VASIMR:

Express Flight to Mars

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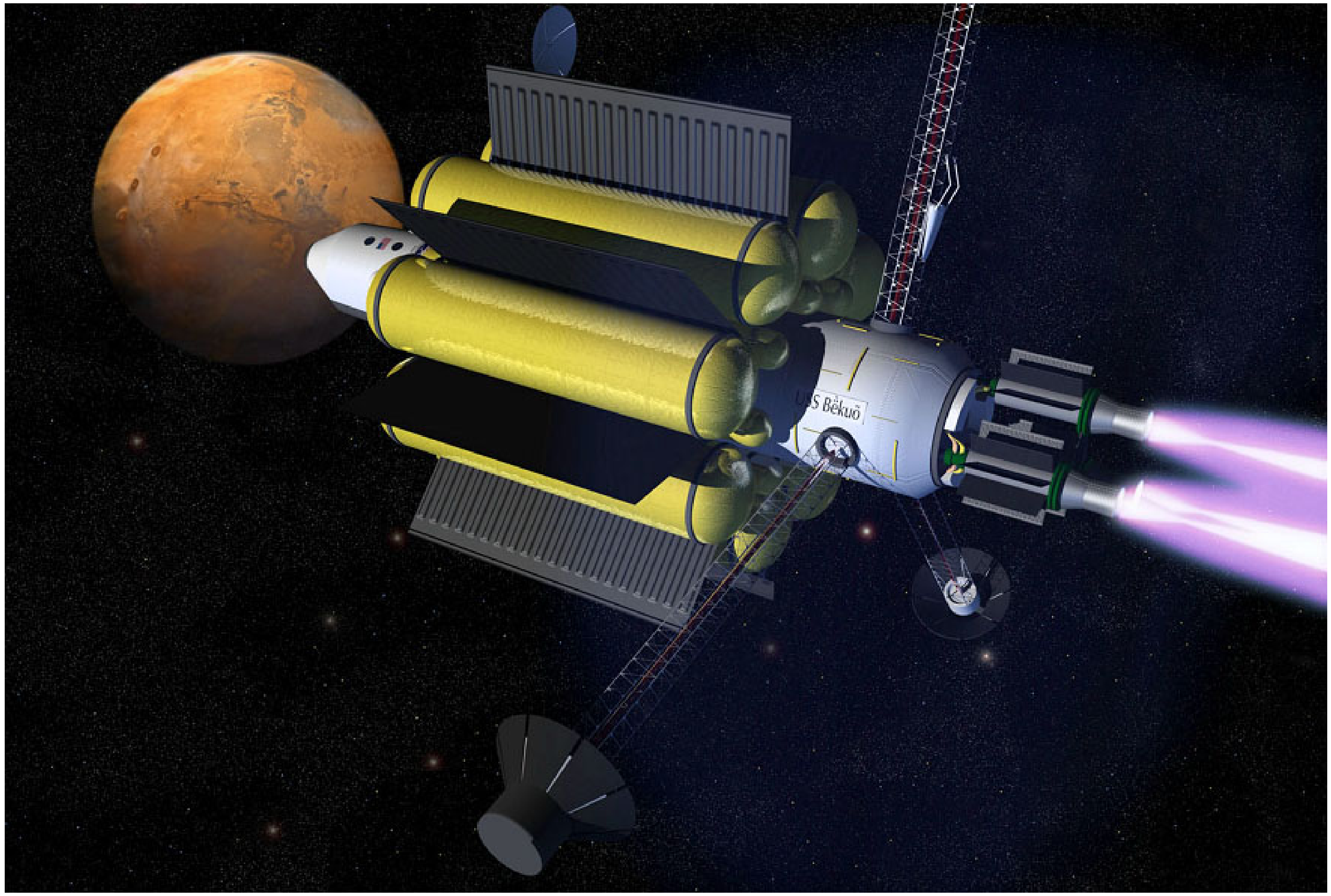
Outline

- Mars Mission Scenario
- Electric Propulsion
- How VASIMR Works
- Experimental Results
- What would flight hardware be like?
- The Bigger Issue

Conceptual Piloted Mars Vehicle



- 190 mT IMLEO
- Exhaust velocity: 30 to 500 km/s.

- 12 MWe nuclear (three 4-MW VASIMR engines).
- 115 days from launch to Mars landing.
- Hydrogen propellant surrounds crew transit module for radiation shielding.

VASIMR Mars Exploration Scenario

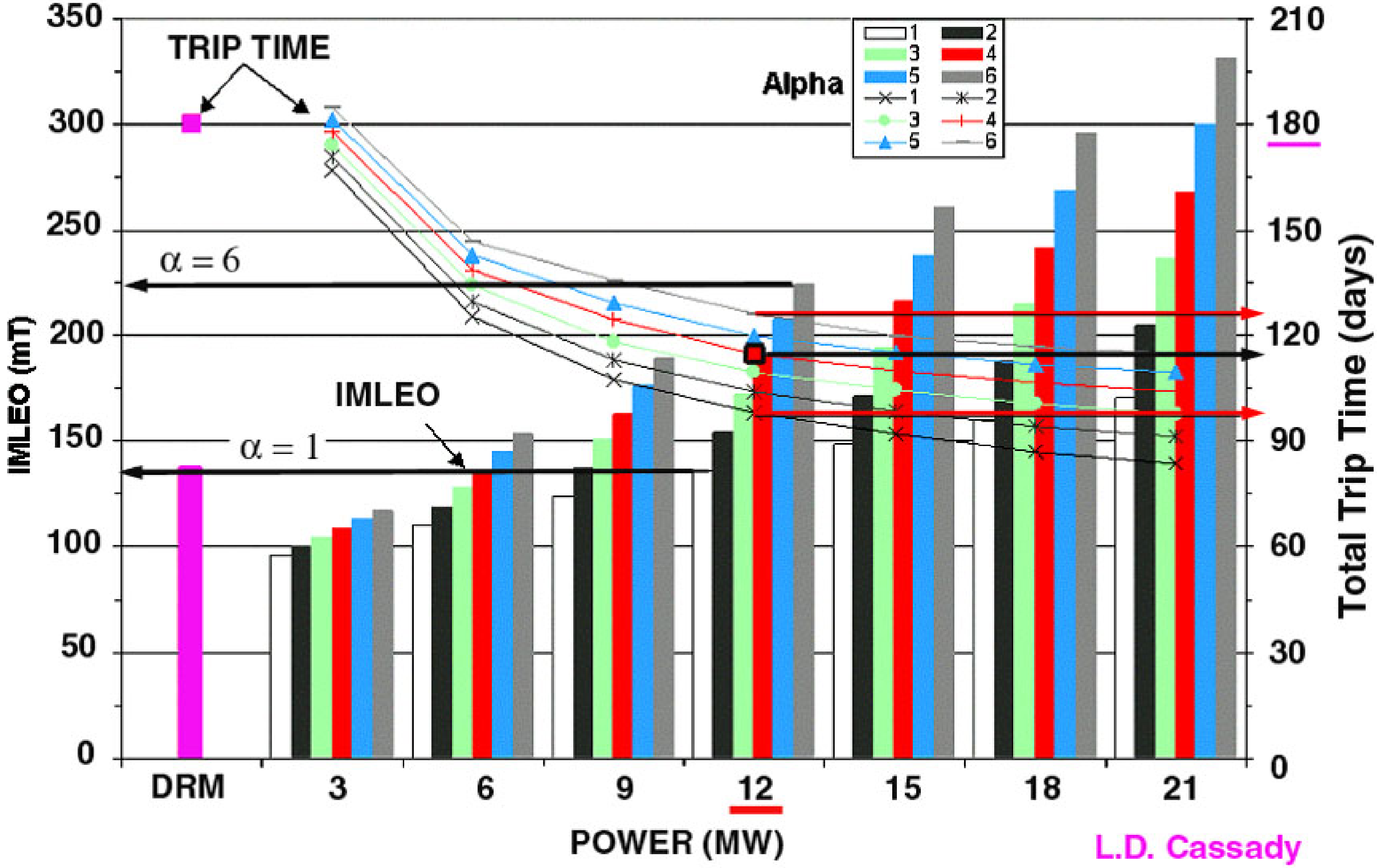
- Based on Design Reference Mission (DRM) 3.0
  - Same payload to surface of Mars.
  - Robotic ship (4 MW) first delivers cargo to surface of Mars and leaves Earth return vehicle (ERV), fully fuelled, in orbit about Mars.
  - Crew flies on crew transfer vehicle (CTV – 12 MW):
    - Outbound: CTV delivers crew, lander, and habitat to Mars orbit.
    - Return: CTV propels ERV with crew back to Earth.

- Differences:

	DRM **Nuclear thermal**	VASIMR * **Nuclear electric**
IMLEO	420 mT	310 – 440 mT
Total *Flight* Time	360 days	170 - 230 days
Total Mission Duration	*3 years*	*10 - 12 months*
Power	1,000 MW **thermal**	12 MWe

* ranges due to uncertainty in α (kg/kW)

Power Trade Study for Crew Flight: why 12 MW?



L.D. Cassady

Note how transit time and IMLEO depend on Alpha (kg/kW).

Mars Cargo Mission

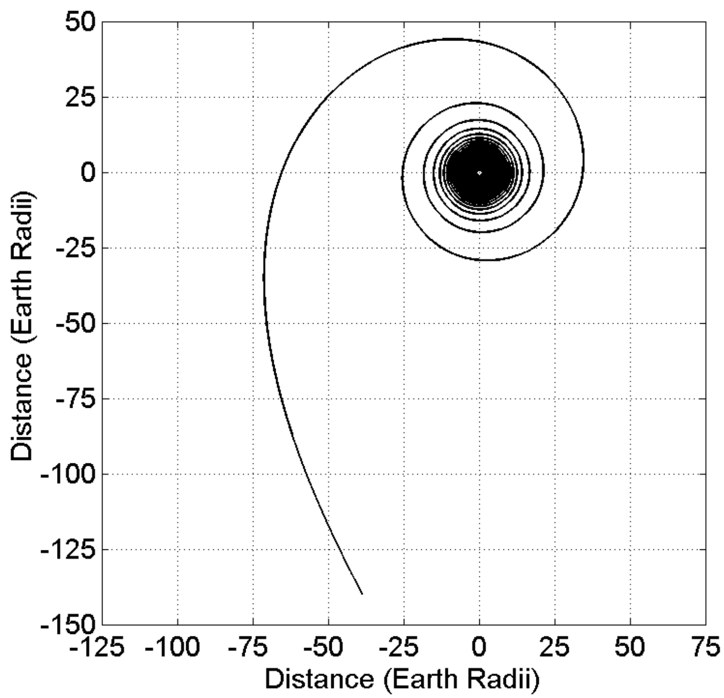
Cargo Vehicle (120 mT Payload)

30 mT Return Habitat / 30mT return propellant / 60 mT Cargo Lander

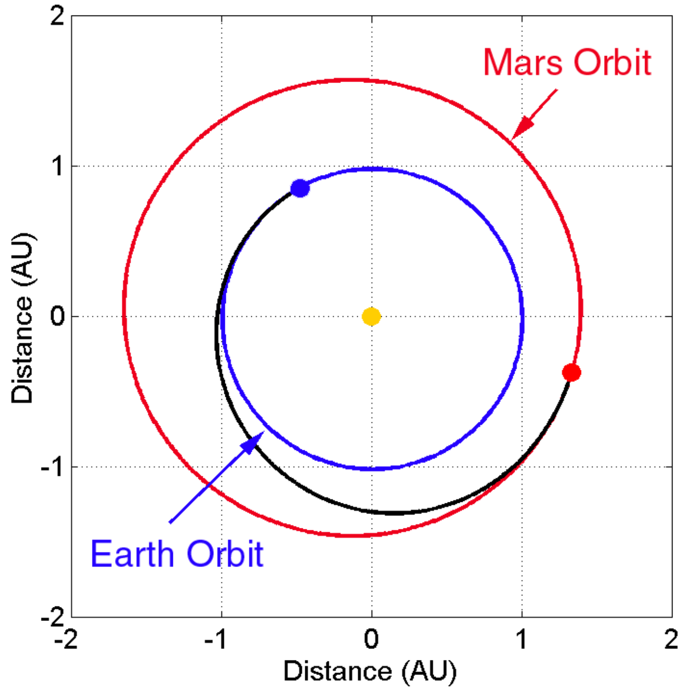
IMLEO is 60 % payload

Departs LEO (1,000 km altitude) August 3, 2016

200 mT IMLEO, 4 MW power plant, α 4 kg/kW



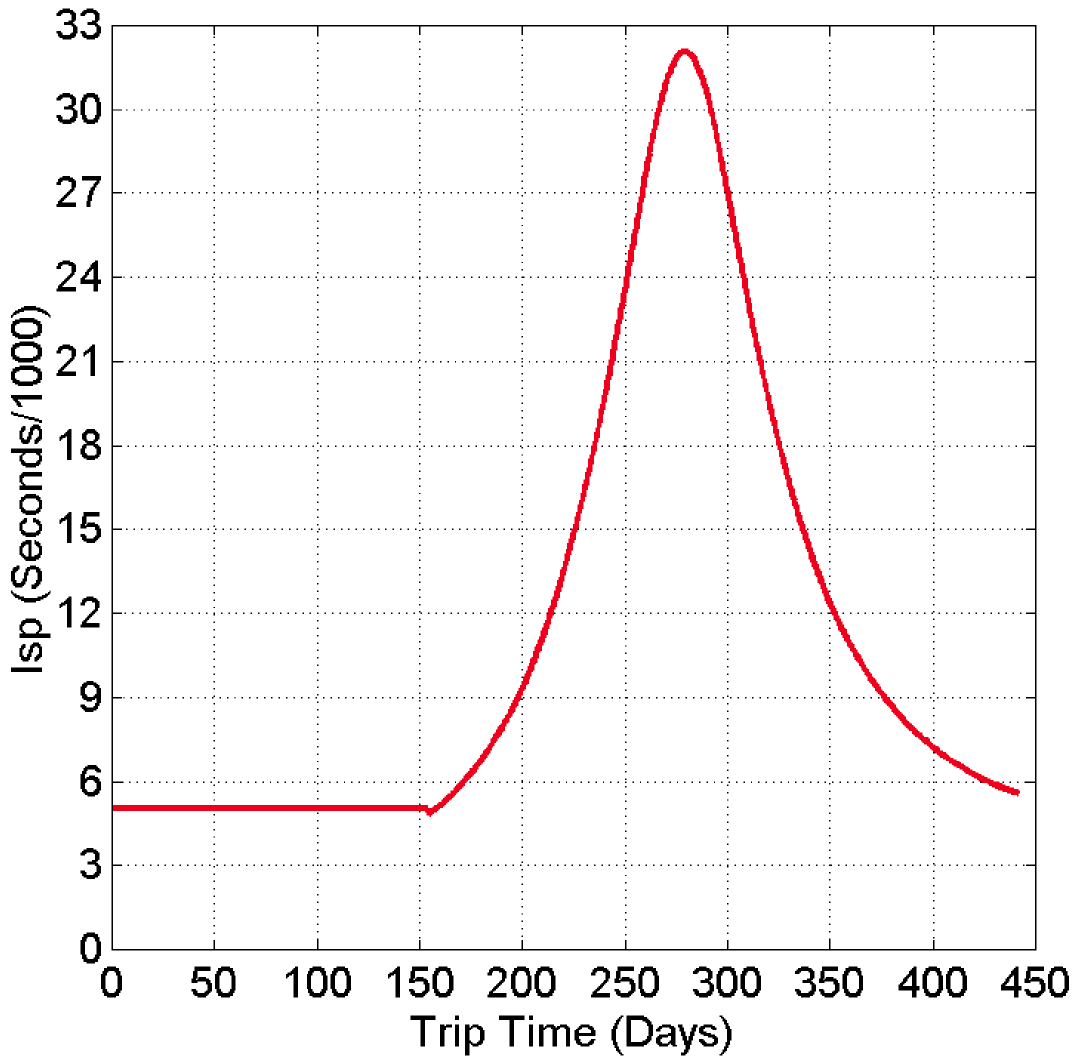
154 Day Spiral



288 Day Heliocentric Transfer

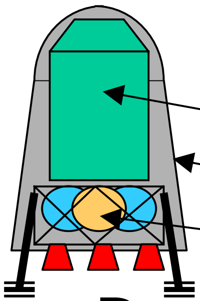
Cargo Mars Mission I_{sp} Profile

- 4 MW engine, 120 mT payload.
- 5 month spiral at 5,000 sec Isp to escape velocity.
- 10 month transit to Mars, *optimized* Isp profile; i.e. , given masses, what Isp profile is needed to minimize transit time?
- 60 % payload fraction.



Outbound Piloted Mars Mission

IMLEO is 30 % payload



Crew Lander (61 mT Payload)

31.0 mT Habitat

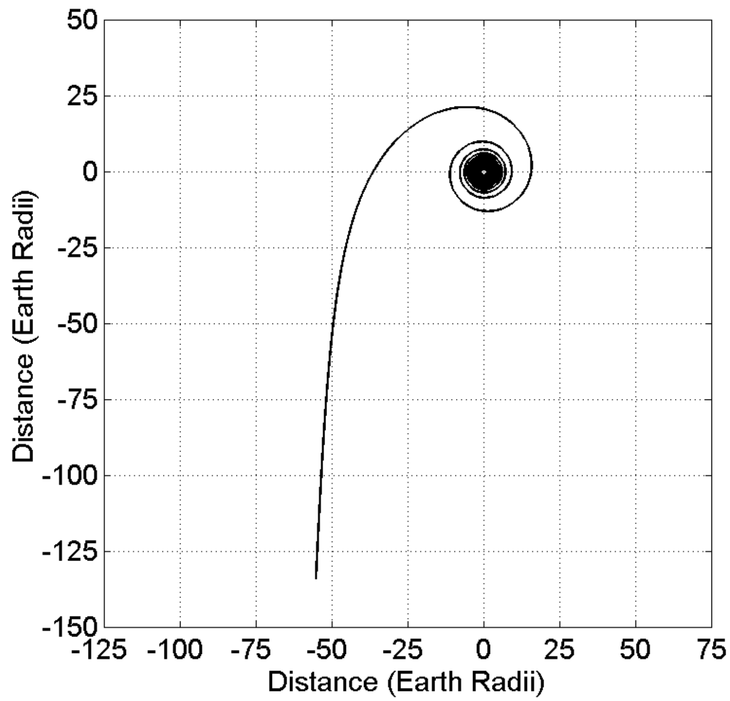
13.5 mT Aeroshell

16.3 mT Descent System

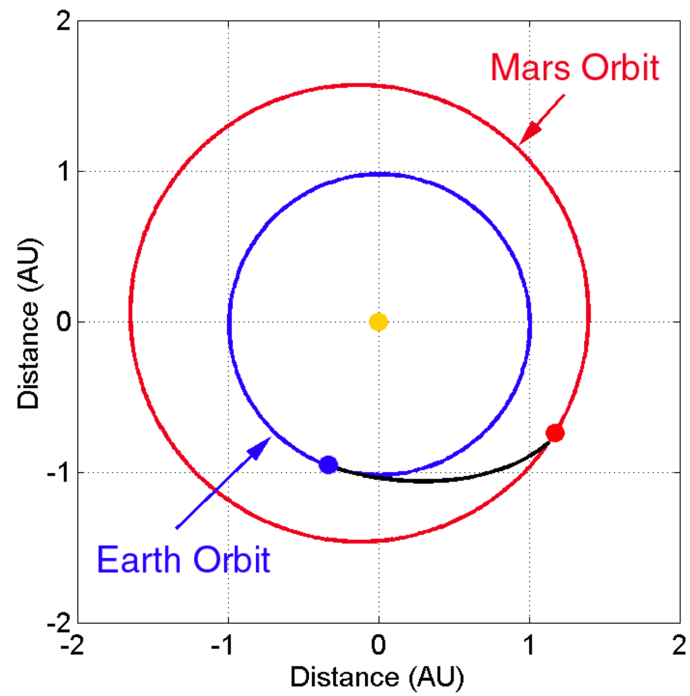
Departing LEO May 6, 2018

188 mT IMLEO

12 MWe power plant, α 4 kg/kW (48 mT)



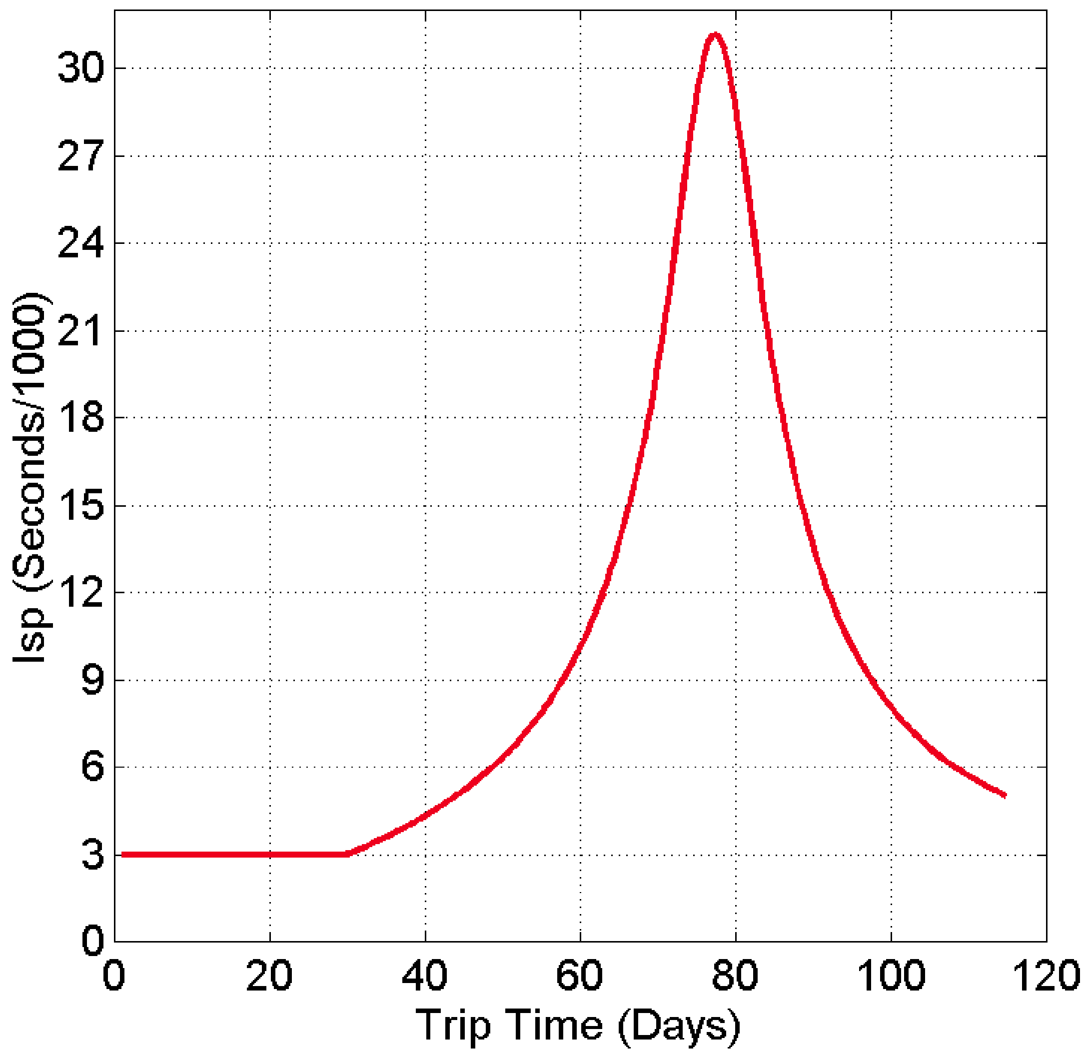
30 Day Spiral



85 Day Heliocentric Transfer

Outbound Piloted Mars Mission I_{sp} Profile

- Payload and transit time as inputs determine Isp profile.
- 3 x 4 MW engines, 61 mT payload.
- 1 month spiral at 3,000 sec Isp to escape velocity.
- 3 month transit to Mars, optimized Isp profile.
- 32 % payload fraction.



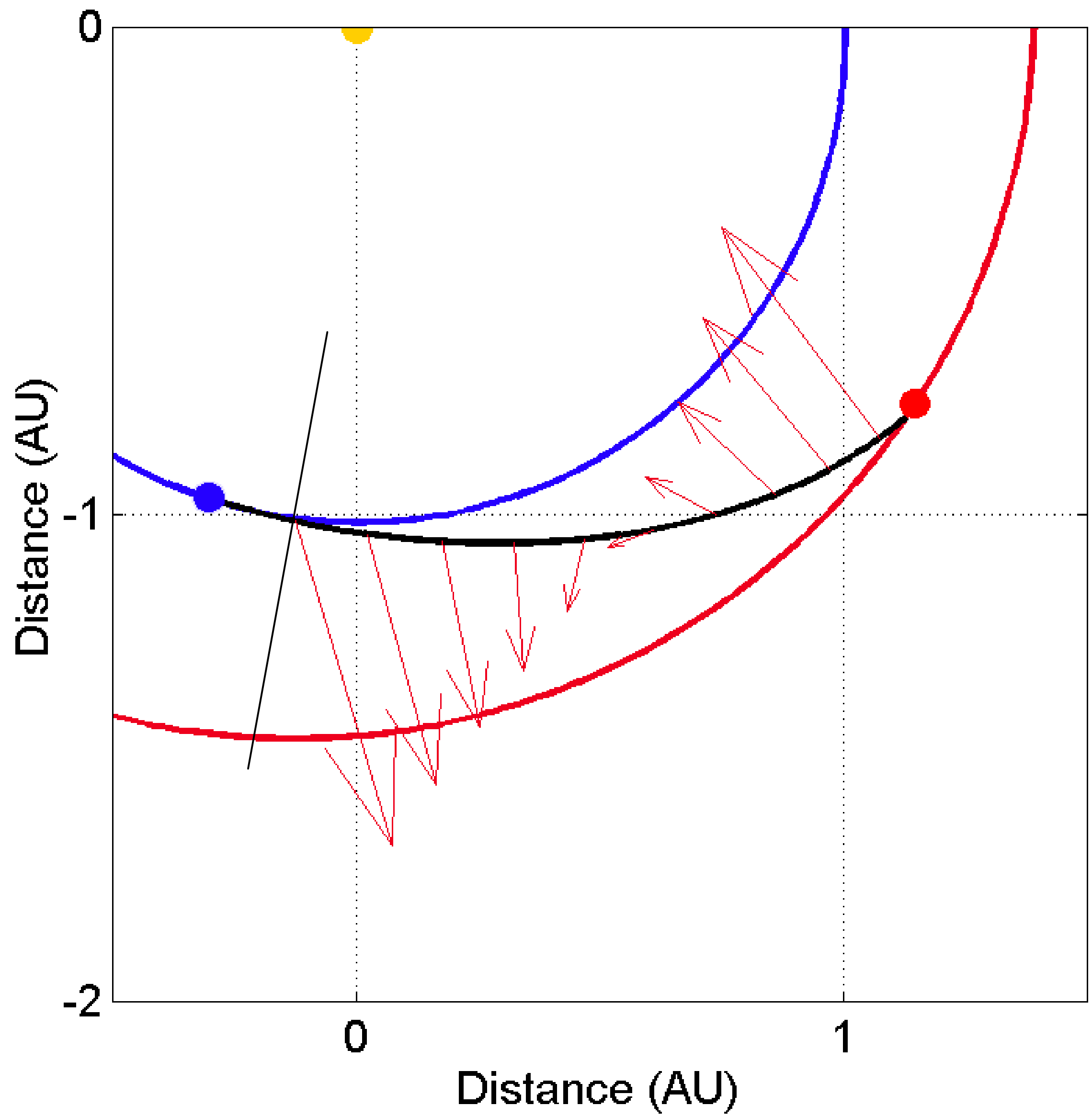
Outbound Piloted Thrust Vector

- Note: thrust not parallel to velocity vector.

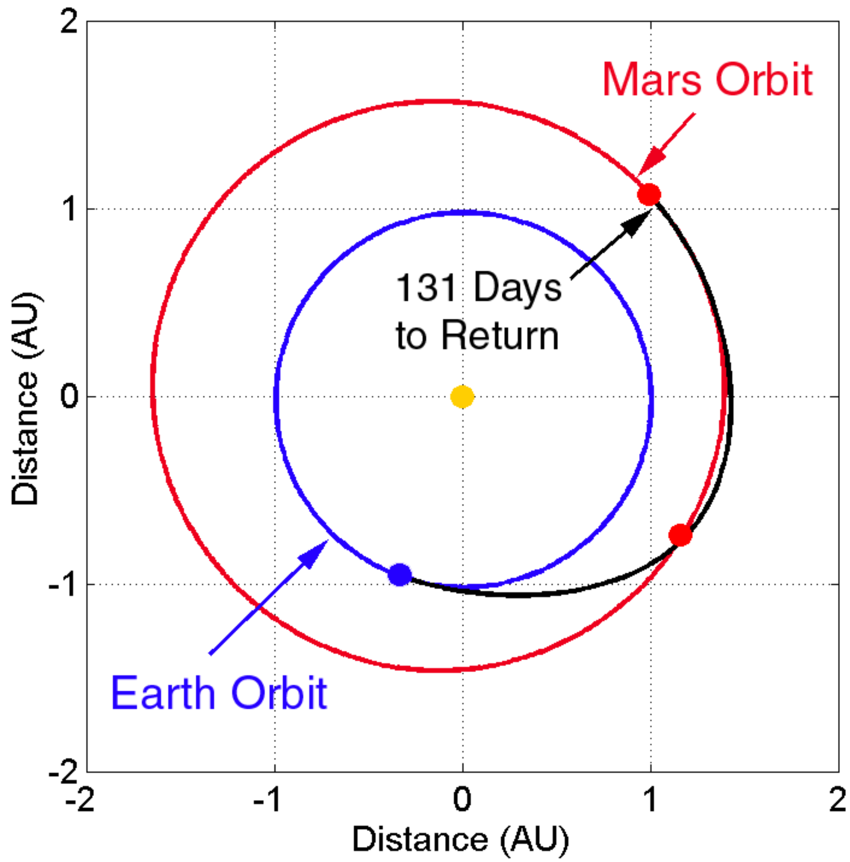
- Transit distance *and* time are reduced, so that average speed is similar to chemical propulsion.

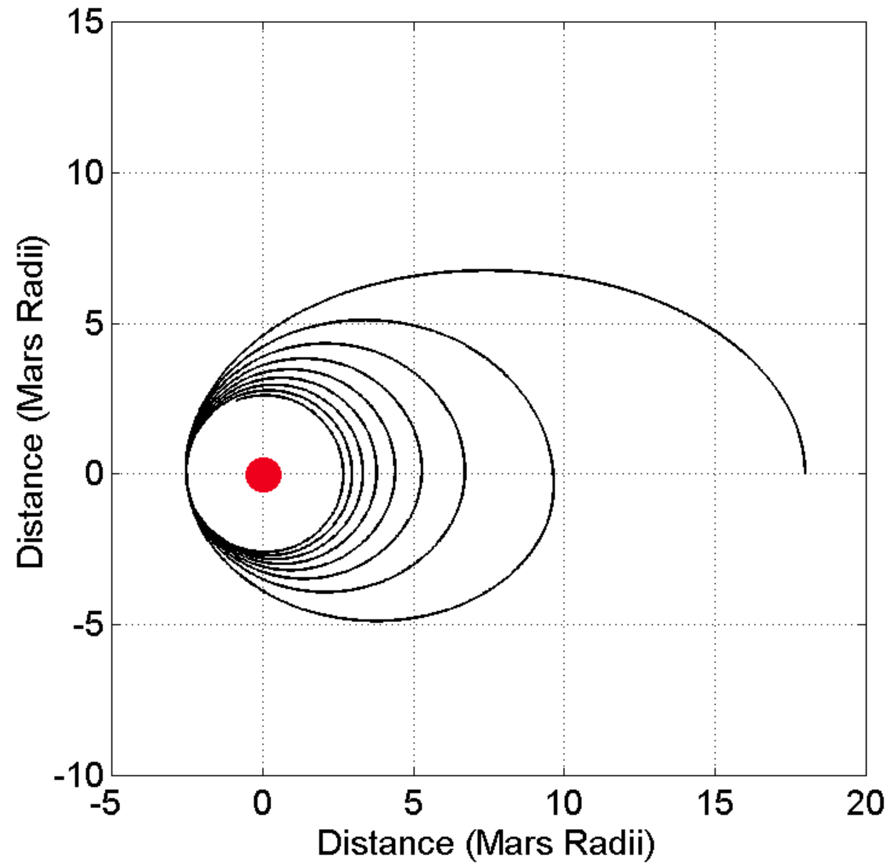
- Continuous, variable thrust and Isp allow for wide range of trajectories.

→ Flexible launch dates, continuum of abort trajectories.



Transit Vehicle Captured after Crew Lands

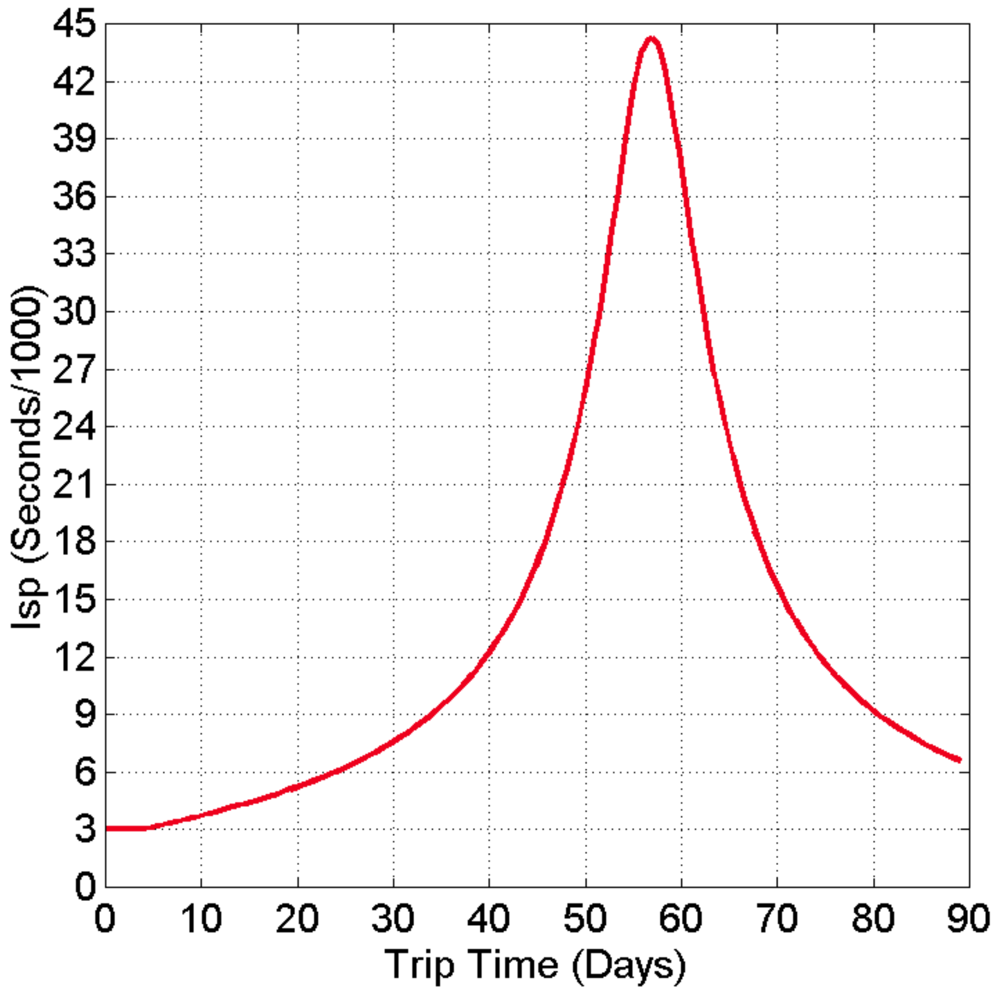




7 Day Spiral

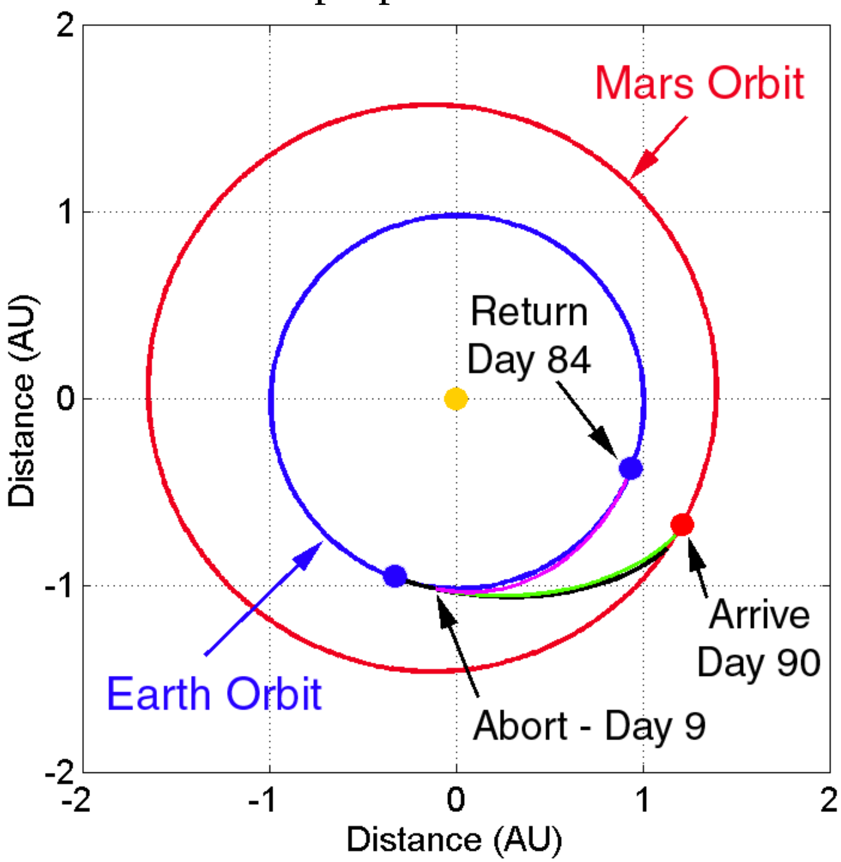
Return Piloted Mars Mission I_{sp} Profile

- Note high Isp (450 km/s exhaust velocity)
- 90 day return to Earth
- With more power, lower α, another mission is possible with only 30 days on Mars, and 100 day transits out and back, total mission of ~ 8 months.

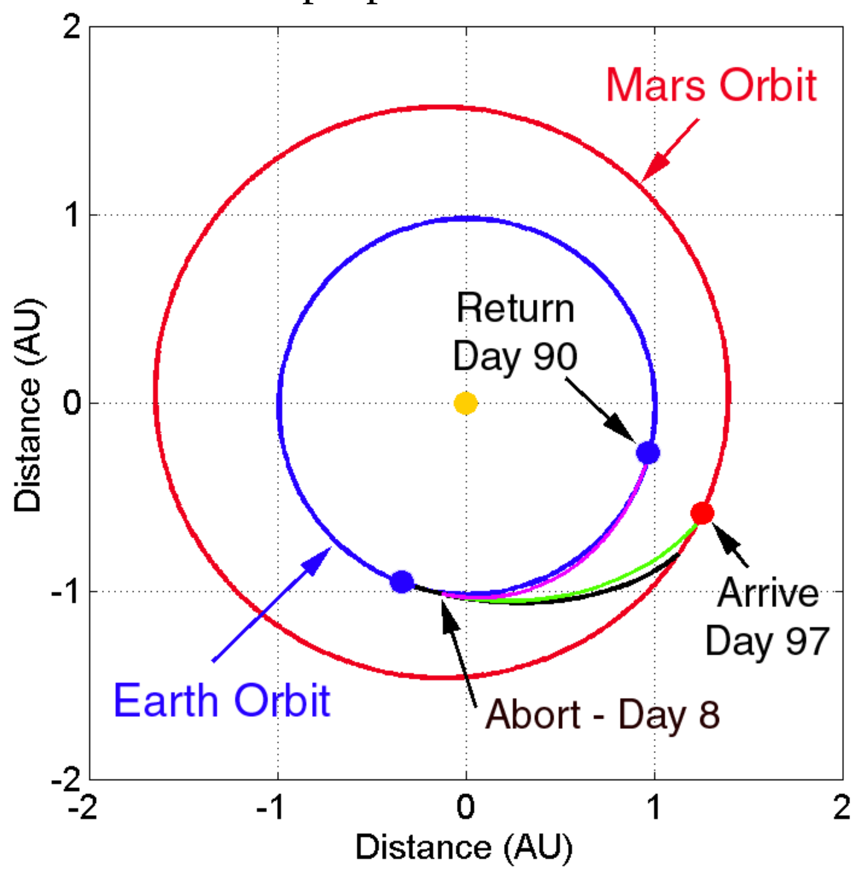


Continuous thrust with high, variable Isp produces a continuum of abort possibilities.

1/3 of remaining propellant lost



1/2 of remaining propellant lost

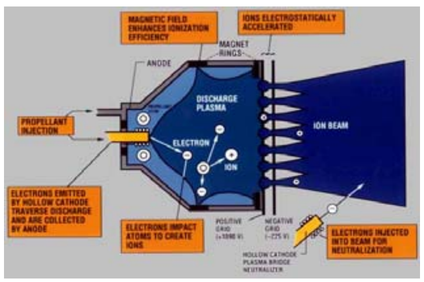


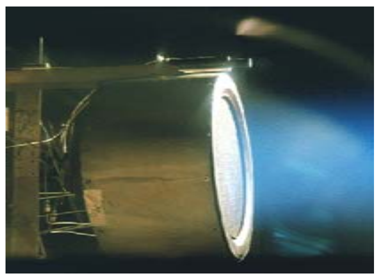
Electric Propulsion: F = qE

The main concepts have been around since the 1960's / 1970's: ion, MPD, Hall

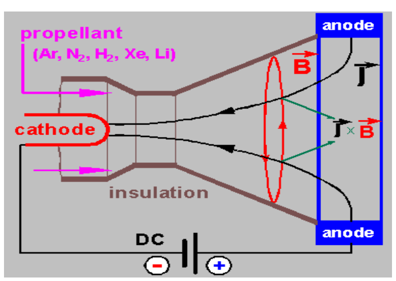
VASIMR idea dates from ~1980.

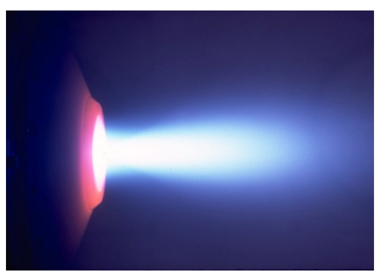
Ion engine Isp ~ 3-8 Ksec



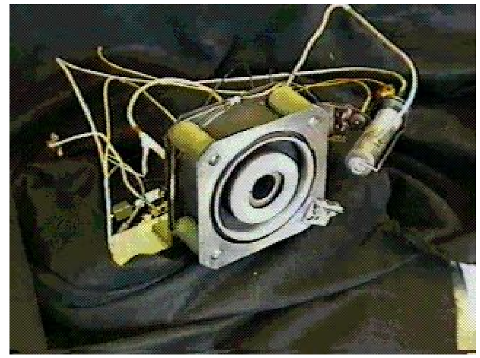


Magneto-plasma-dynamic ~ 3-10 Ksec

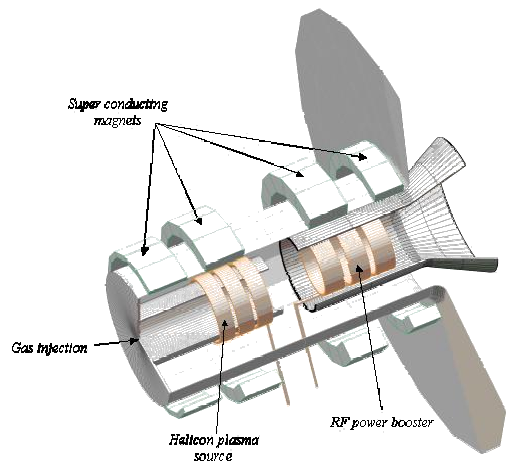


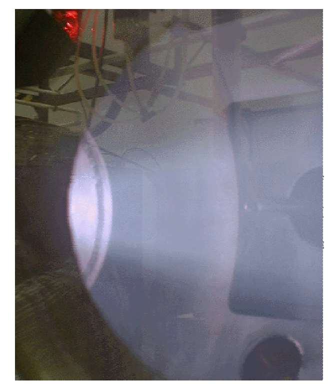


Hall effect thruster Isp ~ 4 Ksec



VASIMR Isp ~ 5 - 50 Ksec





Ion Engine

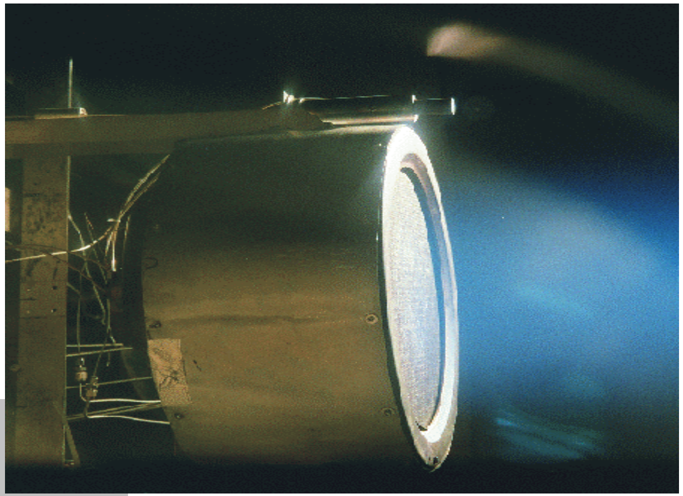
Isp = 3,000 – 8,000 sec

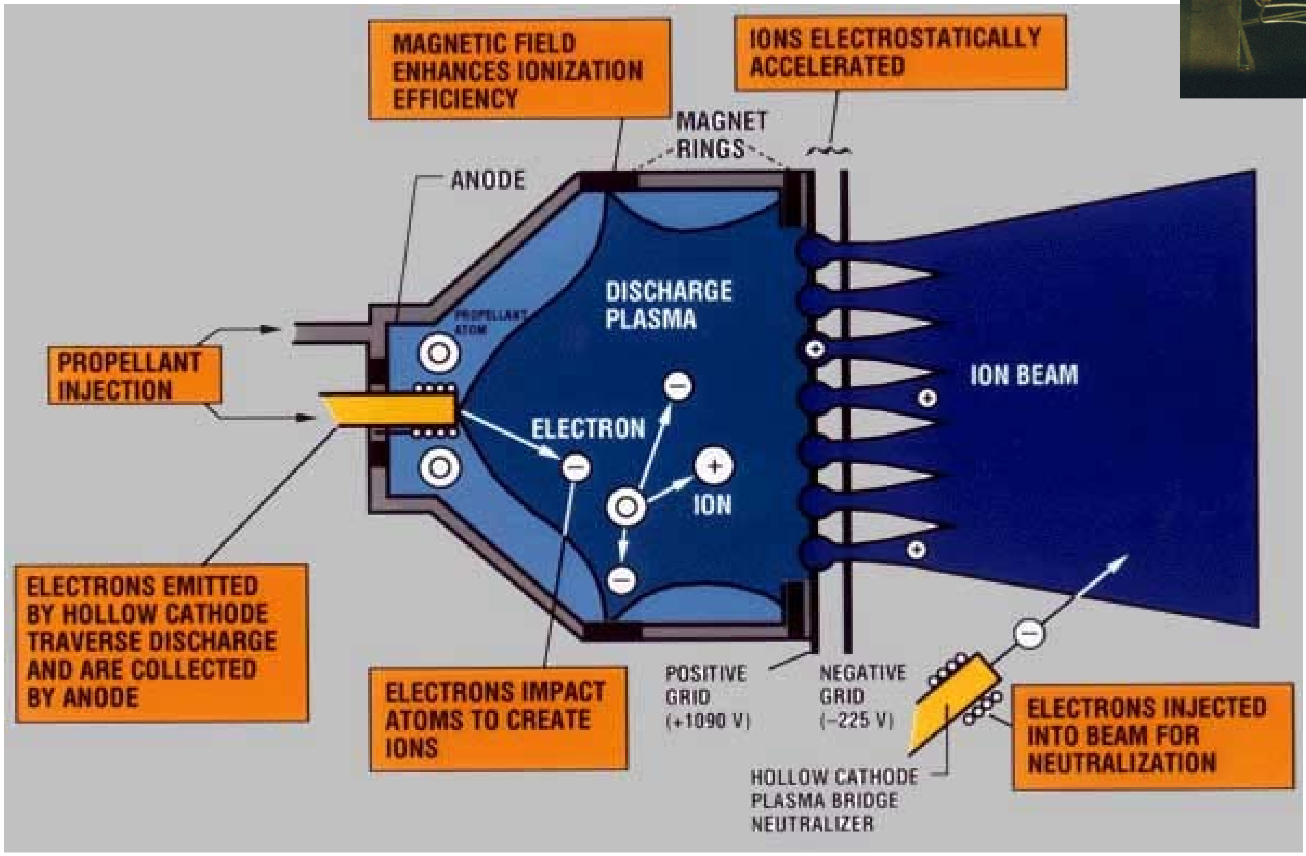
P = 12 kW (HiPEP, Nov. 2003)

[200 kW Hg, ~ 1970]

Efficiency ~ 80%

NSTAR→





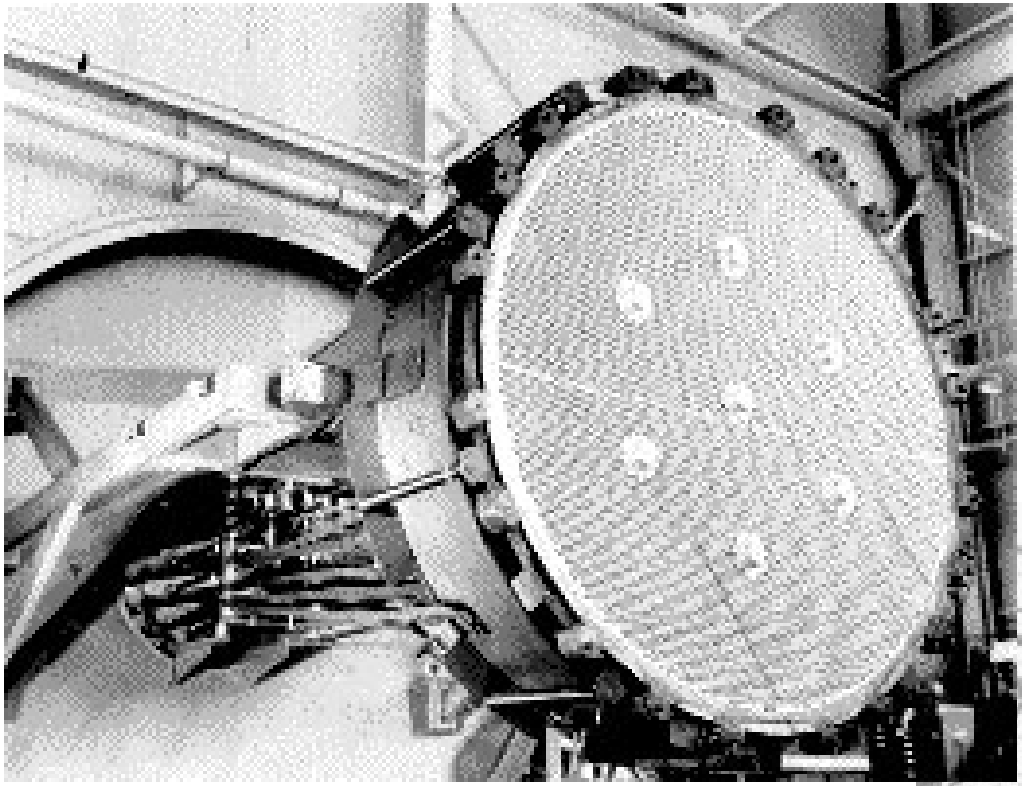
Issues:

scaling to high power

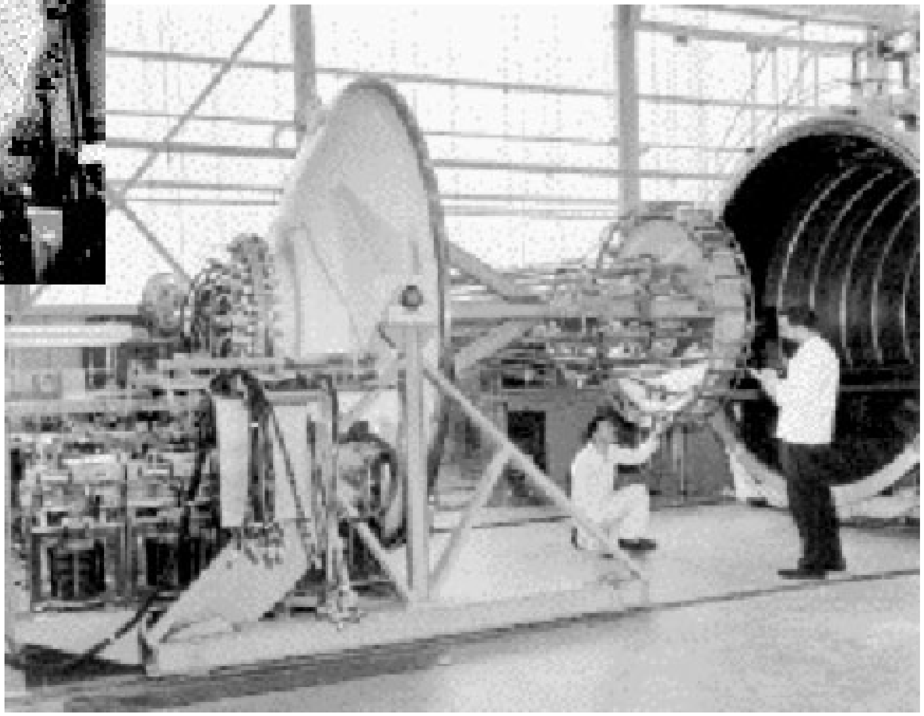
lifetime/ grid erosion

(C-C grids promising)

200 kW Hg Ion Engine (~1970)



Lifetime: ?



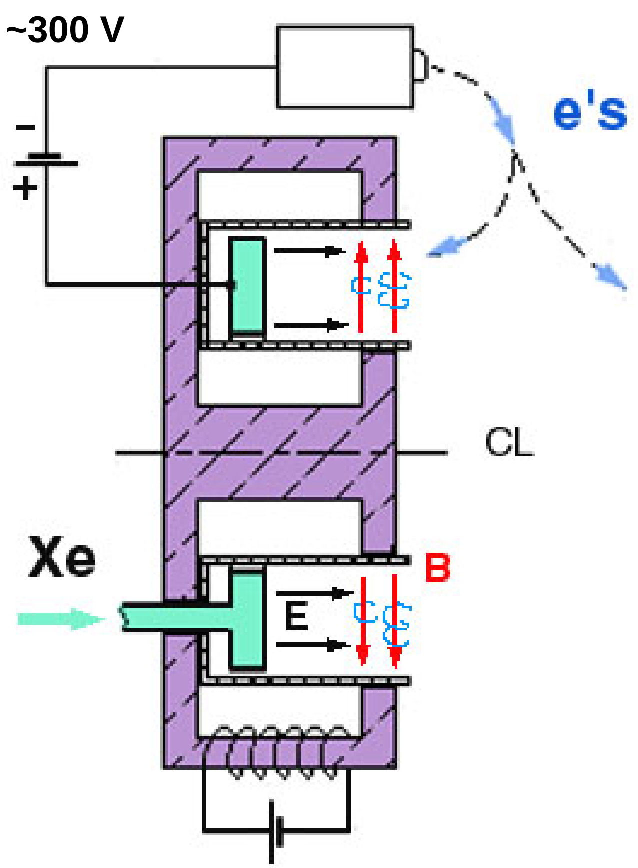
Hall Thruster

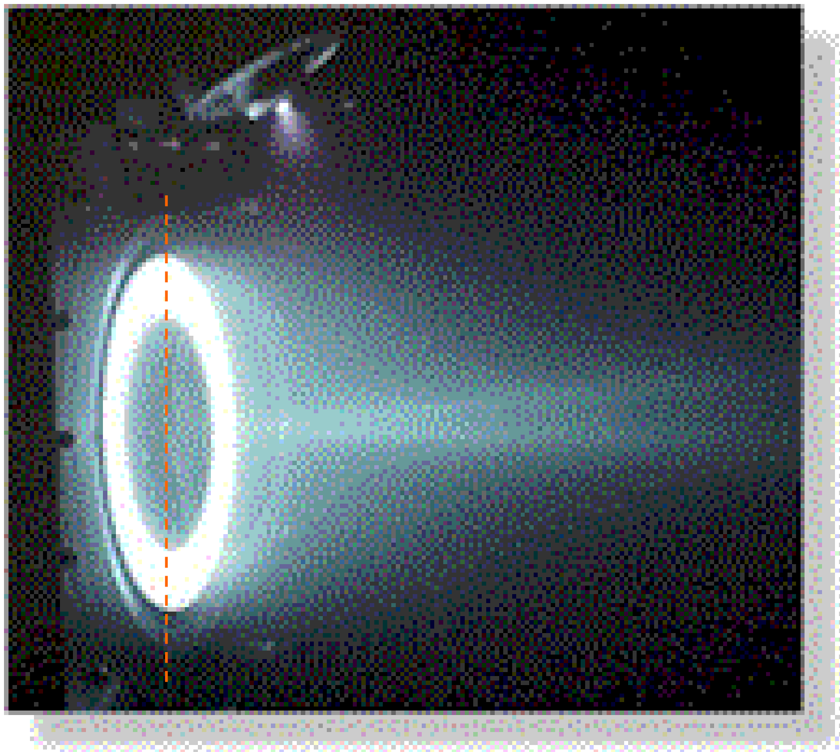
Isp = 1200 – 4,000 sec

Propellant: Xenon

P = 20 kW [100 kW]

Efficiency ~ 60%





<u>Issues</u>:

scaling to high power

propellant scarcity

lifetime/ ceramic erosion

MPD Thruster

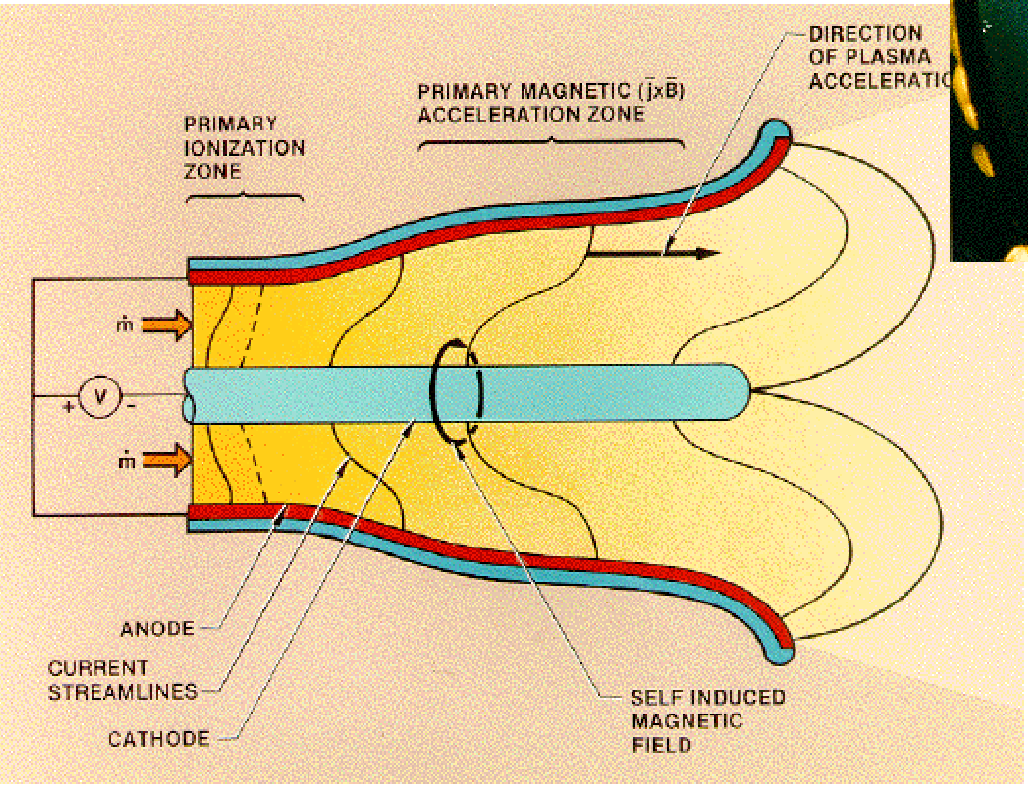
Isp = 1400 – 10,000 sec

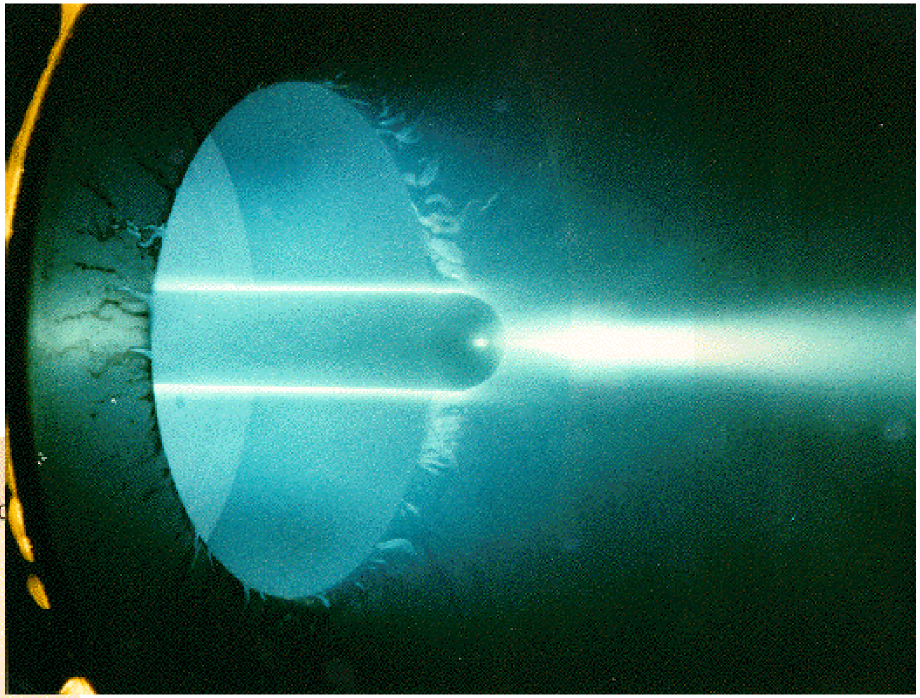
Efficiency (Li) ~ 45% (@120 kW)

Works with almost any propellant.

Efficiency improves with power.

Has been pulsed to 4 MW.





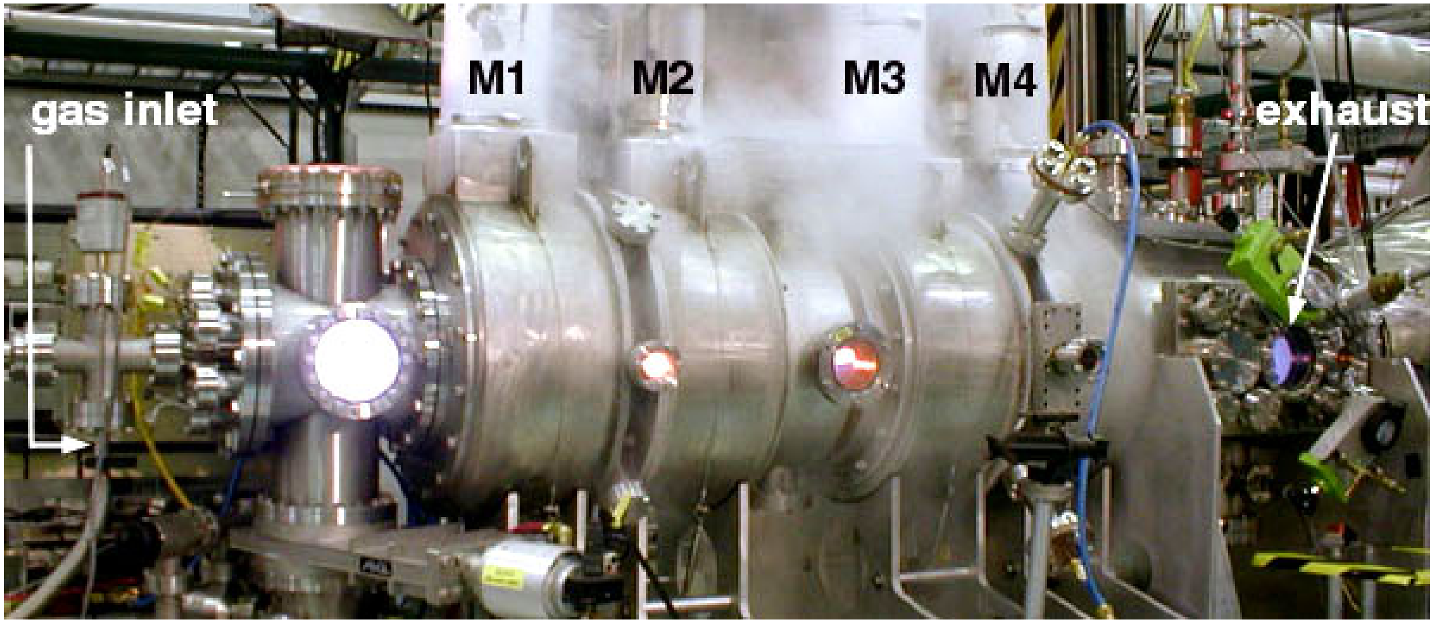
<u>Issues</u>:

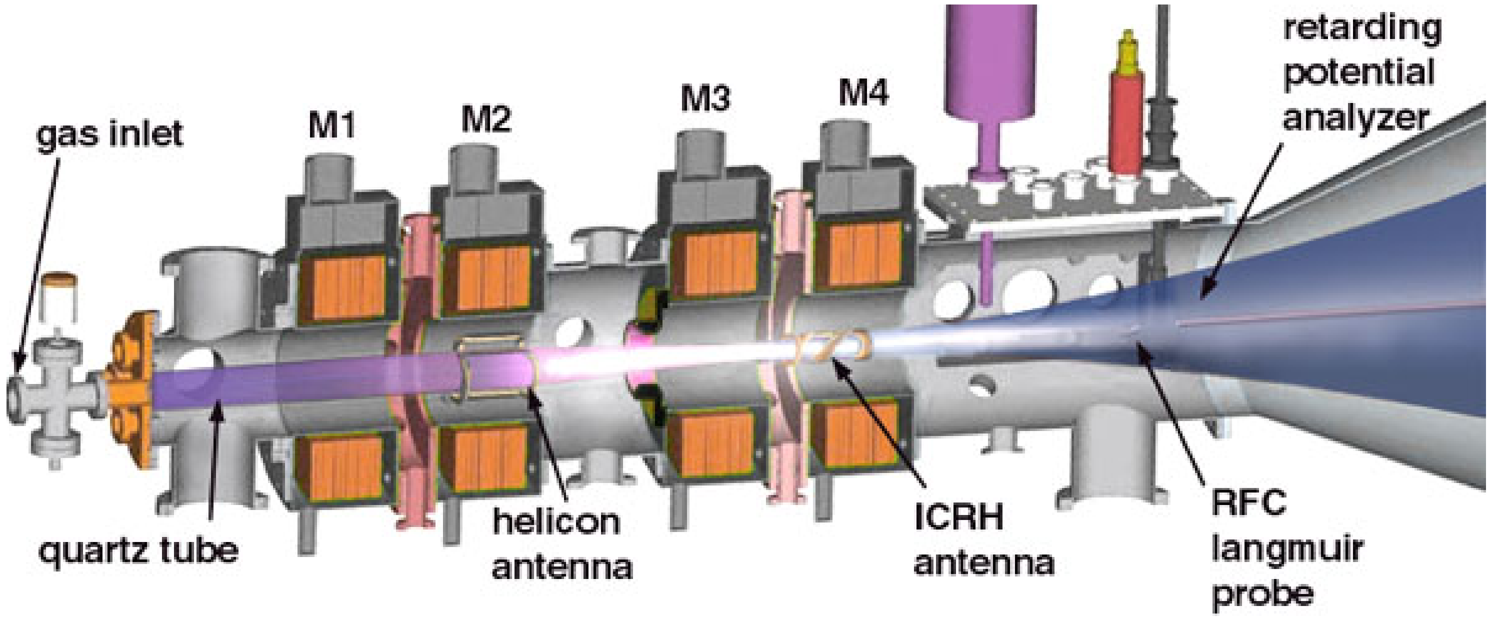
lifetime/ electrode erosion

VASIMR

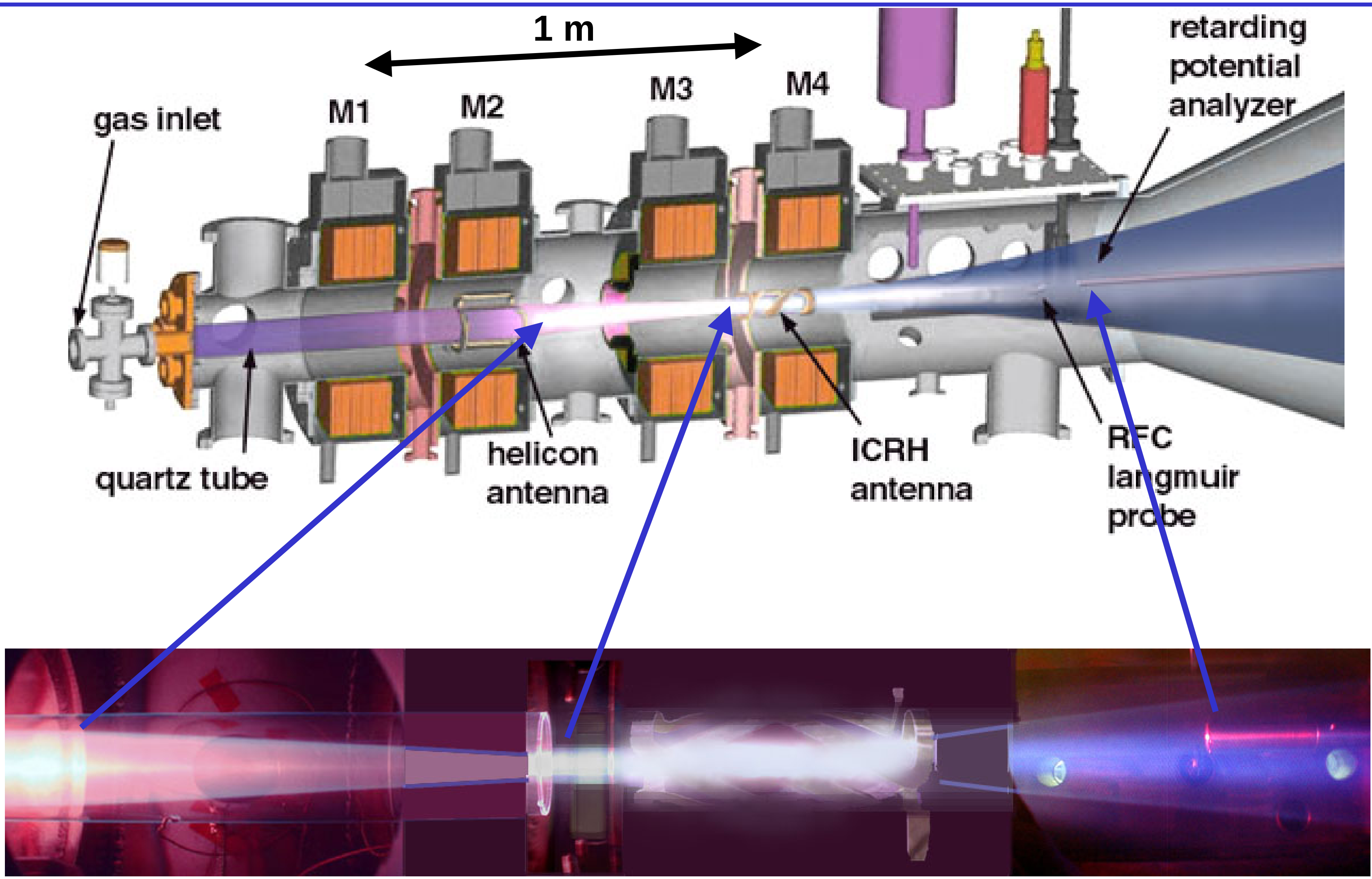
- **VAriable Specific Impulse Magnetoplasma Rocket**
- **Conceived by Franklin Chang Diaz at MIT ~1980**
- **Inspired by magnetic mirror fusion experiments**
- **Aiming for Isp of 3,000 – 50,000 sec (exhaust velocities of 30 – 500 km/sec)**
- **Plasma is generated and accelerated by radio-frequency waves**
- **No contact between plasma and electrodes (no electrode erosion)**
- **Efficiency improves with power**
- **Hydrogen propellant (others possible)**

VASIMR Experiment at ASPL, Johnson Space Center

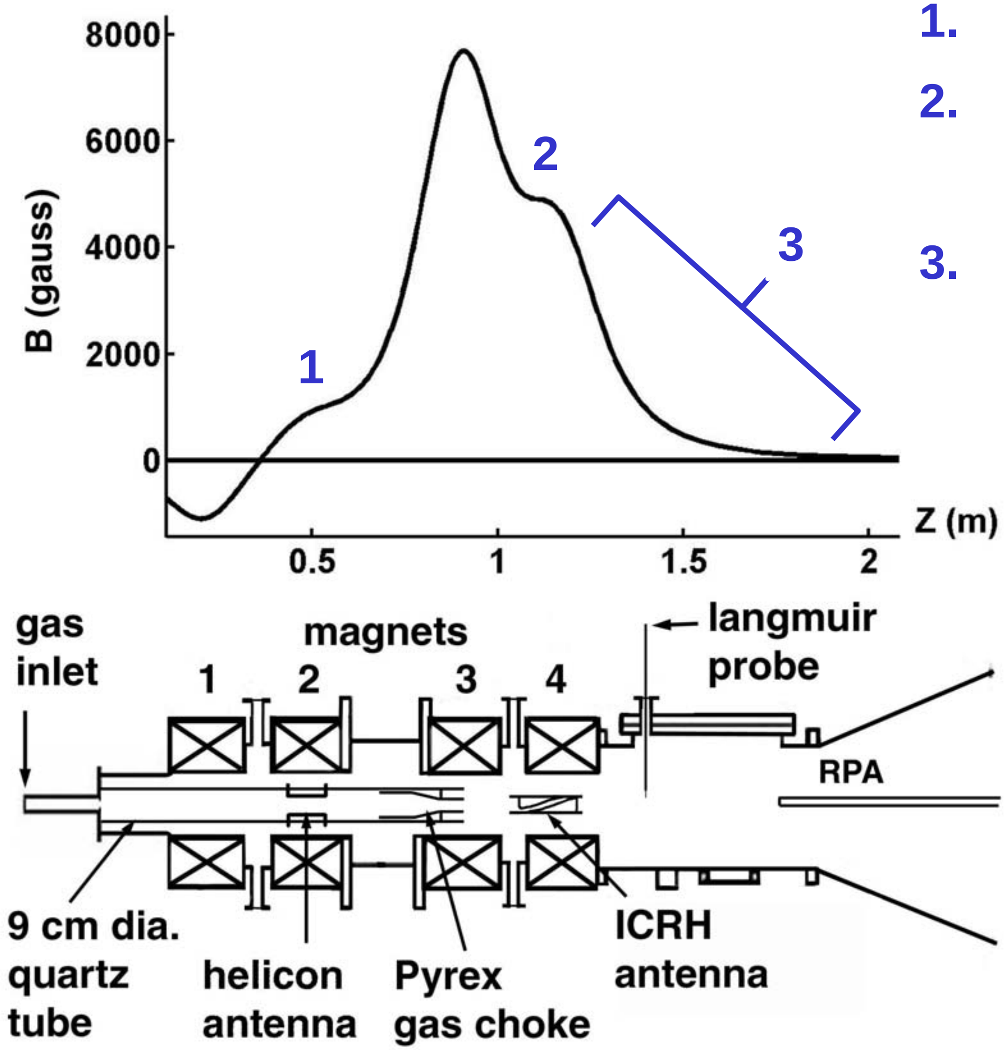




Photos through the VX viewports

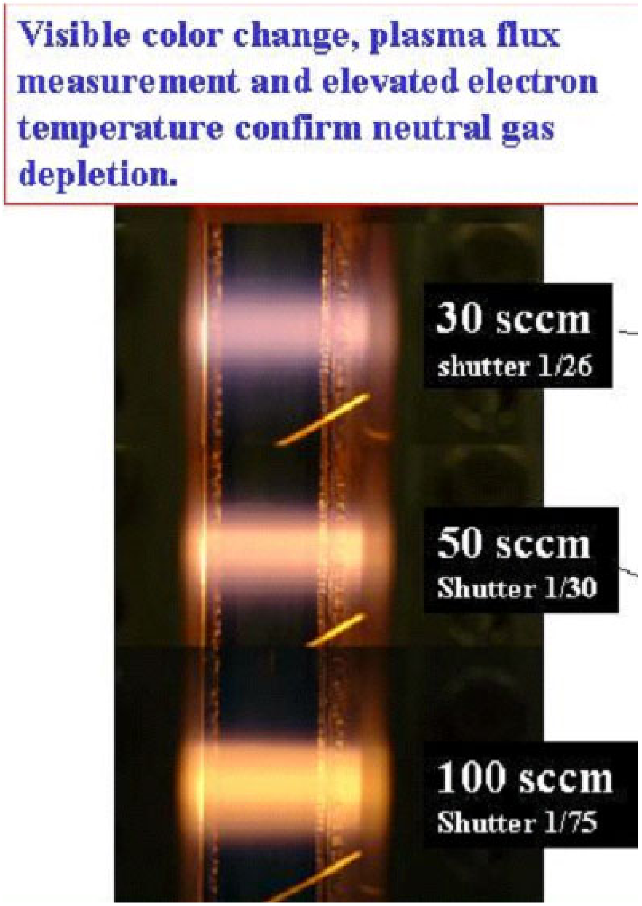


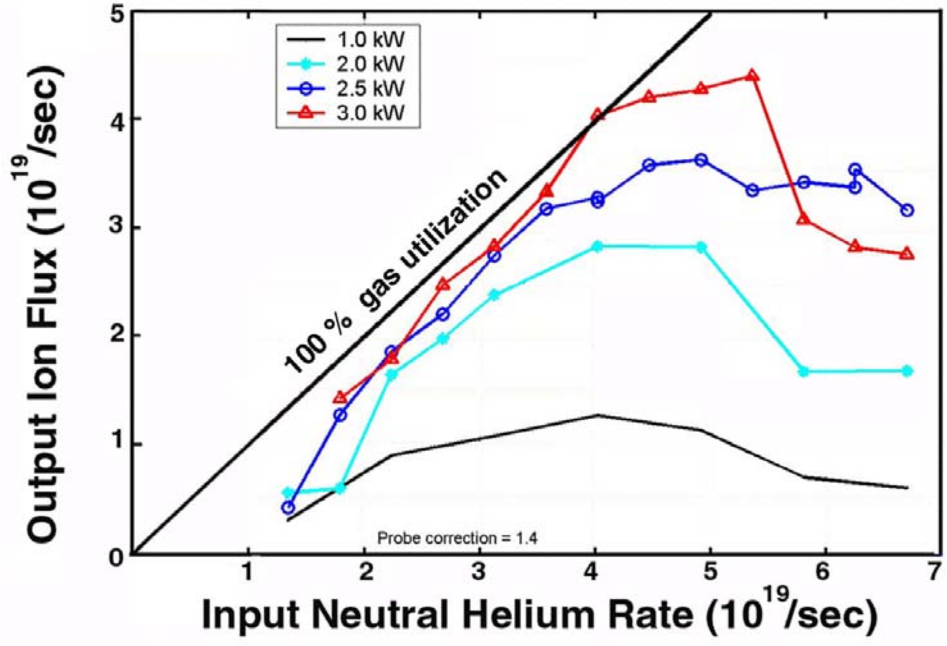
How VASIMR Works: 3 processes



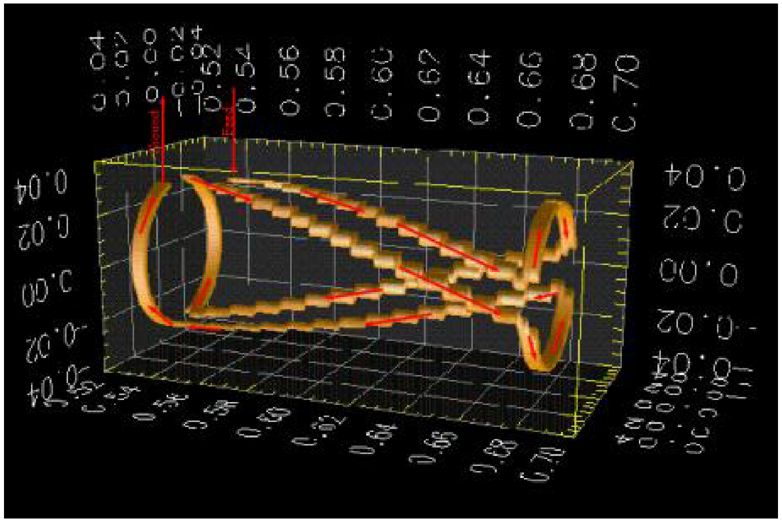
1. **Helicon ionizes propellant gas.**
2. **ICRH antenna boosts ion perpendicular energy.**
3. **Magnetic nozzle converts perpendicular energy to parallel flow.**

- Helicon heats electrons, converts neutral gas to plasma.
- We have demonstrated virtually 100 % propellant utilization.





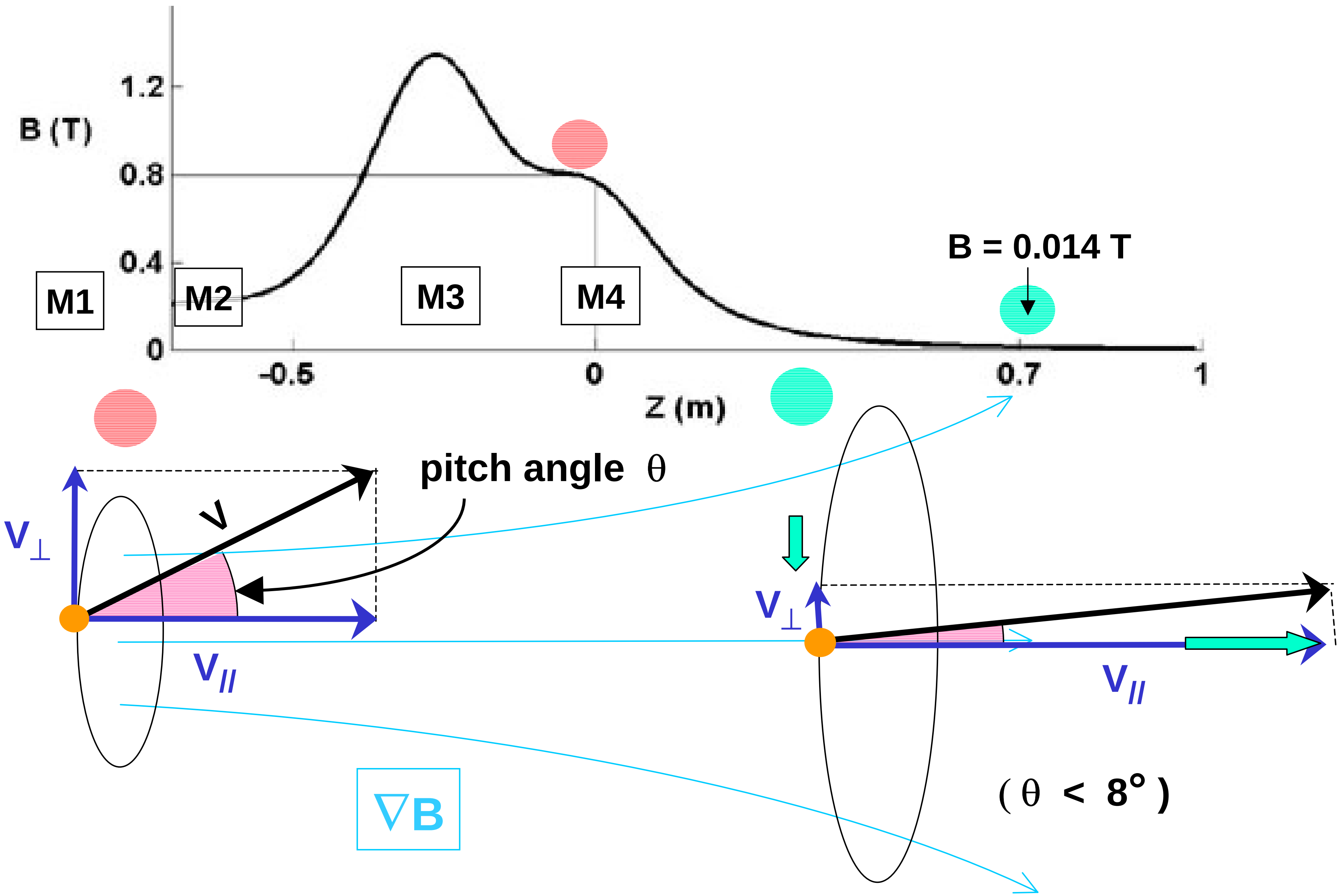
VASIMR process 2: Ion Cyclotron Heating



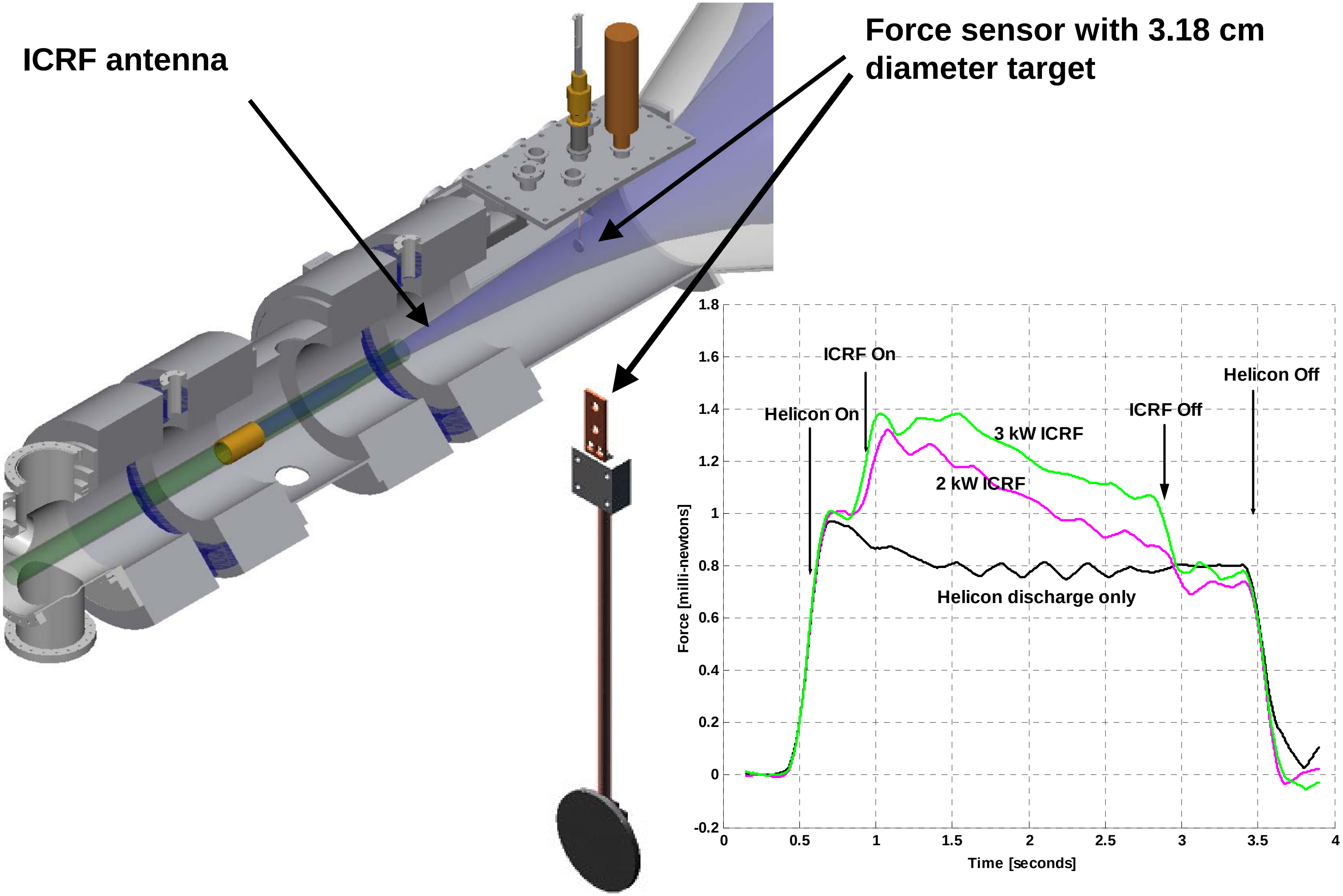
‘twisted loop’ antenna

- **ICRH antenna shakes and twists magnetic field, launching waves.**
- **Wave amplitude proportional to plasma diameter and density (sets minimum plasma size and power).**
- **Difference in ion and electron response results in perpendicular electric field that rotates at input power frequency.**
- **Where ion cyclotron frequency matches applied frequency, ions are accelerated, transferring wave energy to ion kinetic energy (perpendicular).**

VASIMR process 3: magnetic nozzle



Thrust target data



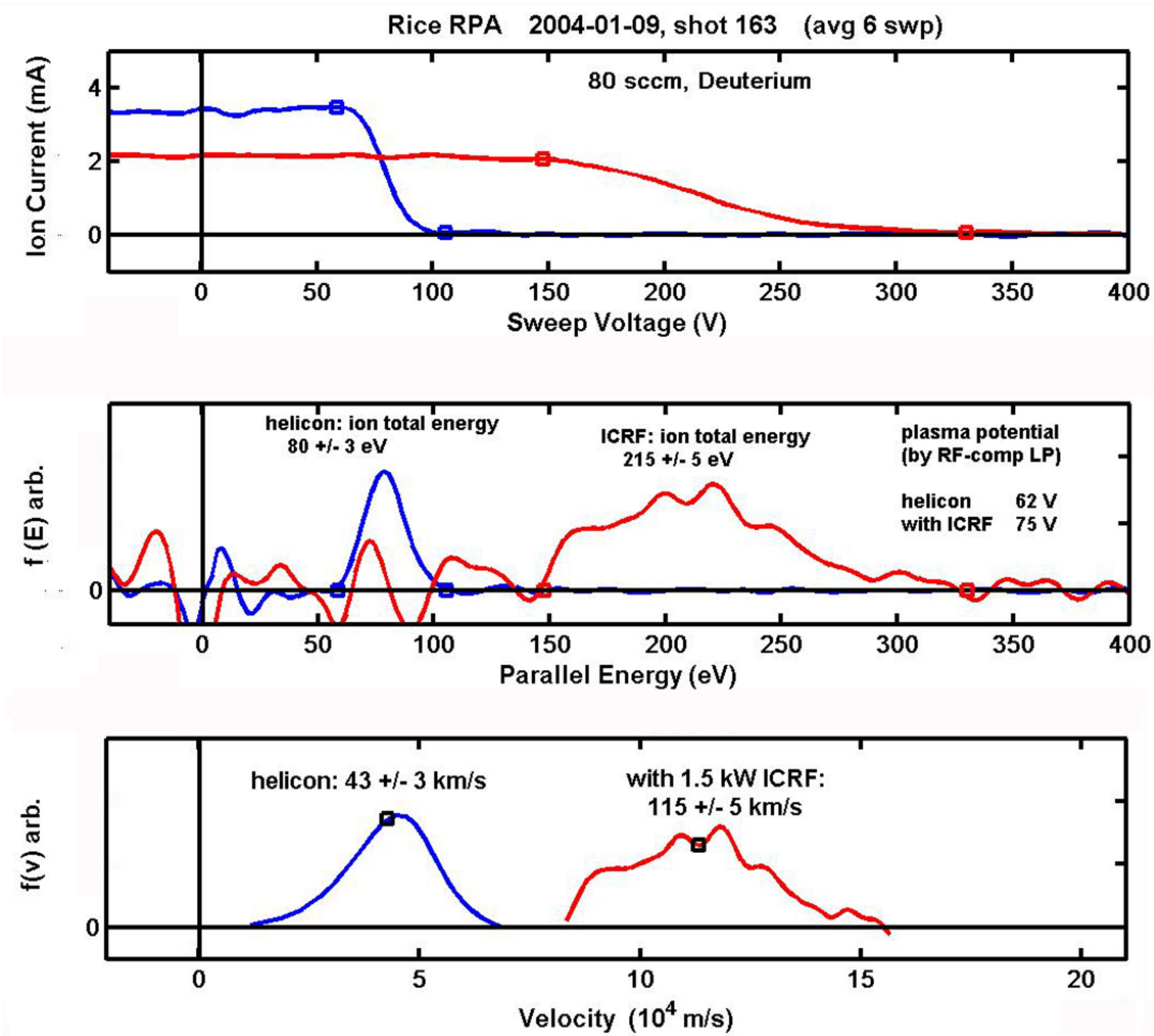
Best (D2) Exhaust Velocity to Date

Flow velocity *at this position* in the nozzle (55 cm) is 115 km/sec.

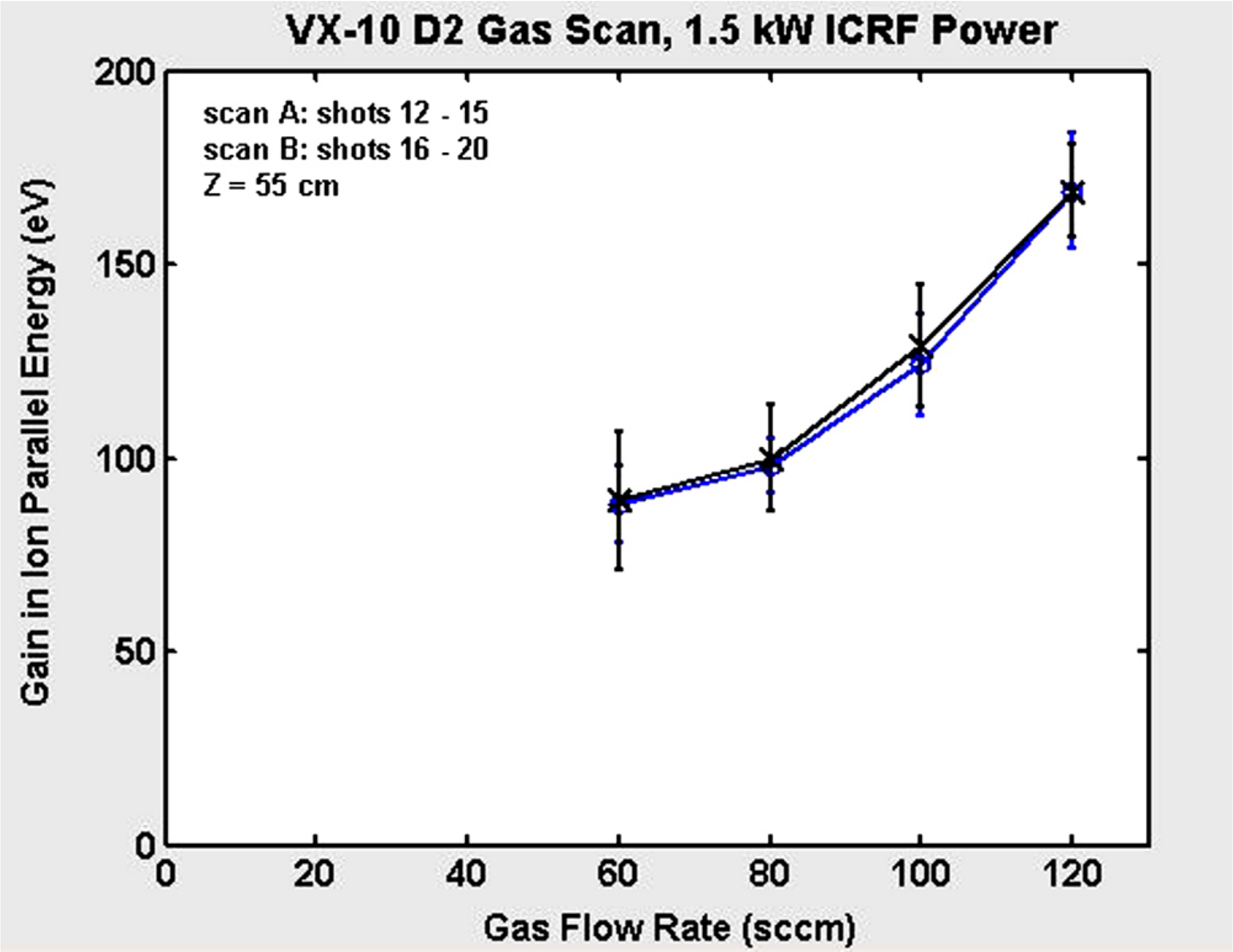
$$v = \sqrt{\frac{2(E_{total} - e\Phi)}{m}}$$

If plasma potential is converted to flow velocity farther downstream, exhaust velocity is 145 km/sec.

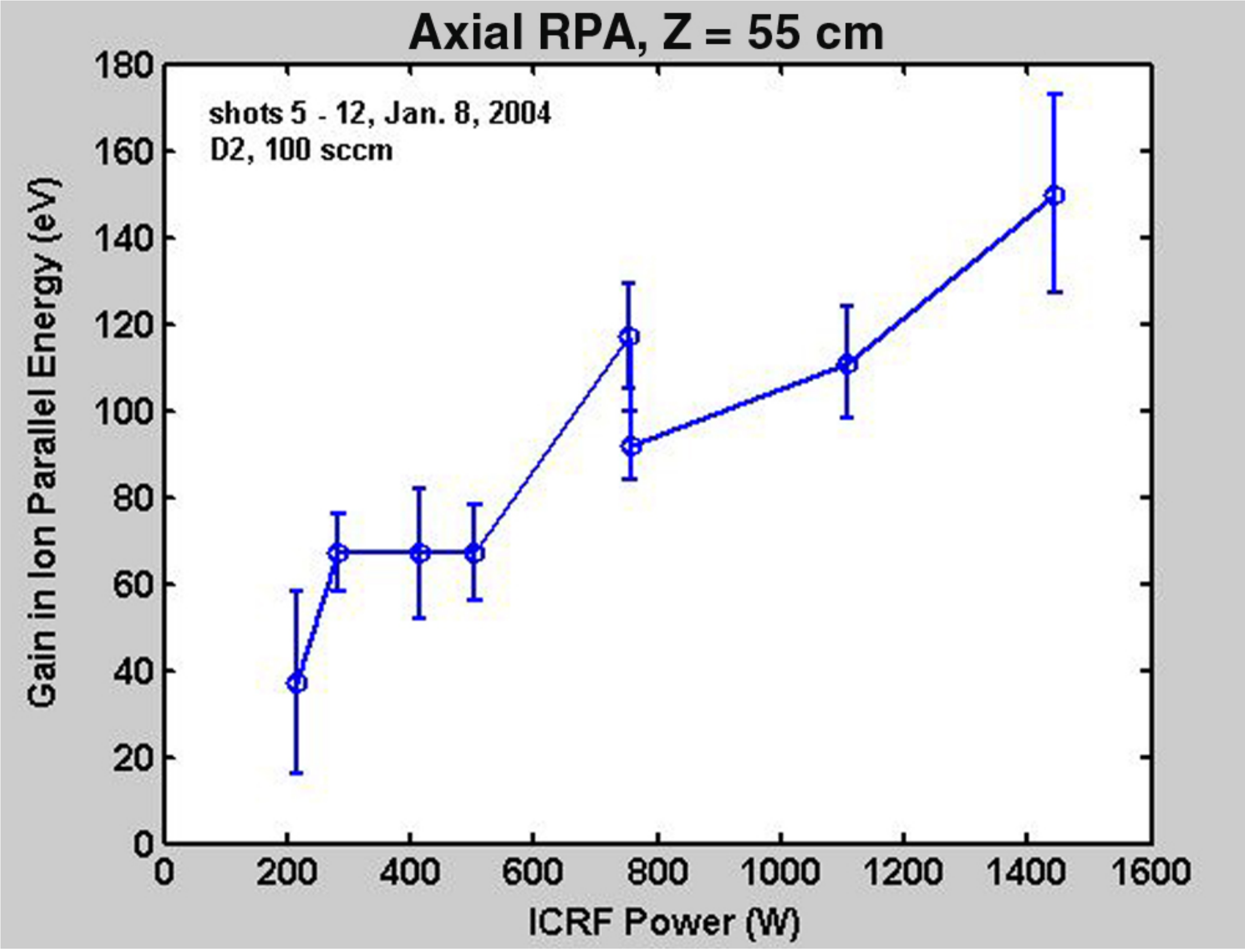
Exhaust velocity: 120 – 145 km/sec



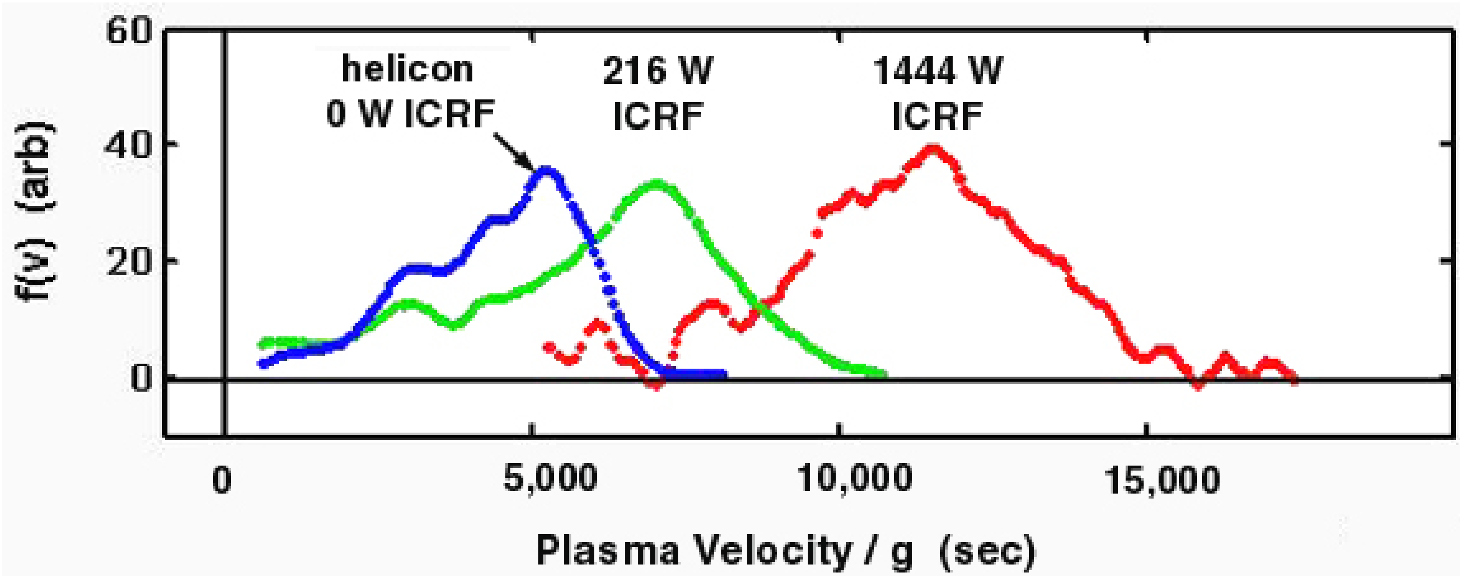
Higher Gas Flow Rate → Higher Ion Energy



Ion Parallel KE ∝ ICRH Power



Exhaust Velocity Distributions, Varying ICRH Power

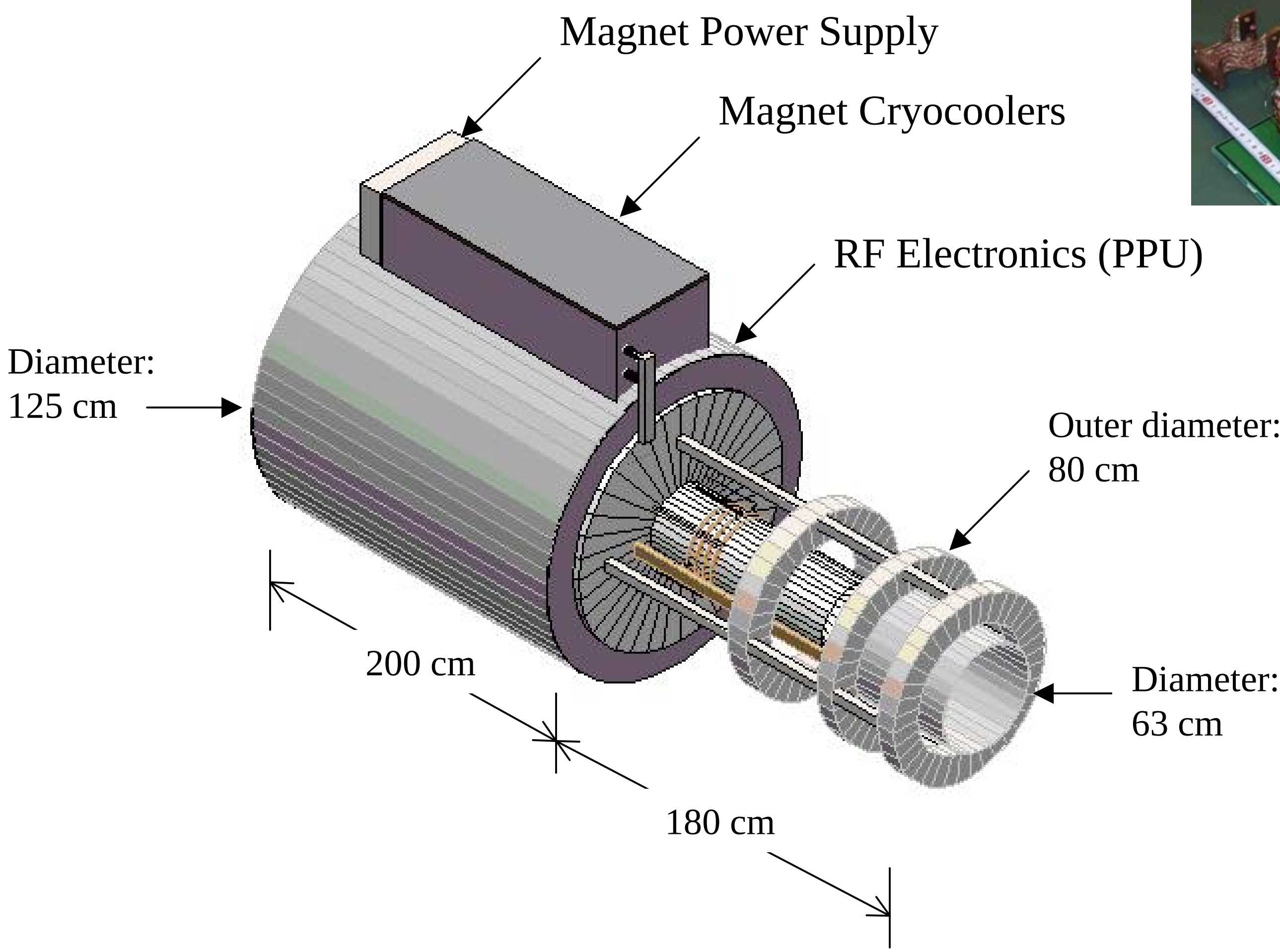


•We are upgrading experiment from 1.5 kW ICRH power to ~10 kW this summer, aiming for 50 kW by fall.

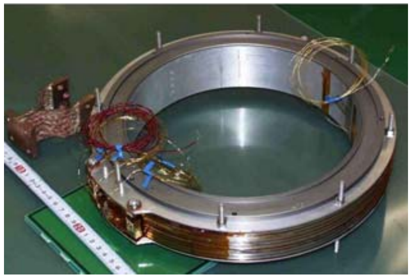
•It will be interesting to see how high the Isp will go….

Flight Hardware: Point Design for One Megawatt Engine

Engine, PPU and Cryocoolers

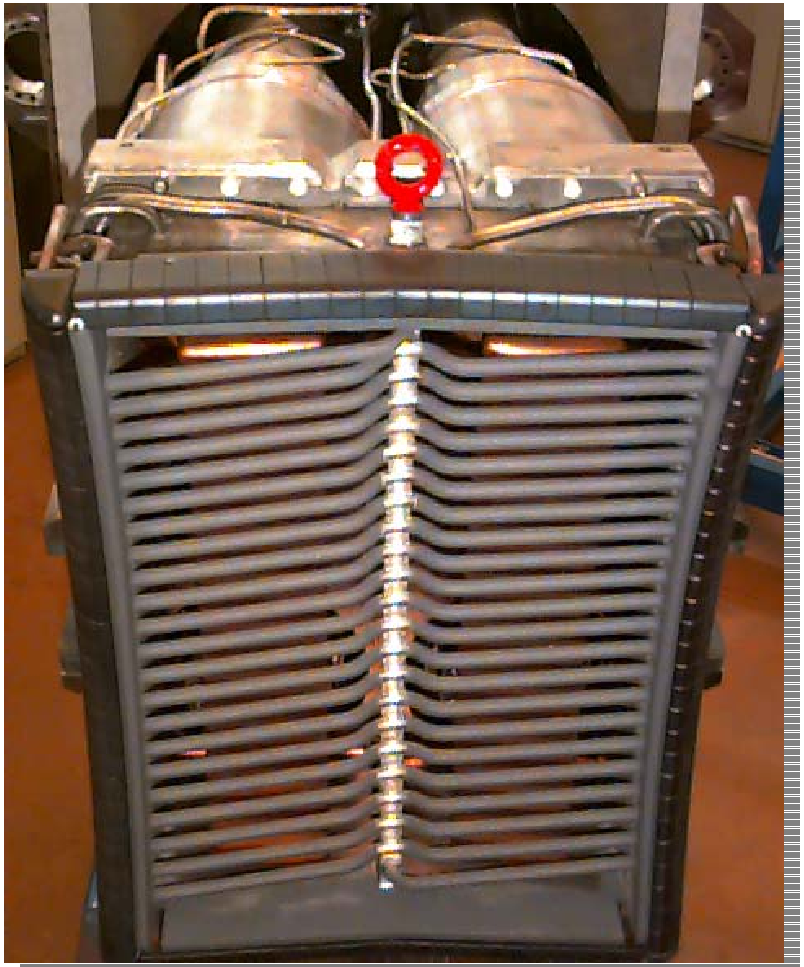


SC magnets



ORNL has a long history of high-power RF development in the fusion program.

- World's highest power, long-pulse ICRF antenna, designed and built by ORNL for the Tore Supra tokamak in France
- 4 MW for 30 seconds, 30-80 MHz
- B_4C coating at plasma interface
- Designed for 1000 A rms in current strap
- Protection bumper brazing and shape designed for 10 MW/m^2



RF power conversion

- The reigning champion is the Eimac 4CM2500KG, with output power of 2.8 MW.
- Power MOSFETs and insulated gate bipolar transistors (IGBTs) are limited to ~1 kW per device.
- Both tubes and transistors require development for space application.
- In Class D operation, efficiency 88% (1960's).

Mass Estimate

Engine	Mass	Dimensions
	(kg)	(cm)
Propellant controller	5	30 x 20 x 10
Engine tube	8.9	72 x 63 dia .4 thick
Helicon tube	15.9	108 x 45 dia .3 thick
Helicon antenna	0.67	8.8 x 45 dia .2 thick
ICRF antenna	0.91	18 x 30 dia .2 thick
Helicon transmission lines	0.3	2 x.5 x 100
ICRF transmission lines	0.5	2 x .5 x 175
Magnet power supply	10	45 x 30 x 10
Magnet cryocoolers (4)	74	115 x 45 x 30
Magnet loop heat pipe	3	300 x 3
Cryocooler radiator	2.7	22 x 115
Magnet coils (3)	117	55 ID 60 OD 5 thick
Magnet support and insulation	18	
Instrumentation	5	
System controller	9	26 x 50 x 9
Engine radiator (1/4 disk)	157	640 cm radius
Engine radiator (panel)	93	180 x 580
Engine support structure	78	
Engine Total	598.88	

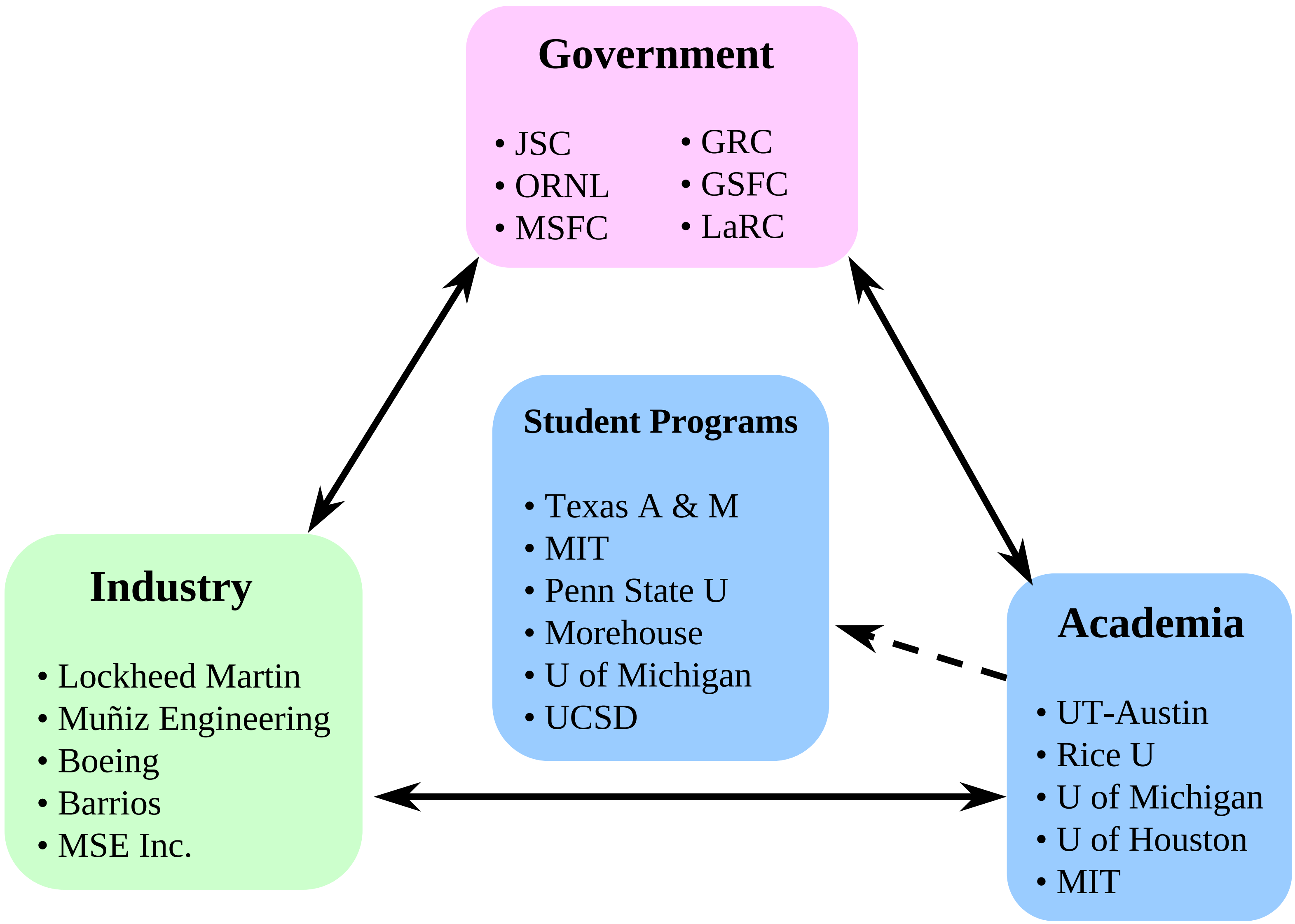
Power Processing Unit	Mass	Dimensions
	(kg)	(cm)
RF power distribution	225	3x(140 x 28 x 10)
Helicon oscillator (4)	5.6	4x(15 x 12 x 5)
Helicon driver (4)	6.5	4x(30 x 20 x 8)
Helicon power amplifier (4)	180	4x(106 x 28 dia)
Helicon tuned line matcher (4)	27	4x(143 x 30 dia)
Shorted stub matcher (4)	27	4x(143 x 30 dia)
ICRF oscillator (4)	5.6	4x(15 x 12 x 5)
ICRF driver (4)	75	4x(21 x 21 x 12)
ICRF power amplifier (4)	200	4x(108 x 23 x 12)
ICRF matching network (4)	125	4x(54 x 12 x 6)
ICRF Antenna tuner (4)	150	4x(54 x 18 x 5)
PPU radiator	103	200 x 580
PPU structure and fittings	169	
PPU Total	1298.7	

Radiator Panel Mass: One-sided: 4.9 kg/m^2 Two-sided: 8.9 kg/m^2
Antenna sizing based on 10 MW/m^2

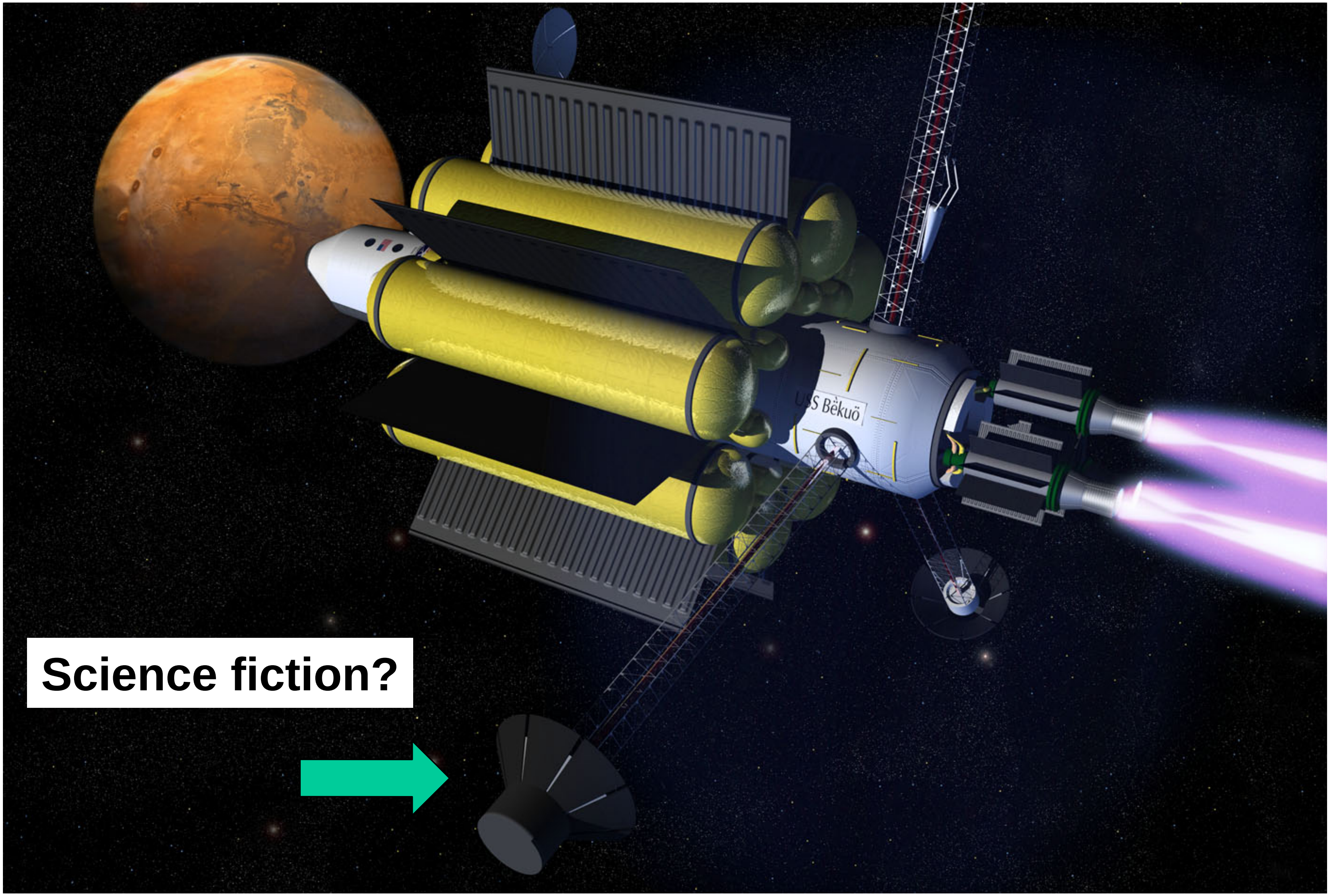
Mass Estimate for 2.5 MW Point Design

Engine:	600 kg	α = 0.24 kg/kWe
PPU:	1300 kg	α = 0.52 kg/kWe
Total System:	1900 kg	α = 0.76 kg/kWe

ASPL Collaboration



The Bigger Issue: POWER and ALPHA

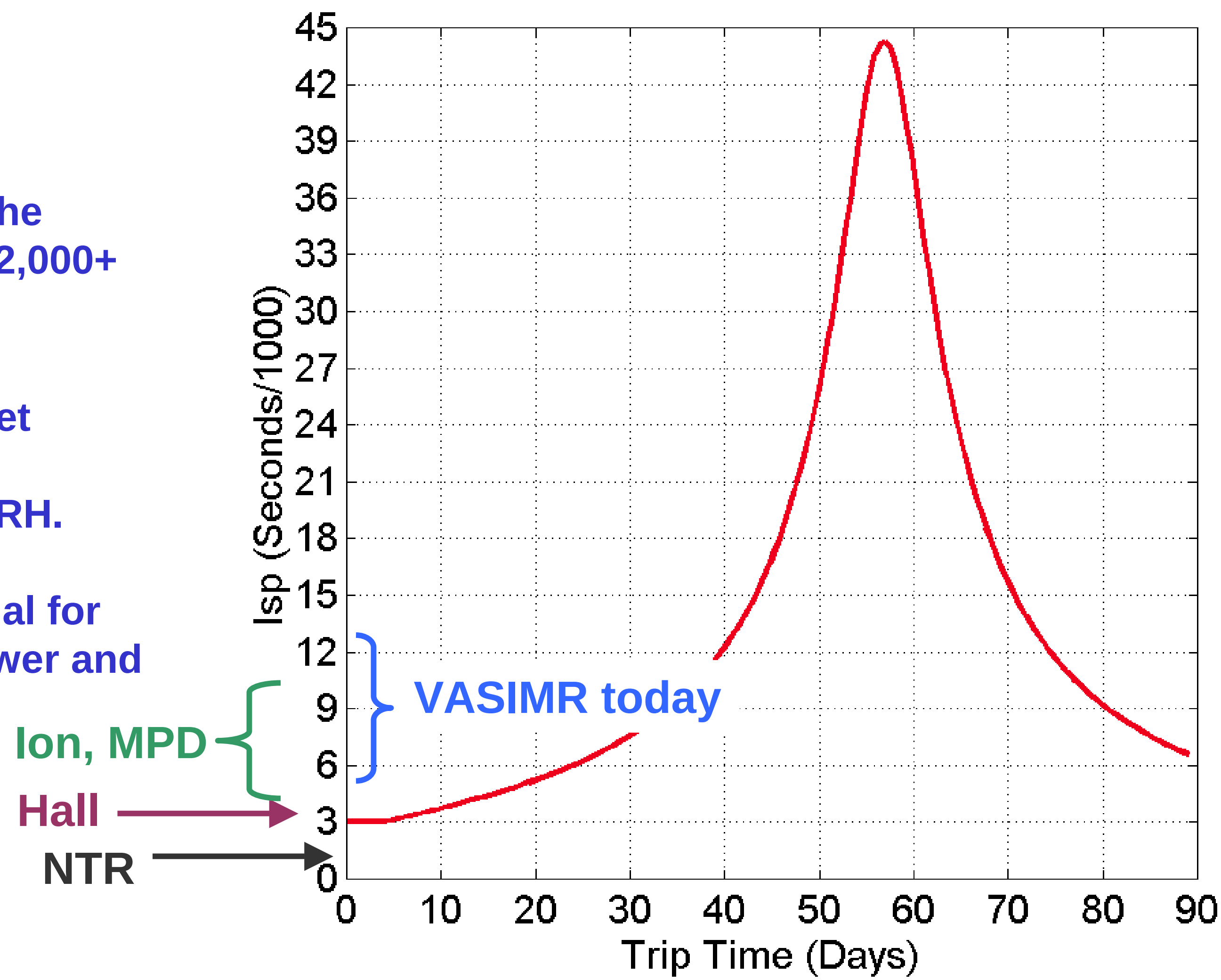


Summary

- VASIMR prototype has demonstrated:
    - 100 % propellant utilization.
    - variable Isp over the range of 5,000 to 12,000+ seconds.

- Preliminary thrust target measurements indicate additional force with ICRH.

- VASIMR shows potential for growth to both high power and highly variable Isp.



… and nobody's going anywhere without dramatic progress in space nuclear power!