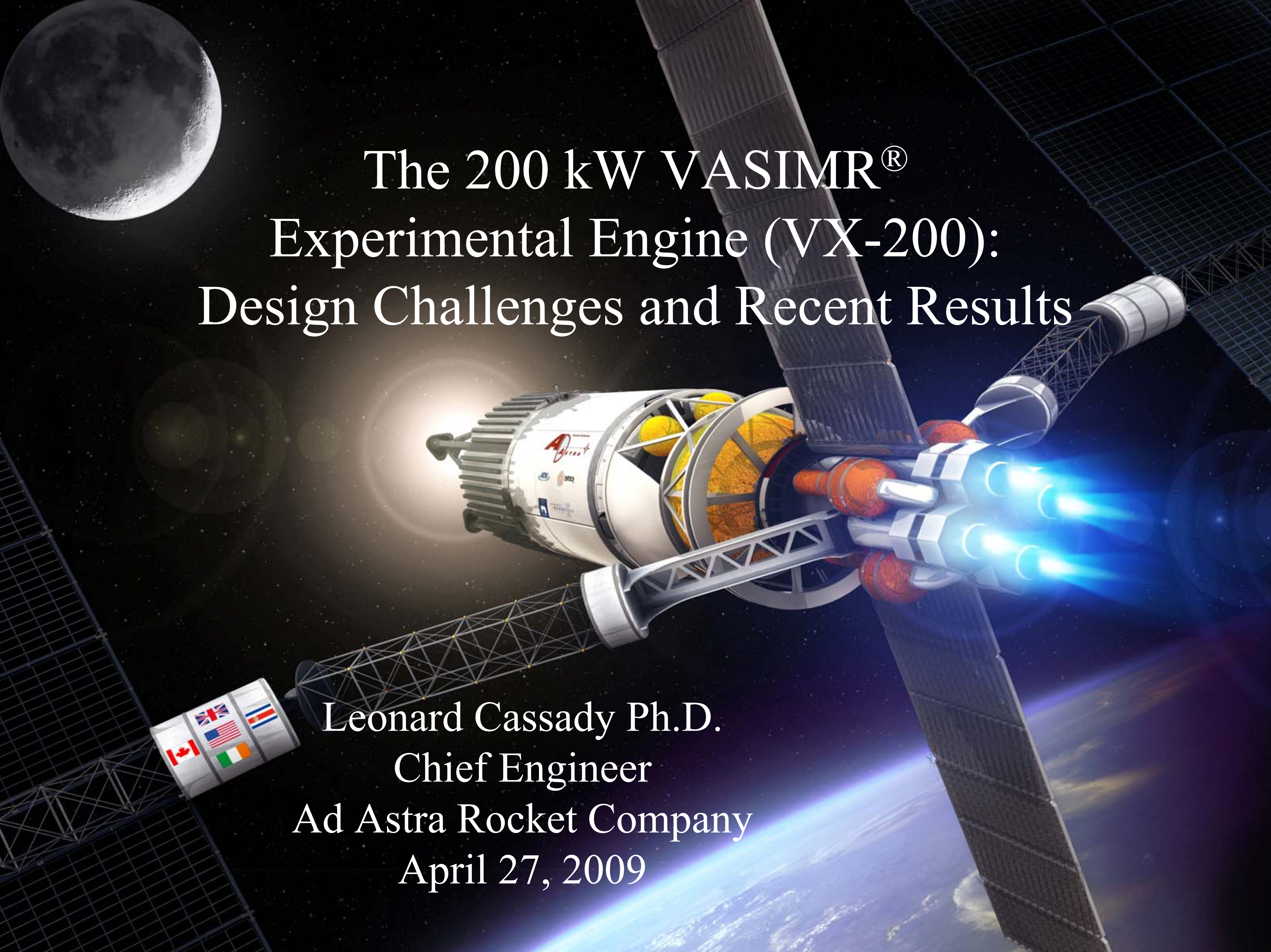
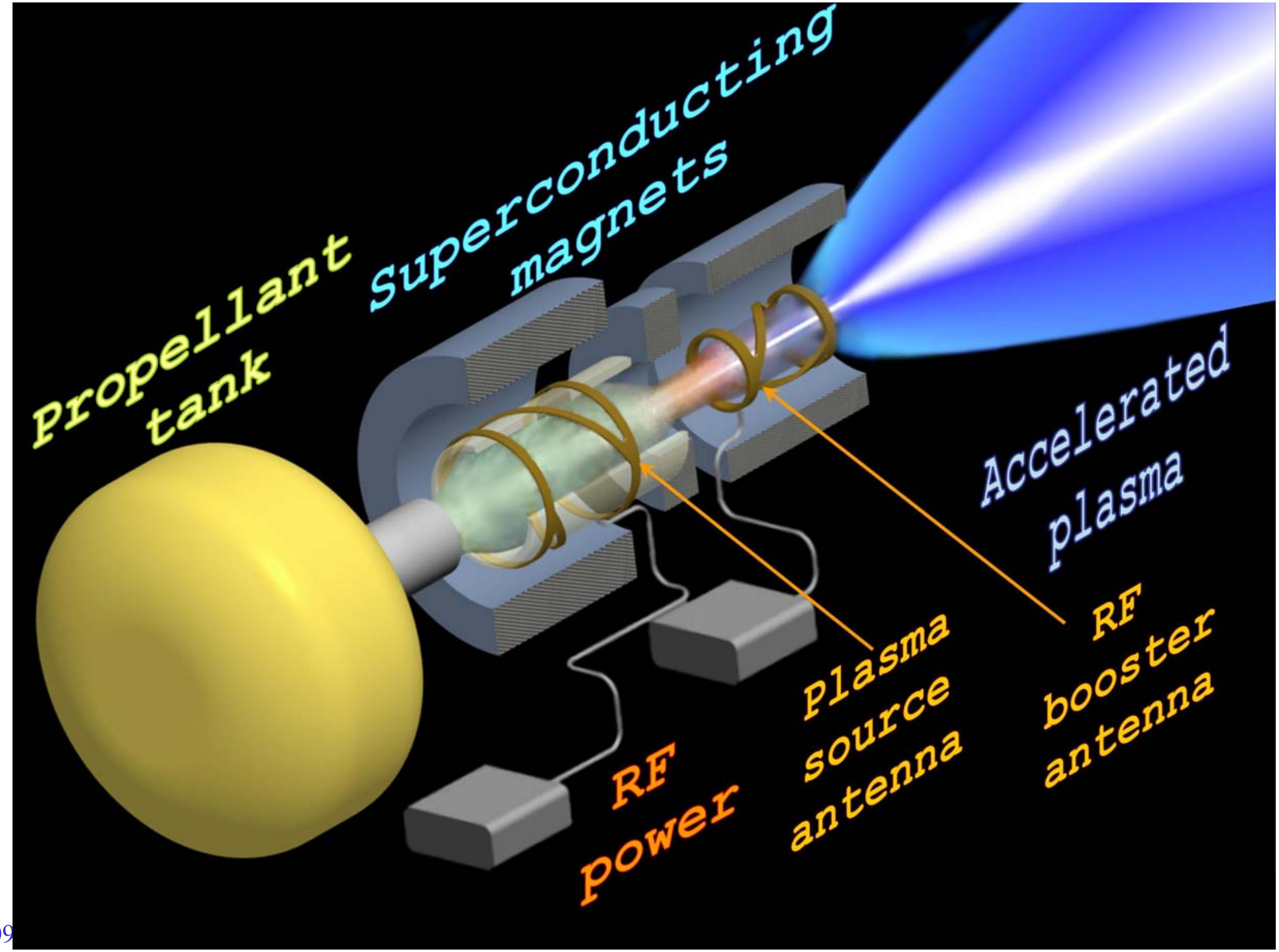
The 200 kW VASIMR®
Experimental Engine (VX-200):
Design Challenges and Recent Results



Leonard Cassady Ph.D.
Chief Engineer
Ad Astra Rocket Company
April 27, 2009

VASIMR® Fundamental Concept

Variable Specific Impulse Magnetoplasma Rocket



Chemical Versus Electric Propulsion

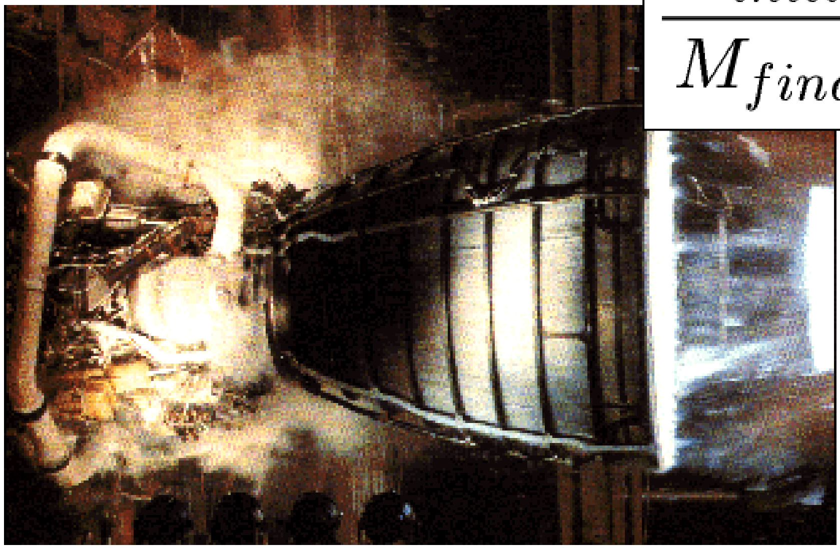
Chemical Propulsion

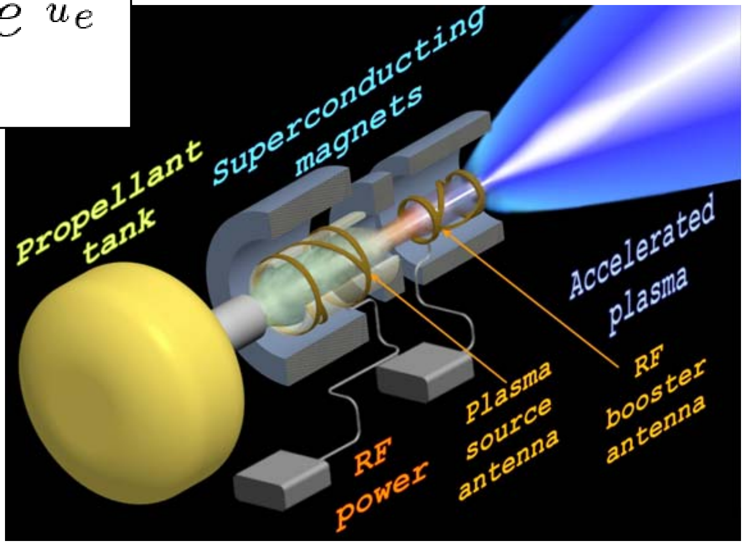
- Low Isp: < 450 s
- High thrust: $10^1 - 10^6$ N
- Short firing: < ~10 min
- Requires fuel & oxidizer

Electric Propulsion

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

$$\frac{M_{initial}}{M_{final}} = e^{\frac{\Delta V}{u_e}}$$





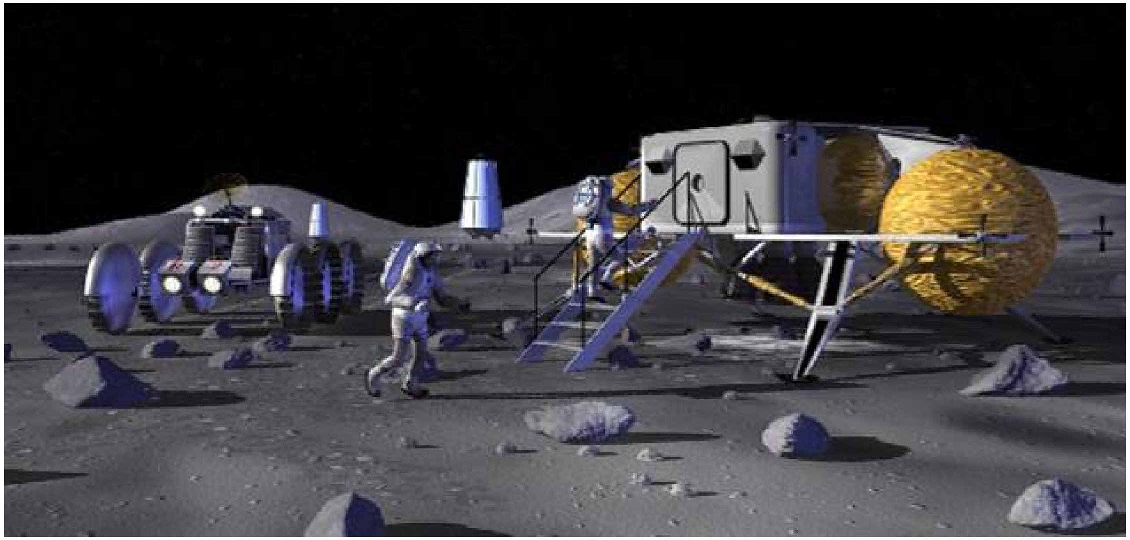
Human Lunar Mission Cargo Delivery

Lunar exploration on the scale of the VSE (Vision for Space Exploration) will require tens of tons of cargo annually, in the form of habitats, machinery, vehicles, and supplies. ***(Chemical cargo lander shown at right).***

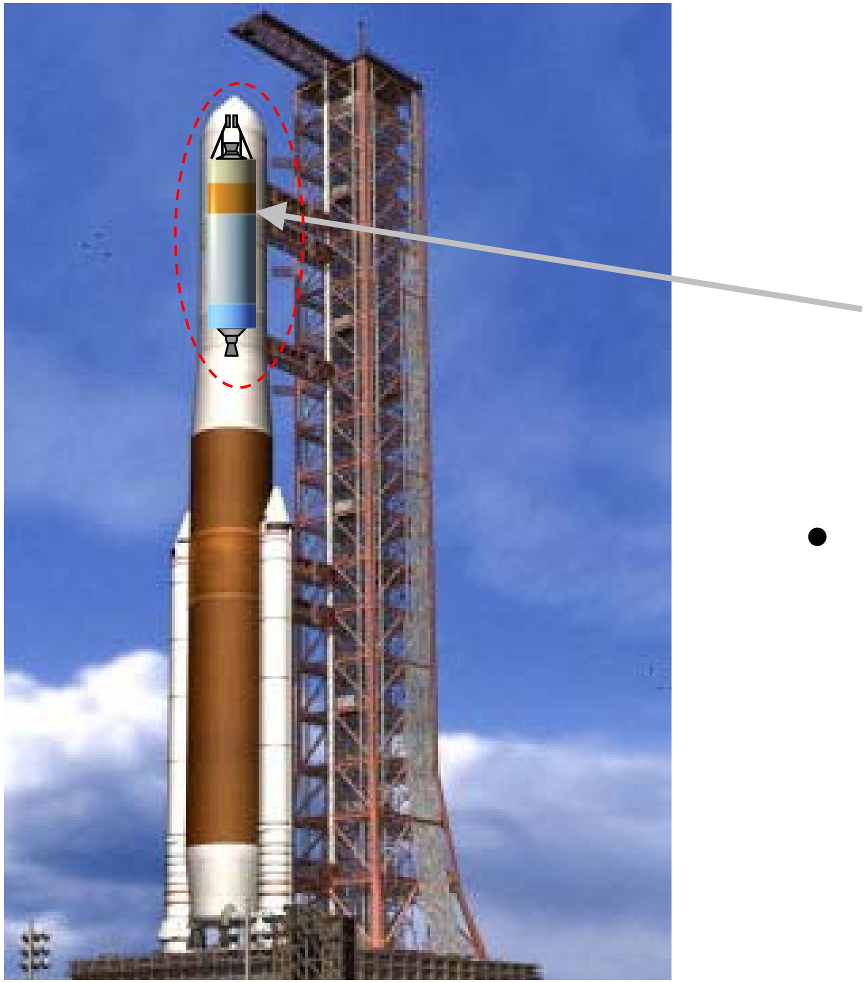
Present planning assumes that all of this cargo will be transferred from LEO to the Moon's surface by chemical propulsion.

An unmanned cargo capability based on electric propulsion could offer significant cost savings to a lunar exploration program.

NASA images



All-chemical Lunar Cargo Flight



- For purposes of this comparison, we assume a heavy lift launcher capable of delivering a 100 mT Trans-Lunar stage to low Earth orbit (LEO), comparable to Ares V.
- The Trans-Lunar stage is dominated by the mass of the LOX and LH2 propellant needed to get the cargo vehicle from LEO to low lunar orbit (LLO).

All-Chemical Lunar Cargo Performance

IMLEO: 100 mT

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

LOI: lunar orbit insertion

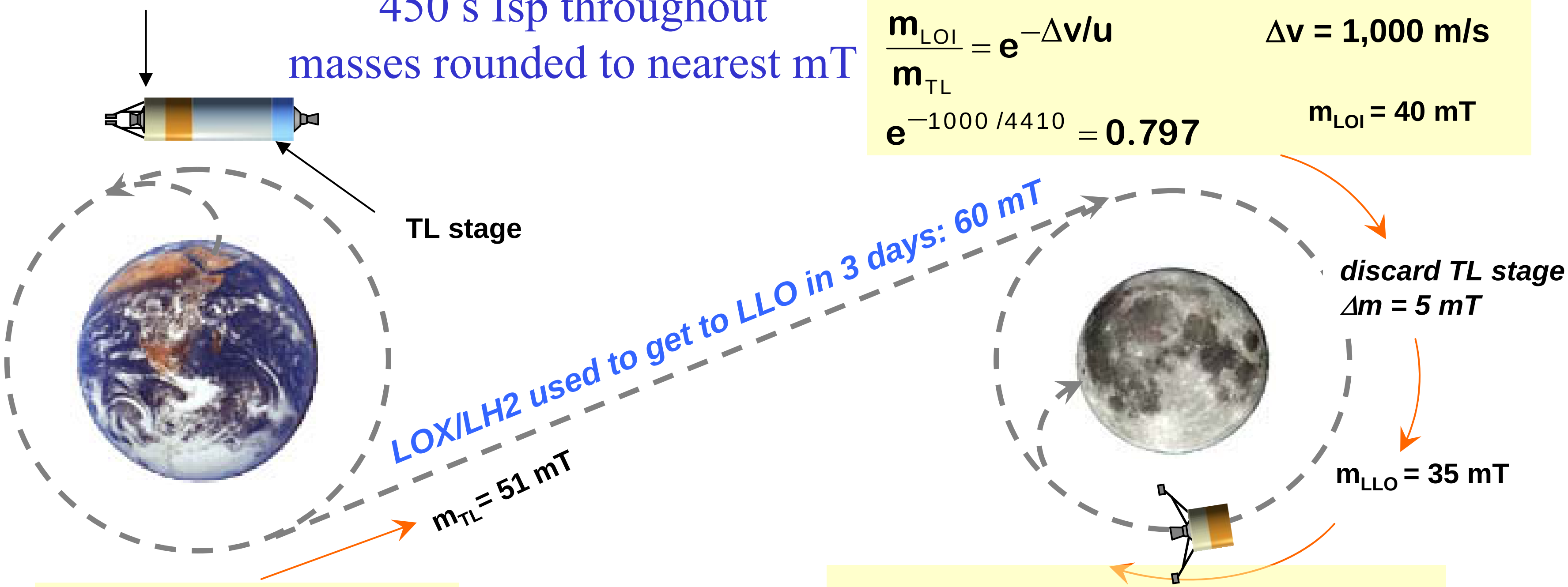
$$\frac{m_{LOI}}{m_{TL}} = e^{-\Delta v/u}$$

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

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:

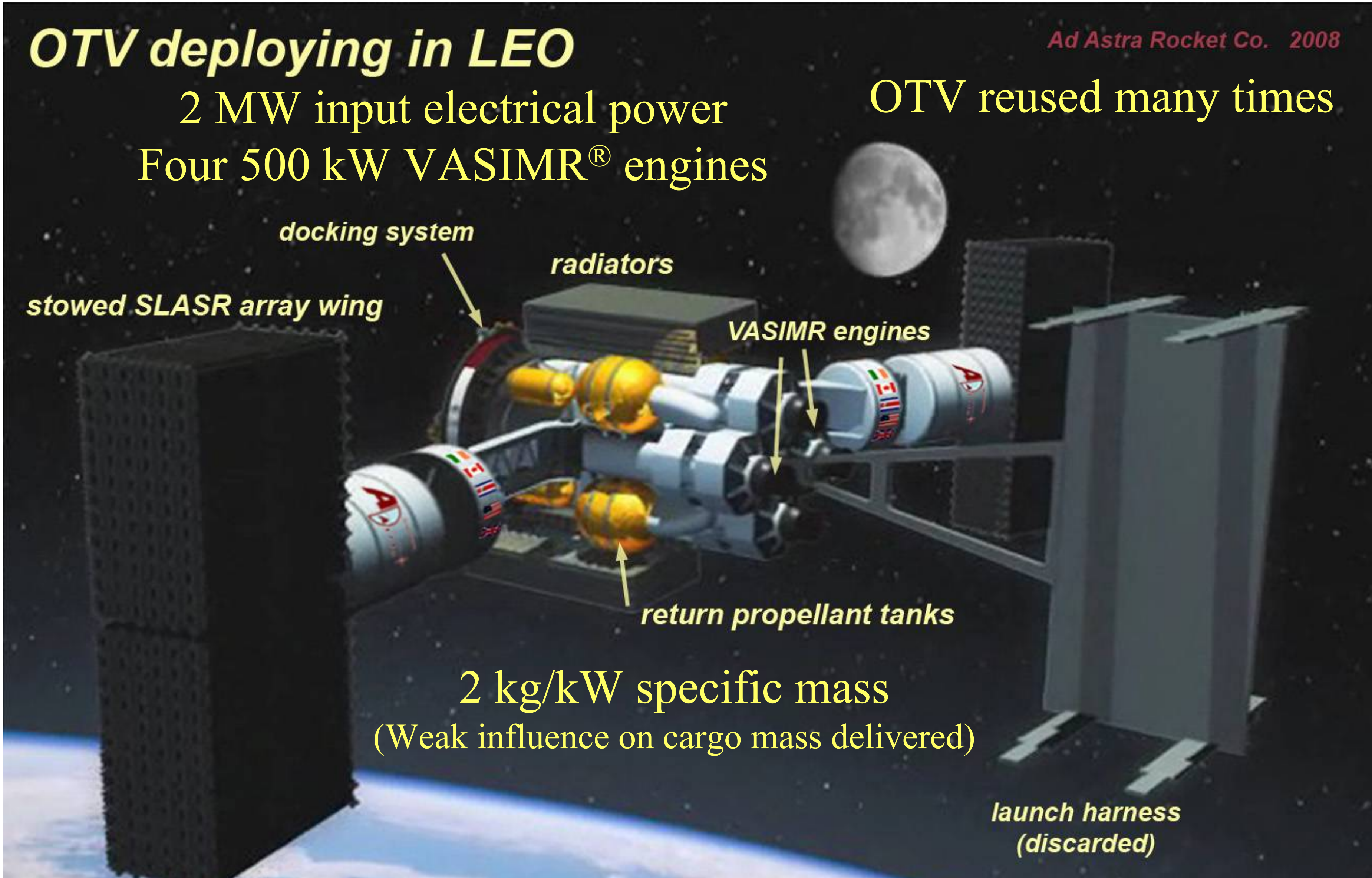
Δv = 2,000 m/s

Assume cargo mass %80 of landed mass

cargo = 0.51 x m_{LLO}

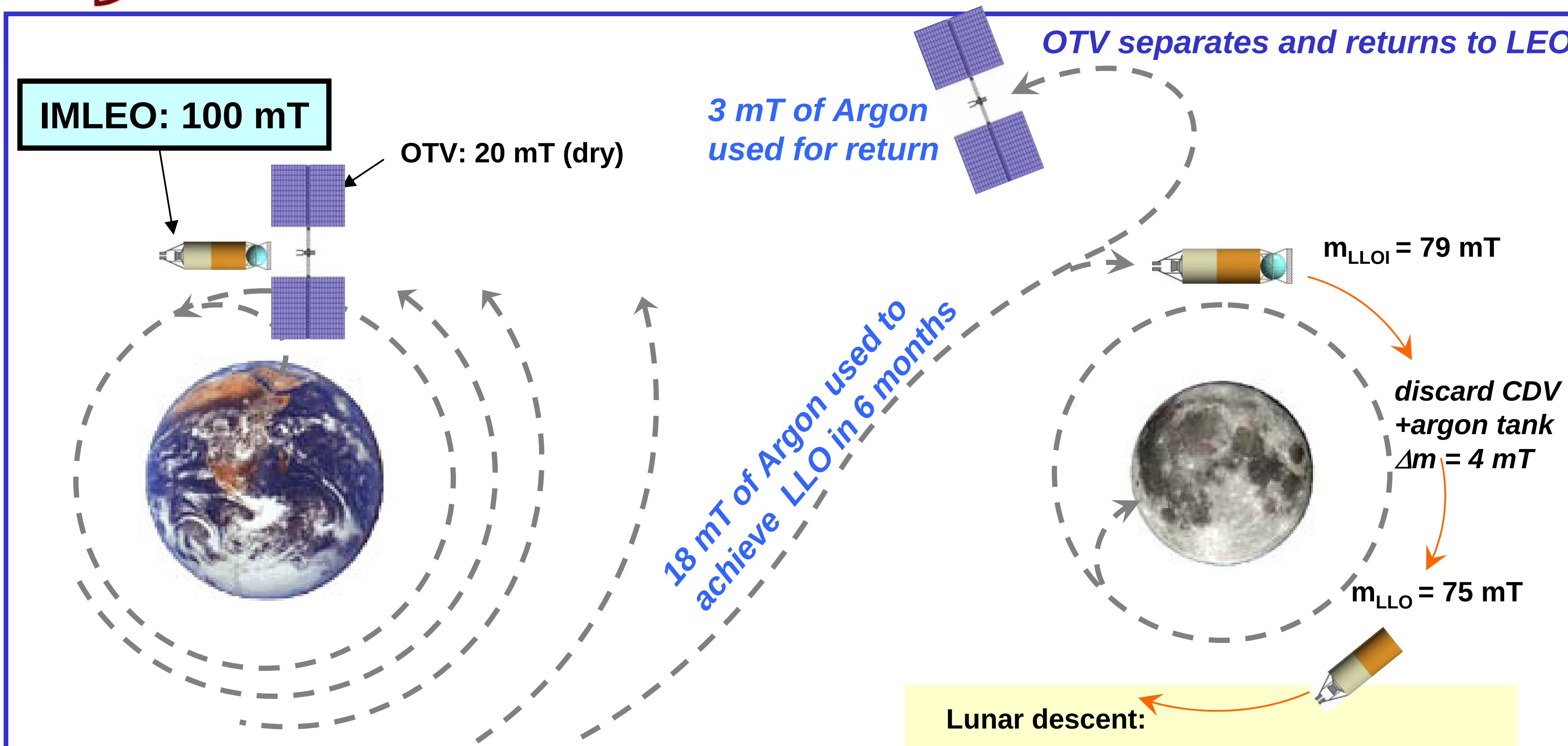
cargo mass on lunar surface = 18 mT

VASIMR® Orbital Transfer Vehicle (OTV)



VASIMR® Lunar Cargo Mission Animation

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:

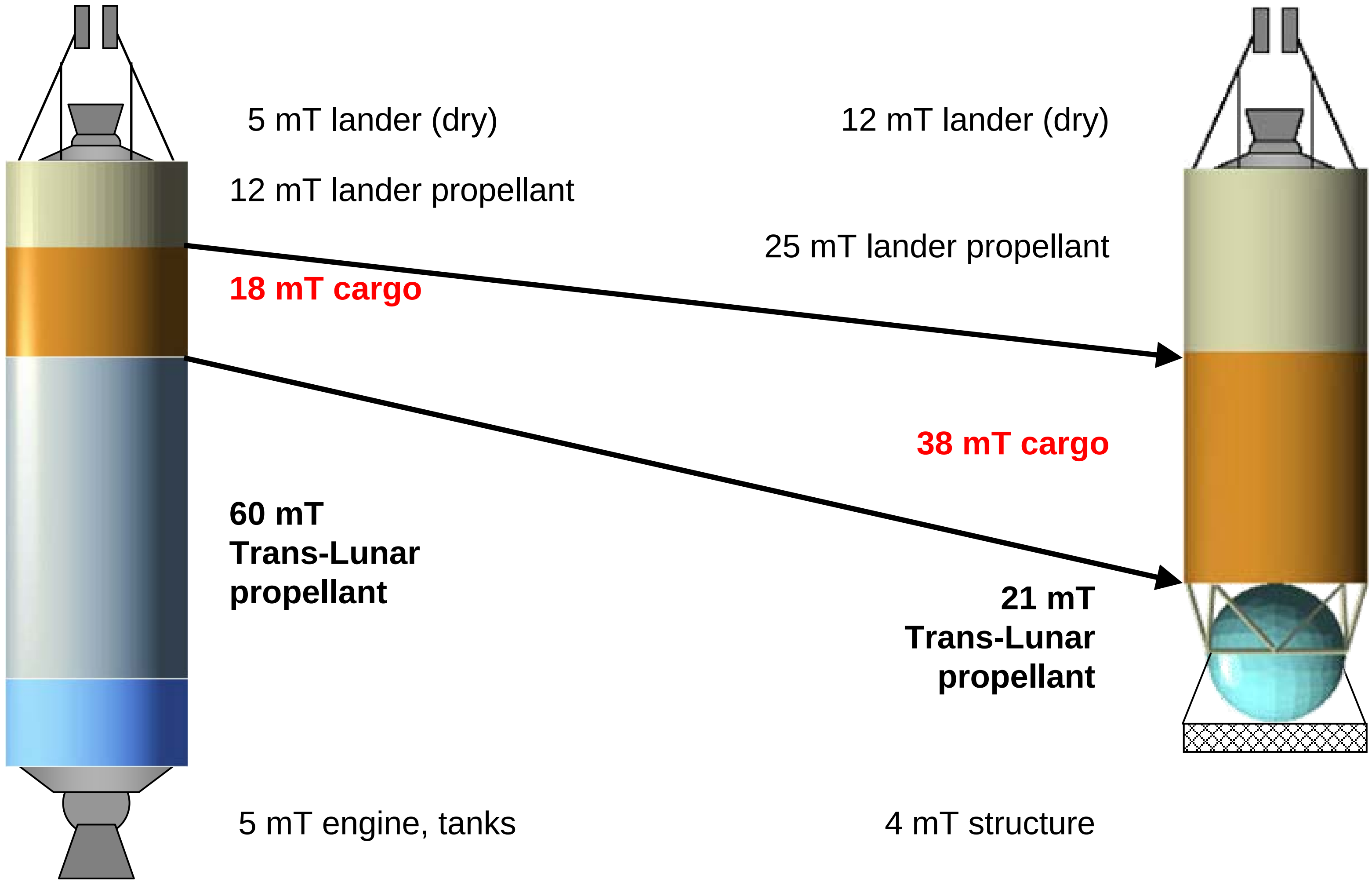
Δv = 2,000 m/s

Assume cargo mass %80 of landed mass

cargo mass = 0.51 x m_{LLO}

cargo mass on lunar surface = 38 mT

IMLEO Mass Allocation Comparison



450 s all-chemical system

5,000 s VASIMR® system

VASIMR®
Reduces number of
Ares V launches in <u>half</u>

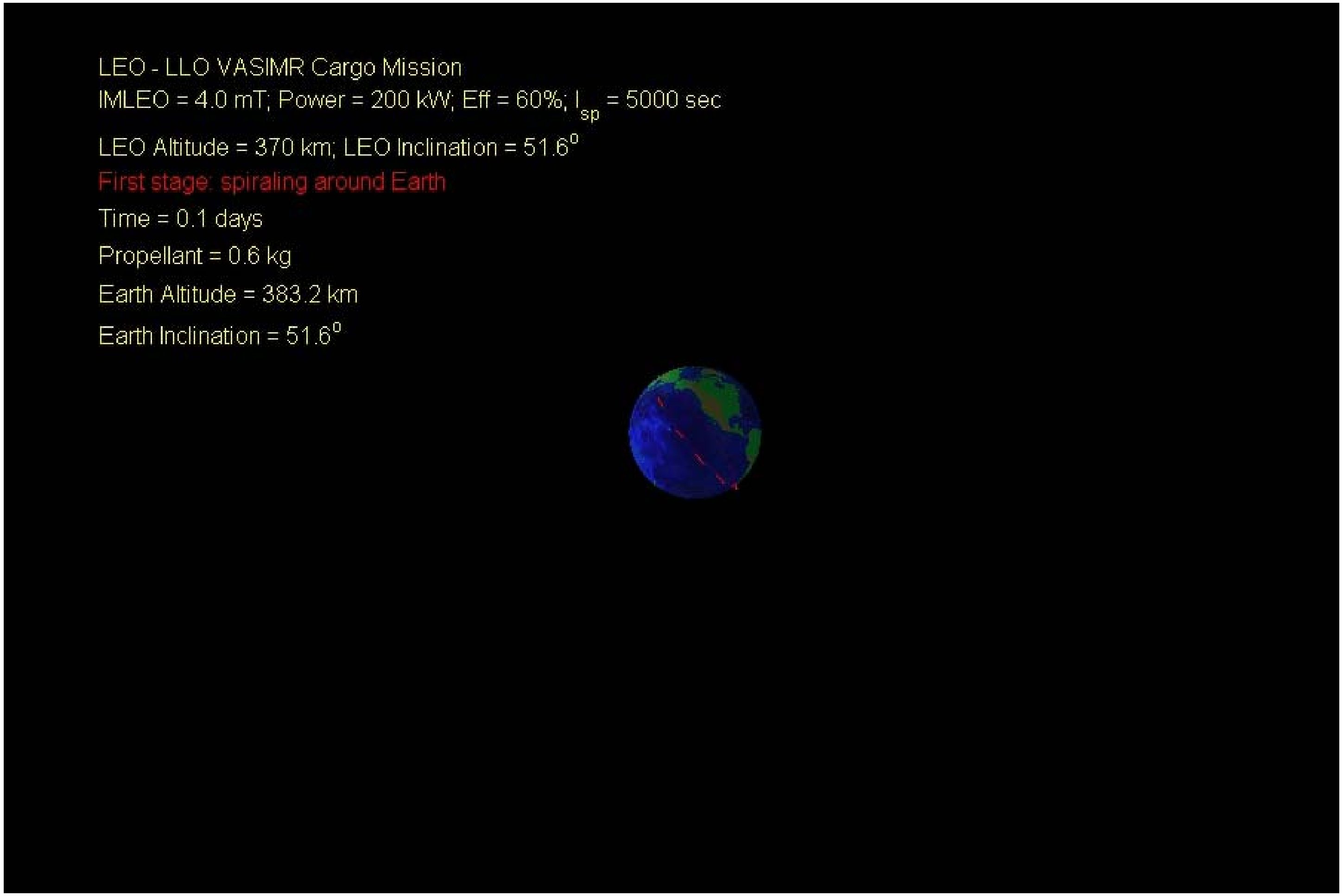
5 Potential Customers for Small Lunar Payloads

- SMD – (NASA Science Mission Directorate)
  - Goal of sending 1- 2 pure science missions to the lunar surface each year
  - Typical payload 300 kg
- ESMD – (NASA Exploration Systems Mission Directorate)
  - Needs access to the lunar surface for applied science projects that will pave the way for manned exploration
  - Examples: regolith characterization, surface testing of exploration hardware
- Foreign market
  - 9 – 16 countries (including India, S. Korea, Canada, Germany, the UK)
  - Their pride is in the hardware they get to the Moon, not propulsion system
- Commercial
  - a number of companies have business plans that involve landing equipment on the lunar surface (including Lunar X-prize), ranging from email routers to observatories.
  - Again, they don't care how they get there, and transit time is not so important.
- Other US gov't agencies – DARPA, other DoD, NSF

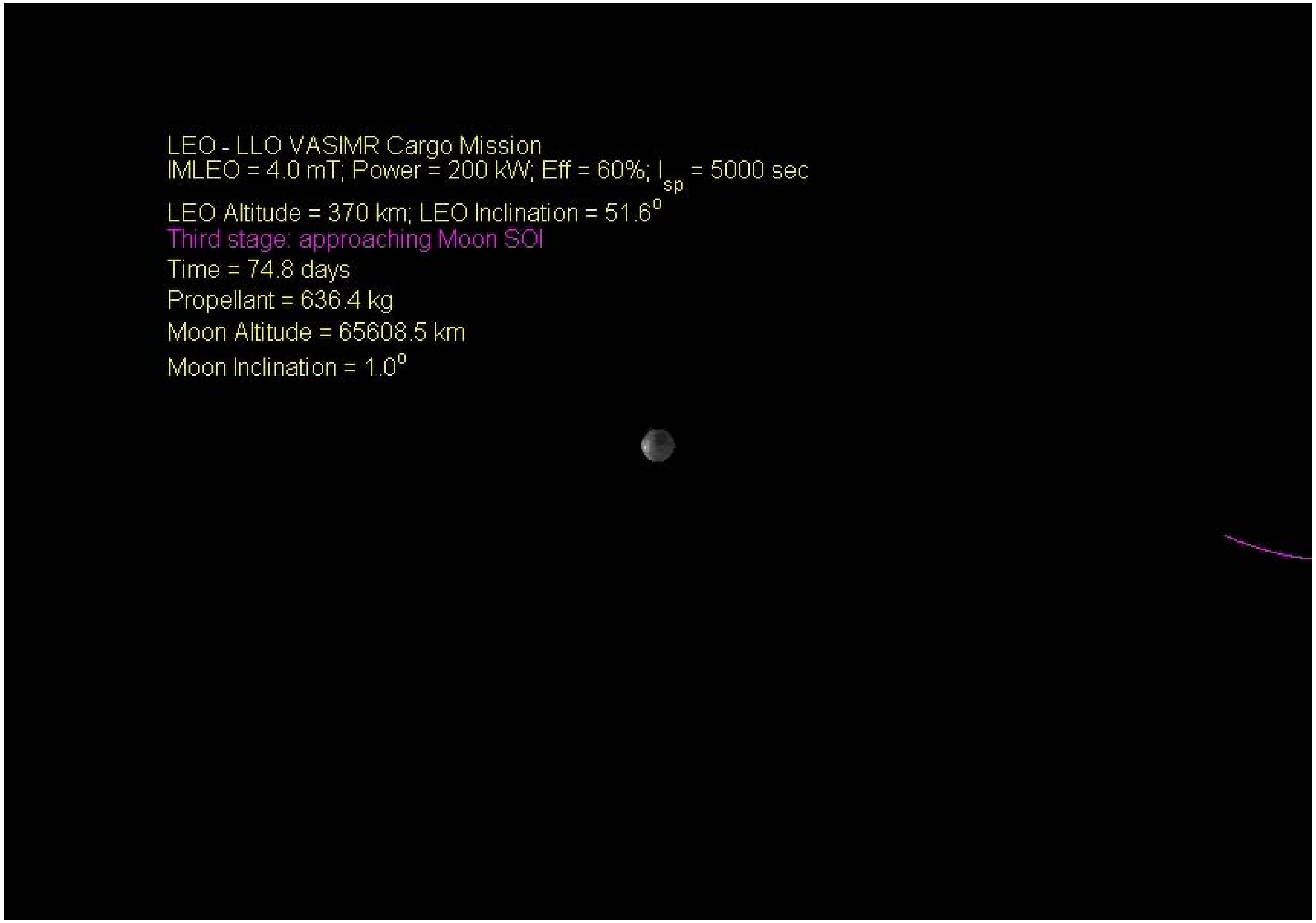
200 kW Lunar Cargo Tug

- Start from low Earth orbit (LEO) similar to ISS
  - Altitude: 370 km
  - Inclination: 51.6°
- Finish at low Lunar orbit (LLO)
  - Altitude: 100 km
  - Inclination: 90° (polar)
- VASIMR® performance assumptions
  - Efficiency: 60%
  - Isp: 5,000 s
  - Specific mass: 5 kg/kW
- Initial Mass in LEO (IMLEO): 4,000 kg
  - Propulsion system mass: 1000 kg
  - Power system (solar) mass: 600 kg
  - Propellant mass: 872 kg
  - Tank mass: 87 kg
  - Cargo mass: **1441 kg (to LLO) [735 kg to surface]**

LEO-LLO Animation (Earth Ref. Frame)



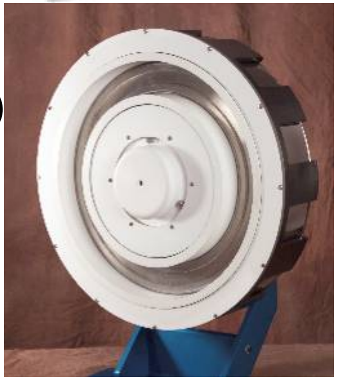
LEO-LLO Animation (Lunar Ref. Frame)



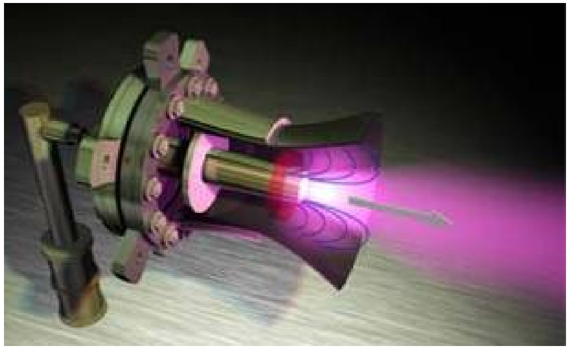
Electric Propulsion Devices

- 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)



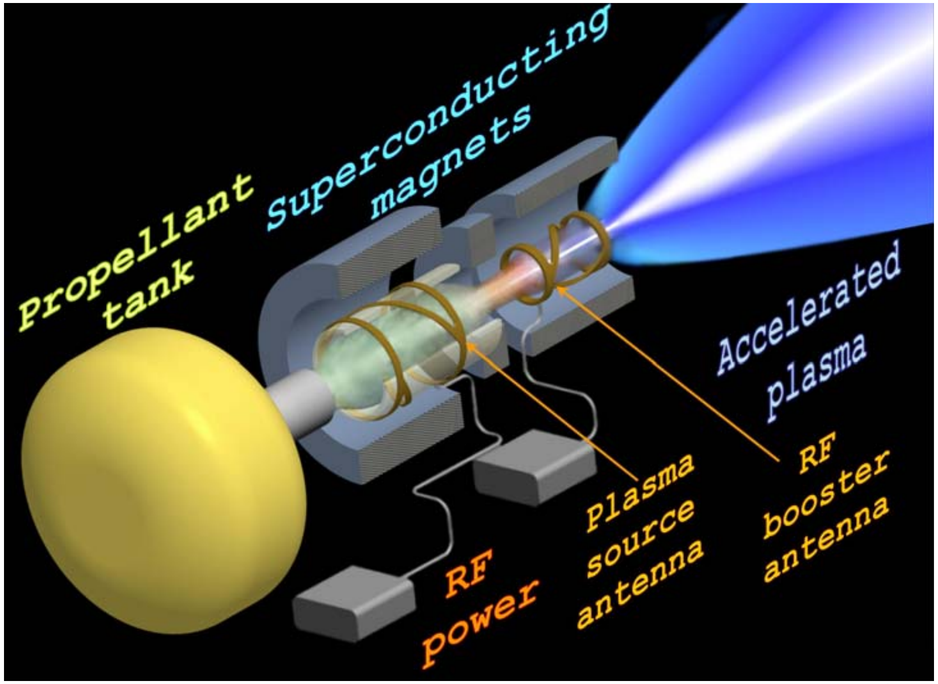
Unique VASIMR® Capabilities

- 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

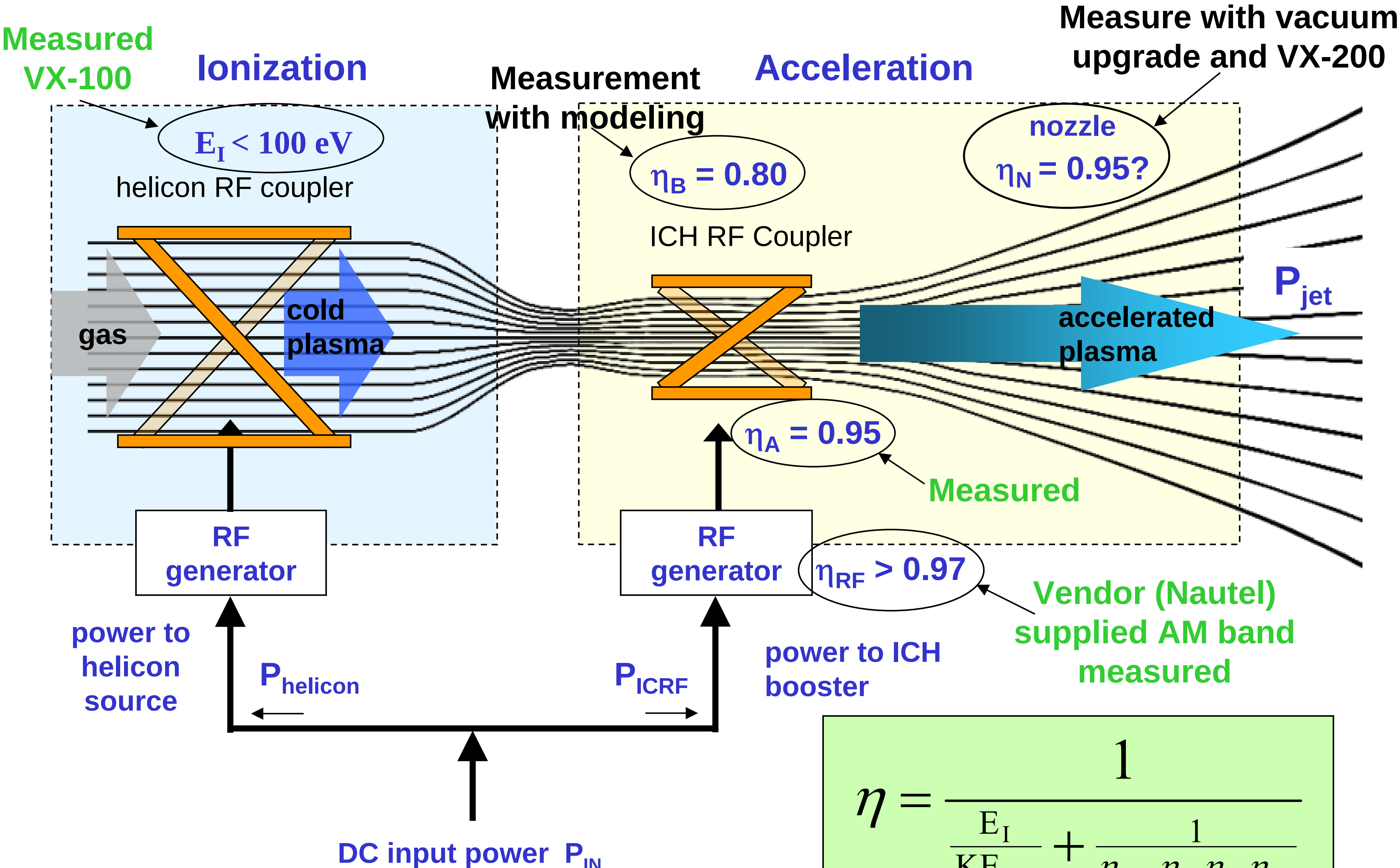
- We believe that very soon there will be a market requiring thrusters that use 200 kW to 20 MW of power and that VASIMR® is best suited to fill that market

VASIMR® 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



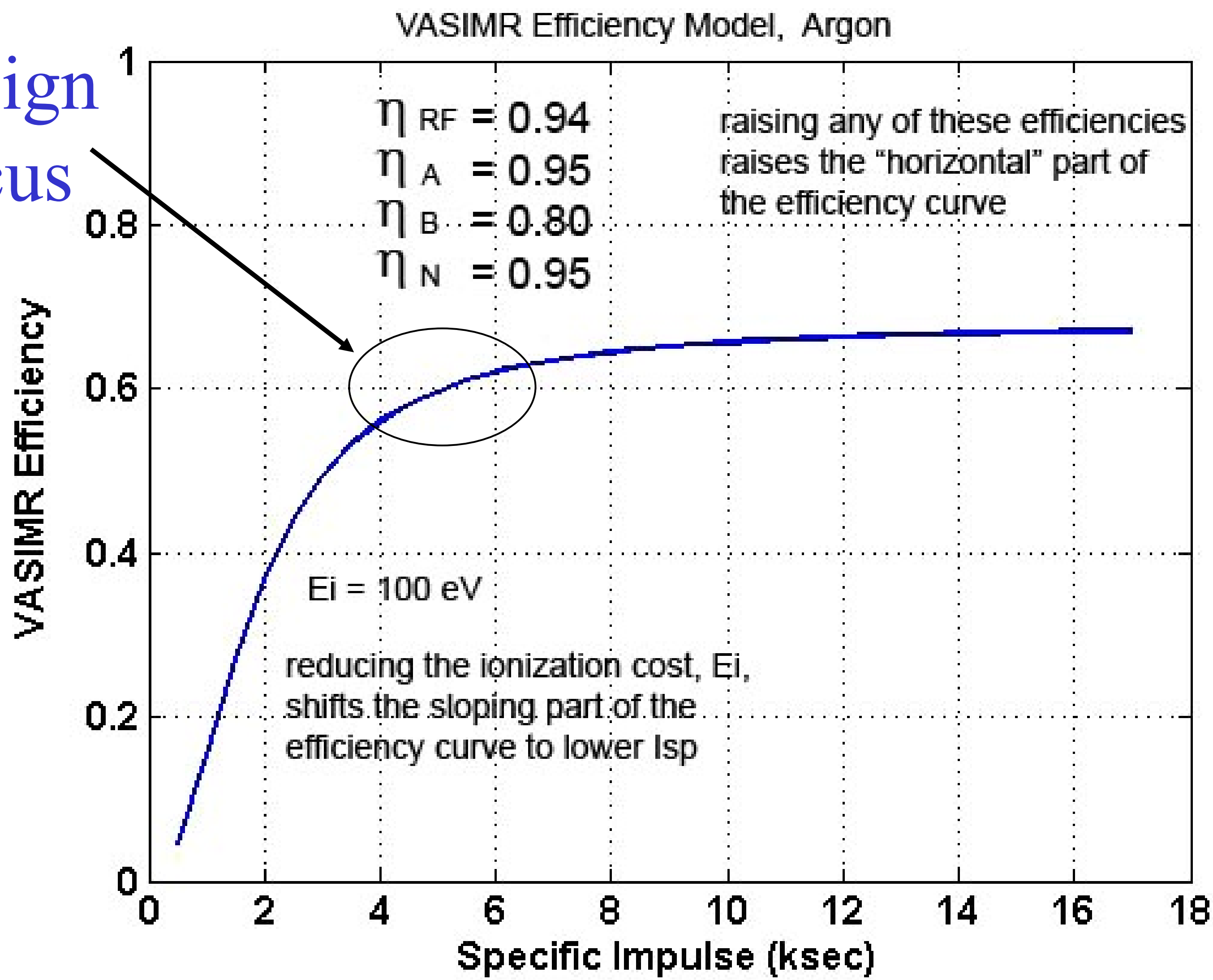
Simple Model of VASIMR® Efficiency



$$\eta = \frac{1}{\frac{E_I}{KE_{ion}} + \frac{1}{\eta_{RF}\,\eta_A\,\eta_B\,\eta_N}}$$

VASIMR® Efficiency Calculation

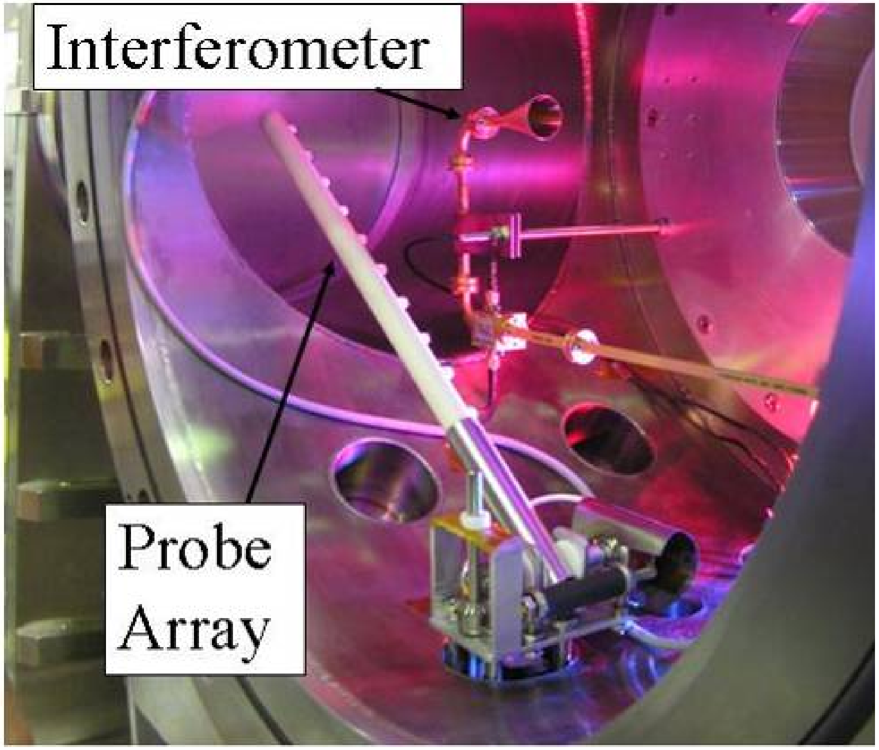
Design focus

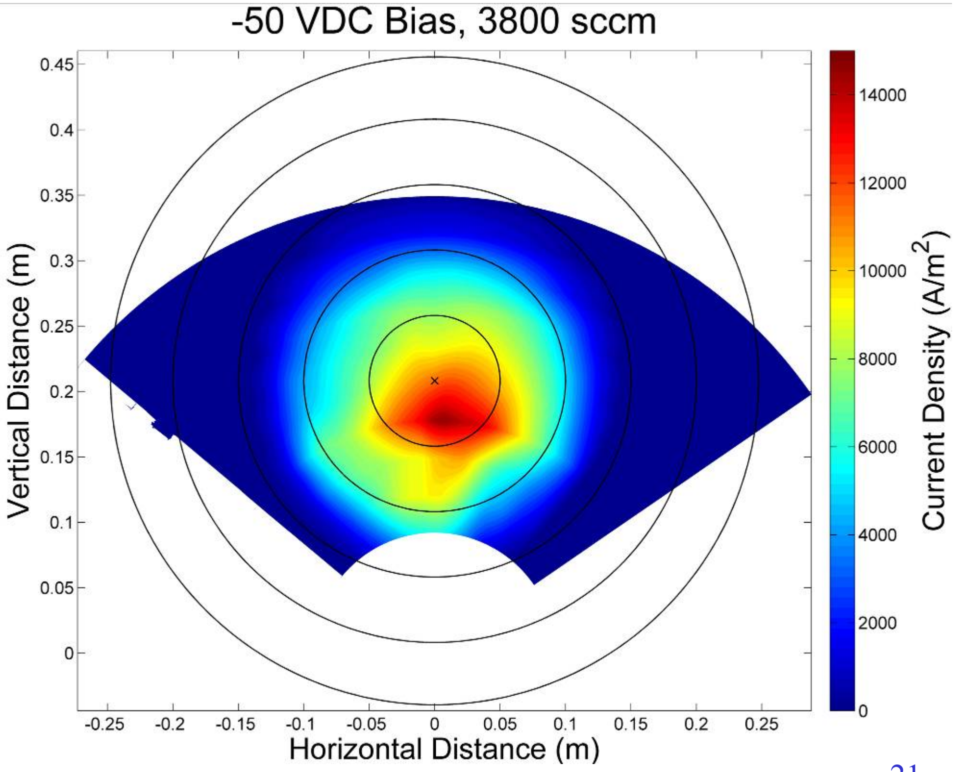


VX-100 Operational May to Oct. 2007

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 Plasma Force Measurement

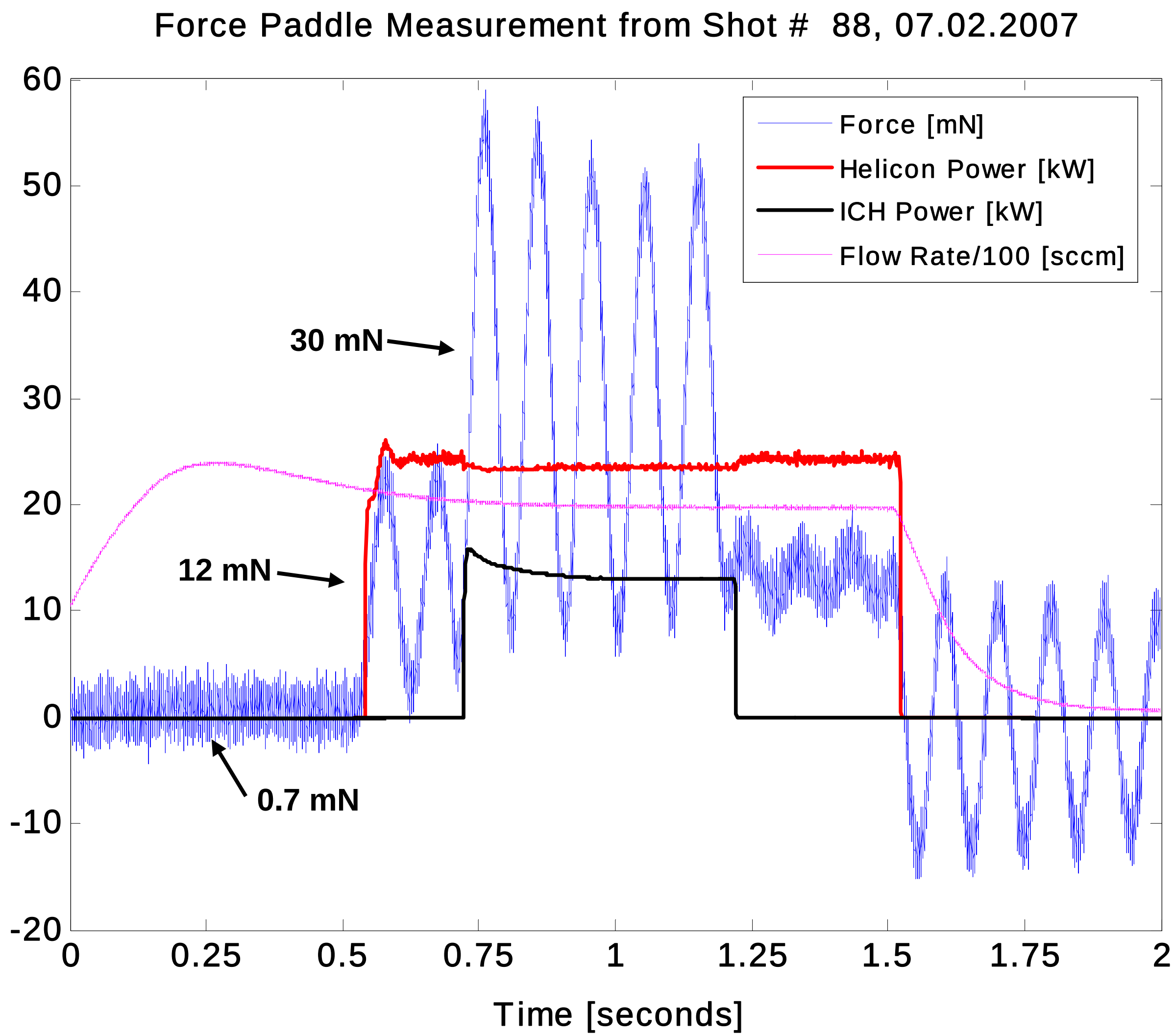
Impact Target Data for 13 kW ICH

2800 sccm Ar → 0.7 mN
25 kW Helicon → 12 mN
13 kW ICH → 30 mN

Total force: 810 mN

Experimental setup:
50-100 eV Ar ions impacting 8.9 cm^2 Alumina (Al_2O_3) target, 21 cm downstream of fast reciprocating Langmuir probe

Validated at Michigan



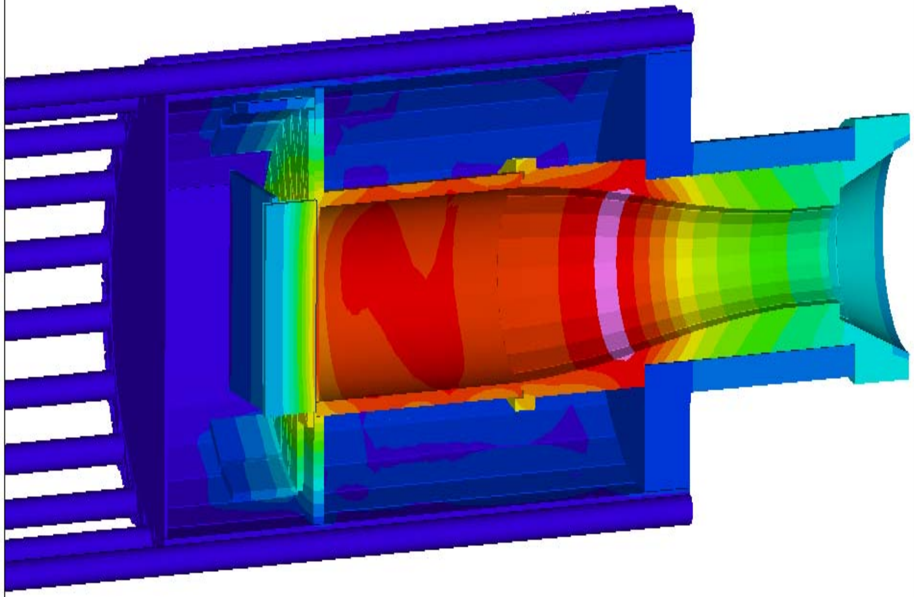
VX-200 Project Goals

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

Thermal Management

- Most RF power sent to first stage will be waste heat
  - Radiation from plasma
  - Some plasma/surface interaction
- Magnet surrounds volume
- Materials must not interfere with RF transmission
- Low mass

Helicon Section



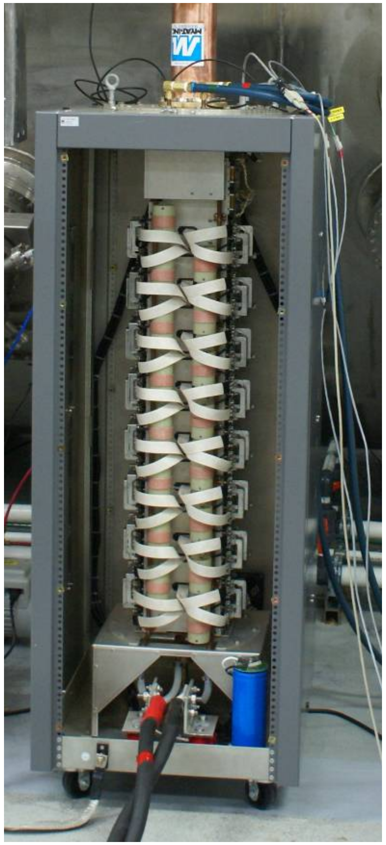
Superconducting Magnet

- VASIMR® requires a high temperature superconducting (HTS) magnet
  - 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
  - Install this week

RF Generator Development

- Nautel Limited designed and manufactured to our specs
  - Solid state
  - High efficiency
  - Very compact
  - Low mass
- Helicon
  - 48 kW
  - 92% efficient
- ICH:
  - 165 kW
  - 97% efficient

Helicon RF Generator



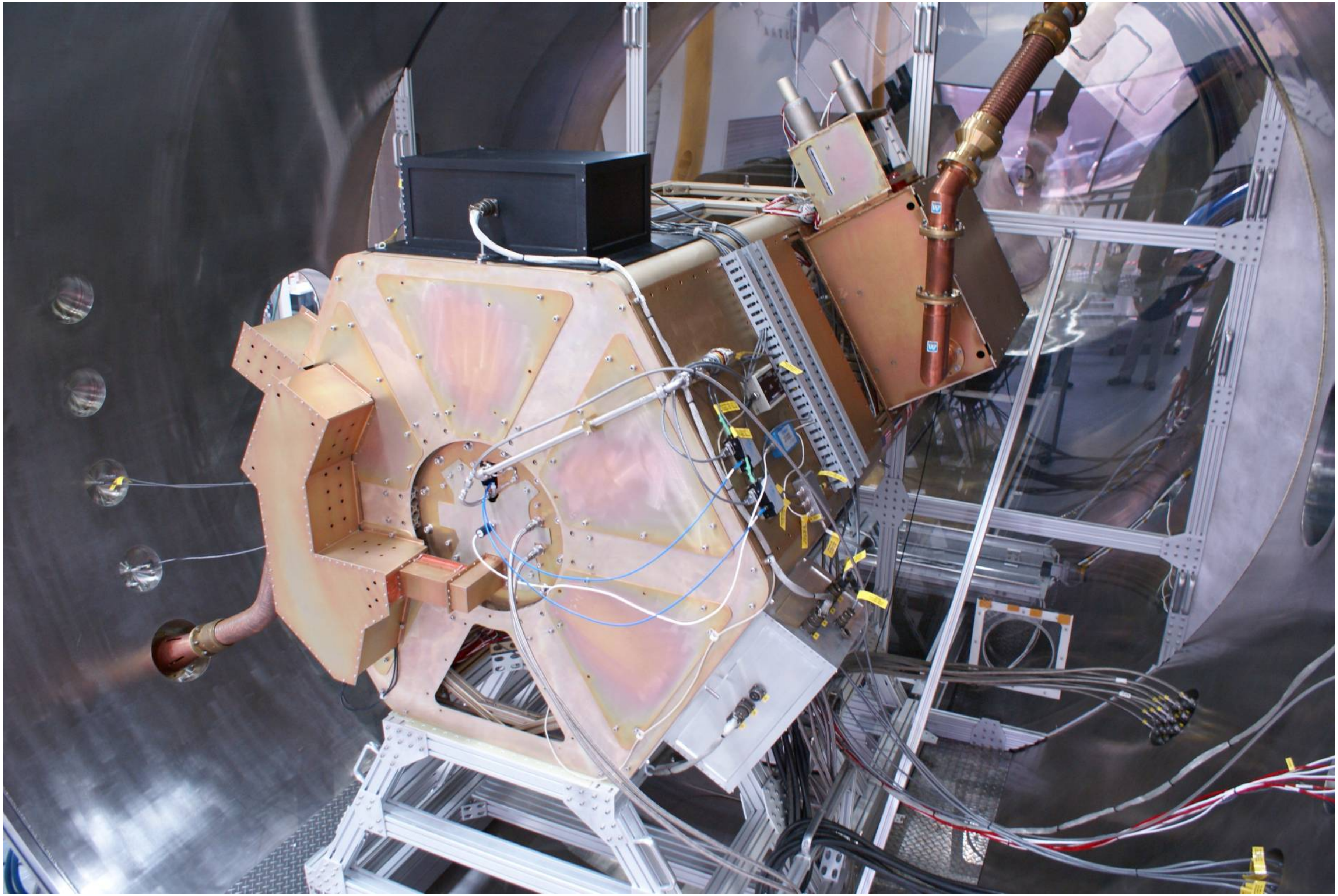
ICH RF Generator

VX-200i

- VASIMR® engineering test bed
  - "i" for interim: superconducting magnet delivered late
  - Magnetic field strength < 5% of design, copper tubing
- Validated operation of:
  - Solid state RF generators coupled to plasma
  - RF power transmission
  - Control avionics in vacuum
  - Propellant feed system in vacuum
  - Plasma diagnostics
  - Facility pumping & operation
- Retired April 9

VX-200i – Starboard Side

VX-200i – Port Side

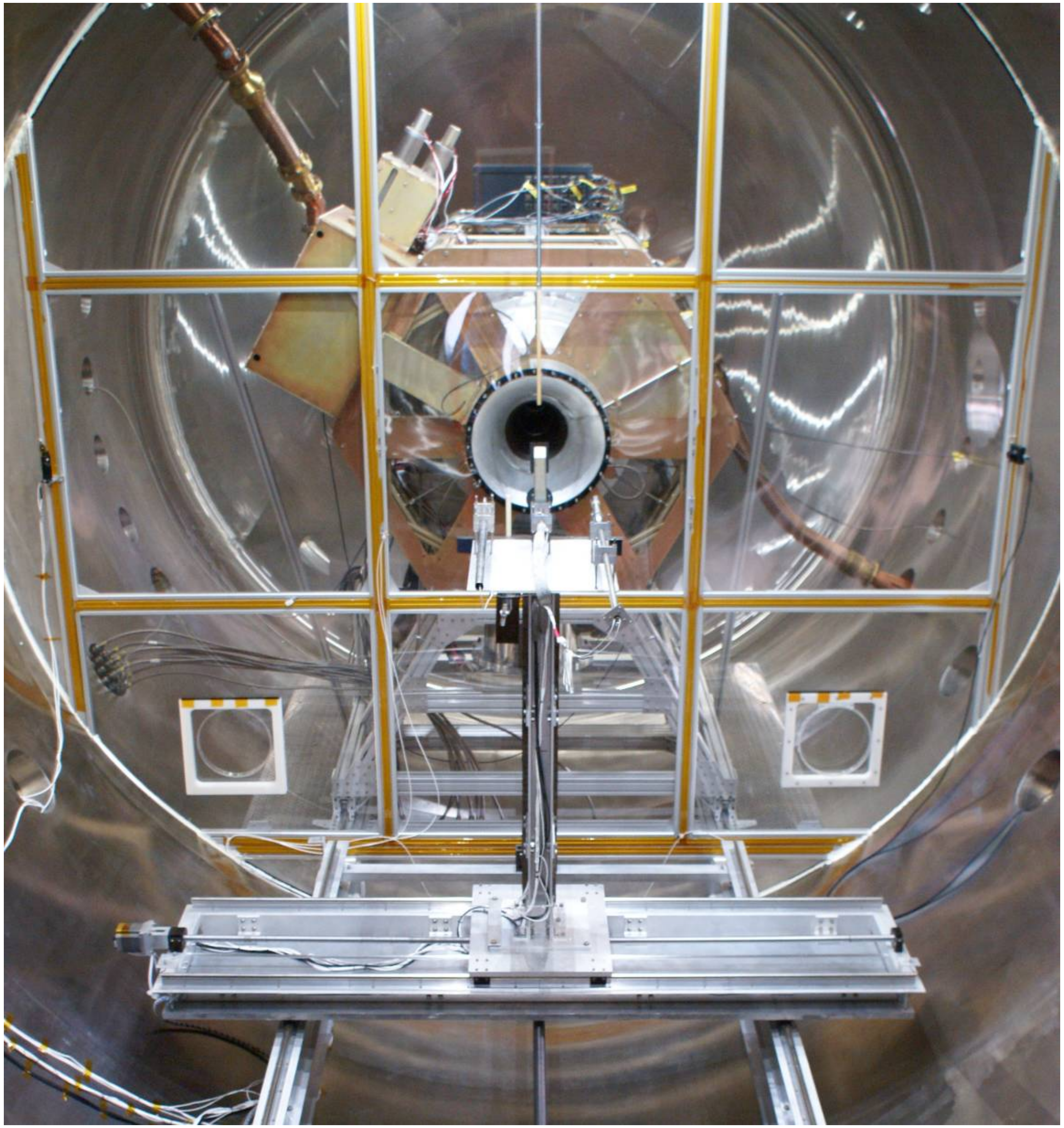


Facility – 150 m^3 Vacuum Chamber

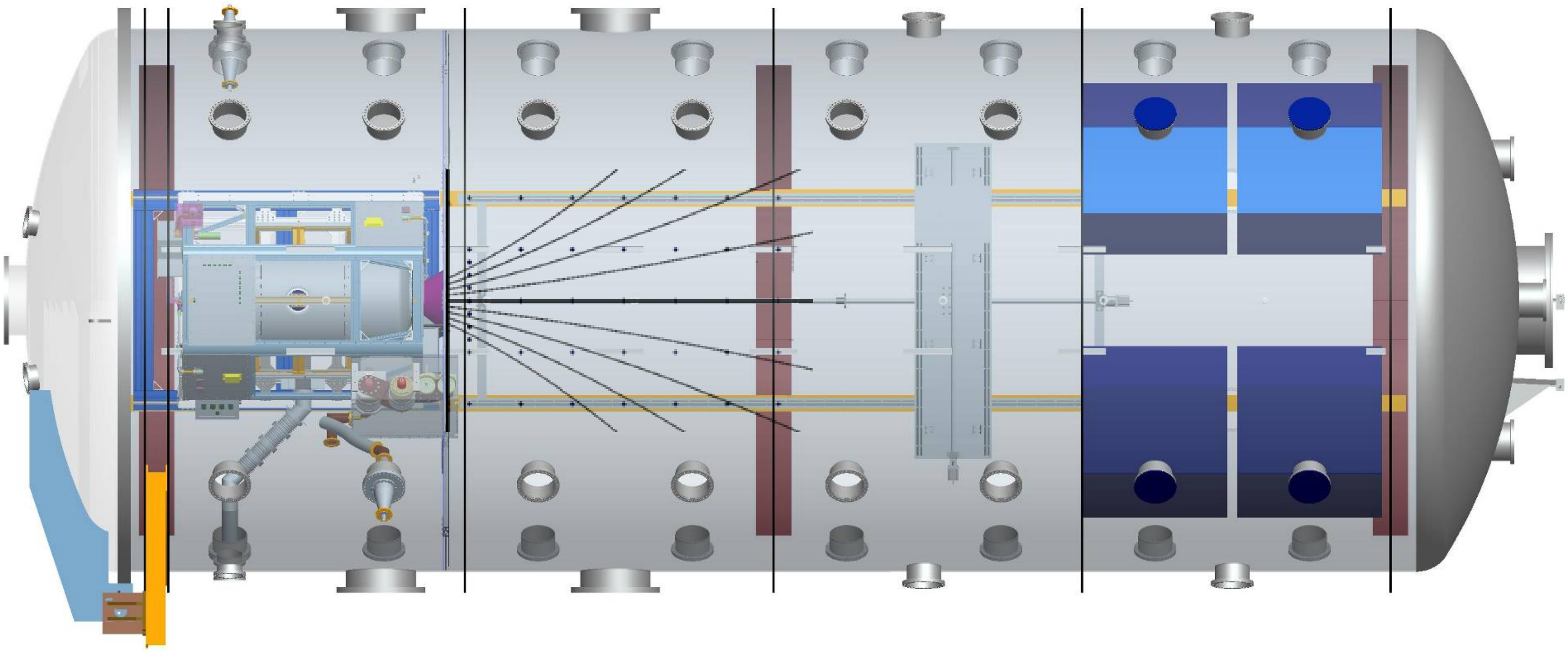
VX-200i & Diagnostics Inside Chamber

- Pumping: 60,000 l/s
- Base pressure:

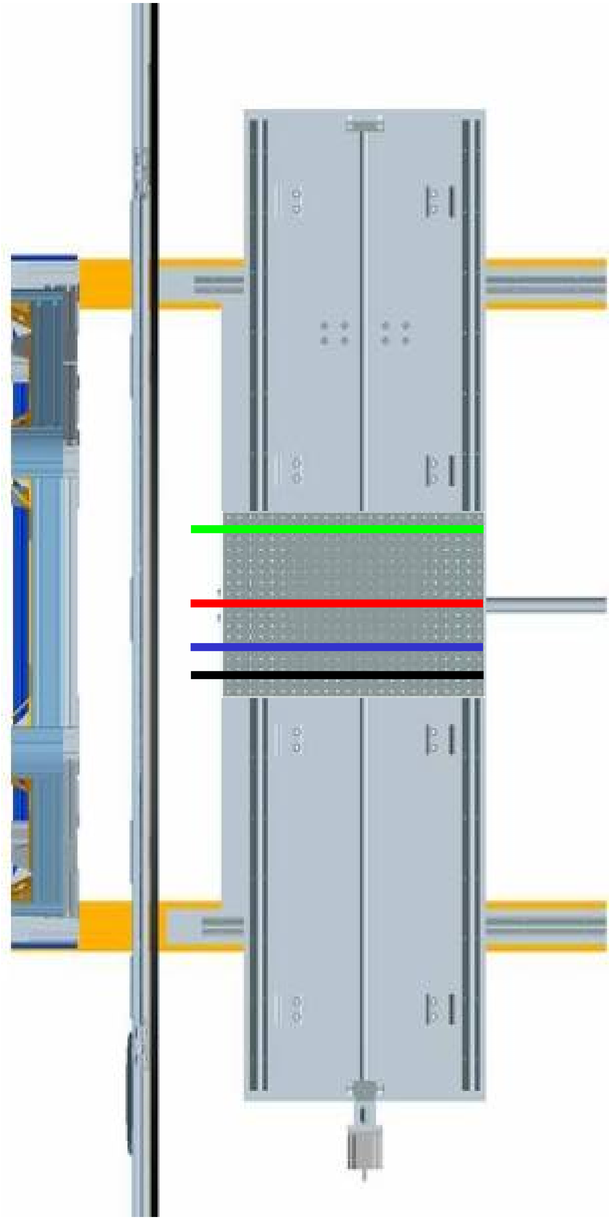
  3×10^{-8} Torr

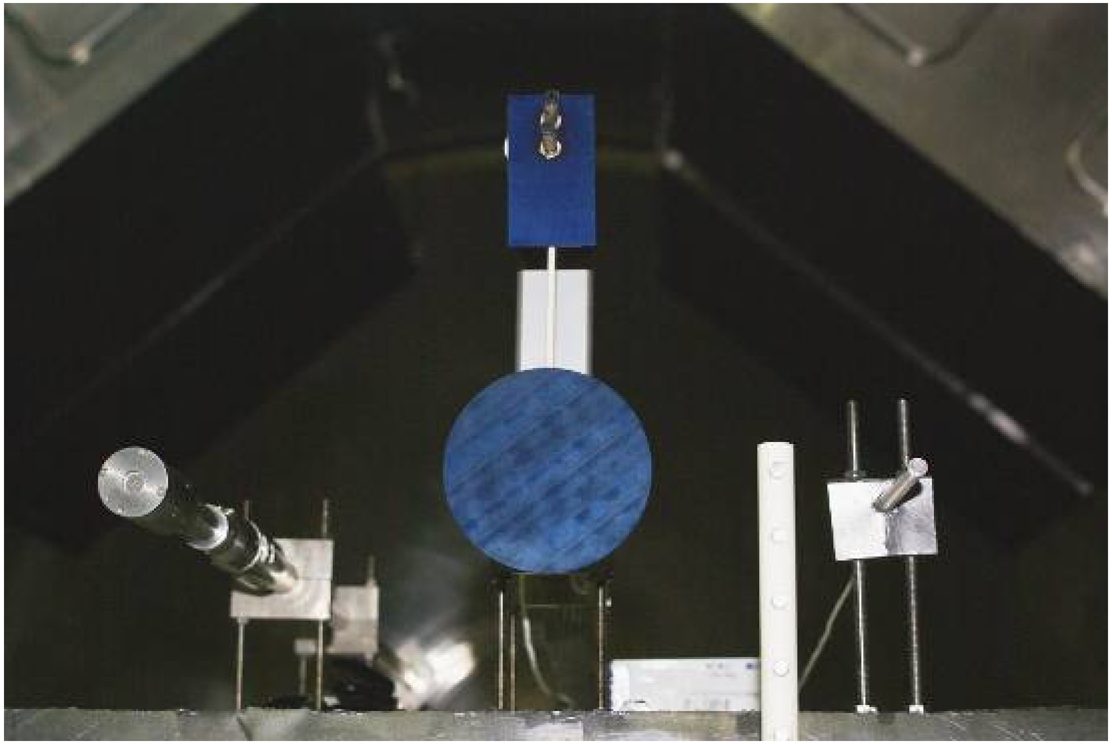


Diagnostics Range & B-field Mapping



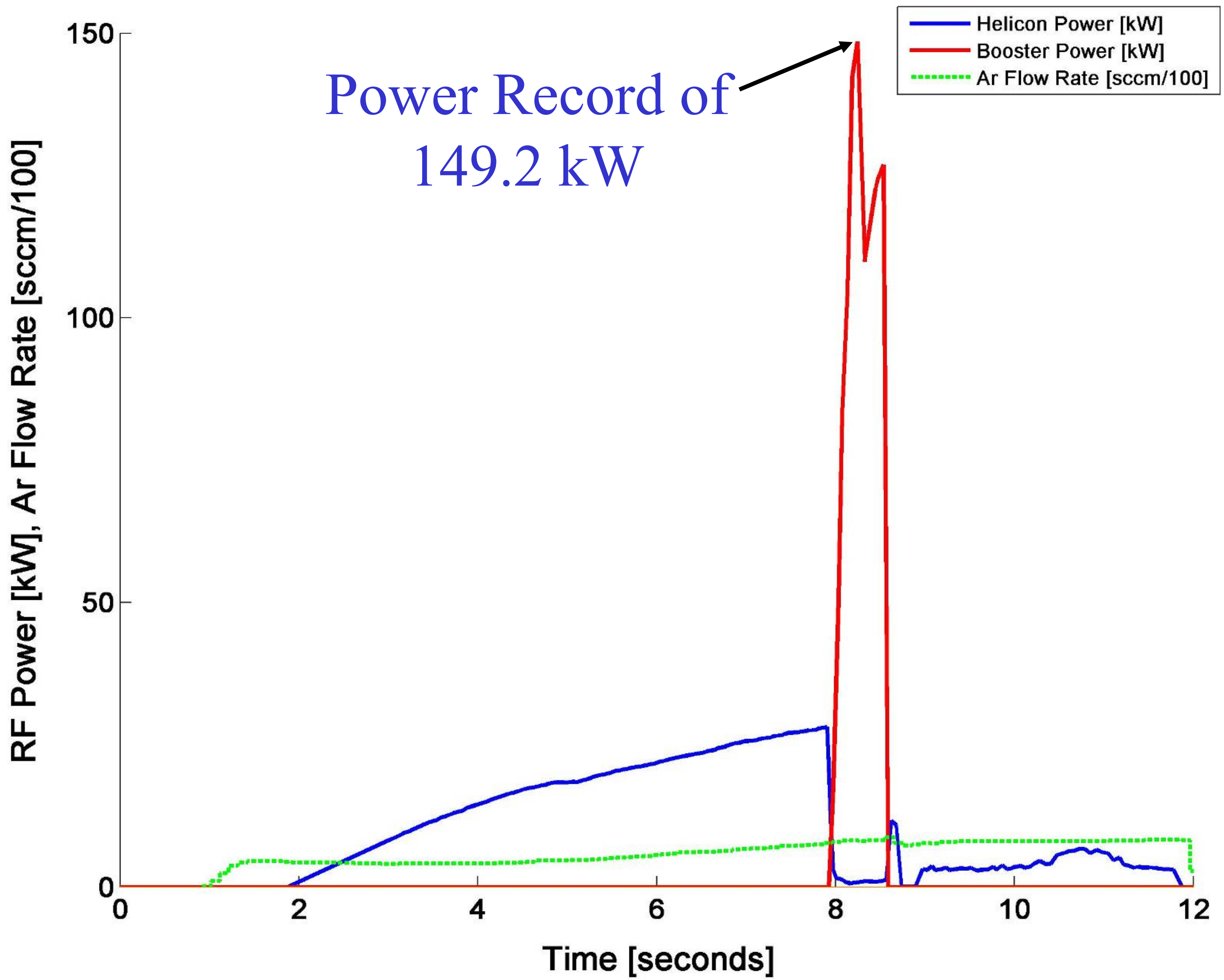
Translation Stage Table and Diagnostics





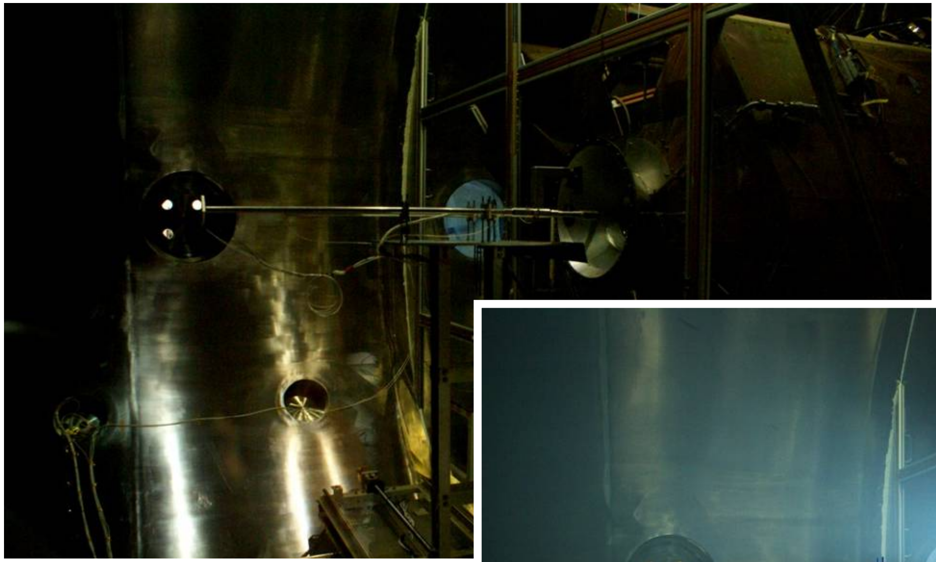
- UH RPA (green line)
- Force Target & Magnetometer (red line)
- Stationary Flux Probe Array (blue line)
- Guarded Flux Probe (black line)

Recent Results

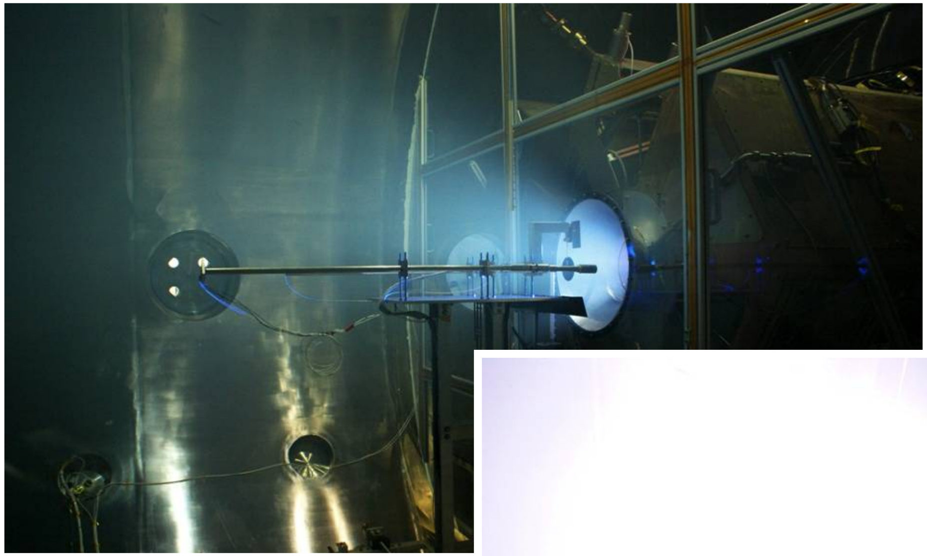


VX-200i Plume Images

Same camera settings for all images



No Plasma

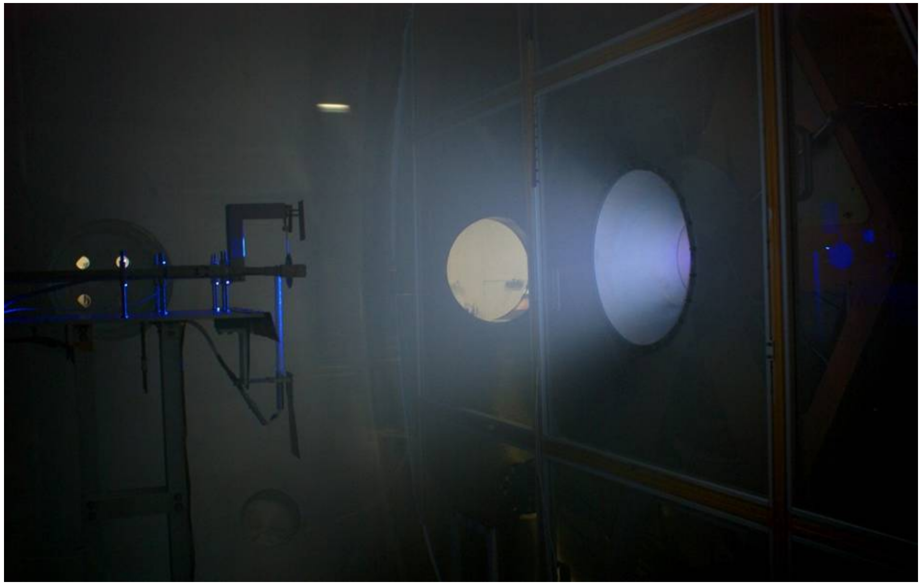


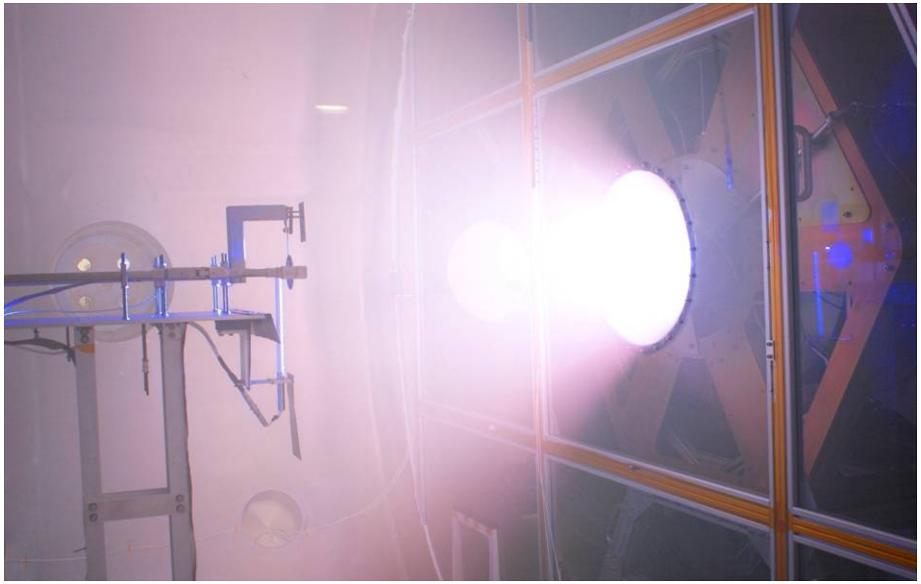
30 kW Helicon Only

148.5 kW Booster &
0.7 kW Helicon

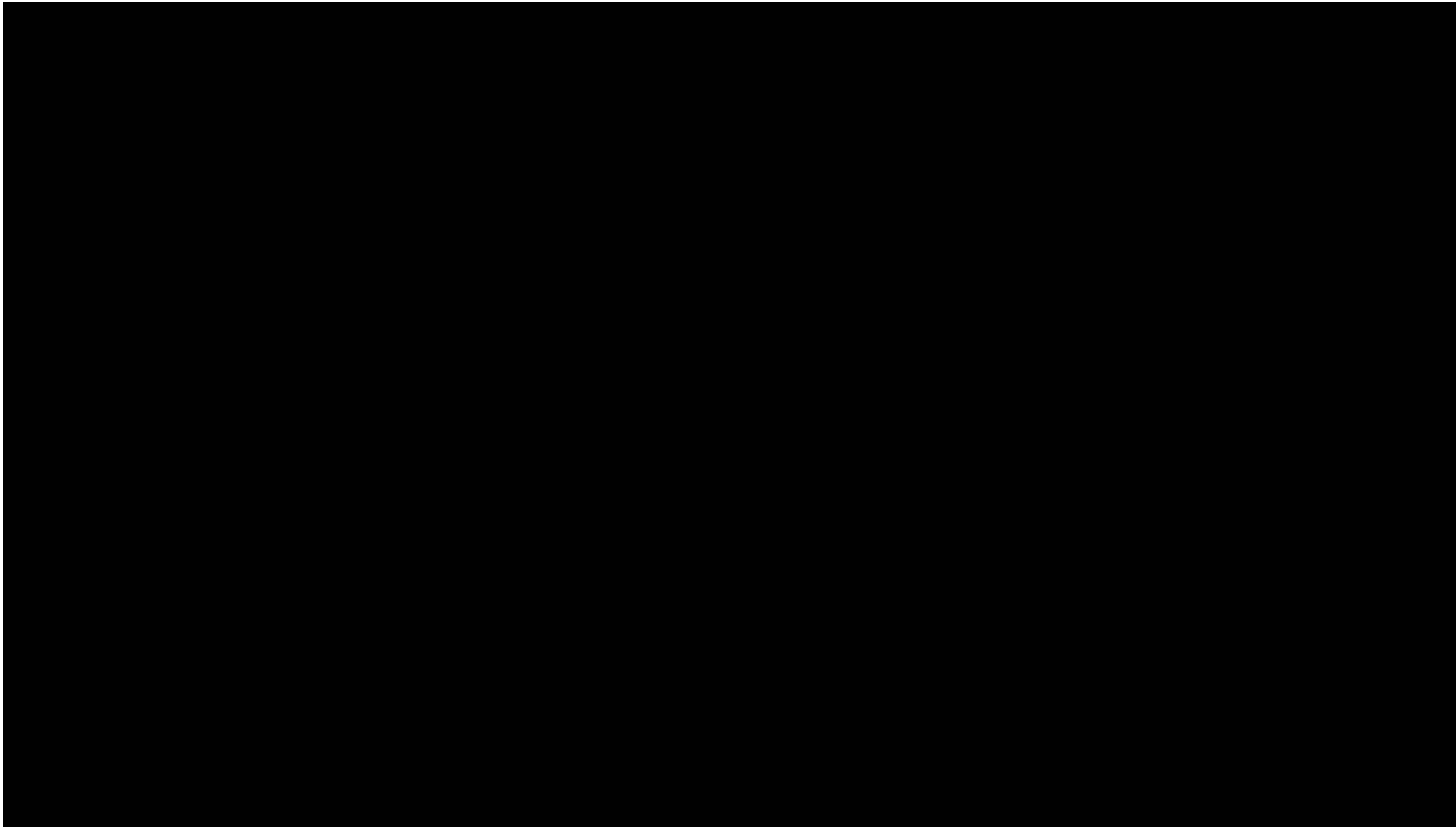
More VX-200i Plume Images

- Less sensitive camera settings than previous slide
- Top Image: 30 kW Helicon only
- Bottom Image: 124 kW Booster
  - 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 here seems to follow the same field lines as the helicon source above

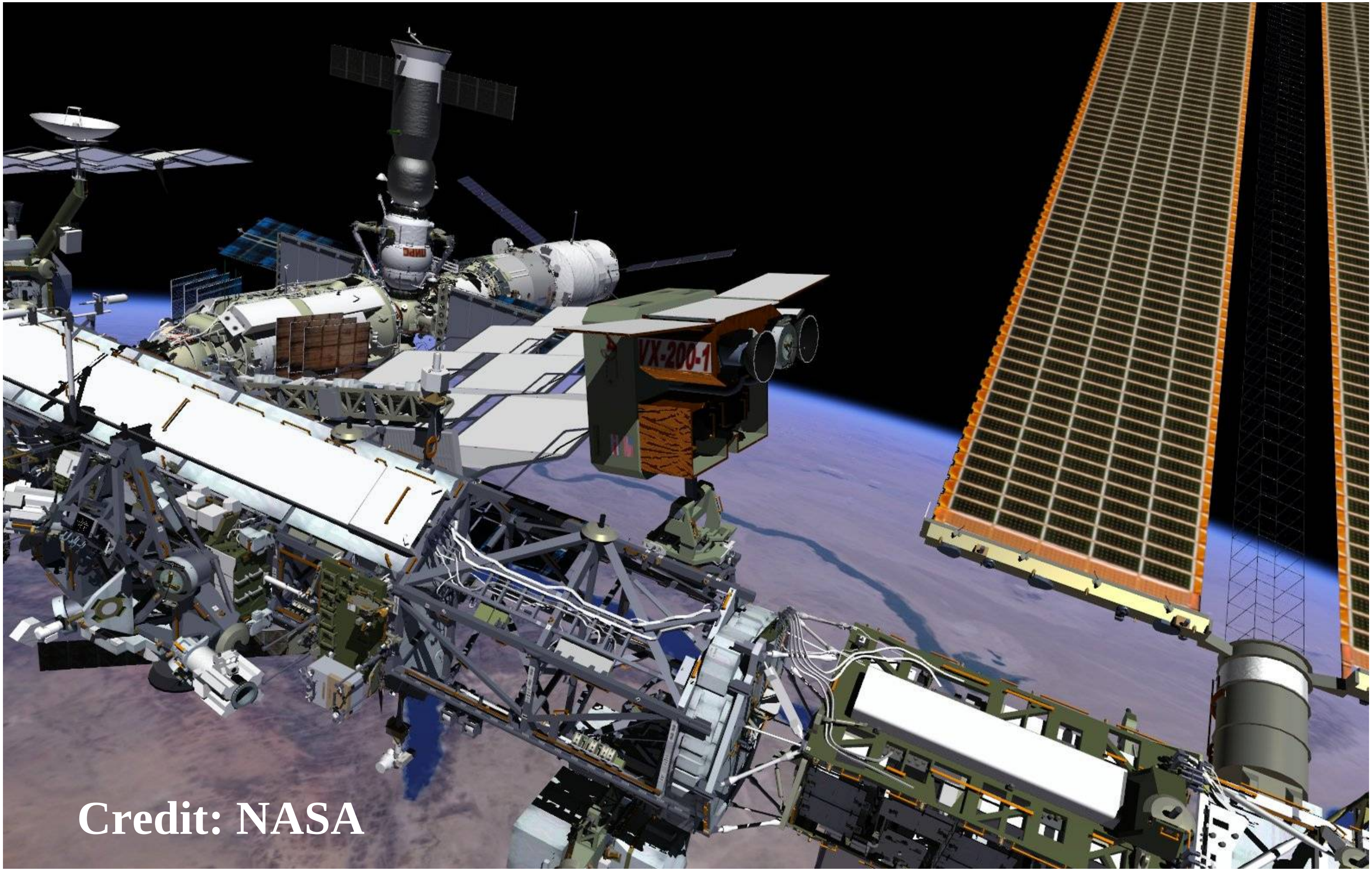




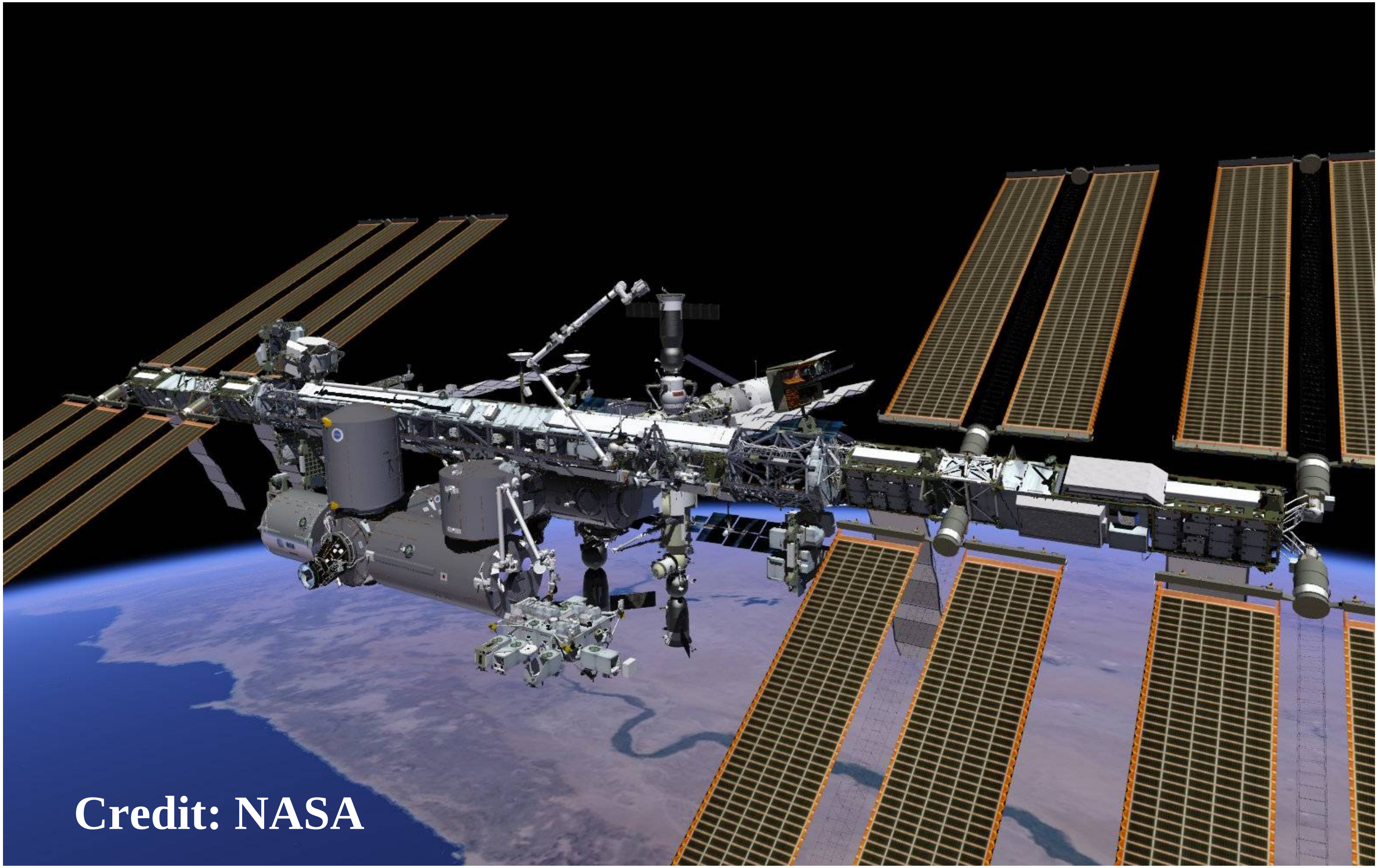
Movie of Firing



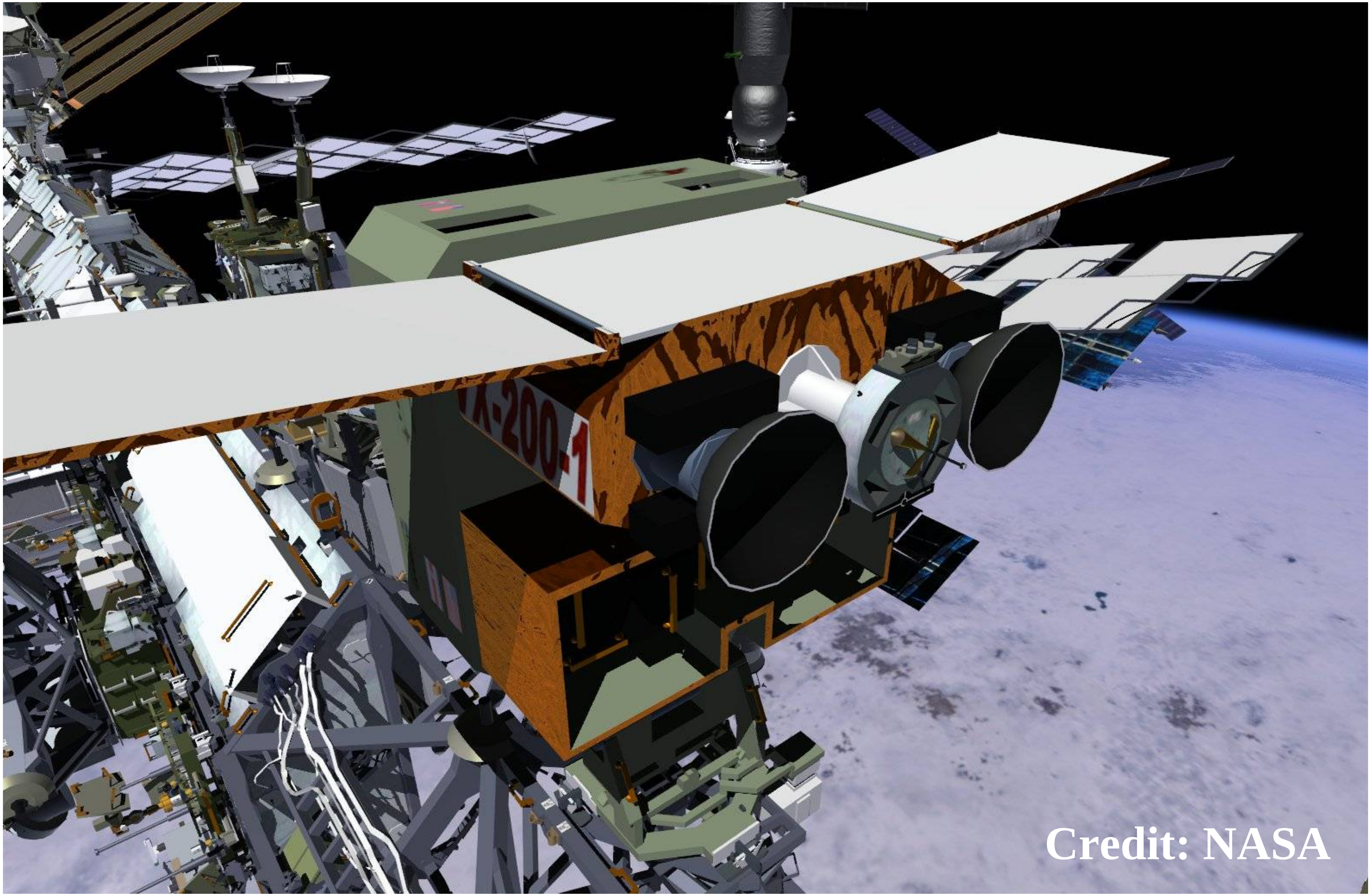
Next Design Project: ISS Mission



ISS Mission Image



ISS Mission Image



Acknowledgements

- Ad Astra Rocket Company coworkers