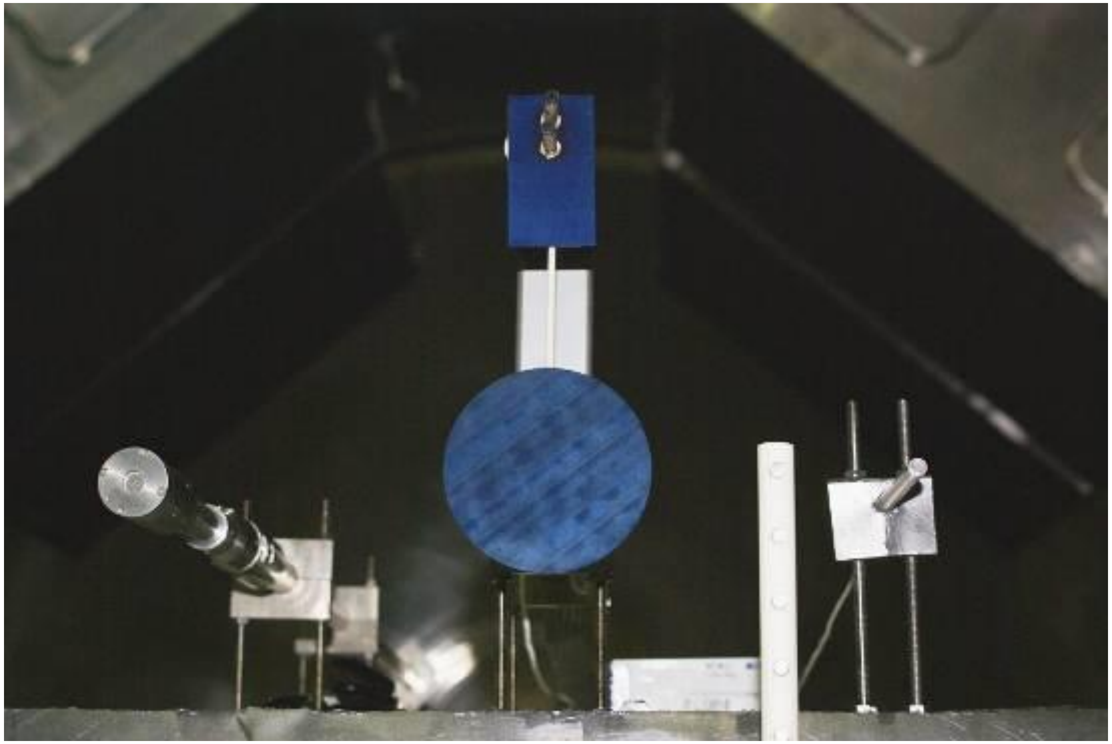


Translation Stage Table and Diagnostics

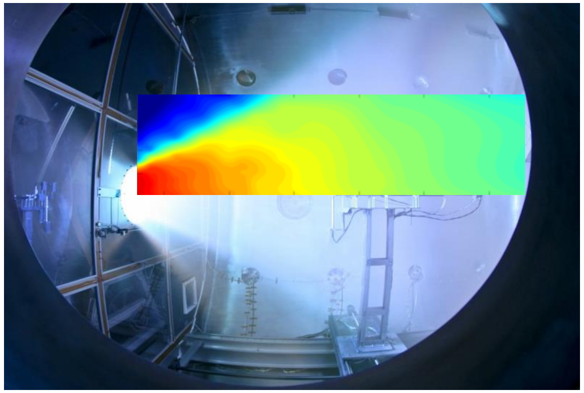


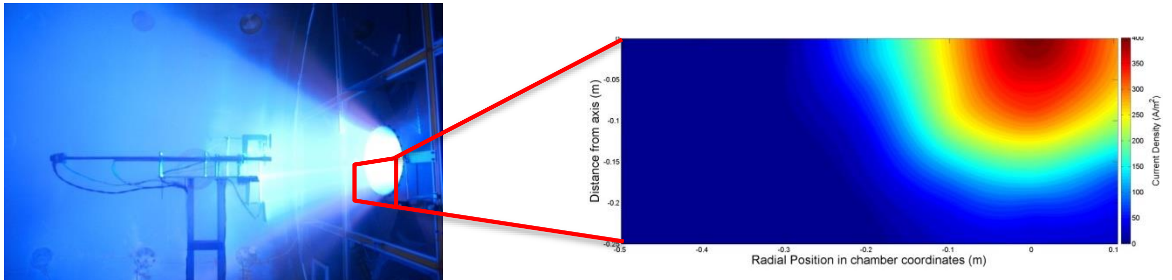


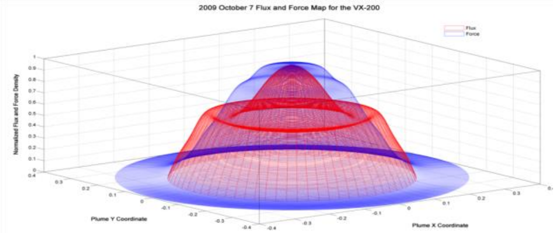
- UH RPA (green)
- Force Target & Magnetometer (red)
- Stationary Flux Probe Array (blue)
- Guarded Flux Probe (black)

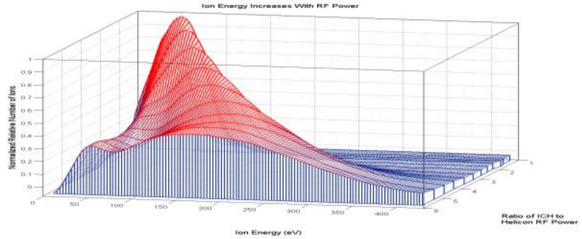
Plasma Measurements

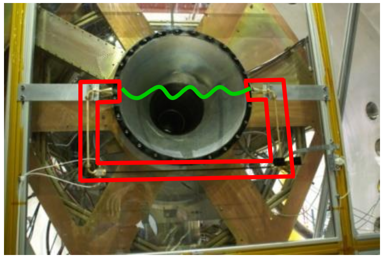
- Diagnostics include:
  - Infrared camera
  - Optical spectrometers
  - Microwave interferometers
  - Residual gas analyzer
  - EMI sensors
  - 3-axis magnetometer
  - Retarding potential energy analyzers
  - Ion flux, single, double, and guarded Langmuir probes
  - Plasma momentum flux and force targets
- 2 axis in-vacuum translation stage
  - 1 mm resolution
  - 5 m by 2 m travel

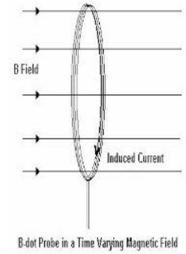












VX-200i used for double layer physics investigation

- **Hershkowitz:** “Double Layers consist of two adjacent charge layers of opposite charge.”
- **Charles:** “An electric double layer is a narrow localized region in a plasma which sustains a large potential jump.”
- **Boswell:** A stationary DL spontaneously forms in a current-free plasma expansion in a divergent magnetic field for low operating gas pressure, less than 2 mTorr.
- **Chen:** “We show here that the “double layers” of Boswell, Charles *et al.* are actually single layers and are predictable from classical sheath theory, normally applied to boundaries”

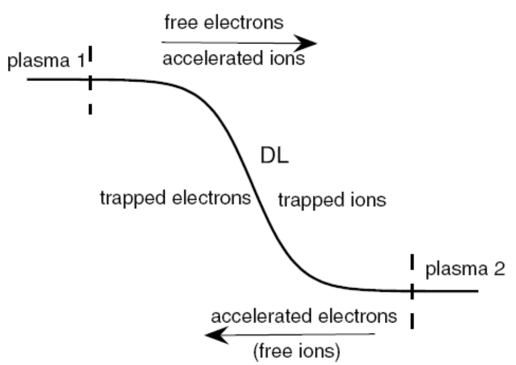
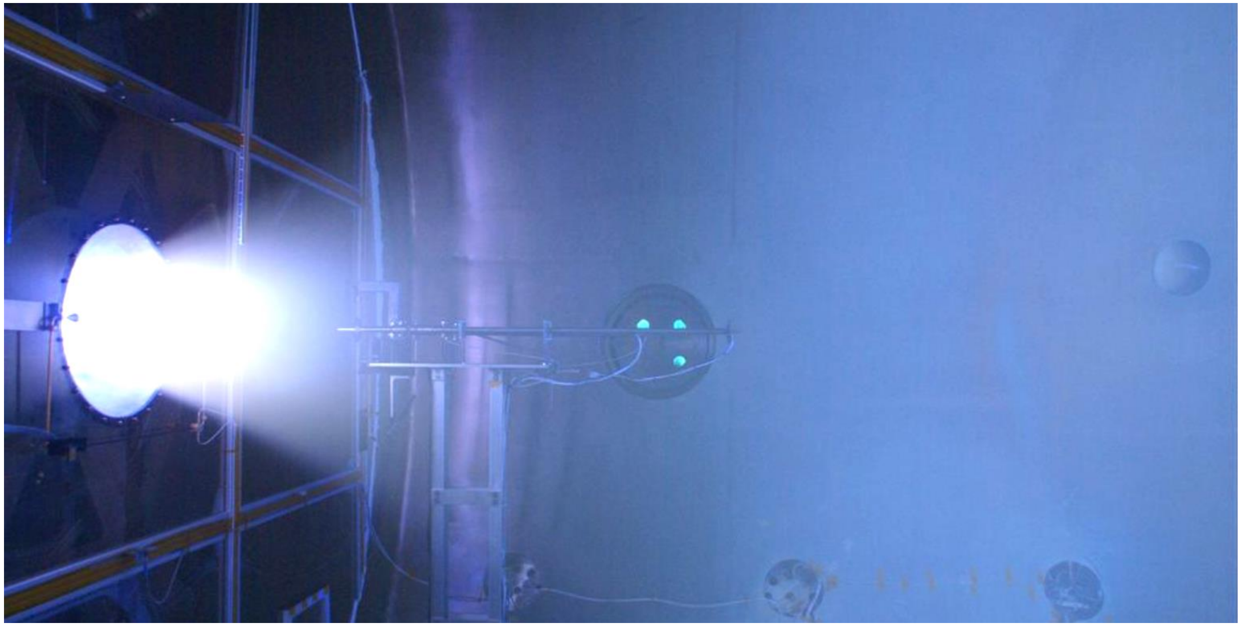


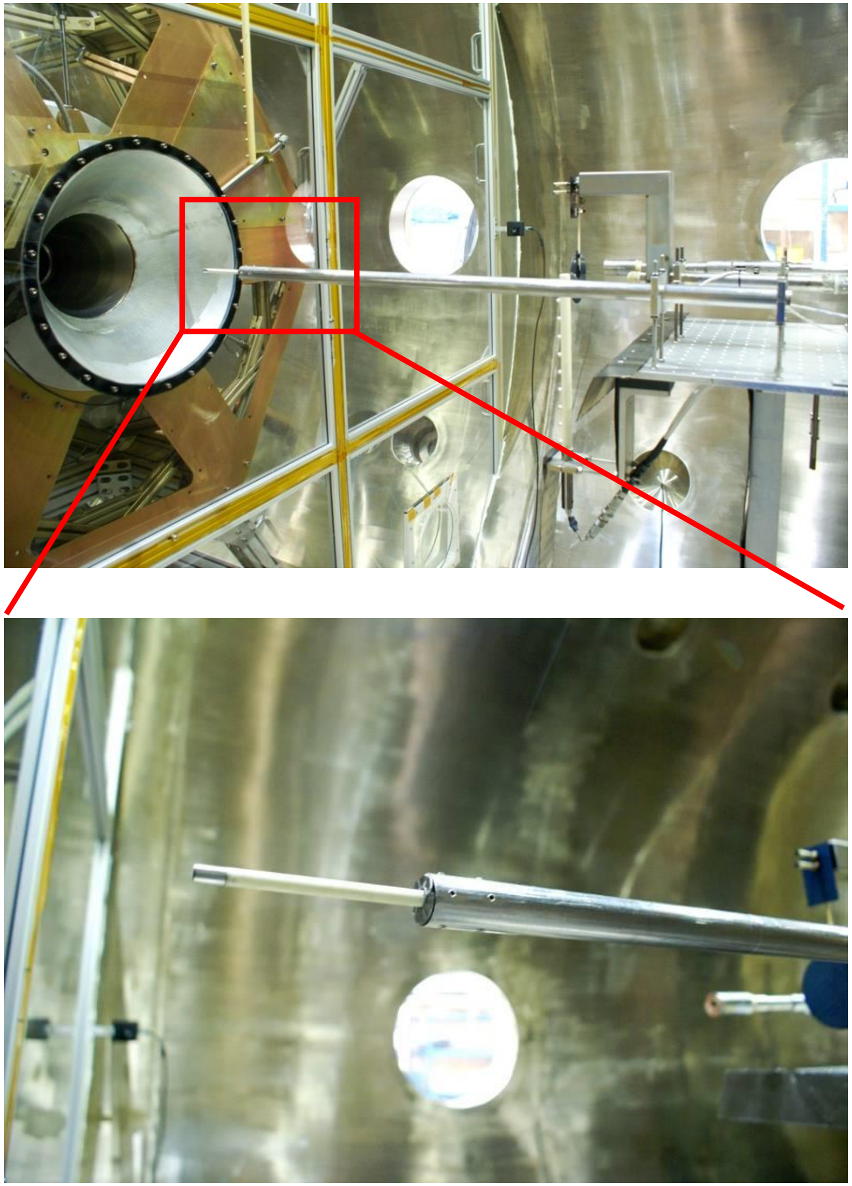
Figure 3. Schematic of potential for a double layer between two plasma sources (grids or aperture as dotted lines) or in an expanding plasma (no dotted lines and plasma 2 = plasma 1). In most cases $kT_i \ll kT_e \ll e\phi_{DL}$ and the free ions term is negligible.

Charles, C., Plasma Sources Sci. Technol. 16 (2007) R1-R25



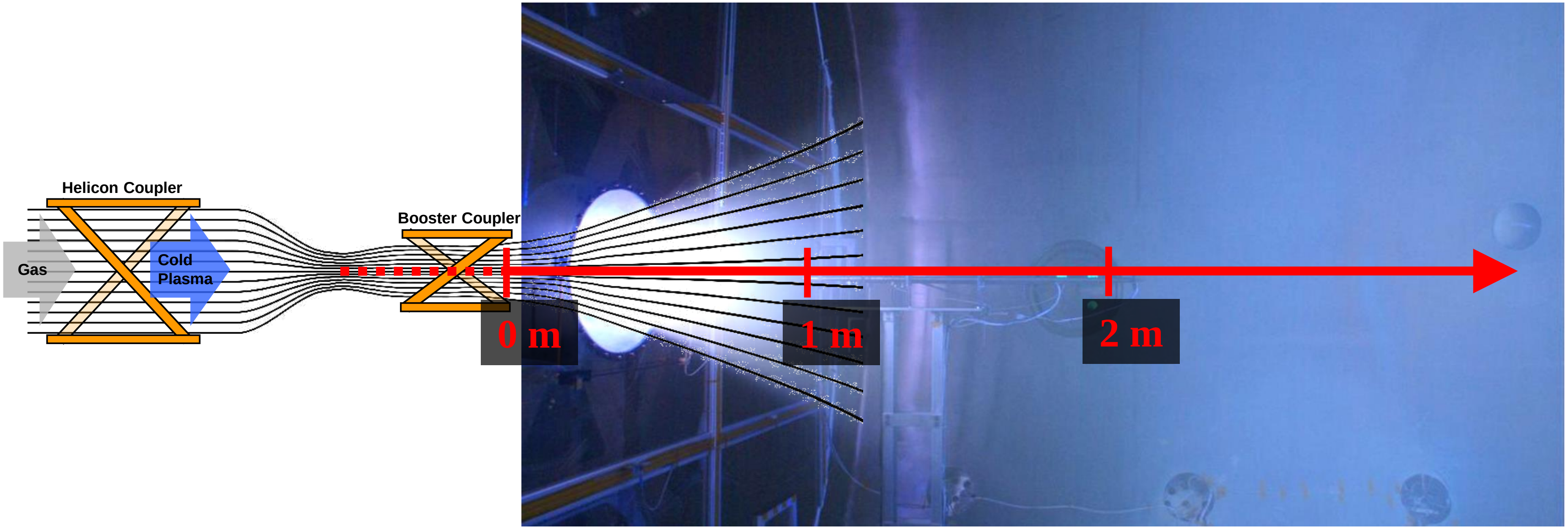
Guarded flux probe, designed for high power

- A robust plasma diagnostic was needed to diagnose the core of a 30 kW helicon source
  - This led to the use of a swept Langmuir probe with a guard ring that was designed for a high heat flux
- 70 cm extension from other probes
  - Tungsten planar probe
  - Alumina probe isolation
  - Graphoil annular shield
  - Stainless steel extension shaft
  - Tried RF and no-RF compensation
    - 0.2 V difference → low amplitude fluctuations in V_p

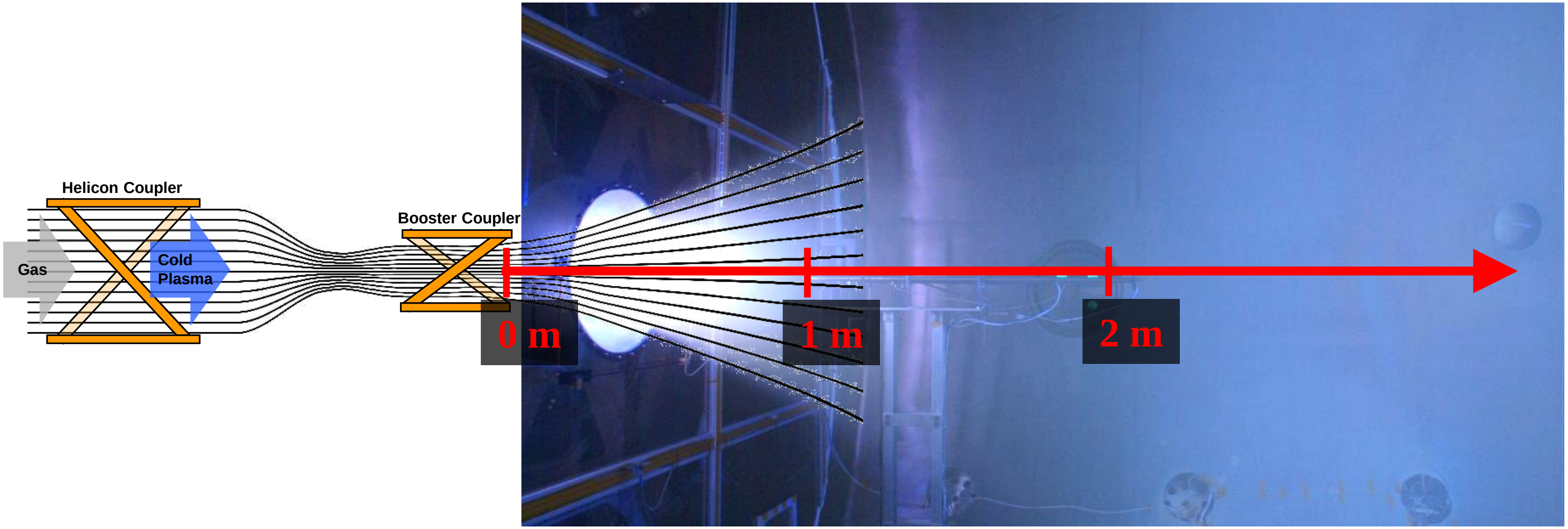


It appears that we do ***not*** see a Double Layer, but rather an ambipolar ion acceleration

- A search for a Double Layer resulted in the observation of a plasma potential structure that we identify as **ambipolar ion acceleration**.
  - A 12 V potential structure was directly observed
    - Scaling N_e with B, an additional 8 V drop is expected farther upstream of position 0 m.
  - Size scale was $10^5\ \lambda_{De}$
  - Based on magnetic field strength and inferred plasma density, a 20 eV ion beam is expected.
  - A 22 ± 3 eV ion beam is observed with an RPA in the downstream plume
  - This results in an argon ion beam with $\sim 4.1c_s$



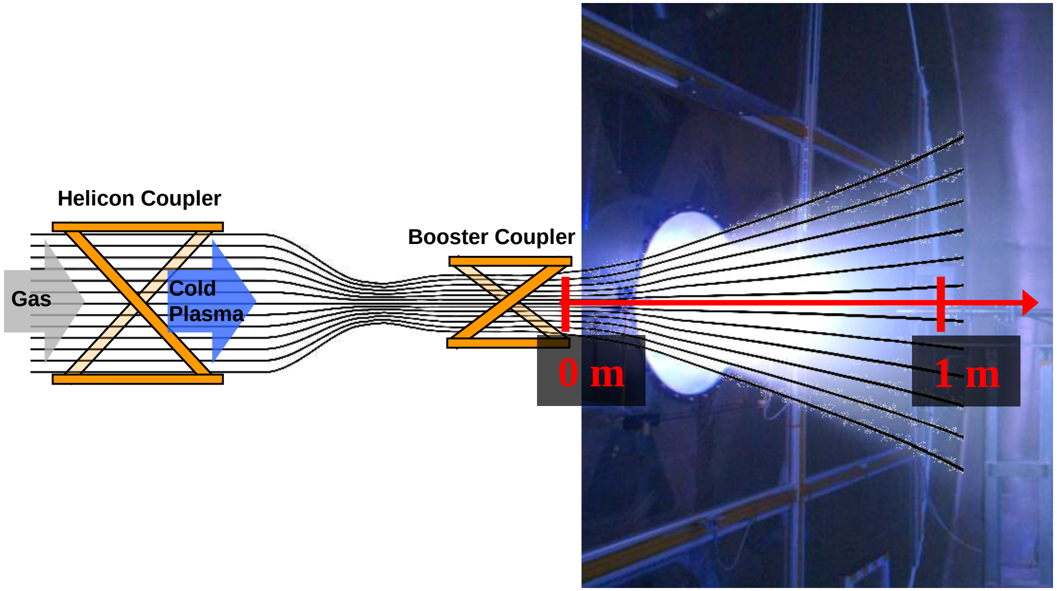
- Flow such that the electron pressure gradient is balanced by the induced electric field

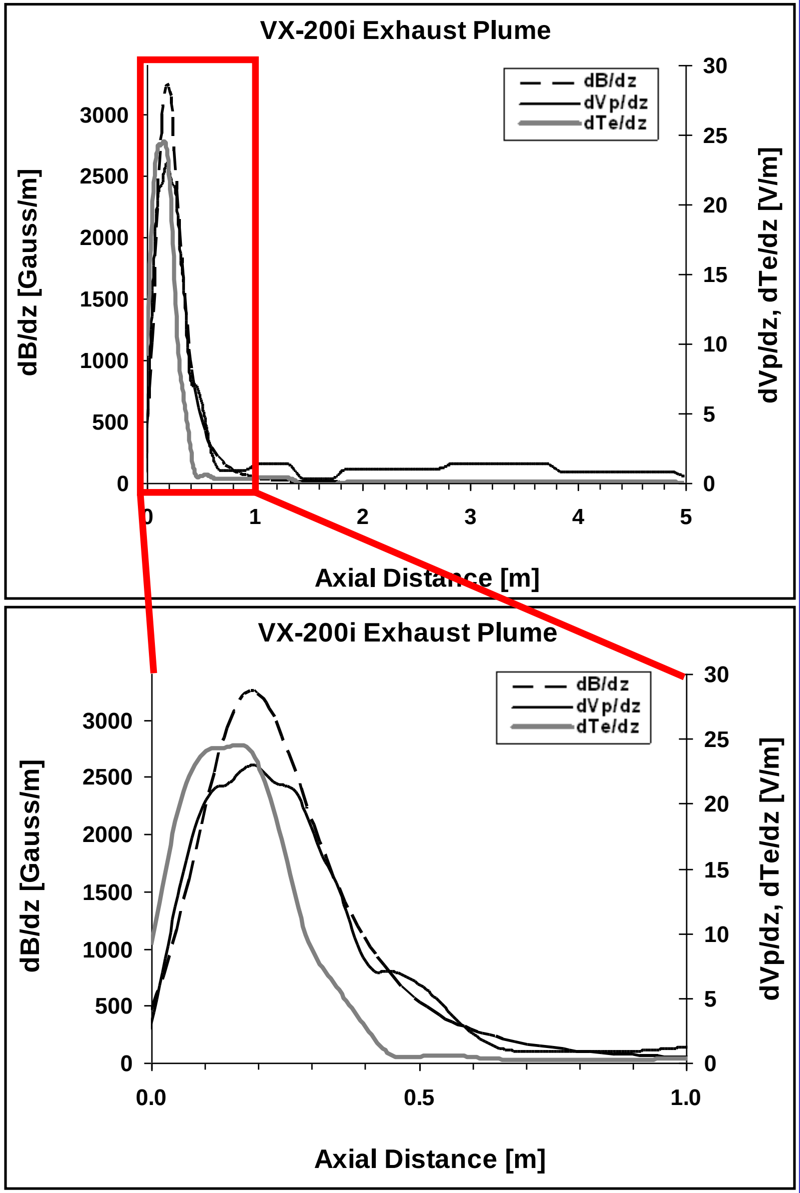


Plasma potential follows size scale of B and N_e

- dV_p/dz (solid black)
- dT_e/dz (solid gray)
- dB/dz (dashed black)
  - Plasma potential and electron temperature measurements have an error ± 1.2 V/m

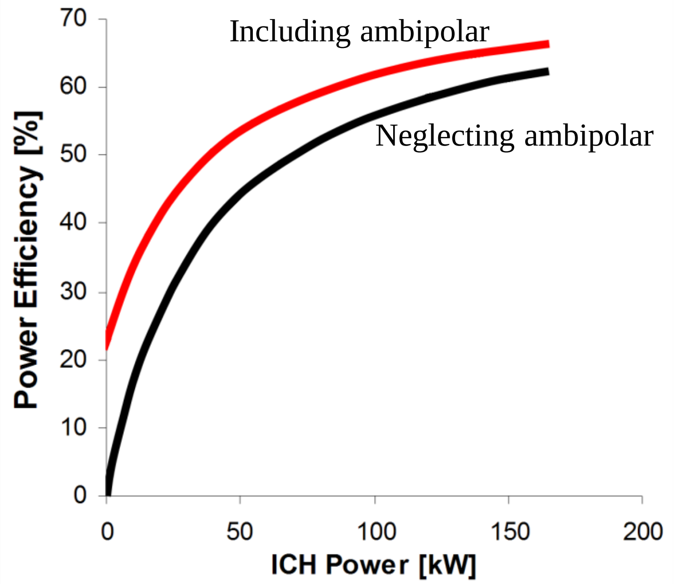
- Discernible shift in location of maximum dT_e/dz, perhaps indicating that the electron distribution losses energy at the expense of ion acceleration in an ambipolar diffusion process

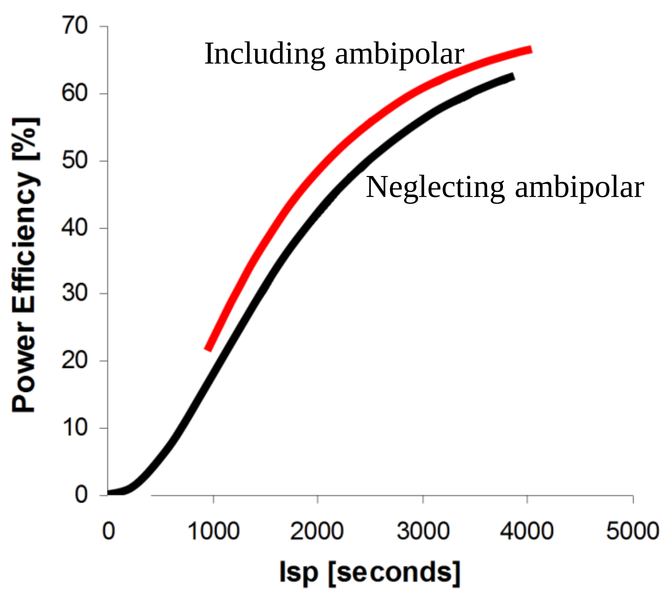




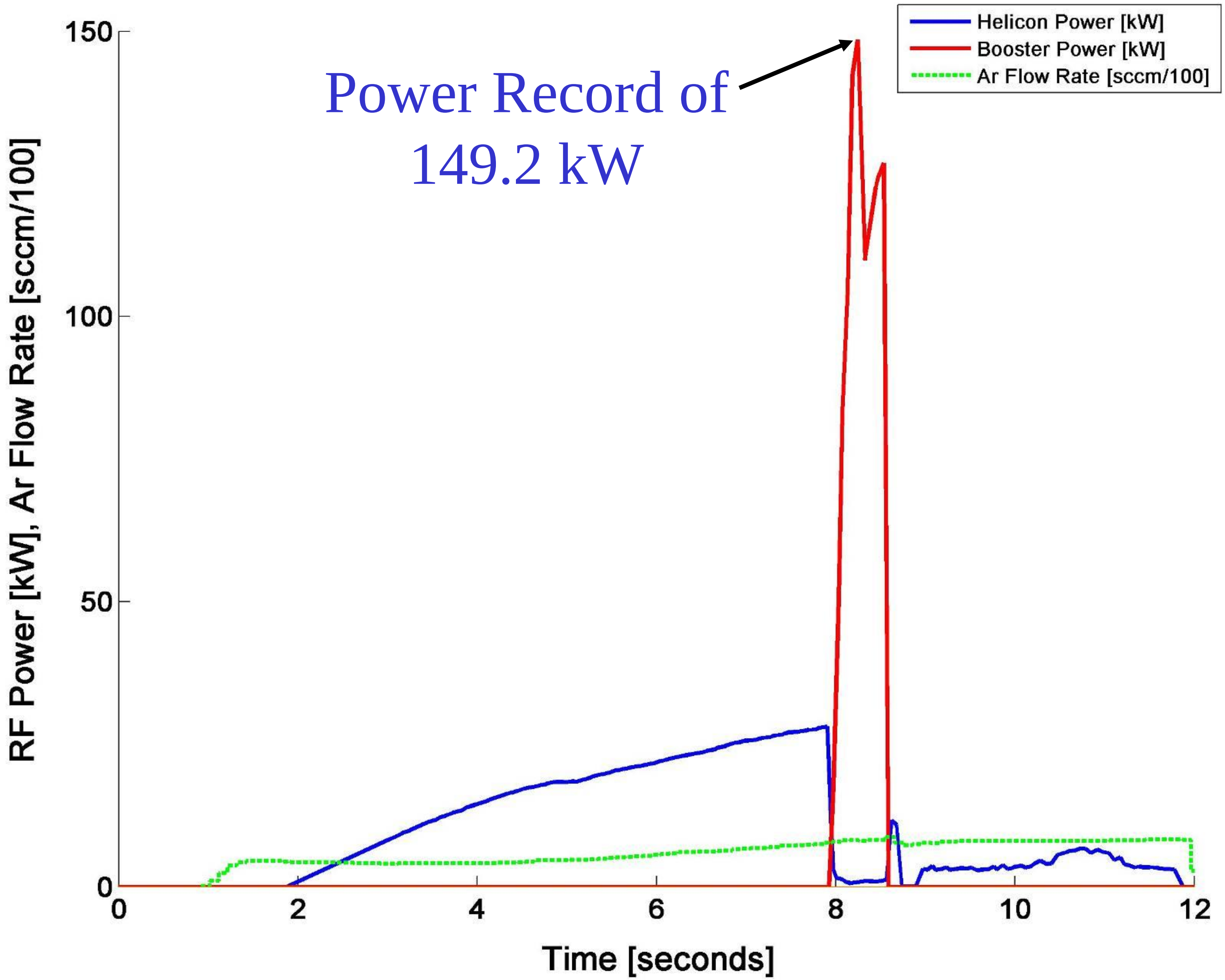
Ambipolar ion acceleration improves VASIMR® efficiency

- Calculated VASIMR® power efficiency as a function of applied **ICH power** (upper) and $\mathbf{I_{sp}}$ (lower).
  - Model assumes constant 36 kW helicon power with (red) and without (black) 20 eV ions from the helicon source.
- Ion energy from helicon-only operation was observed for many years in the operation of earlier VASIMR prototypes
  - The result of including ion energy from the 1st stage helicon source is to shift efficiency curves upward.
- These figures assume ionization cost of E_i=80 eV extracted **[L. Cassady et al., AIAA-2009-5362]**
- It is argued that this ambipolar ion acceleration will exist even when ICH power is applied to VASIMR
  - ICH power should tend to lower the down stream plasma density due to acceleration and will act to further increase $n/n_{\_max}$



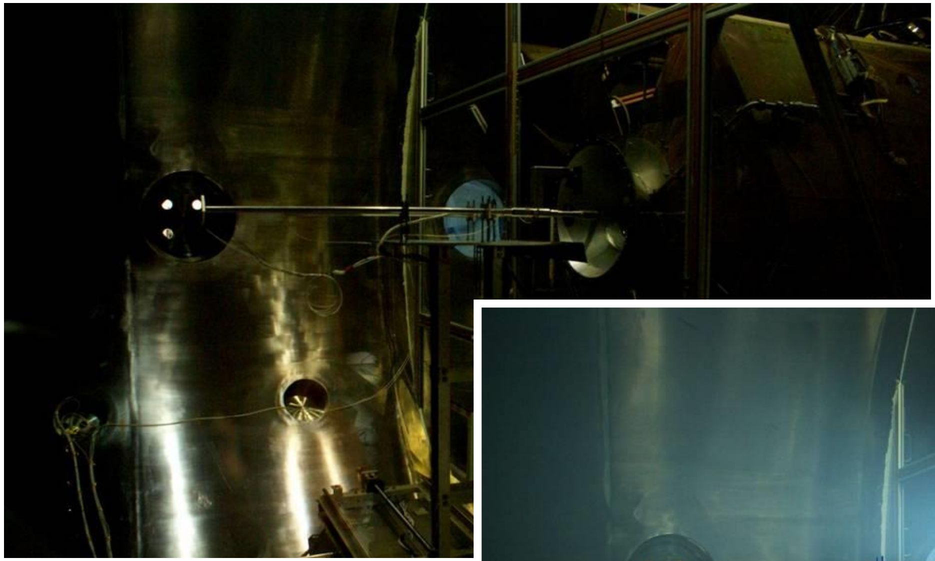


VX-200i technology milestones met

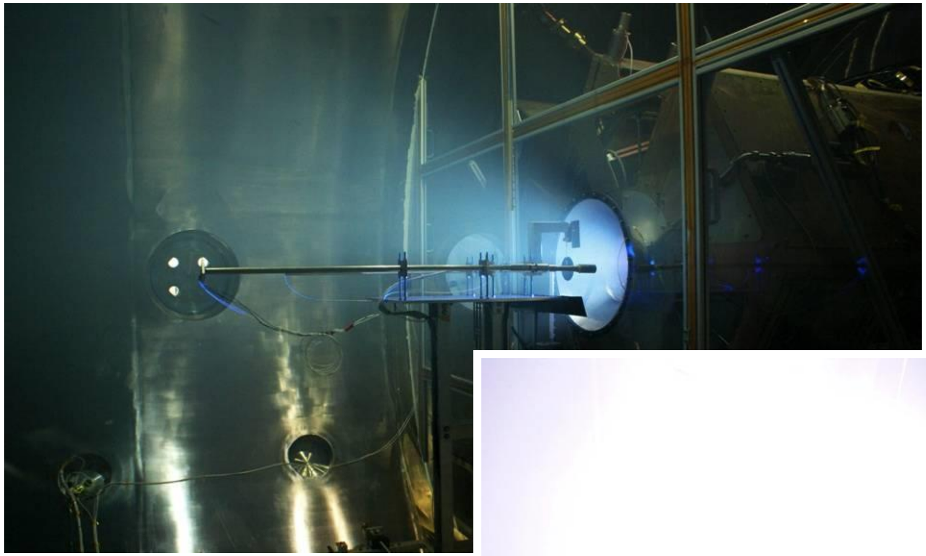


VX-200i exhaust plume images

Same camera settings for all images



No Plasma



30 kW Helicon Only

148.5 kW Booster &
0.7 kW Helicon

Upgraded to the full VX-200, June 2009

- Operate with superconducting magnet ~2 Tesla
- Operate at full power (200 kW)
- Measure rocket performance
- Measure ionization cost
- Measure heat loads on internal components

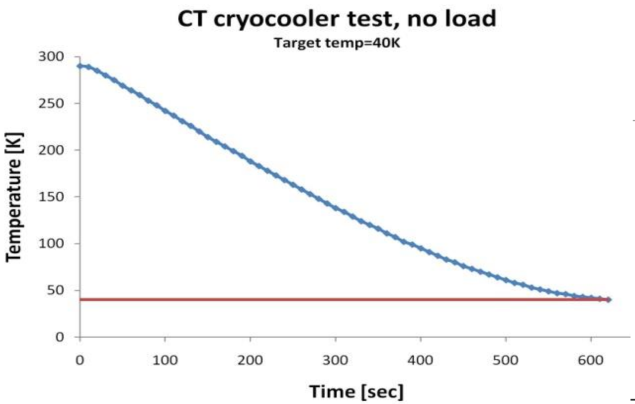
Low temperature superconducting magnet

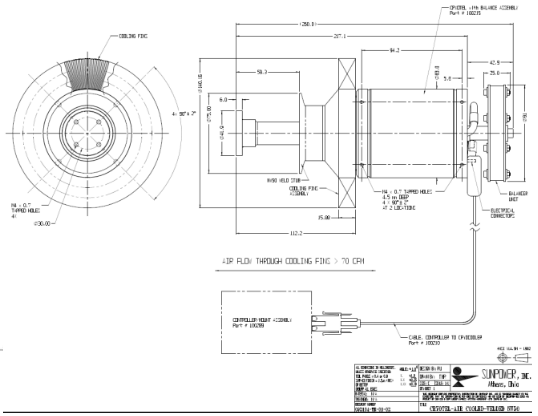
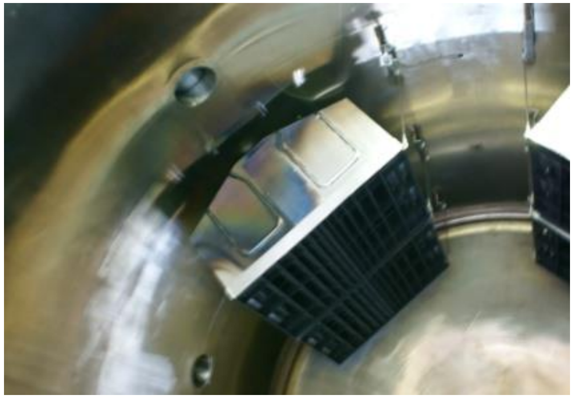
- VASIMR® VF-200 requires a high temperature superconducting (HTS) magnet for flight
  - Peak magnetic field: ~2T
  - Must minimize wasted power (HTS: ~40 K)
- VX-200 has low-temperature superconducting magnet
  - Scientific Magnetics
  - AMS magnet manuf.
  - 4.5 K
  - Lesson in magnet design & development

Cryogenic Testing

- In-house cryogenic testing facilities
  - Flight hardware design and fabrication
  - Low and high temperature superconducting magnet testing and characterization
  - Cryogenic thermal load testing and characterization
  - Three vacuum chambers are used for thermal vacuum insulation
  - 6000 gal. liquid nitrogen bulk tank, April 2010
  - 50 m^3 cryogenic thermal vacuum environment
  - 8 high lift cryocoolers,

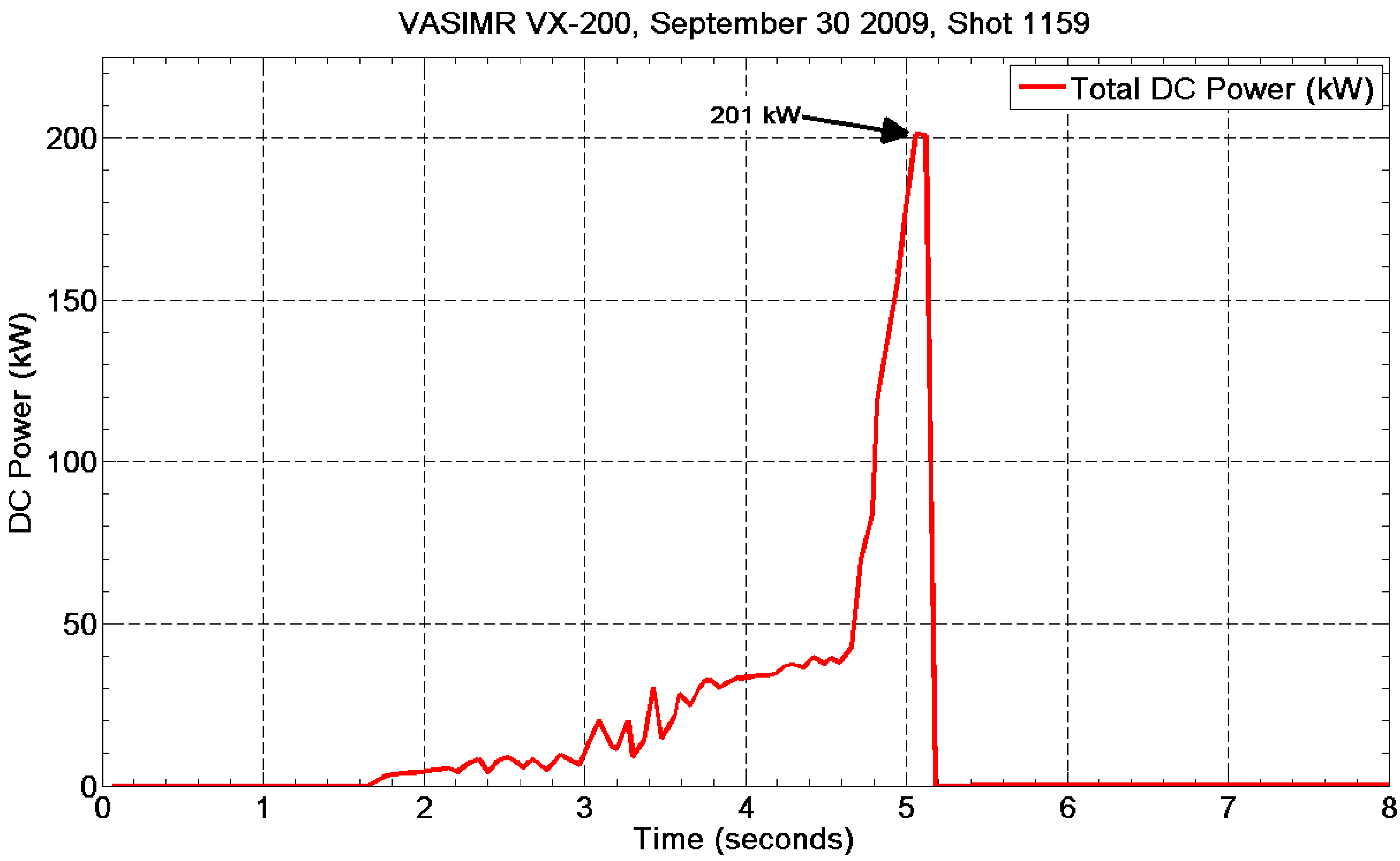




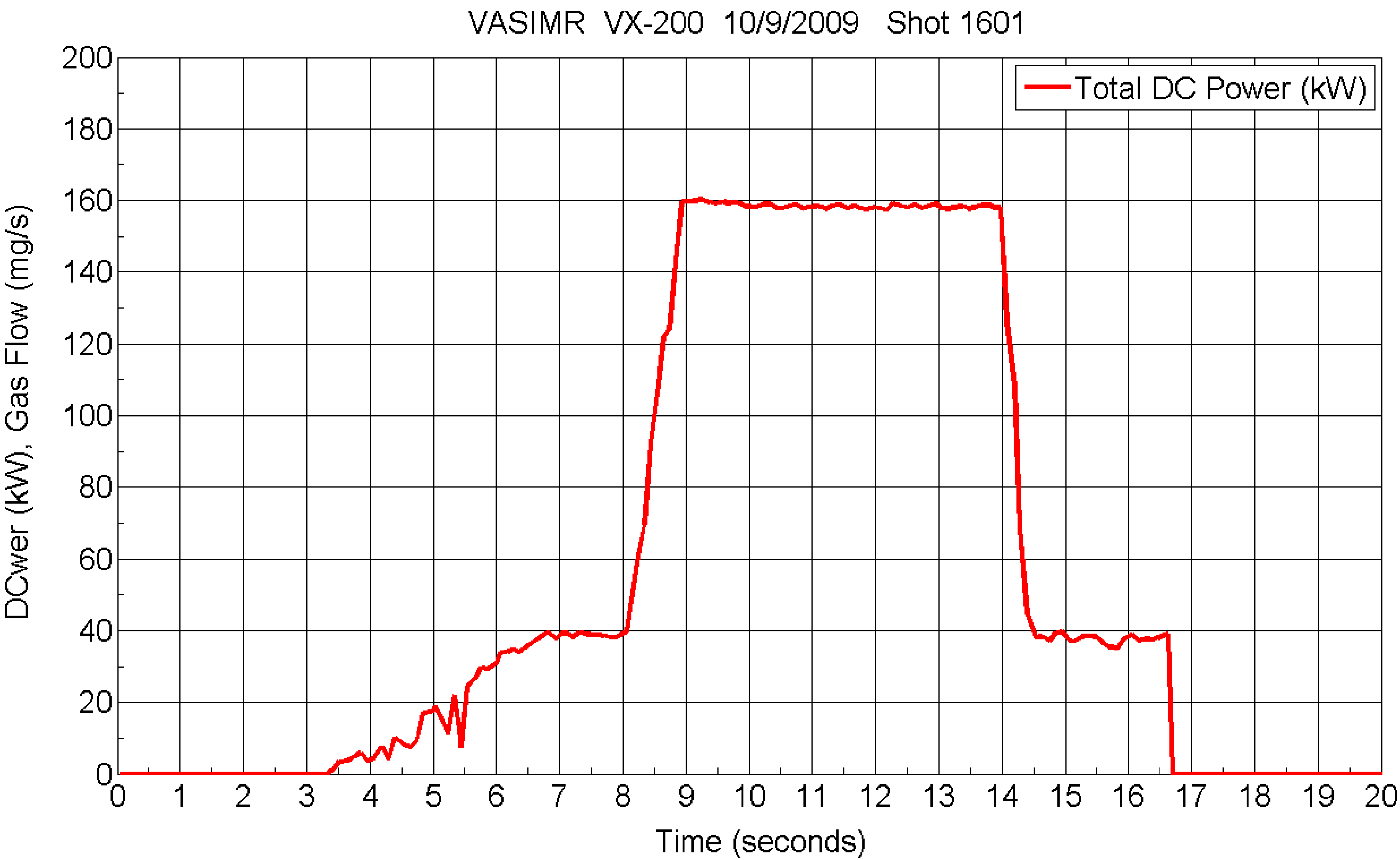





Recent VX-200 results



Recent VX-200 results



VX-200 exhaust plume images

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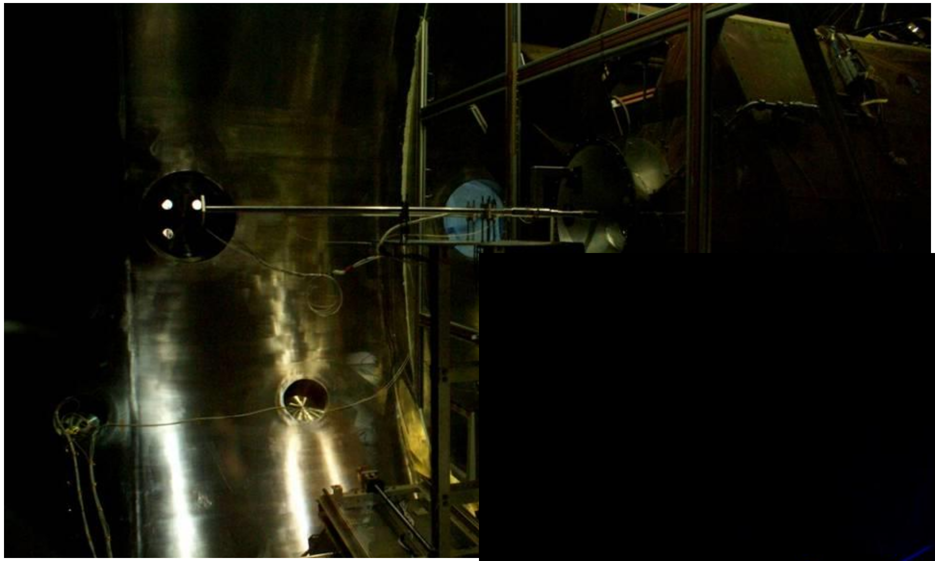
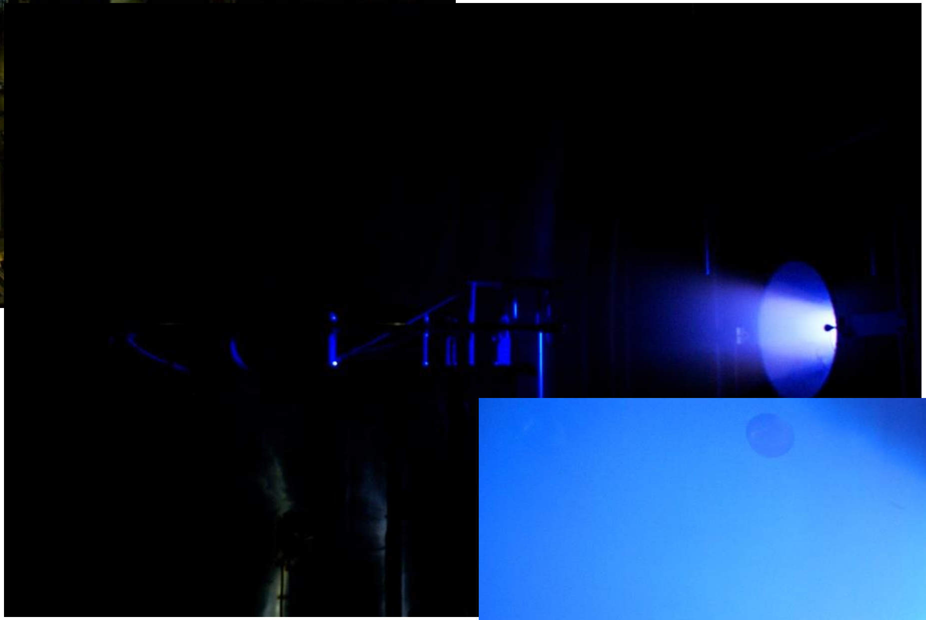
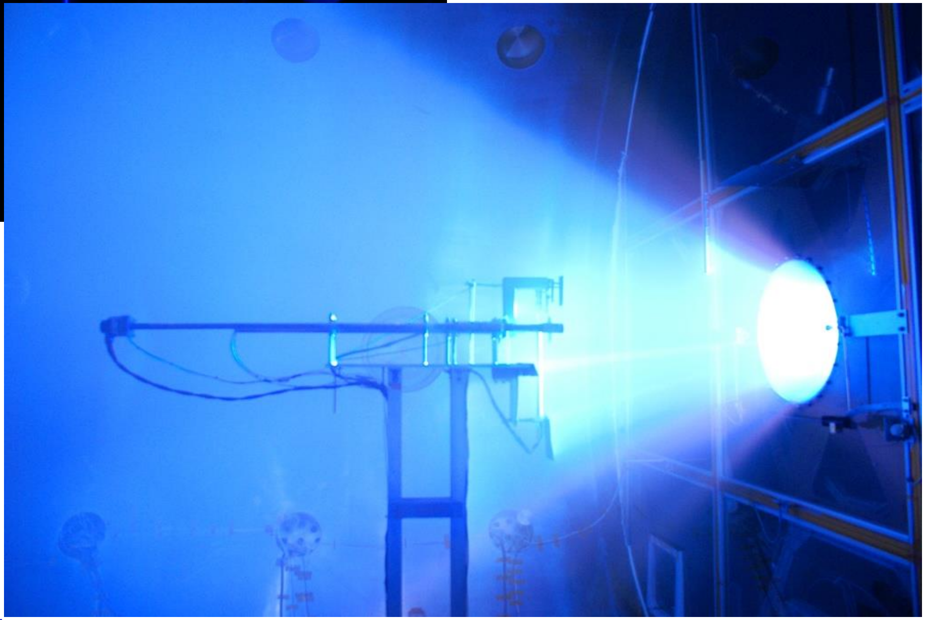


No Plasma



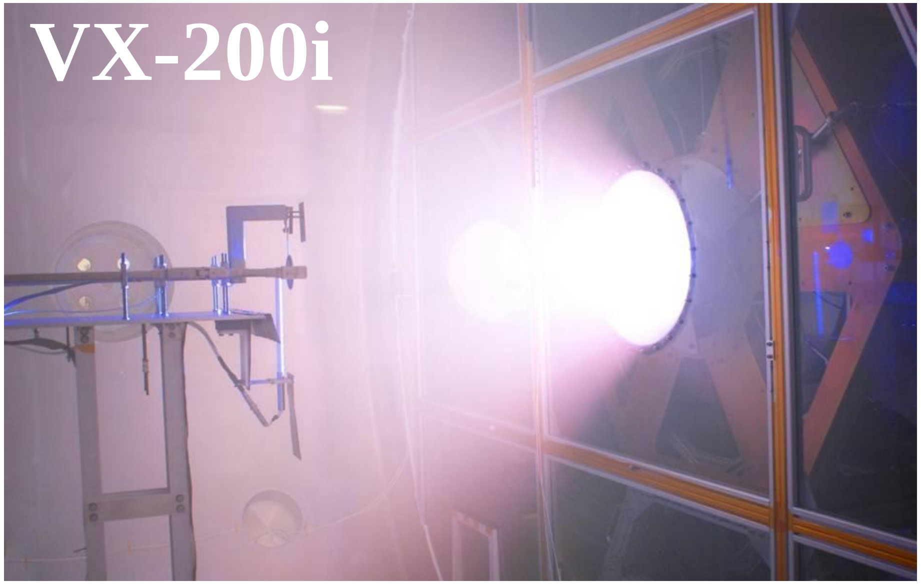
30 kW Helicon Only

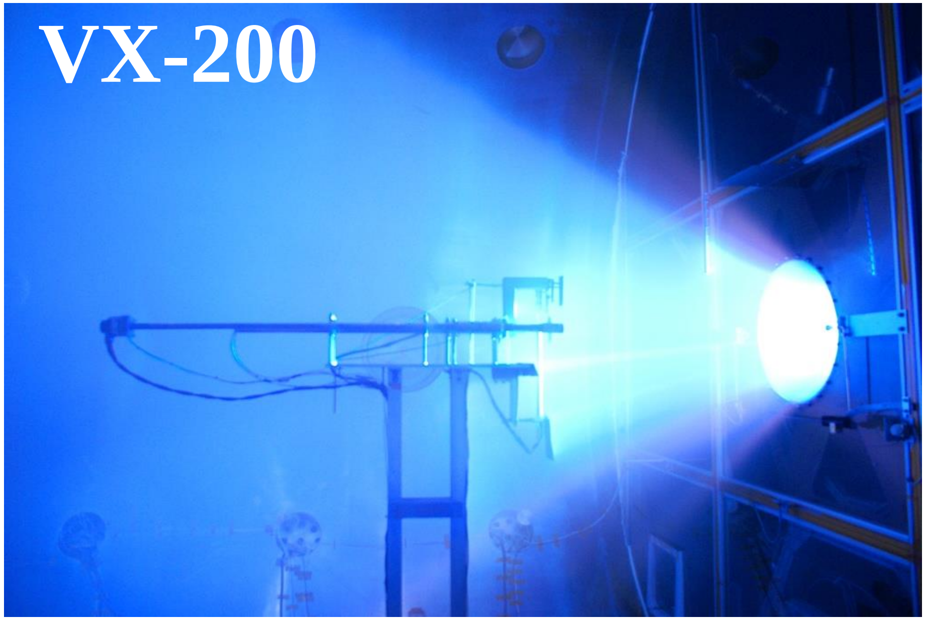


200 kW Total

VX-200 vs. VX-200i

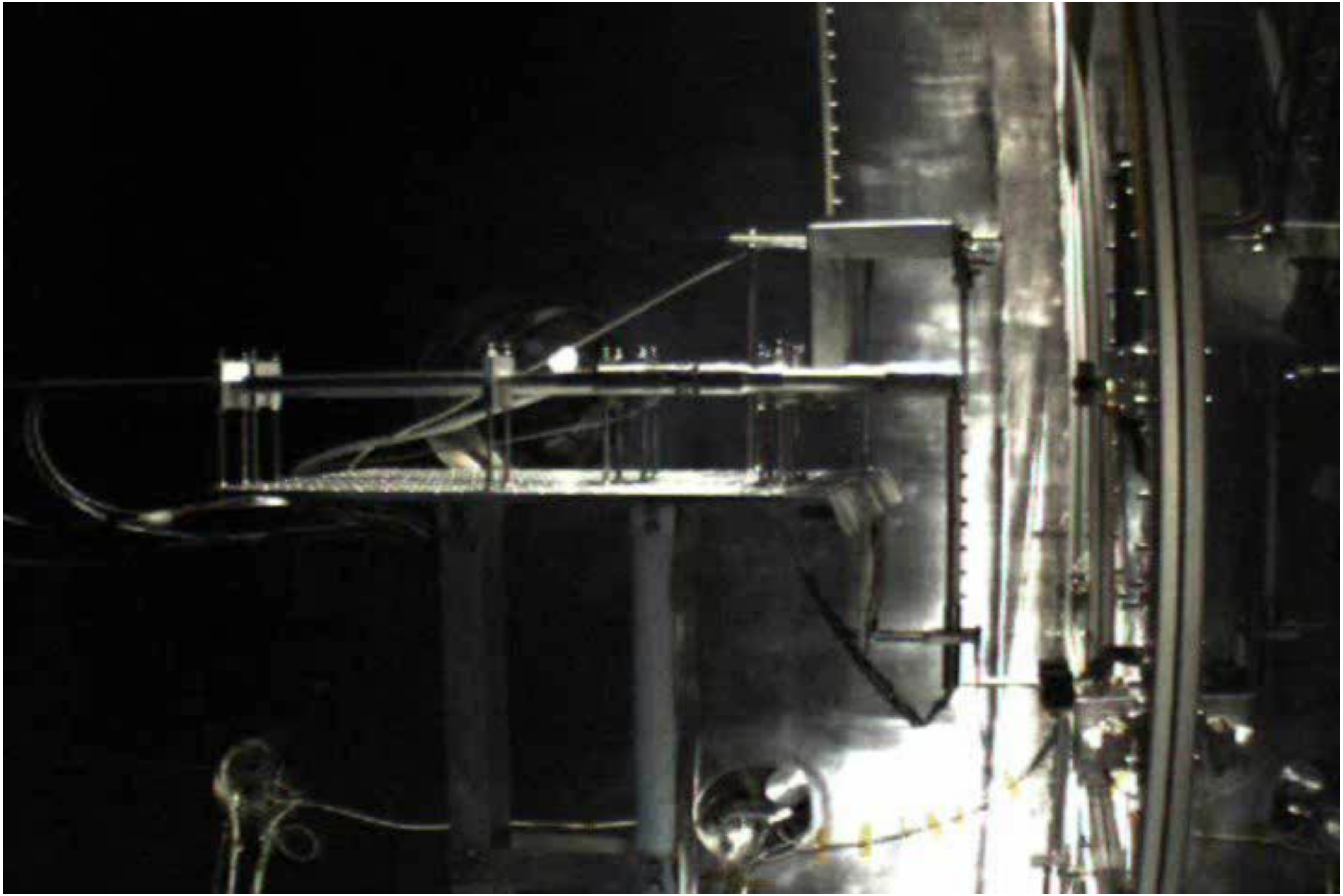
- Top Image: VX-200i
- Bottom Image: VX-200
  - Notice there is an outer cone and an inner cone
  - Outer cone likely due to cold charge exchange plasma or plasma that is generated outside of the magnetic field lines from the interior of the rocket
  - Inner cone of VX-200 is much more directed than the VX-200i plume





Movie of VX-200 firing

Movie of VX-200 firing



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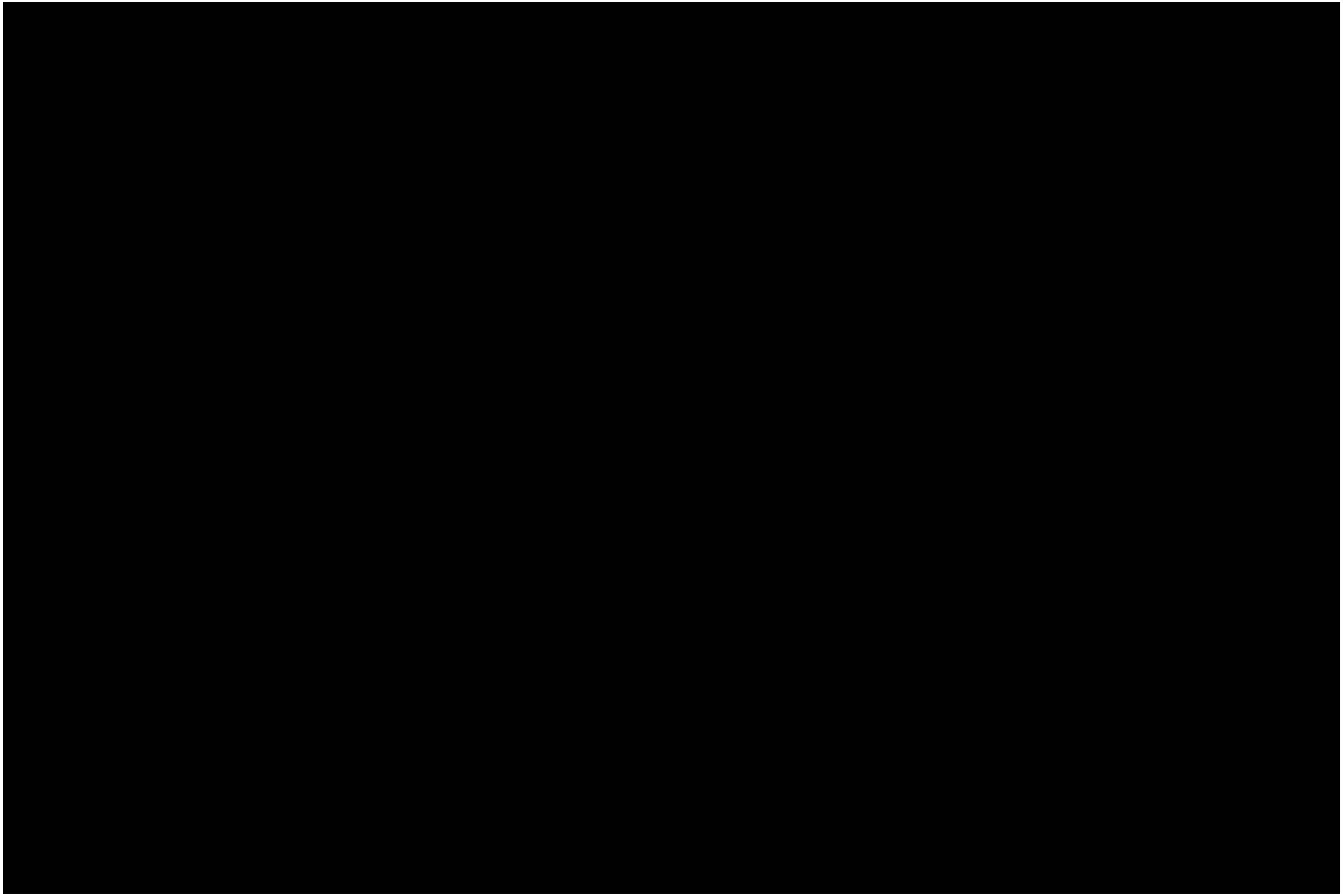
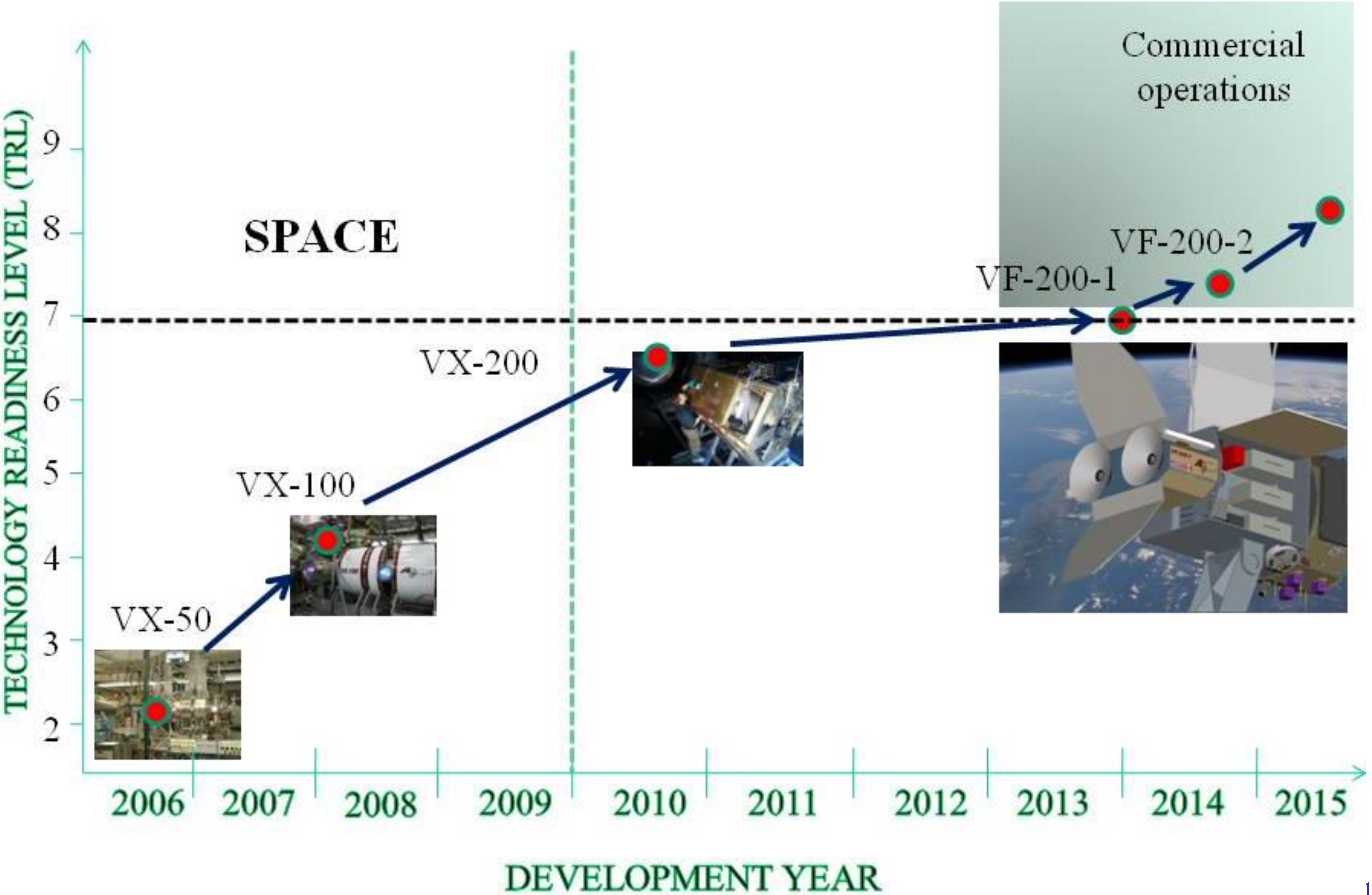


Movie of VX-200 firing

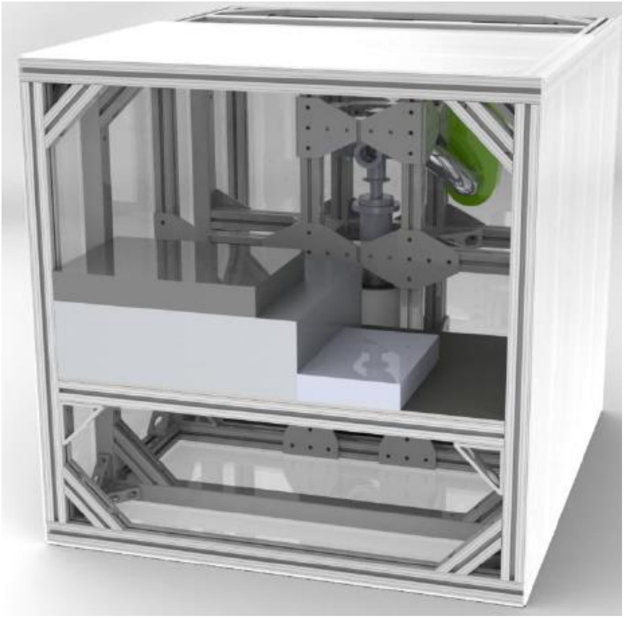
The Road to Space

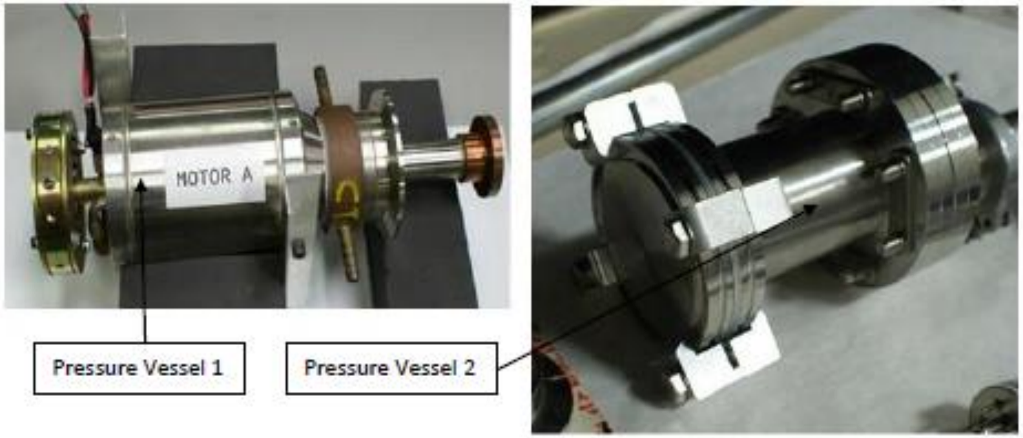


Cryogenic Testing in Microgravity

- UNL undergraduate team
  - Flying cryocooler on the “Vomit Comet” April 15 and 16, 2010
  - Will validate energy efficiency in microgravity at several temperature set points
  - Will validate “lift” under thermal load in microgravity

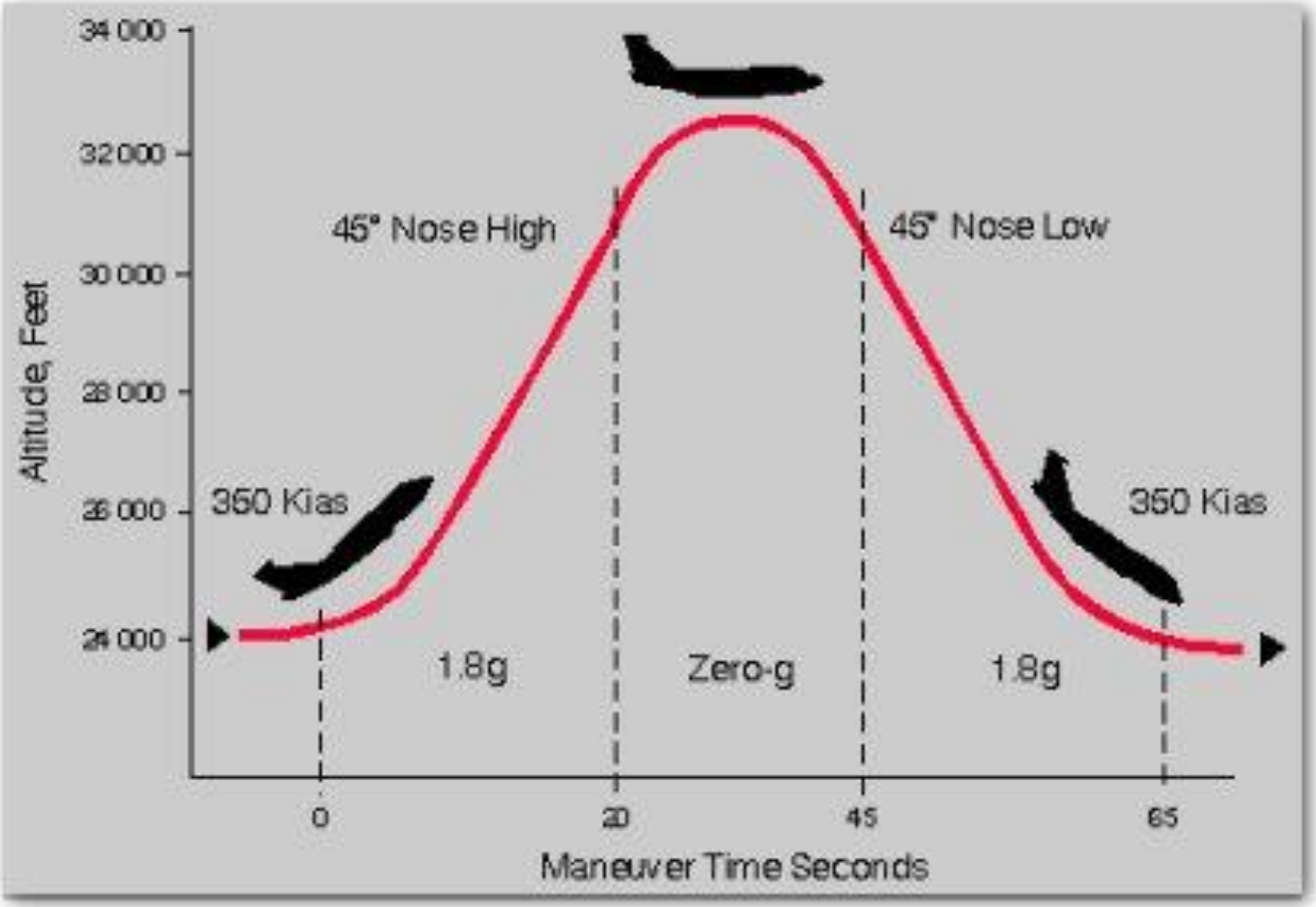
NEBRASKA
MICROGRAVITY
UNIVERSITY





Reduced Gravity

KC-135A, DC-9, 727




NASA

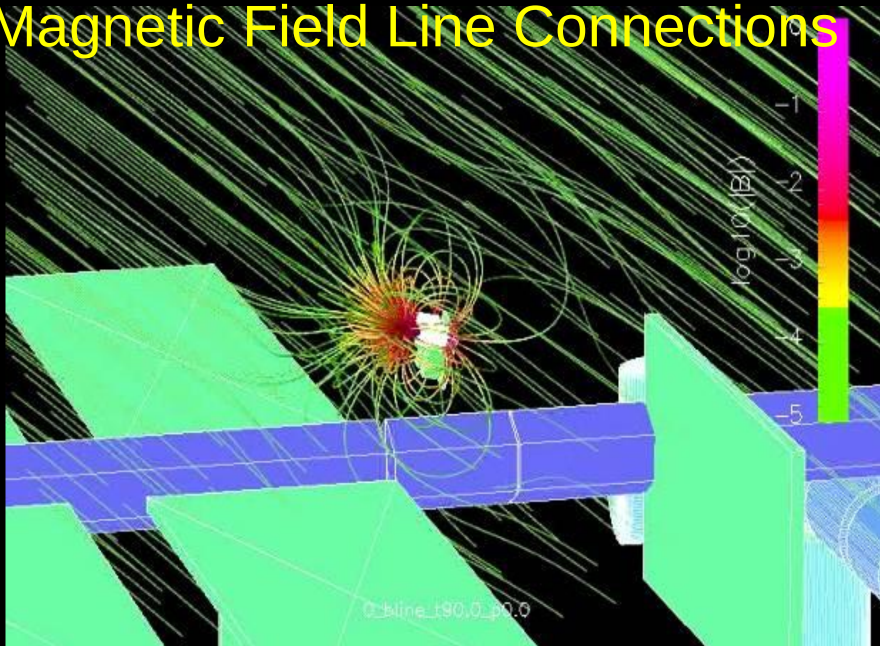
NASA

Hypobaric Chamber Training

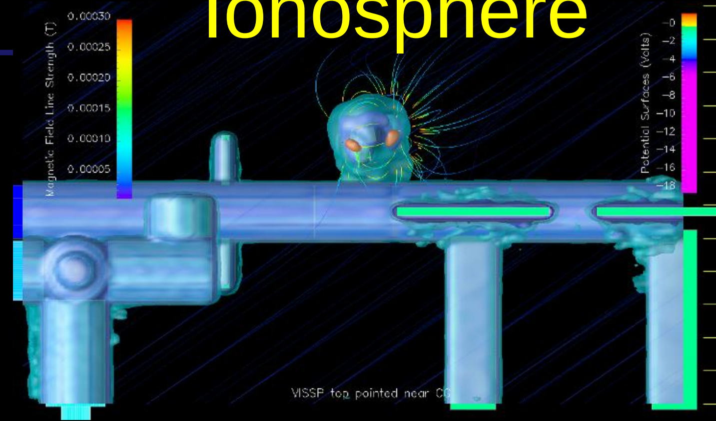
The Zero-G parabola

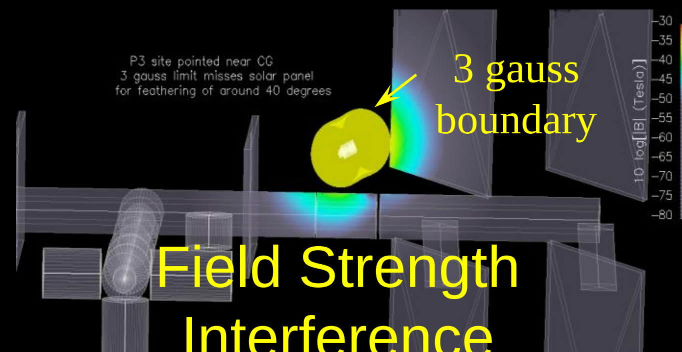
Plasma Modeling

Magnetic Field Line Connections

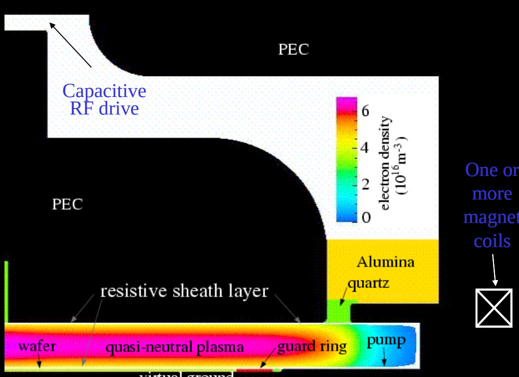


Ionosphere

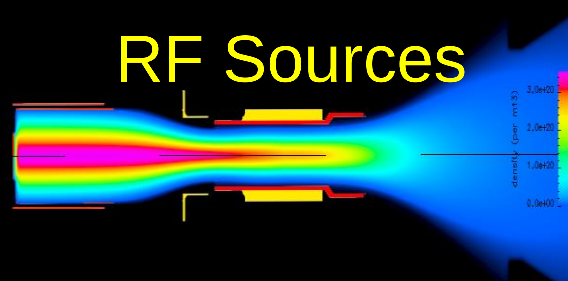




Field Strength Interference

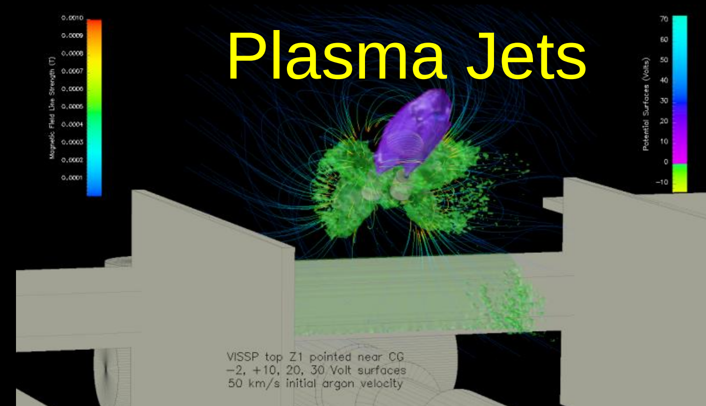


Plasma Reactors

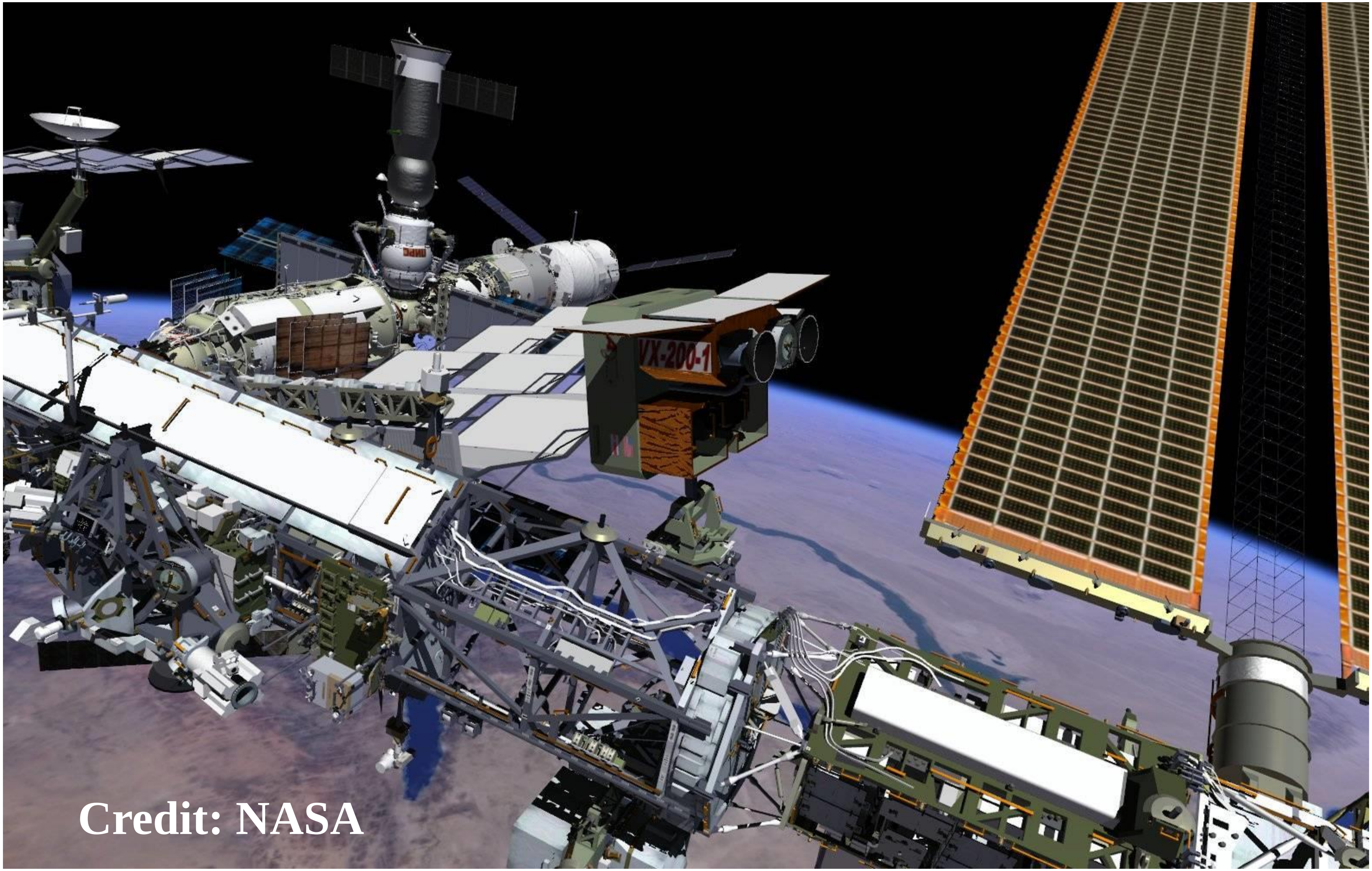


RF Sources

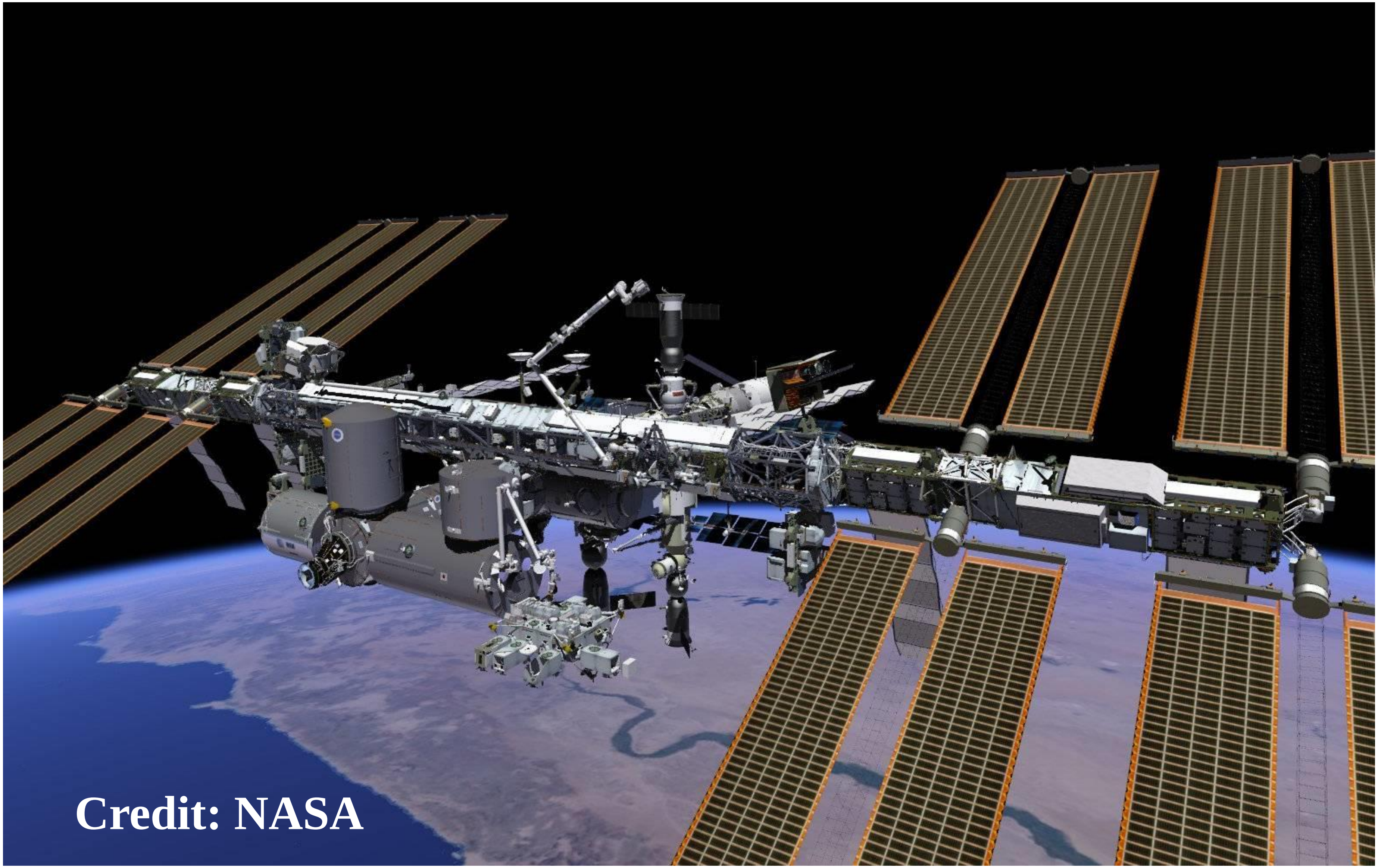
Plasma Jets



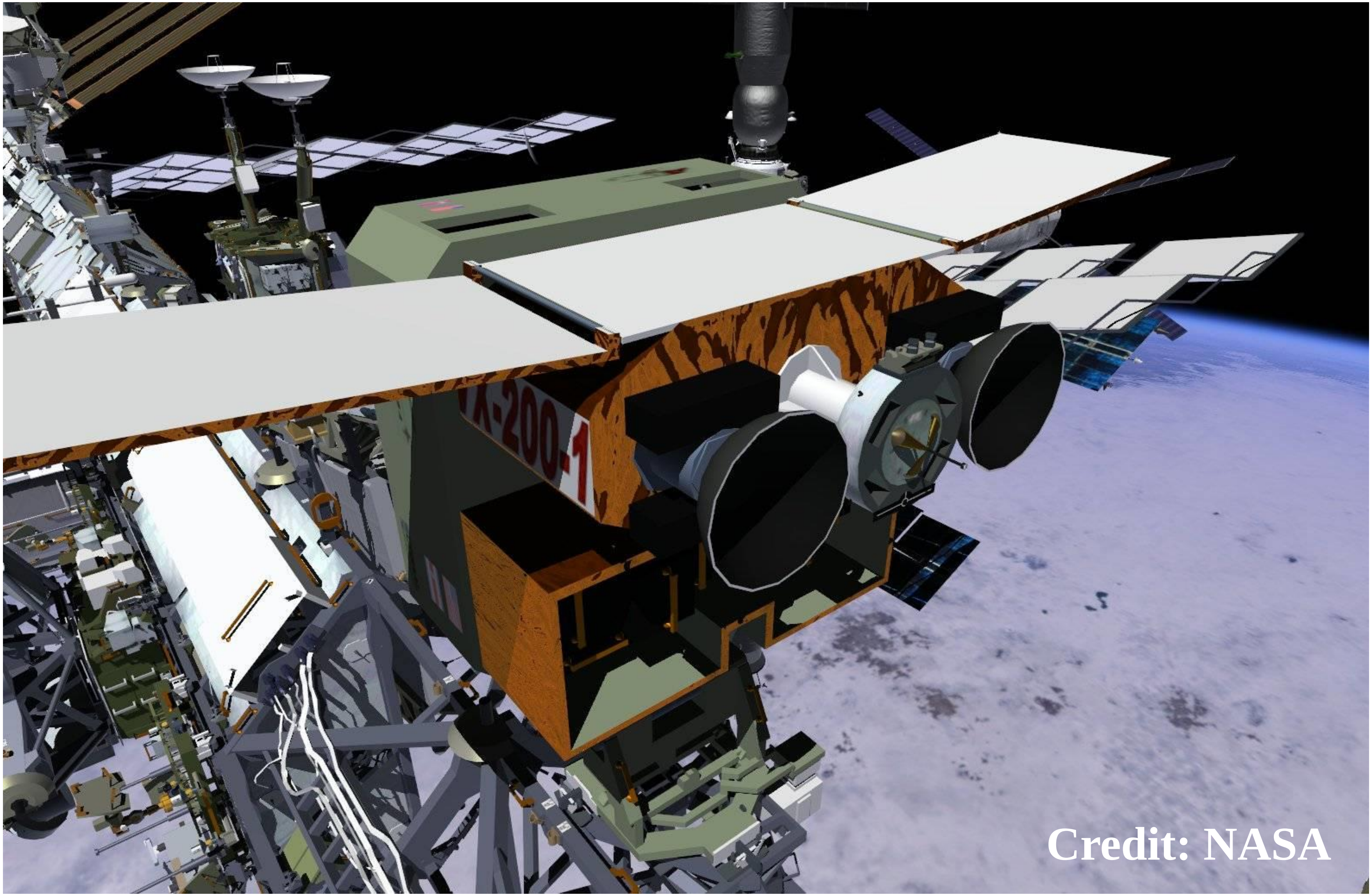
Next design project: ISS mission



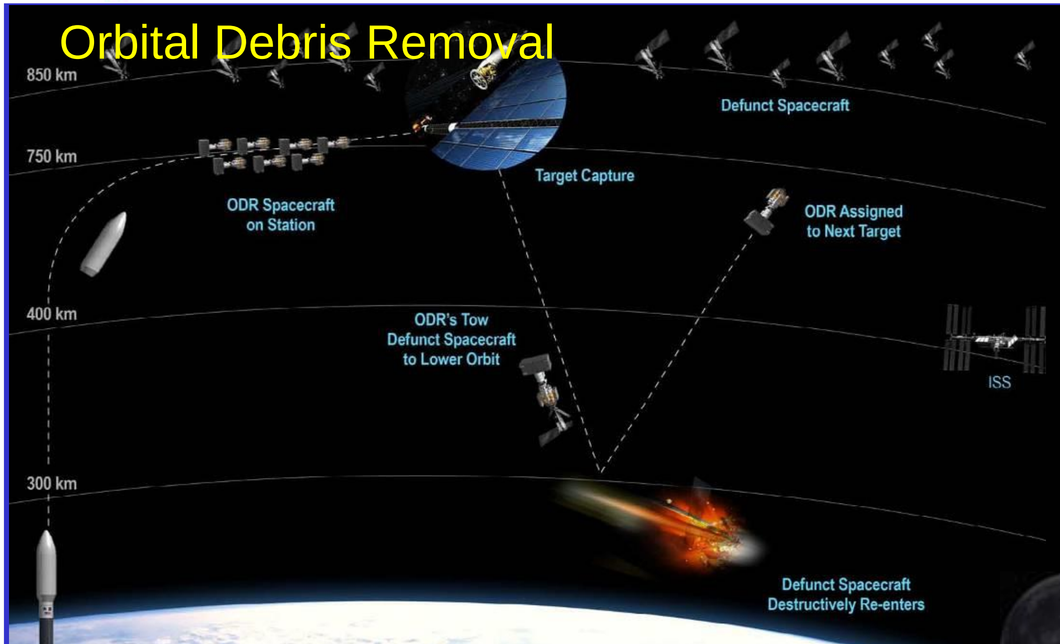
ISS mission image

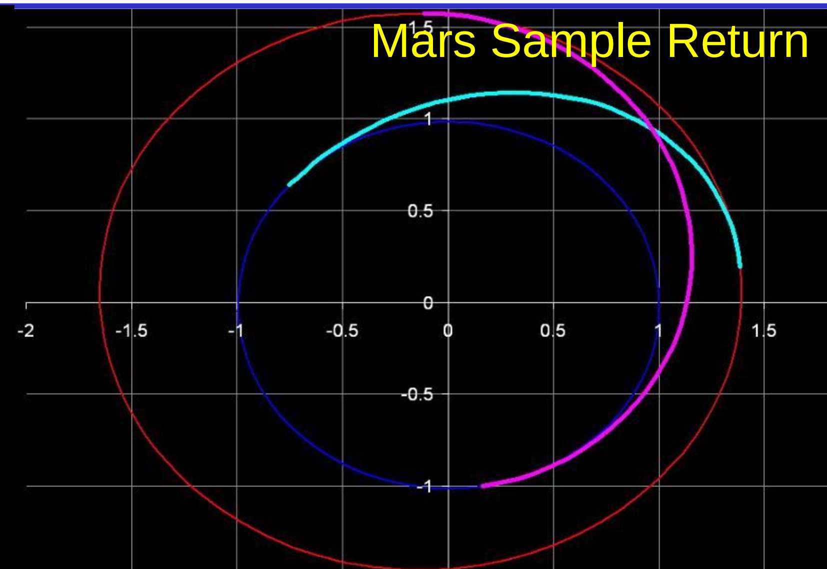


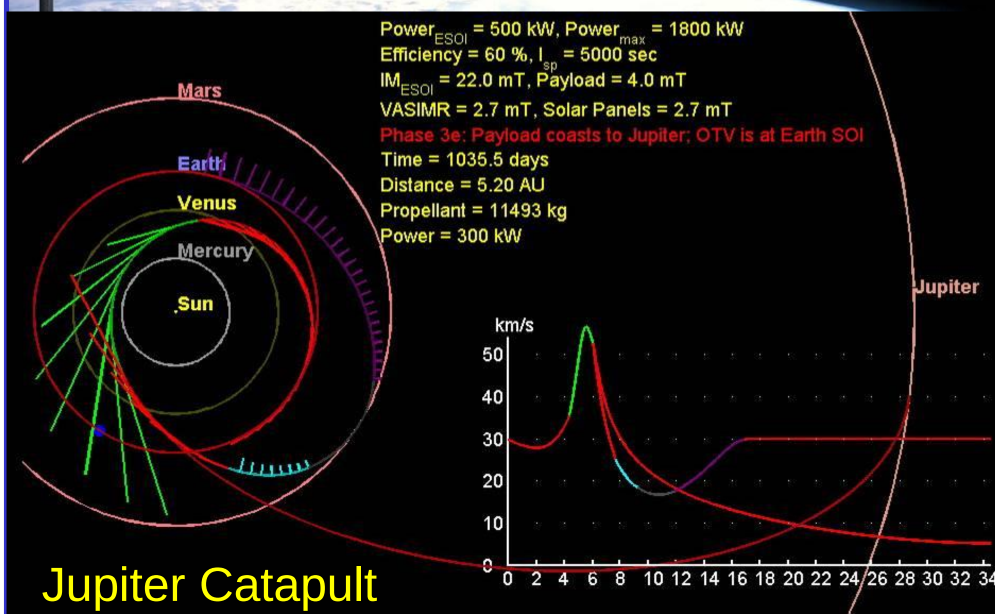
ISS mission image



Electric Propulsion Mission Analysis



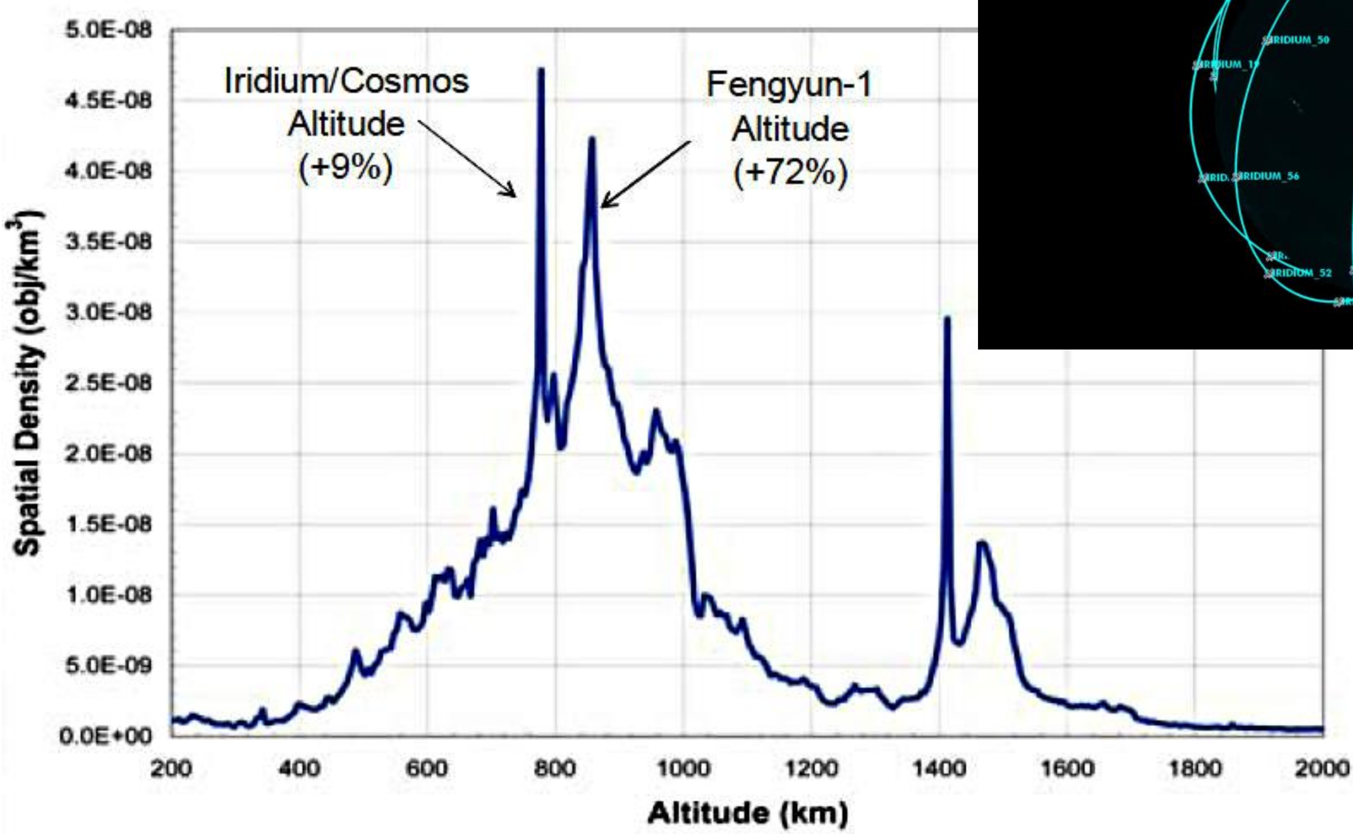


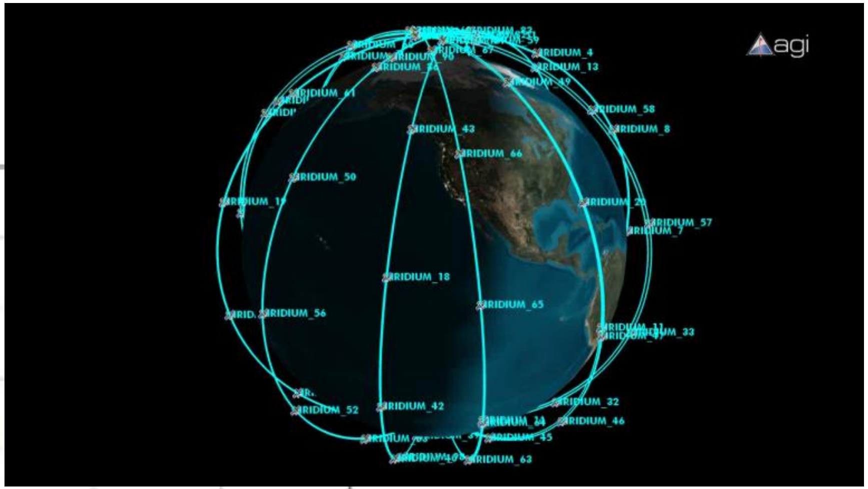


[redacted]

Orbital Debris Problem in LEO

Kessler Syndrome: when the number of objects in similar orbits becomes high enough, the risk grows that there will be a cascade of collisions, filling the space enclosing the orbits with small, fast-moving debris. The collision hazard becomes too high to risk placing new satellites in this region, making what was once a very *valuable* area of space unusable.



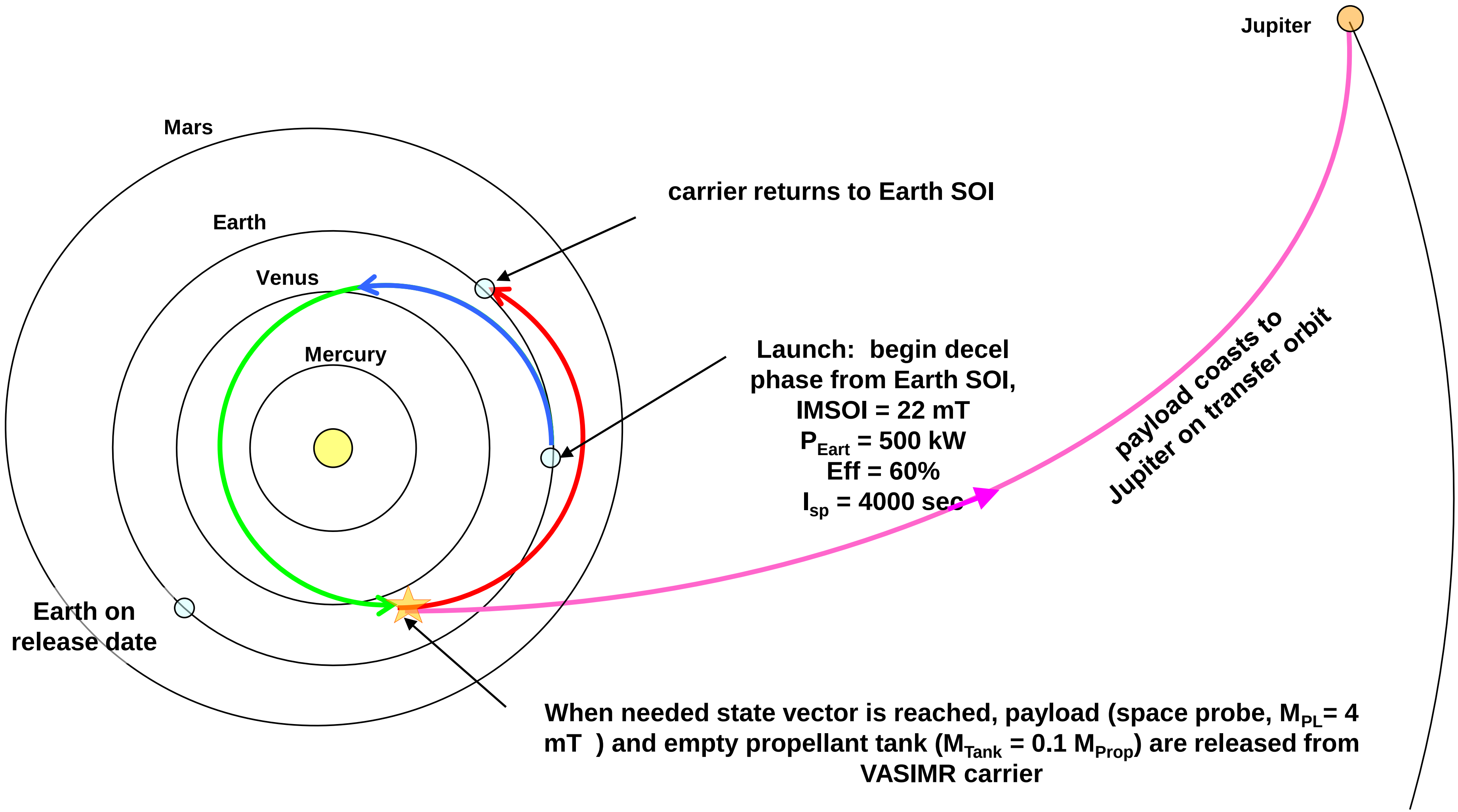


VASIMR Ejector Concept – Jupiter Catapult Trajectory

Phase 1: blue – deceleration to send vehicle on close solar pass; thrust T ⊥ R and opposite to V.

Phase 2: green – acceleration at high solar power; T parallel to V. Maximum power can be limited (P_{max}).

Phase 3: red – Earth return phase; complex thrust vector schedule needed to optimize performance.



Acknowledgements

- Ad Astra Rocket Company and UH teams