High Power Electric Propulsion for Deep Space Missions

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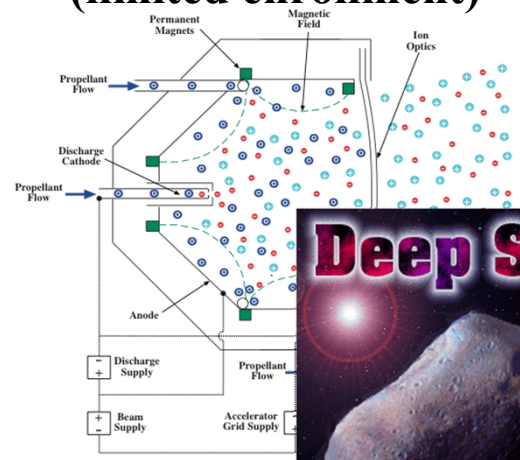
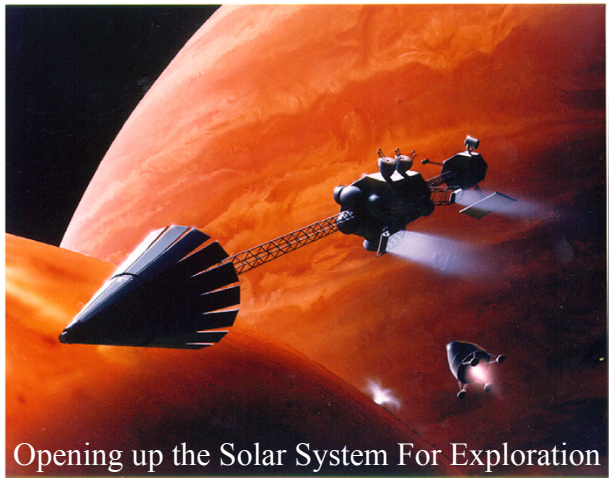
An Overview of Electric Propulsion for Deep Space Missions

- An Electric Propulsion Primer
- The Flexible Path and the Electric Path
  - A New Plan for Human Exploration
  - The Role of Electric Propulsion
- High Power Electric Thrusters
  - Hall Thrusters
  - Magnetoplasmadynamic Thrusters
- Challenges for the Next Generation of Advanced Propulsion Technologists

Electric Propulsion 101
(limited enrollment)

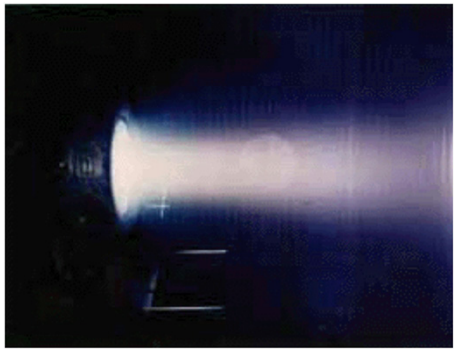




Electric Propulsion Provides High Exhaust Velocity for Improved Fuel Efficiency

I_{sp} = 323 sec
Thrust = 445 N
Thrust Power = 705 kW

Aerojet Bipropellant Thruster



I_{sp} = 1800-3000 sec
Thrust = 0.02-0.09 N
PPU Power = 0.6-2.5 kW

NSTAR Ion Thruster

Chemical Propulsion

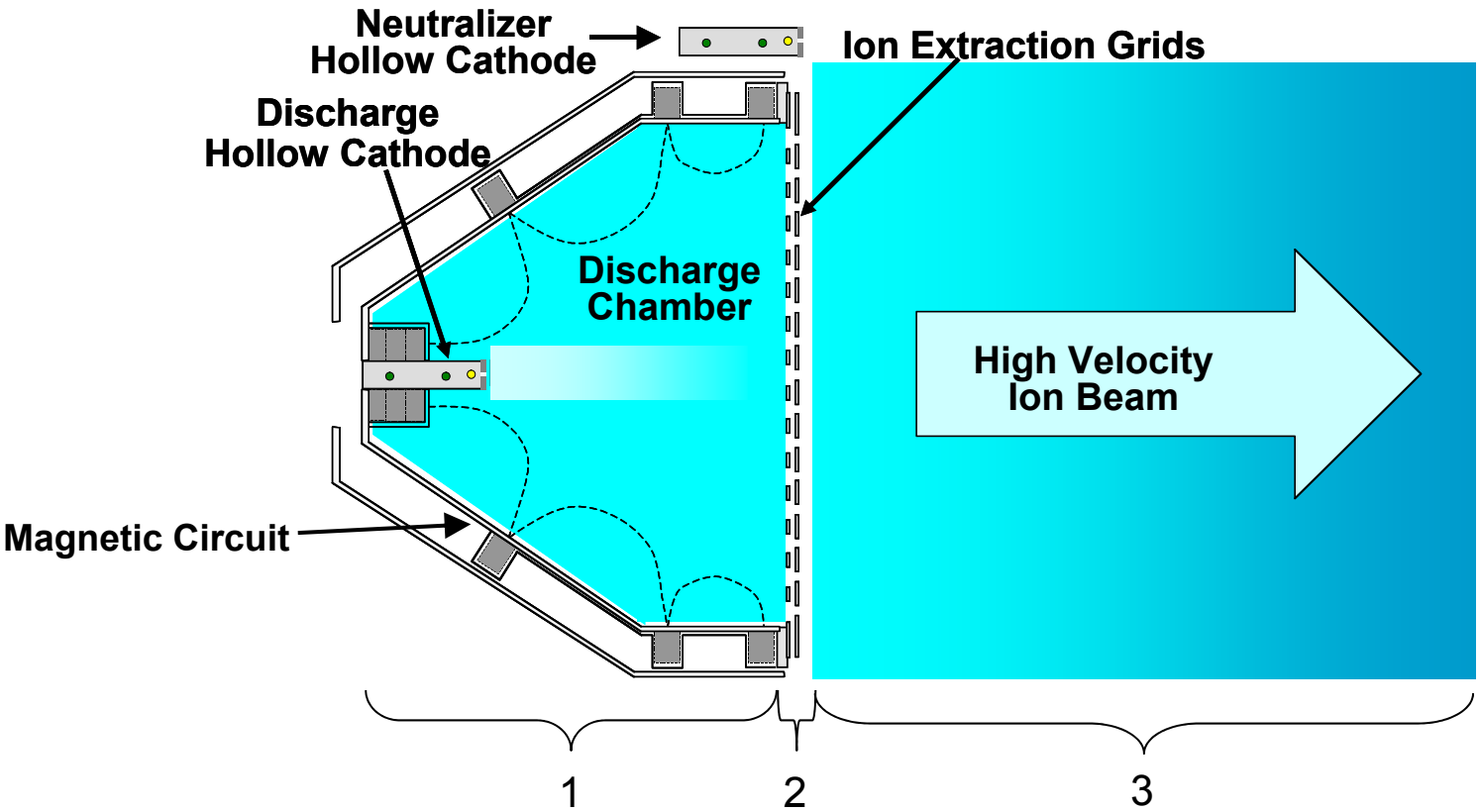
- **Electric Propulsion devices operate at <u>much higher specific impulse</u> than chemical thrusters**
  - High specific impulse = much lower propellant mass
- **EP devices require electric power produced by external power system**
  - Thrust limited by power available from spacecraft
  - Low thrust results in very long burn times

Electric Propulsion

$$\frac{m}{m_0} = e^{-\frac{\Delta V}{V_{exhaust}}} = e^{-\frac{\Delta V}{I_{sp} g}} = e^{-\frac{\Delta V}{9.8 I_{sp}}}$$

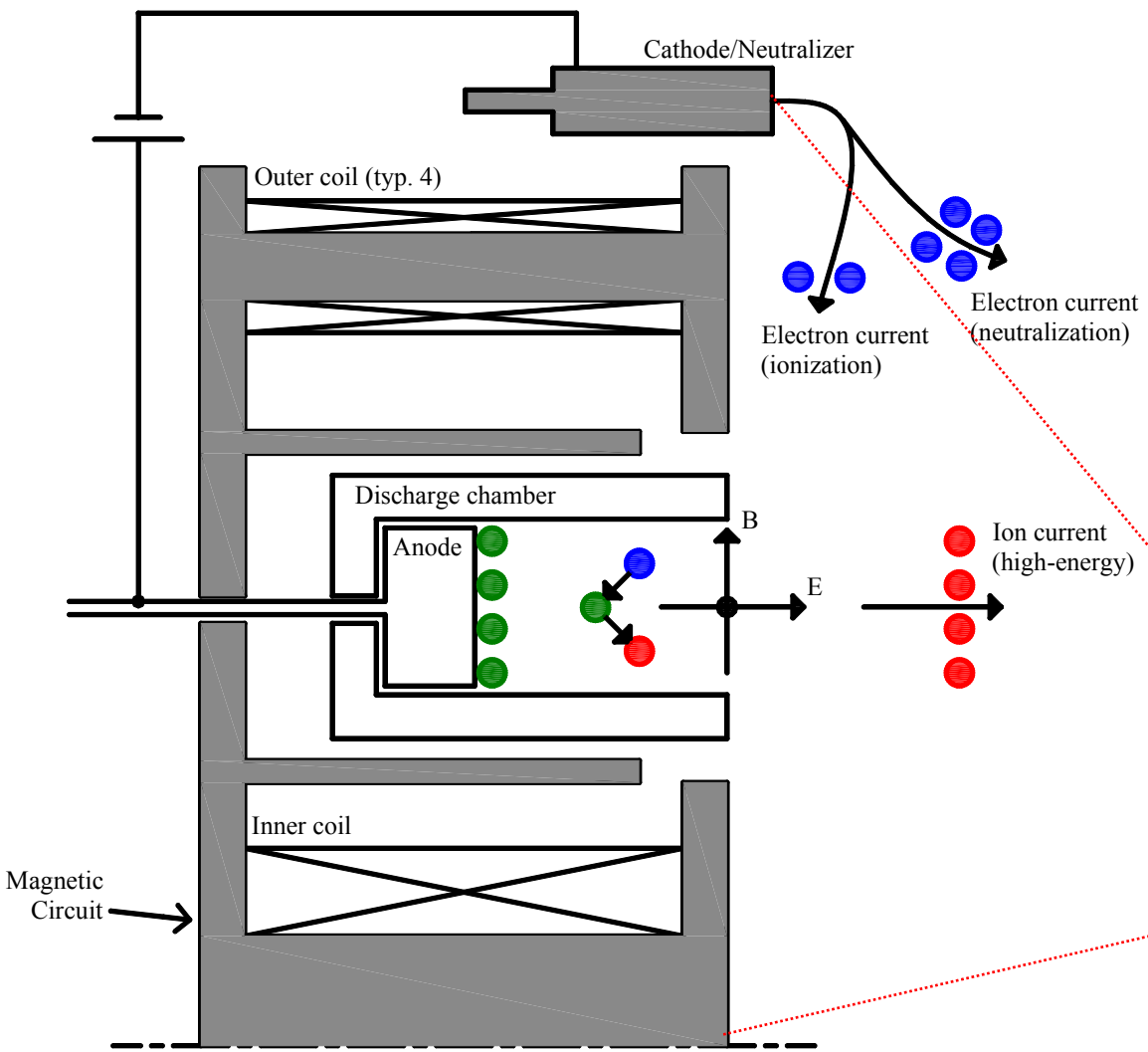
Electric Propulsion's high Isp increases delivered mass for missions that require large ΔV

Ion Thrusters Use Electrostatic Forces to Accelerate Ions to Produce Thrust

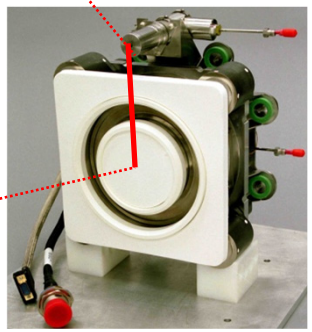


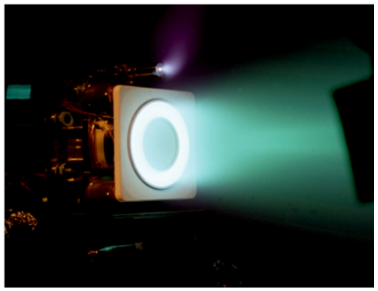
1. Xenon gas **ionized** in the discharge chamber
2. Ions **accelerated** by voltage between grids
3. Ion beam **neutralized** by neutralizer electrons

Hall Thruster Operation is Similar, but the Processes Overlap In a Near Continuous Fashion.

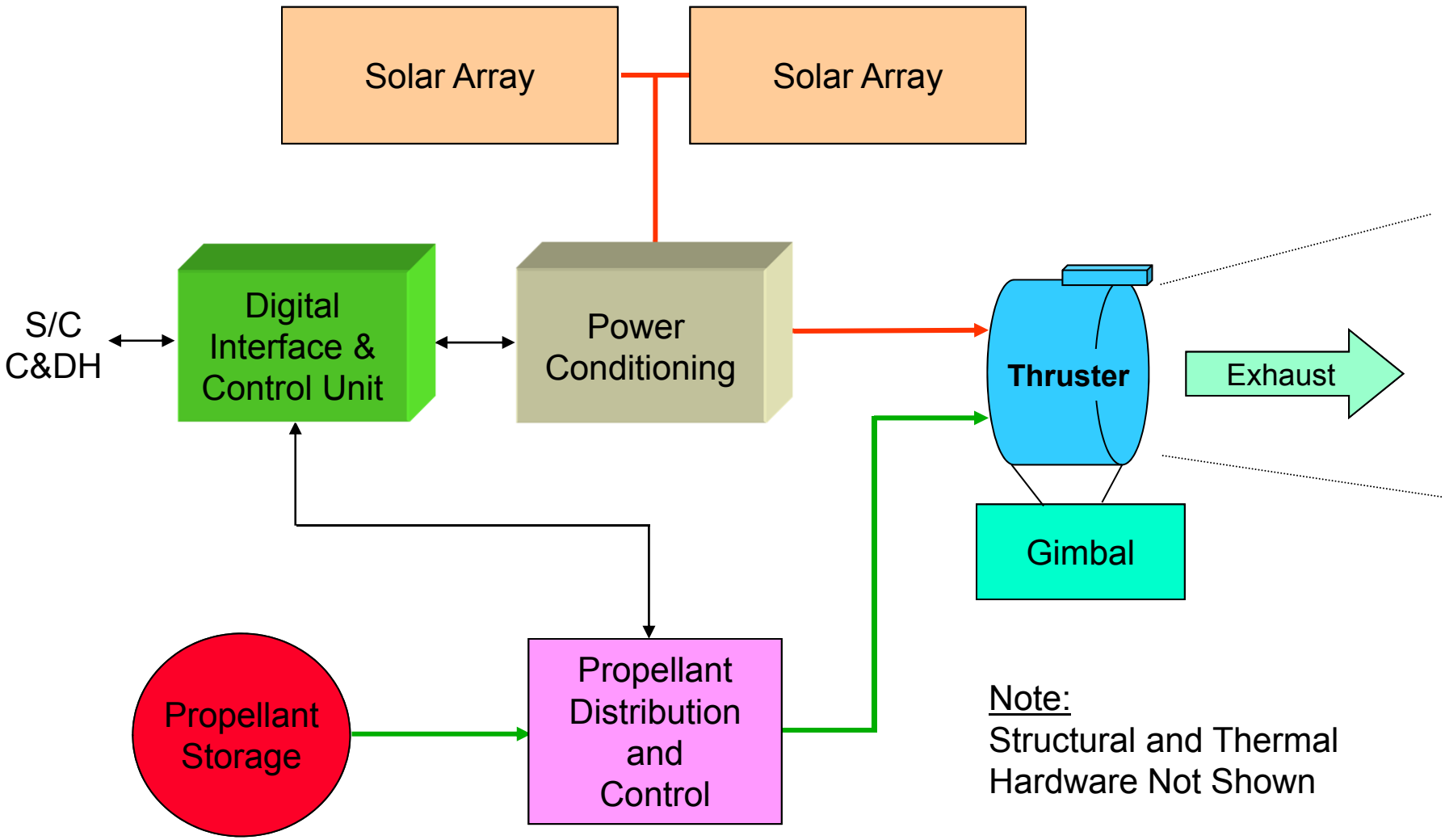


1. **Electrons from the cathode are trapped in an azimuthal drift by the applied electric (E) and magnetic fields (B).**
2. **Neutral propellant gas is ionized by electron bombardment.**
3. **Ions are accelerated by the electric field producing thrust.**
4. **Electrons from cathode neutralize ion beam.**





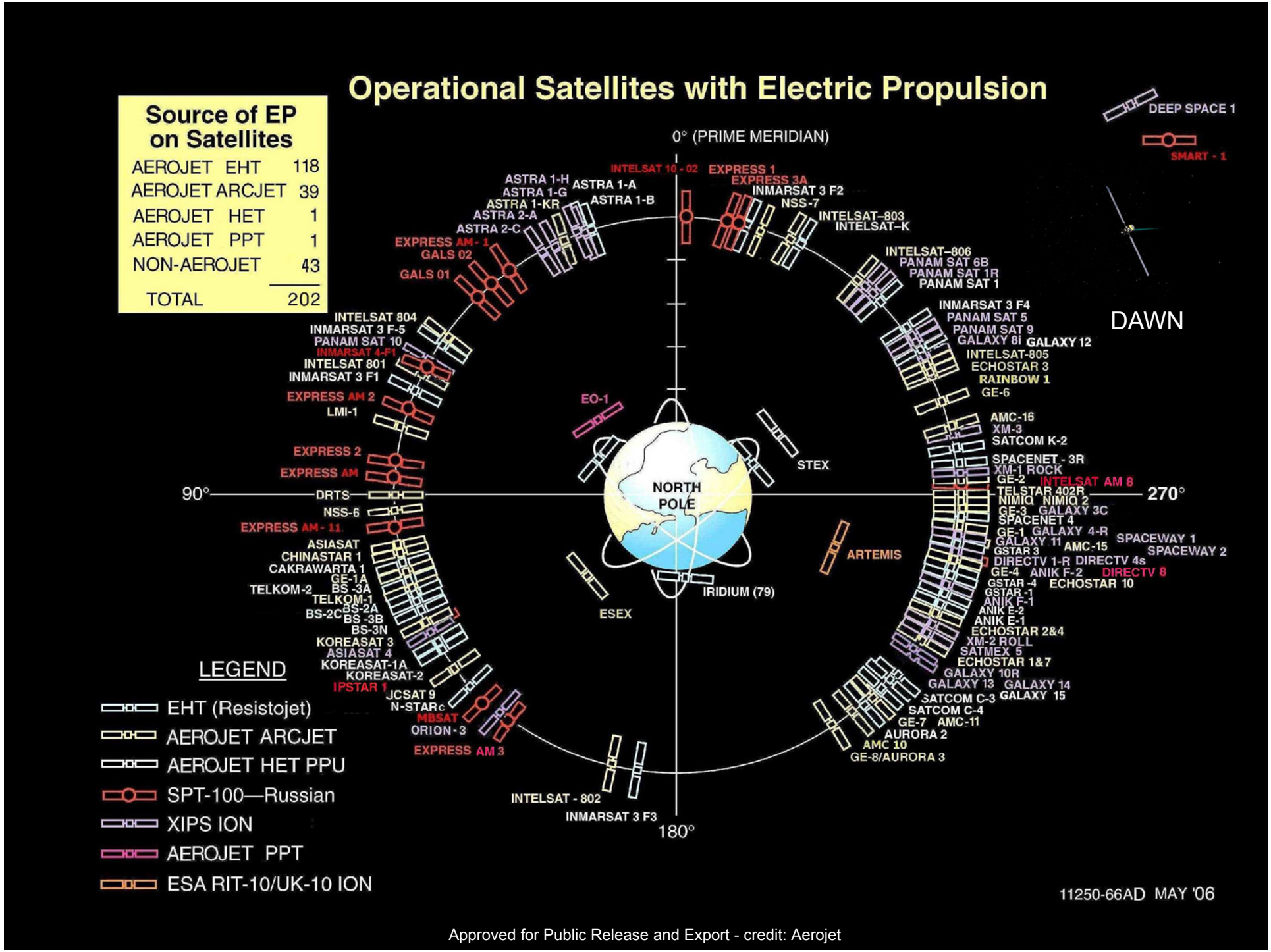
Solar Electric Propulsion (SEP) System Elements



Note:
Structural and Thermal
Hardware Not Shown

Electric Propulsion-That Crazy Futuristic Technology

Operational Satellites with Electric Propulsion



Approved for Public Release and Export - credit: Aerojet

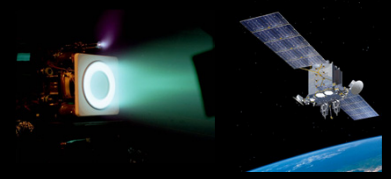
Hall Thruster Space Flight Heritage

241 thrusters on 51 s/c have flown since 1971 with 100% success

1960 - 1971
Early US/USSR
Hall Thruster Development

1971 - 2010
241 Hall thrusters flown on 51 Russian, US, & European s/c.

Dec 1971
Fakel SPT-60 flies on Soviet Meteor s/c.
1st Hall thruster spaceflight.



Aug 2010
Aerojet BPT-4000 flies on Advanced EHF.
1st flight of US Hall thruster on GEO s/c.

Nov 1998
Russian D-55 flies on NRL STEX.
1st flight on US s/c.

Mar 2004
Russian SPT-100 flies on Loral MBSAT.
1st commercial flight on US s/c.

Early 1990 s
Russian Hall thrusters introduced to US.

Sep 2003
SNECMA PPS-1350 flies on lunar orbiting ESA SMART-1.
1st Hall thruster used for primary propulsion on a science mission.

Dec 2006
Busek BHT-200 flies on TacSat-2.
1st flight of US Hall thruster.

Electric Propulsion Has Been Used on 4 Deep Space Missions by NASA, ESA, and Japan

- **NASA**
  - Deep Space 1 launch in 1998
    - GRC/L-3 NSTAR ion thruster/PPU
    - Tech demo mission integrated by JPL
  - DAWN launched September 27, 2007
    - JPL mission with 3 NSTAR thrusters
    - Science mission to Vesta and Ceres
- **International**
  - Hayabusa launch in 2003 (0.34 kW)
    - ISAS/JAXA microwave ion thrusters
    - Science mission to Itokawa
  - SMART-1 launch in 2003 (1.2 kW)
    - Snecma SPT derived thruster
    - ESA tech demo mission to moon
- **Future**
  - Bepi-Colombo: ESA mission to Mercury
  - Multiple Discovery/NF proposals likely to use electric propulsion (EP) for primary propulsion

Flexible Path for Human Exploration of Multiple Destinations

Review of U.S. Human Space Flight Plans Committee **(Augustine Committee)** ***defined "Flexible Path" as:***

"Steadily advancing…human exploration of space beyond Earth orbit…successively distant or challenging destinations…"

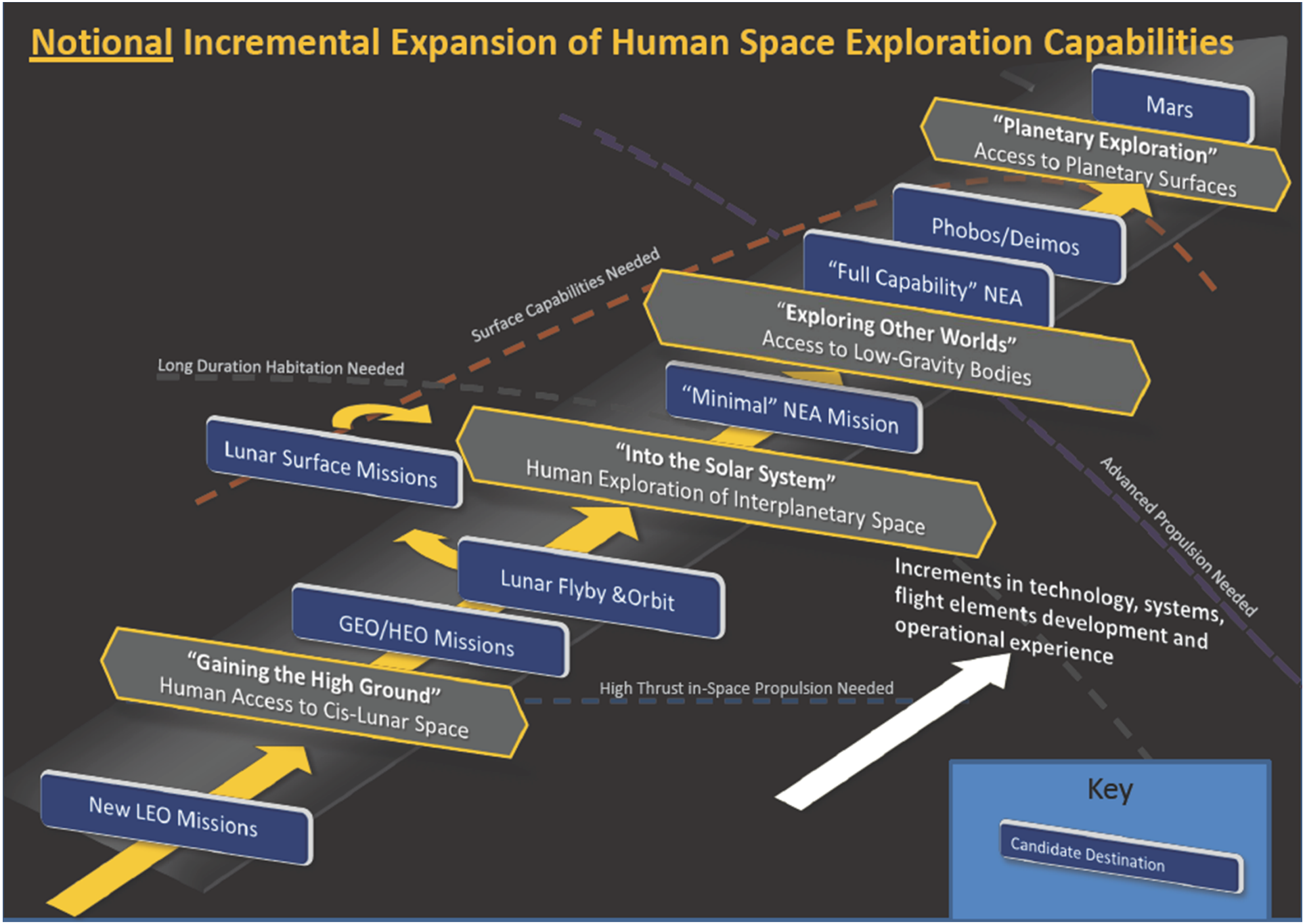
Destination options include:

- **Low Earth orbit (LEO) and the International Space Station (ISS)**
- **High Earth Orbit (HEO), Geosynchronous Orbit (GEO)**
- **Cis-lunar space (Lagrange/Libration points, e.g., L1, L2), lunar orbit, and the surface of the moon**
- **Near-Earth asteroids (NEAs), near-Earth objects (NEOs)**
- **The moons of Mars (Phobos, Deimos), Mars orbit, surface of Mars**

Can multiple paths get us where we want to go?

Can the program keep its basic shape despite unforeseen events?

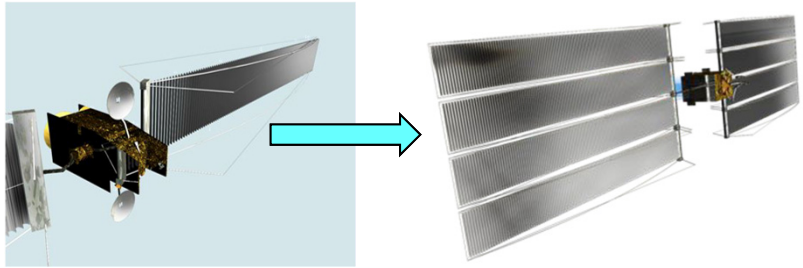
Can milestones stretch out without the program breaking?


Notional Incremental Expansion of Human Space Exploration Capabilities
Mars
"Planetary Exploration"
Access to Planetary Surfaces
Phobos/Deimos
"Full Capability" NEA
"Exploring Other Worlds"
Access to Low-Gravity Bodies
"Minimal" NEA Mission
"Into the Solar System"
Human Exploration of Interplanetary Space
Lunar Surface Missions
Lunar Flyby &Orbit
GEO/HEO Missions
"Gaining the High Ground"
Human Access to Cis-Lunar Space
New LEO Missions
Surface Capabilities Needed
Long Duration Habitation Needed
High Thrust in-Space Propulsion Needed
Advanced Propulsion Needed
Increments in technology, systems, flight elements development and operational experience
Key
Candidate Destination

SEP Stages with system power levels of 100-300 kW are achievable with near-term technology development

New solar array technologies (e.g. FAST, Ultraflex, SLASR) could provide the power for a high-power SEP stage (with specific powers of 130-220 W/kg).

DARPA/Boeing FAST array modularity could enable scaling from basic 15-kW modules to > 100 kW systems



50 kW Hall Thrusters have been demonstrated in the lab (at NASA GRC) that could be clustered together for high-power SEP stages.

"Immortal" Hall Thrusters can now be made that will eliminate wall erosion, the principal life time limiter of past Hall Thruster designs [Mikellides et al., Paper AIAA 2010-6942]

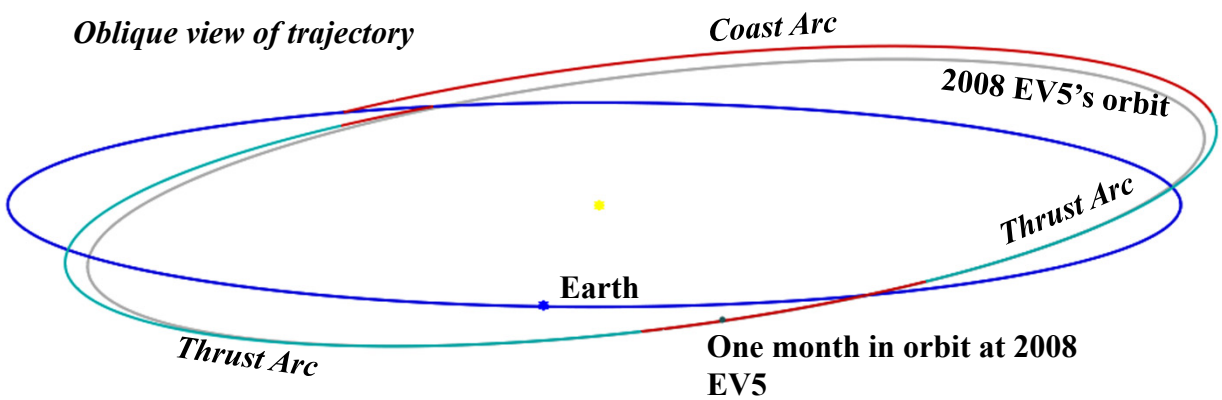
The "Electric Path"

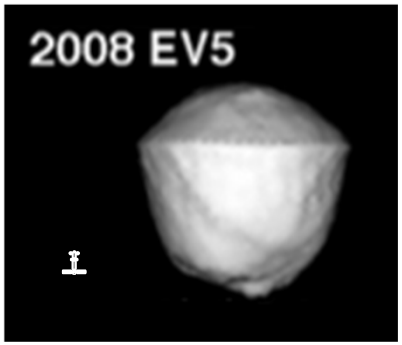
An Architecture for Human Exploration of the Inner Solar System

***Electric Path** human missions to asteroids in the 2020s can be realized with the demonstrated capabilities of high-power Hall thruster technology.*

- Uses Solar Electric Propulsion (SEP) boost stages to pre-position caches of supplies and cryogenic chemical propulsion boost stages for human transport.
- Flexible-path architecture that scales from lunar flybys to asteroid missions to Moon and Mars surface
- Requires only EELV class launch vehicles
- Missions to 6 large asteroids (> 200 m) are available in 2020s
- Uses 200 kW SEP system with Hall thrusters and chemical boost stages
  - High-thrust (10 N) & high specific impulse (2000-3000 s) of a 200 kW Hall thruster system optimum for these missions

Example: 1-year SEP Mission to 2008 EV5 (Type-C, 450 m) in 2024

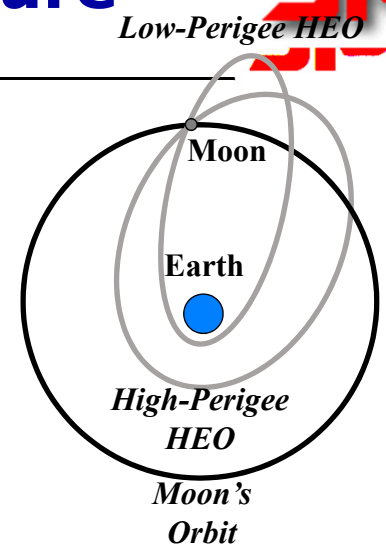




Radar image of 2008 EV5 with spacecraft shown to scale

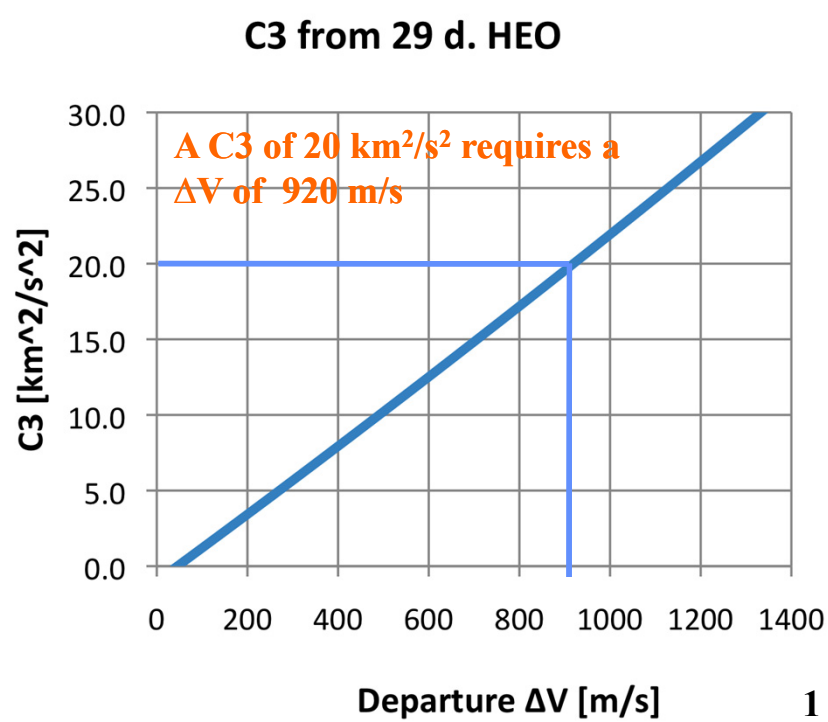
Staging Prior to Earth Departure

- A SEP Boost (SB) stage is used to spiral the uninhabited Deep Space Vehicle (DSV) to a High Earth Orbit (HEO)
- The crew uses an Orion-like Crew Module (CM) and a Chemical Boost (CB) stage to rendezvous in HEO
- A second CB stage is used with the inhabited DSV to escape



Which HEO?

- A C3 of -1 km^2/s^2 (**29** d period), is assumed in the paper but orbits with a C3 from -2 to -0.**5** **km^2/s^2 would also work**
- Lunar Gravity Assists (LGAs) are used to move perigee **above the Van Allen belts and to rotate the HEO's line of nodes and change its inclination as needed prior to crew launch**
- A LGA is then used to lower the perigee to 200 km before crew arrival for efficient Earth escape.



Component Mass Assumptions

Component	Description	Assumed Mass
Habitation Module (HM)	Module providing life support and accommodations for 4 astronauts	22,000 kg
Chemical Boost Stage (CB)	Cryogenic fuel booster with active cooling to prevent propellant boil off (20% inert mass for stage)	22,000 kg (wet) 4,400 kg (dry)
Crew Module (CM)	Orion-like crew capsule for trip from ISS to DSV and for Earth re-entry	9,000 kg
SEP Boost Stage (SB)	Stage with 250 kW solar arrays, electric propulsion system, and Xenon tanks (20 kg/ kW inert mass for stage)	22,000 kg (wet) 5,000 kg (dry)
Fuel Module (FM)	Module for additional Xenon Fuel needed by Phobos mission (14% inert mass)	22,000 kg (wet) 3,000 kg (dry)
Provisions	Consumables and supplies to support a crew of 4 for one year (5.5 kg/person/day)	8,000 kg

Components sized to 22 ton capability of Delta IV Heavy to ISS

Architecture 1: Pre-Placed CB Stages

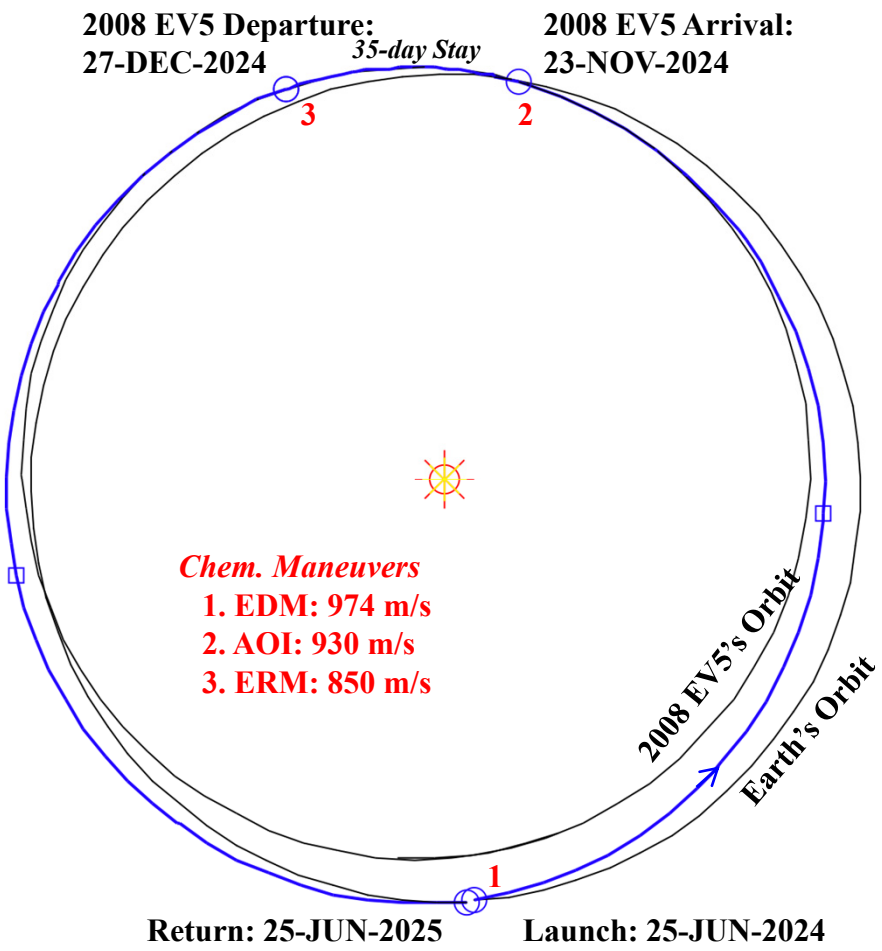
- SEP Boost (SB) stages are used to stage the DSV in HEO prior to Earth departure
- SB stages are used to pre-position Chemical Boost (CB) stages for use by the crewed DSV
- When crew is on the DSV, all maneuvers are done with the CB stages and the SB stage is only used for uninhabited elements
- This architecture allows the CB stages to be sized just to push the DSV mass for a maneuver and the SB stages are used to push the propellant needed for future maneuvers

Architecture 2: Piloted SEP

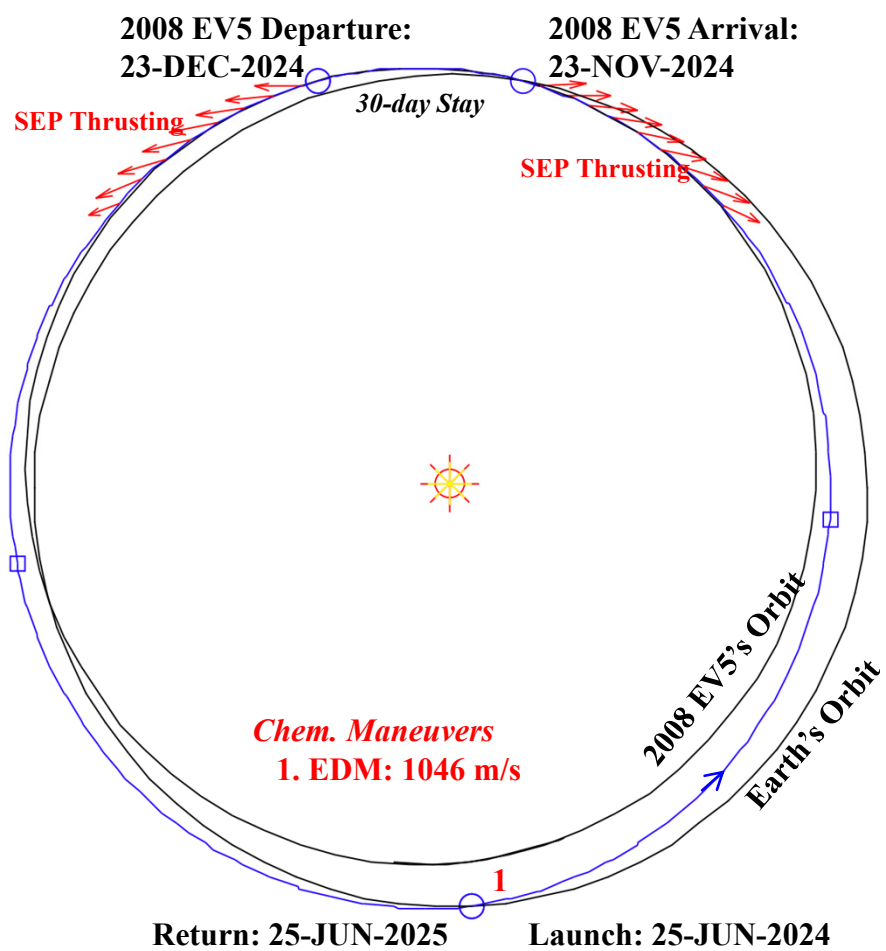
- Like Arch. 1, SB stages are used to stage the DSV in HEO prior to Earth departure
- The only CB stage is used for the Earth Departure Maneuver (EDM)
- SB stages are used to push the DSV with crew on board
- If there is enough power for the SB stages, this architecture offers significant performance benefits over Arch. 1
- Arch. 1 can be used as a technology fallback if it turns out it is more difficult than expect to develop a SB stage at the desired power level

NEO (2008 EV5) Trajectories

Pre-Placed CB Trajectory



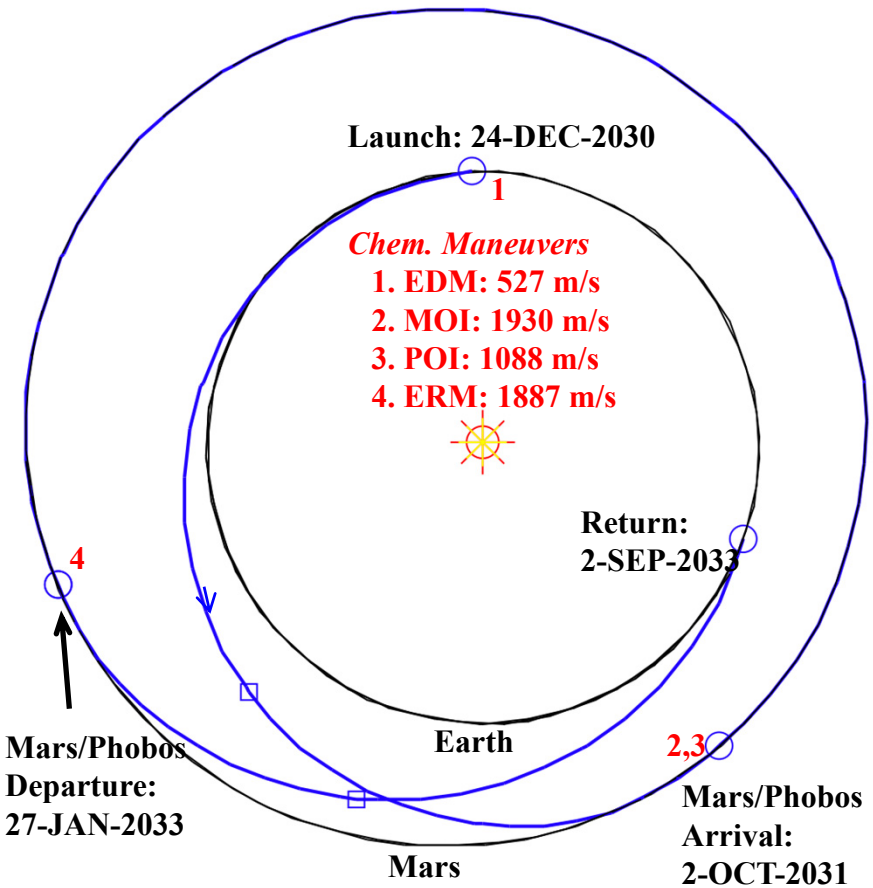
Piloted SEP Trajectory



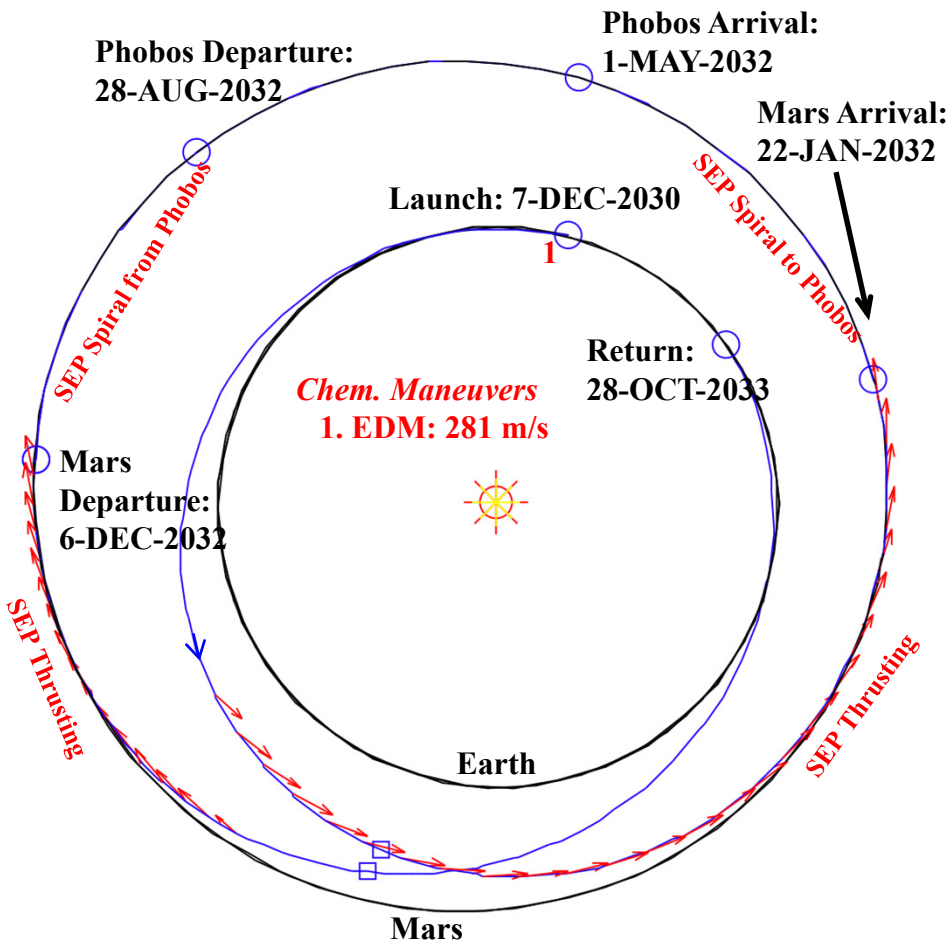
250 kW SEP Stage; 2000 sec. Isp

Phobos Trajectories

Pre-Placed CB Trajectory



Piloted SEP Trajectory



2 x 250 kW SEP Stage; 2000 sec. Isp

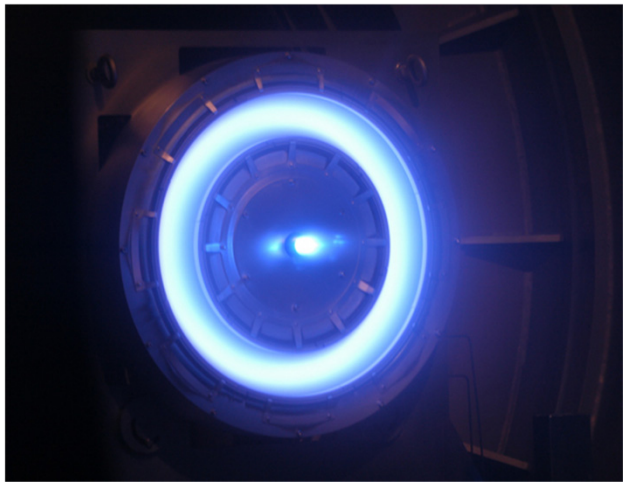
Injected Mass to Low Earth Orbit (IMLEO)

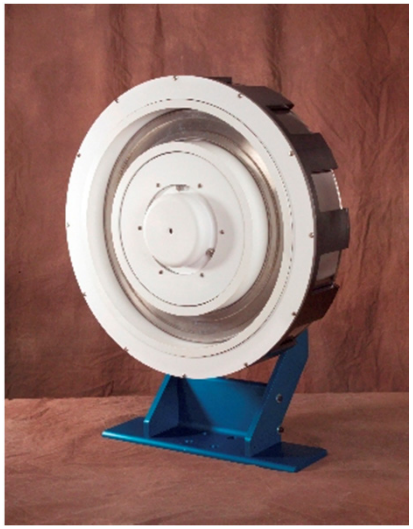
	IMLEO [tons]	No. of 22 t Launches
NEO All Chem	244.6	12
NEO: Pre-Placed CB	137.9	7
NEO: Piloted SEP	93.3	5
Phobos All Chem	722.0	33
Phobos: Pre-Placed CB	259.3	12
Phobos: Piloted SEP	167.6	8
NEO to Phobos Delta: Pre-Placed CB	232.9	11
NEO to Phobos Delta: Piloted SEP	134.0	7
NEO+Phobos Total: All Chem	**966.6**	**44**
NEO+Phobos Total: Pre-Placed CB	**370.8**	**17**
NEO+Phobos Total: Piloted SEP	**227.3**	**11**

Conclusions

- One-year Human NEO missions are possible with SEP stages at 140-250 kW power levels
- Three-year Human Phobos missions are possible with SEP stages at 500 kW power levels
- To do a NEO and Phobos mission, the Piloted SEP architecture requires ¼ of the IMLEO and number of launches of an all chemical approach
- High-power SEP modules at powers of 150-250 kW are achievable in the near term and have a clear potential to reduce the cost, complexity, and risk of human deep space missions to asteroids and to Mars.

HIGH-POWER HALL THRUSTERS





High-Power Hall Thruster Technology Readiness

Hall thruster technology has a demonstrated 1000X range of power from 100 W to 100 kW.

< 5 kW (TRL 8-9)

Hall thrusters are routinely used on commercial GEO communications satellites for orbit raising and stationkeeping.

Over 130 SPT-100 Hall thrusters are on-orbit, including several satellites built by Space Systems Loral.

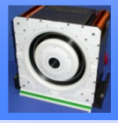
Aerojet BPT-4000 on DOD AEHF s/c launched Aug 14, 2010.

5 – 50 kW (TRL 4)

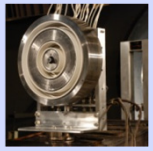
Thrusters in this range have achieved 3N thrust, >70% efficiency, and specific impulses of 1000-5000 s.

NASA lab thrusters tested from 2000-2005.
-NASA-457M operated to 100 kW.
-NASA-400M operated to 5000 s.
-Engineering model 457M fabricated.

AFRL has developed 20 kW technology to TRL 4. Could be leveraged for near-term flight demos.



50 – 200 kW (TRL 3)



Concentric channel thrusters identified by NASA as one path to very large thrusters. Sub-scale models have been tested at U of Michigan.

Designs for a 150 kW thrusters were developed under ESR&T in 2005 before program was ended. A 600 kW system was awarded to Aerojet in 2005 under ESR&T based on the 150 kW thruster.

200 – 1,000 kW (TRL 2)

Clustering of 200 kW thrusters is a credible path to reaching >1 MW. Clustering has been demonstrated at power <10 kW.

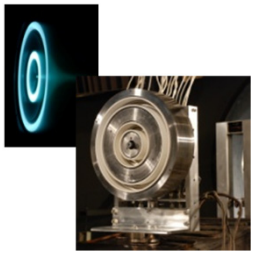
Largest single thruster size that could be practically tested and built for flight is unknown due to limited research performed to date.

Hall thruster technology is very scalable in power and specific impulse

- Power scaling
  - Assuming we desire clusters to consist of no more than four thrusters …
    - Annular Hall thrusters can be fabricated up to ~100 kW per thruster, allowing for 0.4 MW clusters
    - Nested Hall thrusters can be fabricated up to ~250 kW per thruster, allowing for 1 MW clusters
  - Hall thruster systems spanning 0.1-1.0 MW can meet ESMD mission requirements in the near- to mid-term while the MW-class thruster and power technologies are brought to flight readiness (20+ years)

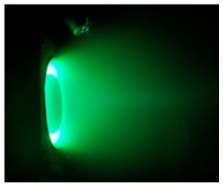
- Specific impulse scaling
  - 2000 s Isp xenon Hall thrusters are flight qualified (TRL 9)
  - 3000 s Isp xenon Hall thrusters under development (TRL 4)
    - Can be flight qualified in three years
  - High-Isp Hall thrusters can be realized in the mid-term through propellant changes
    - 5000 s Krypton Hall thrusters (TRL 3) have been demonstrated at high-power
    - 5000-8000 s Magnesium Hall thrusters (TRL 2) could form the basis of an ISRU architecture for NEO and Mars exploration

Annular Hall thruster's up to 100 kW per thruster



Nested Hall thruster's up to 250 kW per thruster

Krypton Hall thruster's up to 5000 s Isp



Magnesium Hall thruster's up to 8000 s Isp

Lifetime

- Hall thruster lifetime is primarily limited by erosion of the discharge chamber walls due to impact of high-energy ions.
- Other failure modes, such as cathode erosion, anode deposition, magnet shorting, etc. have not been observed to be significant life-limiting factors in American Hall thrusters.
  - Cathode erosion and magnet shorting have been observed in Russian (SPT-100) and French (PPS-1350) Hall thruster life tests.
- Channel erosion tends to be localized to a region near the exit plane, on the order of 1 cm in length. In this region, the ions have sufficient energy to sputter erode the walls.
- Upstream of the erosion zone, redeposition of sputtered wall material can occur. The rate of redeposition, like the rate of erosion, decreases with time as the walls recess causing the angle of the ions with respect to wall to become increasingly shallow, which reduces the erosion and redeposition rates.

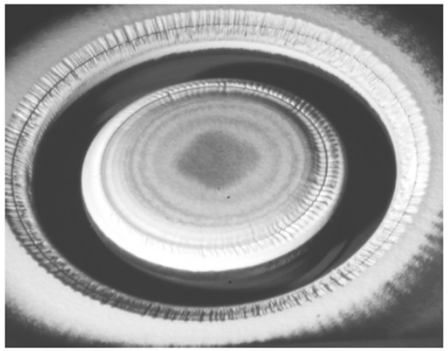
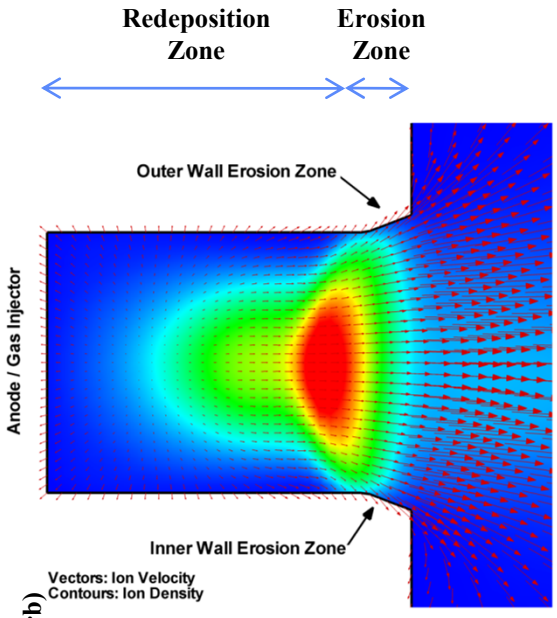
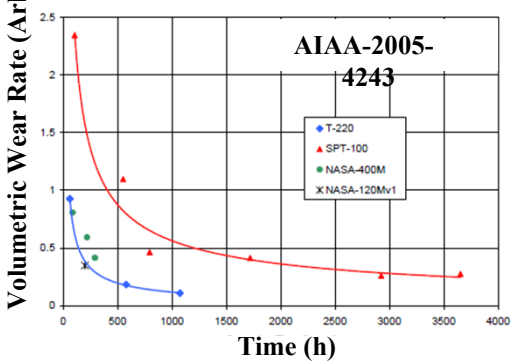


Figure 10 - In-Situ Photograph of Thruster at 10,400 hrs of Operation

De Grys, K. H., et al., AIAA Paper 2010-





The volumetric erosion rate decreases with time as the ion incidence angle becomes increasingly shallow.

Soft vs. Hard Failures

- Hall thruster life is primarily limited by erosion of the discharge chamber walls due to high-energy ion sputtering that eventually exposes the magnetic circuit.
- Hall thrusters continue operating long after the magnetic circuit is first exposed [1-3], often without significant performance changes, and for this reason this moment in time is sometimes called a "soft failure."
- Whether or not a spacecraft can tolerate deposition from the metallic sputter products of the now exposed magnetic circuit is mission dependent.
- Given a sufficiently long enough time the gradual erosion of the magnetic circuit would presumably lead first to performance degradation and eventually to difficulties starting and maintaining the plasma discharge. However, to our knowledge this hard failure point has never been documented in a long duration life test, but is known to be at least several thousand hours of additional operation [1,2].

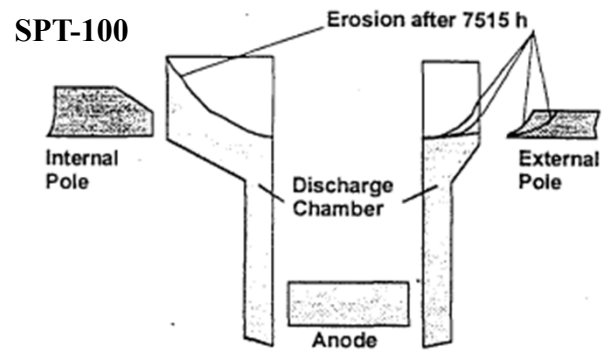
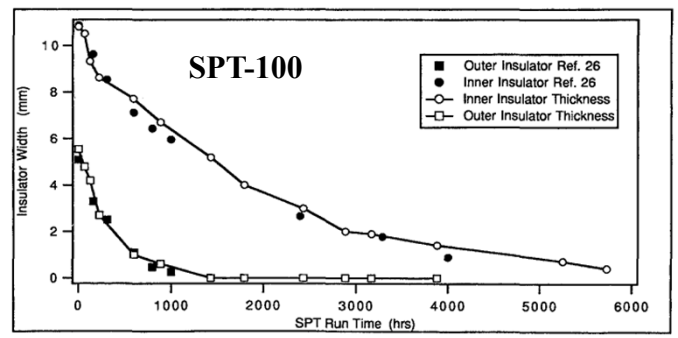
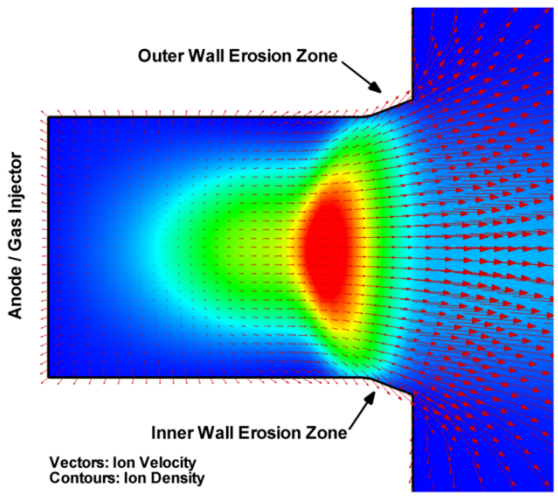


Fig. 19 Diagram of Erosion of the Discharge Chamber Isolator and the Outer Magnetic Pole after 7515 hours of operation



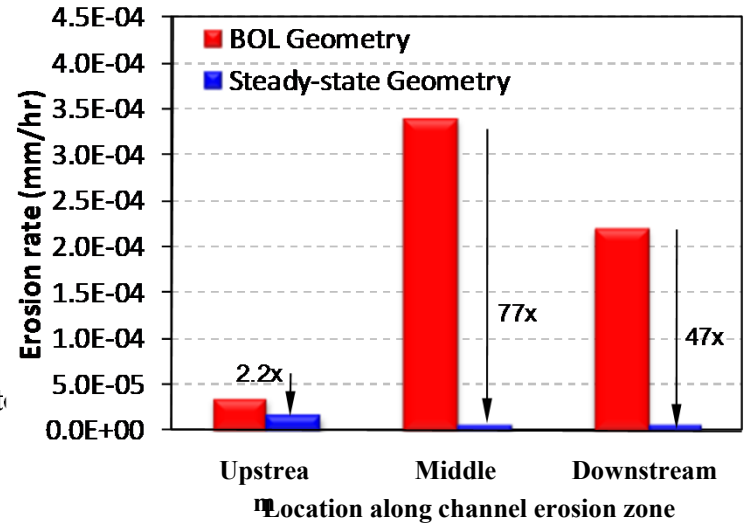
1. Cornu, N., Marchandise, F., Darnon, F., and Estublier, D., "The Pps-1350-G Qualification Demonstration: 10500 Hrs on the Ground and 5000 Hrs in Flight," AIAA Paper 2007-5197, July 2007.
2. Gnizdor, R., Kozubsky, K., Koryakin, A., Maslenikov, N., Pridannikov, S. et al., "SPT-100 Life Test with Single Cathode up to Total Impulse Two Million Nsec," AIAA Paper 1998-3790, July 1998.
3. Garner, C. E., Brophy, J. R., Polk, J. E., and Pless, L. C., "A 5730 Hr Cyclic Endurance Test of the SPT-100," AIAA Paper 95-2667, July 1995.

Immortal Hall Thrusters
A Major Breakthrough in EP Technology



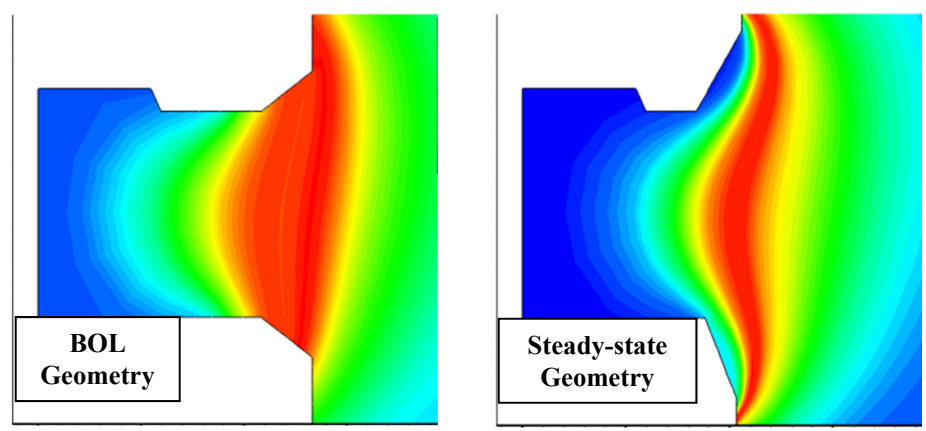
Insulator ring erosion by high-energy ion impact is the primary life limiting mechanism in Hall thrusters. Recent advances may eliminat this erosion mode completely.

Erosion Rate in the BPT-4000 Observed to Effectively Stop



- Qualification life testing showed that the BPT-4000 exhibits the unique behavior that it erodes to a steady-state geometry and then essentially stops eroding
- This behavior represent one of the most significant technological breakthroughs ever in electric propulsion history
- Through physics-based modeling, JPL has identified the mechanism responsible, which we call Magnetic Shielding, and developed the design tools to apply this technology in future thrusters
- Hall thrusters with magnetic shielding technology are essentially immortal and will lead to radically expanded mission capabilities

JPL physics-based model explains how "Magnetic Shielding" works:
Erosion stopped when the channel eroded to a local shape of the magnetic field that had the "right" curvature and field strength



Nested Hall Thrusters

A credible path to MW-class propulsion systems

STATUS QUO

Current State Of the Art (SOA) in electric propulsion (EP) systems.

- *Power < 10 kW*
  - *NSTAR 2.3kW ion thruster (TRL 9)*
  - *BPT-4000 4.5kW Hall thruster (TRL 8)*
  - *NEXT 7kW ion thruster (TRL 5)*
- *Power > 10 kW*
  - *AFRL HPPS 20 kW Hall thruster (TRL 4)*
  - *NASA-400 series 50kW Hall thrusters (TRL 4)*
  - *NEXIS, HiPEP 20kW ion thrusters (TRL 4)*

NEW INSIGHTS

First key insight.

•High-power (0.1-1.0 MW) and high-thrust (5-50 N) EP systems are currently within reach of Hall thruster technology.

Second key insight.

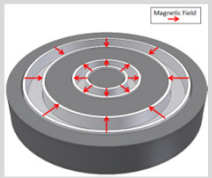
•As Hall thruster power levels are scaled higher, key design philosophies emerge that enable the Hall thruster alpha (kg/kW) and footprint area to decrease with power.

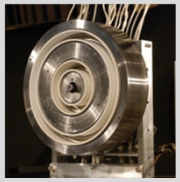
• Hall thruster propulsion technology is not only limited to low power missions.

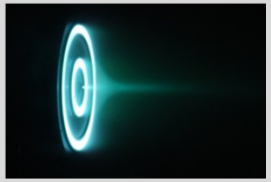
ACHIEVEMENT

MAIN ACHIEVEMENT:

By expanding on the successful flight history of Hall thruster and implementing the concentrically Nested Hall Thruster (NHT) design philosophy new low alpha and footprint high power propulsion option is possible.







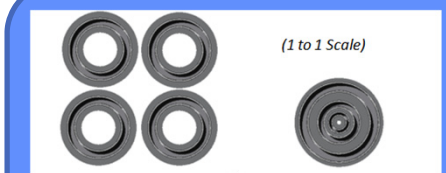
H

50 kW Traditional Hall (1 Channel)	200 kW Traditional Hall (1-Channel)	200 kW Nested Hall (2-channels)
Isp ~ 1000 to 5000 sec. & Efficiencies up to 65%		
< 2.5 N	< 10 N	< 10 N
100 kg (~ 1kg/kW)	200 kg (~ 1 kg/kW)	110 kg (~ 0.55 kg/kW) 45% mass savings
0.6 m Dia.	1.5 m Dia.	0.7 m Dia. ~70% footprint savings

ASSUMPTIONS AND LIMITATIONS:

- **Maximum power that can practically be processed by an NHT likely limited by manufacturing and thermal constraints.**

QUANTITATIVE IMPACT



200 kW Clustered Configuration (4 50-kW Thrusters)	200 kW NHT Configuration
~ 320 kg (1.6 kg/kW)	~ 100 kg (0.5 kg/kW)
~1.2 m² Footprint	~0.33 m² Footprint

- **NHT shows improved thruster alpha compared to single and clustered configurations.**
- **NHT has a greatly expanded operating envelope and has favorable scaling to >100 kW levels.**

END-OF-TASK OBJECTIVES

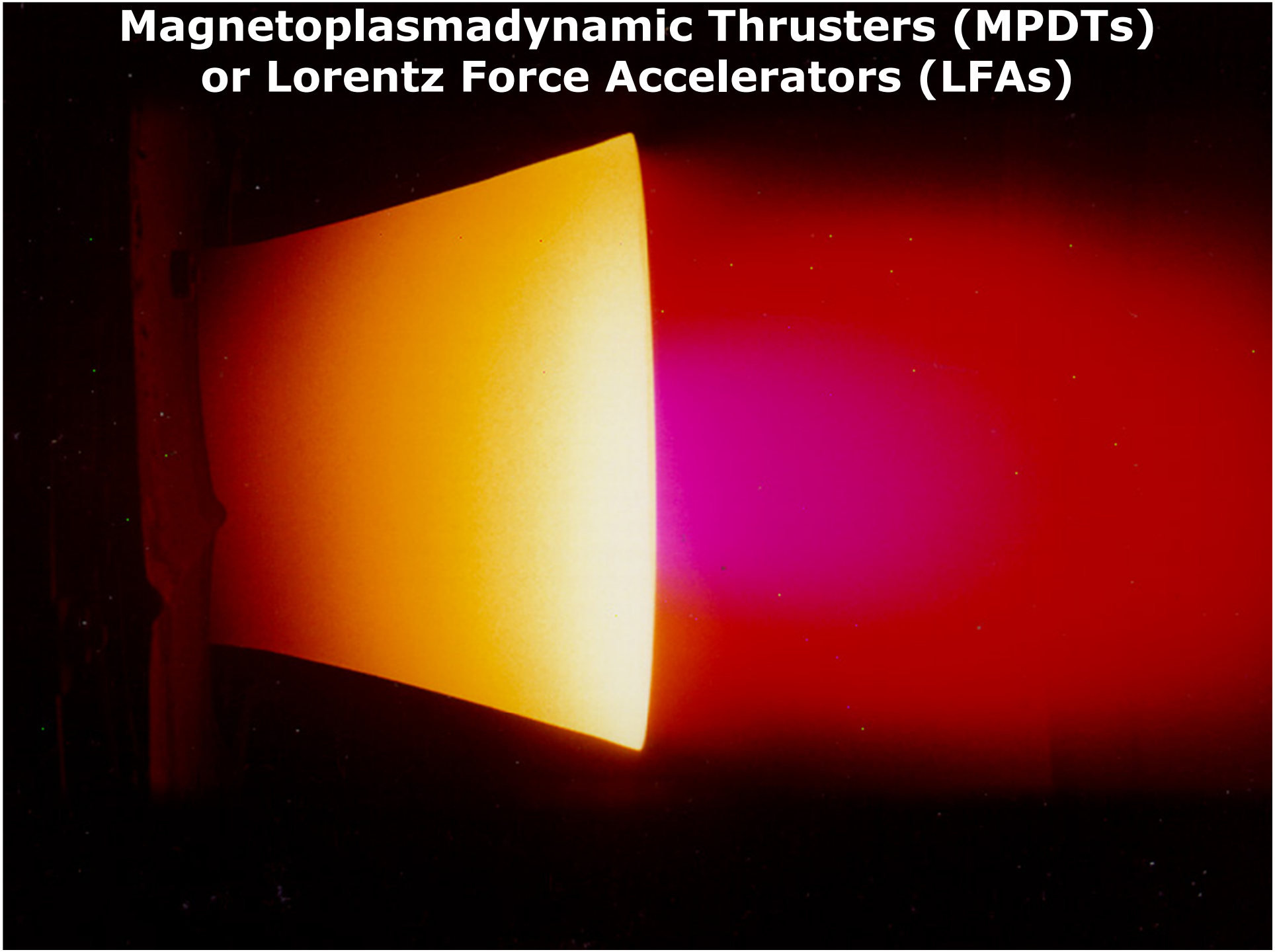
•Demonstrate a 250 kW thruster

•Demonstrate a 1 MW cluster

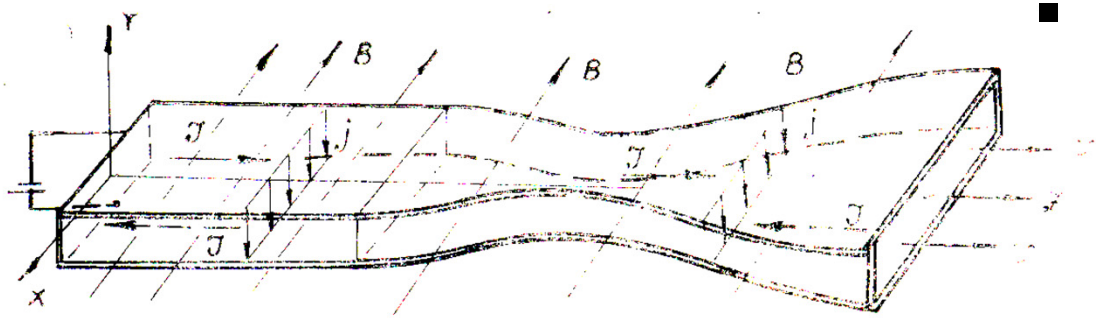
Partners: U of Michigan, EDA, JPL, GRC, AFRL

Scaling analysis provided by Electrodynamics Applications, Ann Arbor, MI

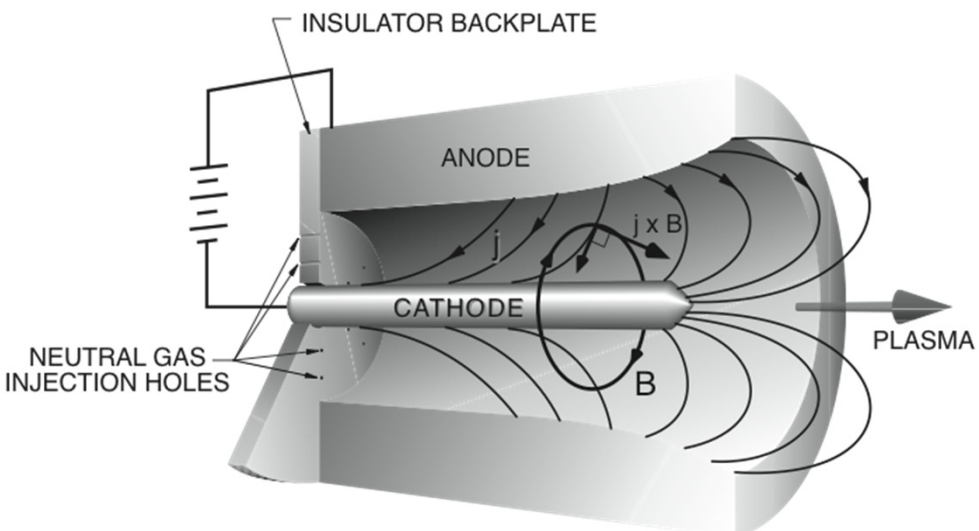
Magnetoplasmadynamic Thrusters (MPDTs) or Lorentz Force Accelerators (LFAs)



Overview of Accelerator Geometries



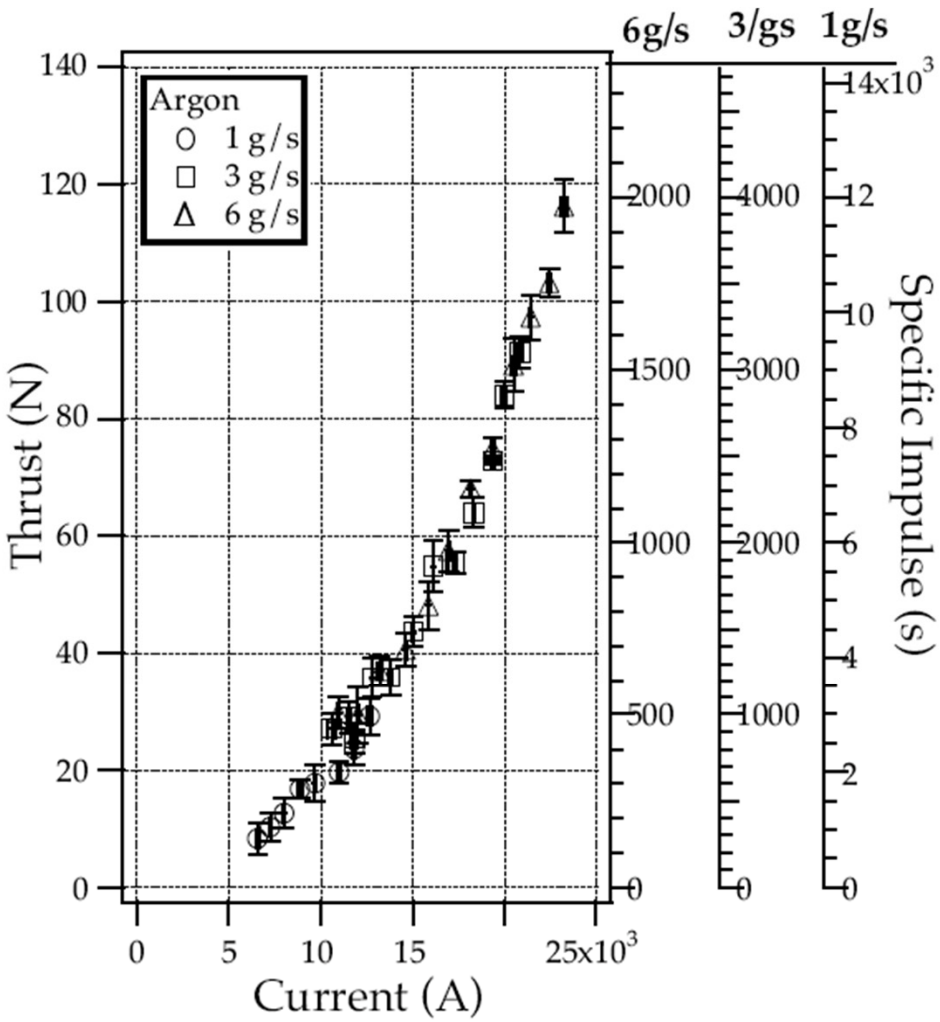
Quasi-1D Crossed Field Accelerator

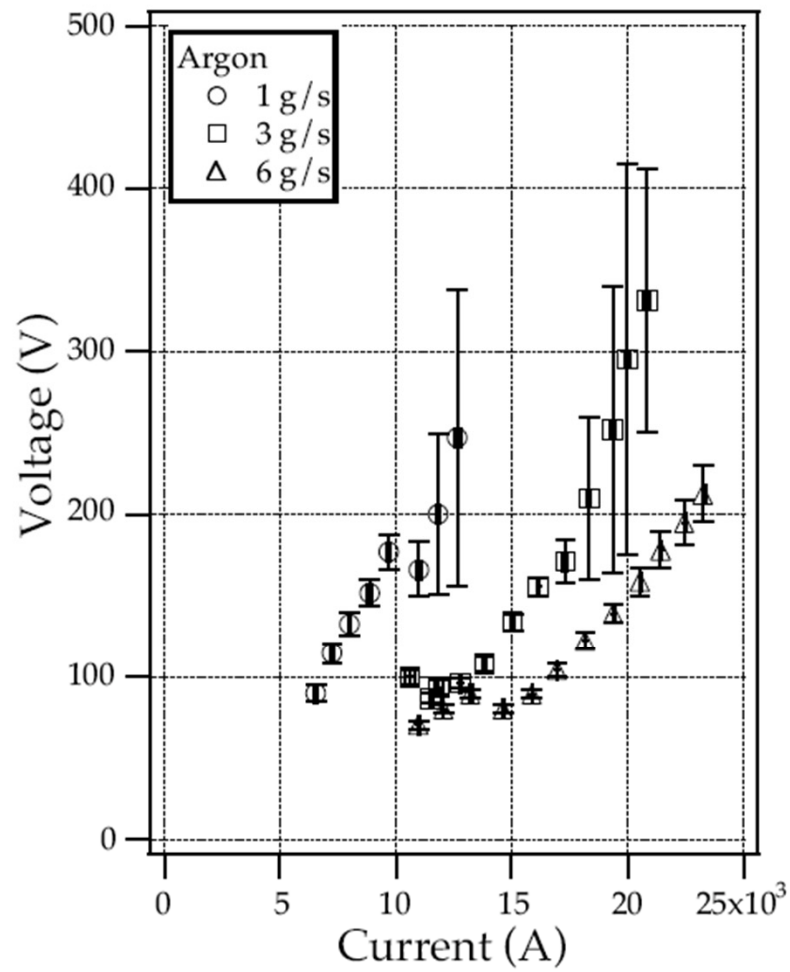


Coaxial Self-Field Thruster

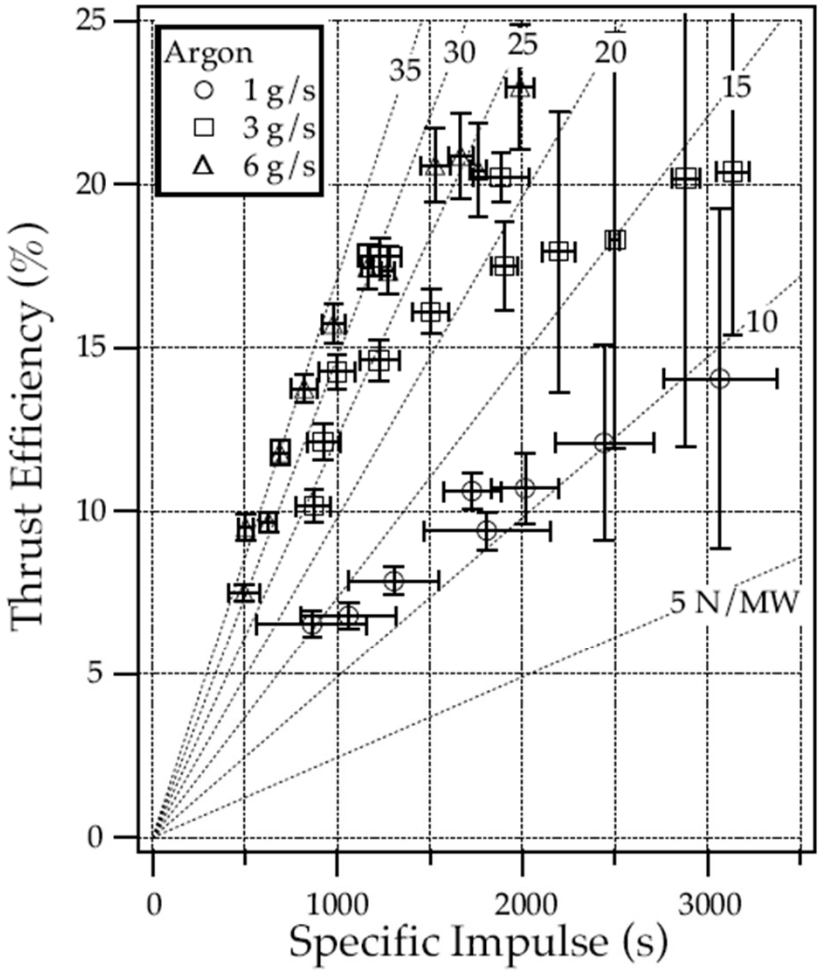
- All geometries rely on high currents to ionize propellant and a combination of JxB and gasdynamic forces to accelerate plasma
- Crossed Field Accelerator employs externally applied magnetic field
- Coaxial thrusters use self-field generated by discharge current

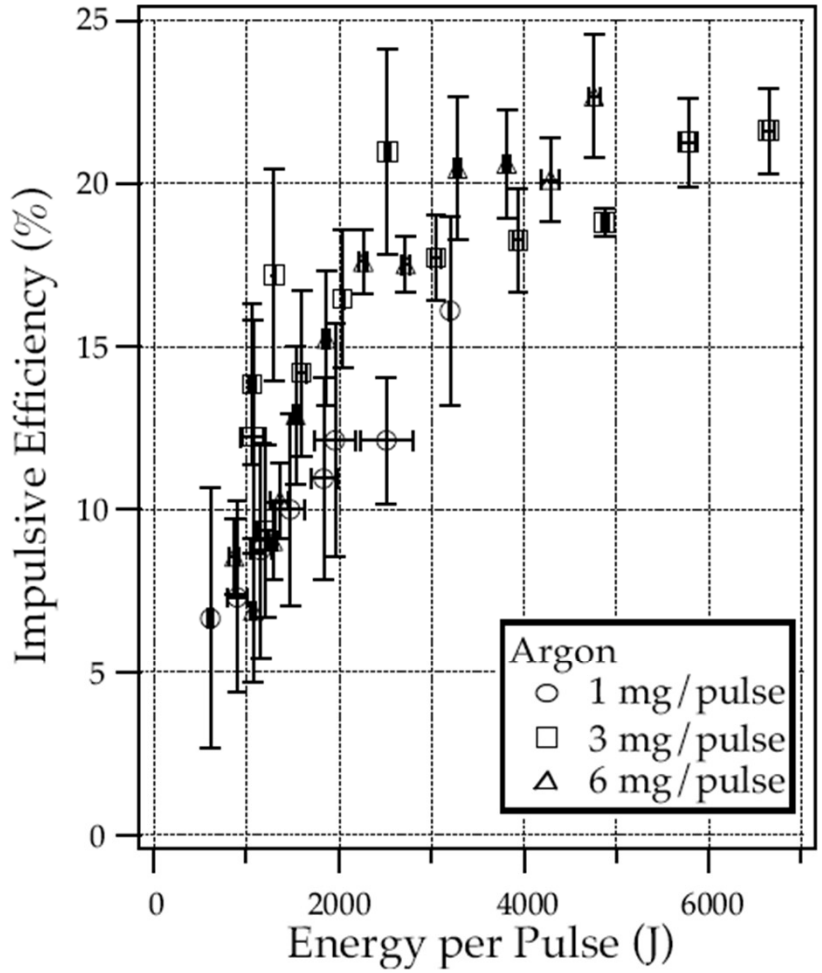
Operating Characteristics of Self-field Thrusters



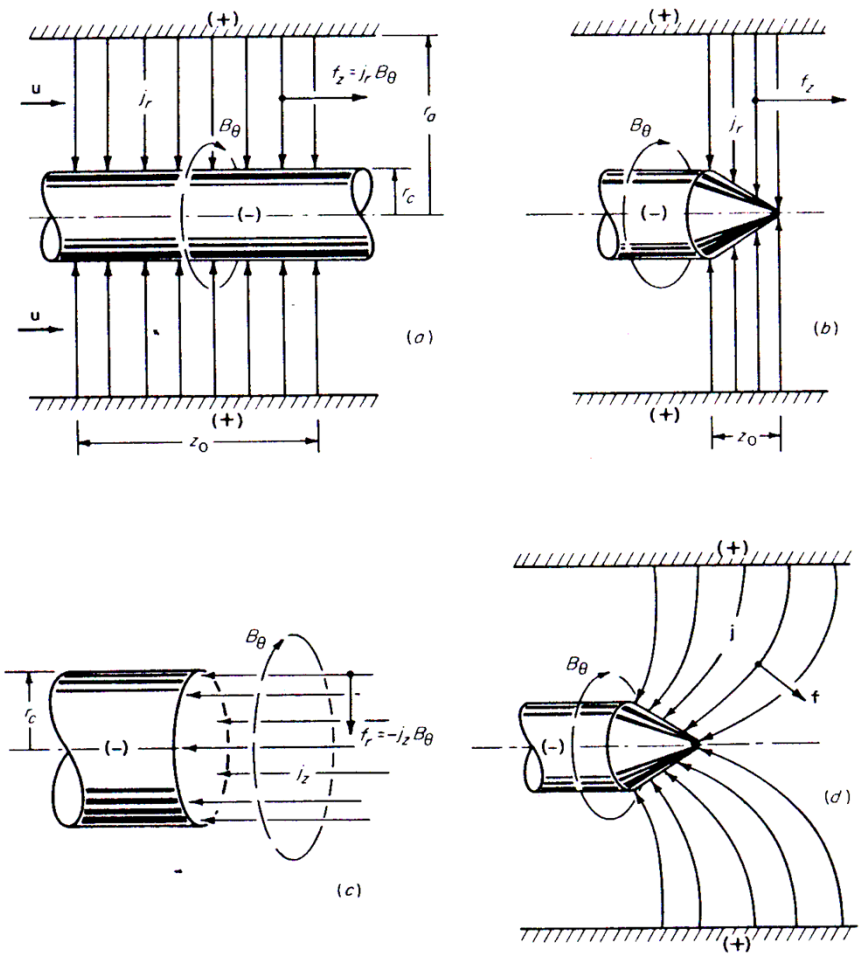


Operating Characteristics of Self-field Thrusters





Electromagnetic Thrust in Self-Field Accelerators



Idealized current distributions used to calculate Lorentz forces on the plasma

- Two force components:
  - $j_r B_\theta$ blowing forces
  - $j_z B_\theta$ pumping forces (radial pressure gradients)
- Ca[illegible]nt:

$$B_\theta(r,z) = \frac{\mu J}{2\pi r}\left(1 - \frac{z}{z_0}\right)$$

$$f_z(r,z) = j_r B_\theta = \frac{\mu J^2}{4\pi^2 r^2 z_0^2}(z_0 - z)$$

$$F_z = \frac{\mu J^2}{4\pi^2 z_0^2}\int_0^{z_0}\int_0^{2\pi}\int_{r_c}^{r_a}\frac{z_0 - z}{r^2} r\,dr\,d\theta\,dz = \frac{\mu J^2}{4\pi} ln\frac{r_a}{r_c}$$

$$F_z = \frac{\mu J^2}{4\pi}\left(ln\frac{r_a}{r_c} + \frac{1}{2}\right)$$

- Including current into face of cathode (uniform j

$$F_z = \frac{\mu J^2}{4\pi}\left(ln\frac{r_a}{r_c} + \frac{1}{4}\right)$$

- Includi

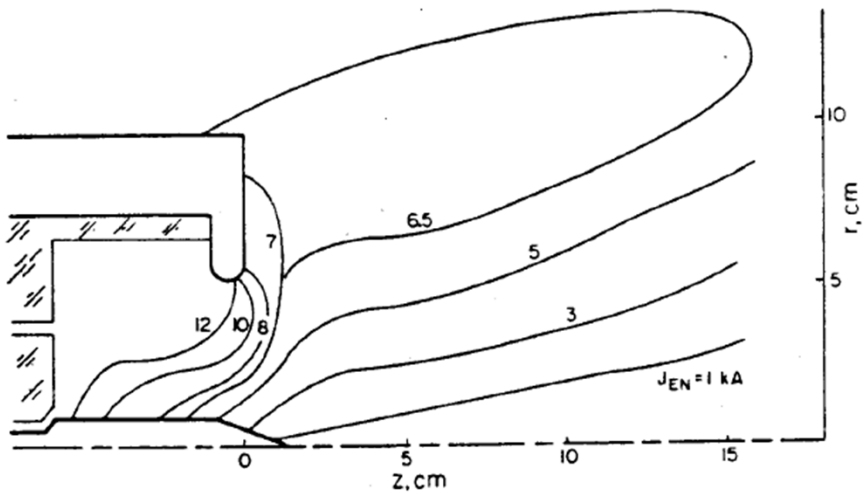
$$F_c = 2\pi\int_0^{r_c}(p - p_0) r\,dr = \frac{\mu J^2}{8\pi}$$

e of cathode (j_r ~ 1/r):

$$F_z = \frac{\mu J^2}{4\pi}\left(ln\frac{r_a}{r_c} + \frac{3}{4}\right)$$

- Estimate of pumping force on cathode

"Onset" Phenomenon Limits MPDT Performance

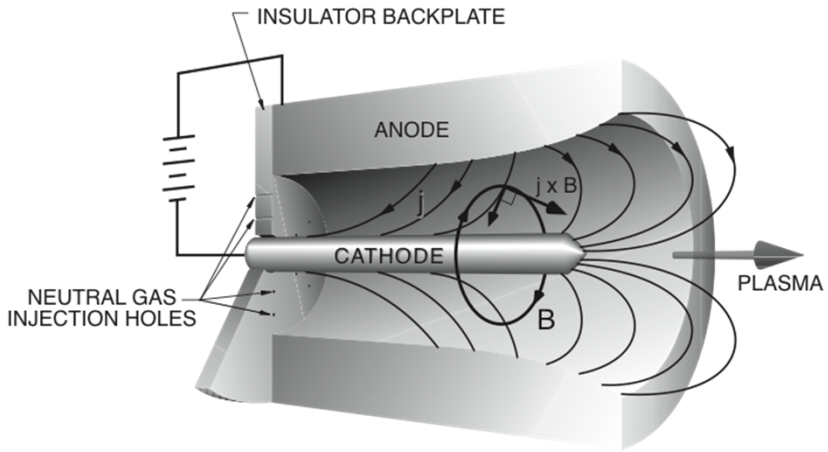


Enclosed current contours for a quasi-steady thruster operating at 15.3 kA and 6 g/s of argon

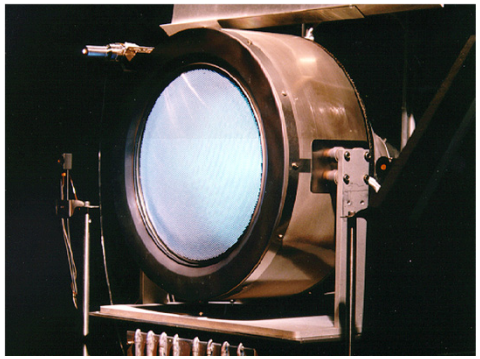
Anode damage at the onset current limits the achievable thrust, Isp, and efficiency in MPD thrusters

- **High magnetic Reynolds number leads to convection of magnetic field downstream**
- **As current pattern gets blown downstream, $j_z B_\theta$ forces pinch plasma toward centerline**
- **Depletion of plasma in anode region increases Hall parameter, resulting in higher j_z component**
- **Lack of charge carriers in anode region causes onset phenomenon**
  - Higher anode fall voltage required to conduct electron current
  - Anode spots form to supply additional plasma

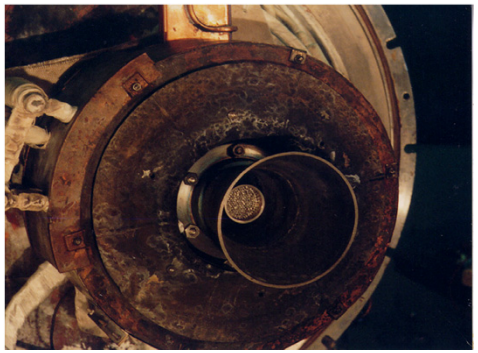
Lorentz Force Accelerators are Ideal for Very High Power Applications



J X B forces accelerate plasma axially and radially



2.3 kWe NSTAR Ion Thruster



200 kWe MAI Li- LFA

Electromagnetic acceleration allows >80 times the power of the NSTAR ion engine to be processed in the same volume

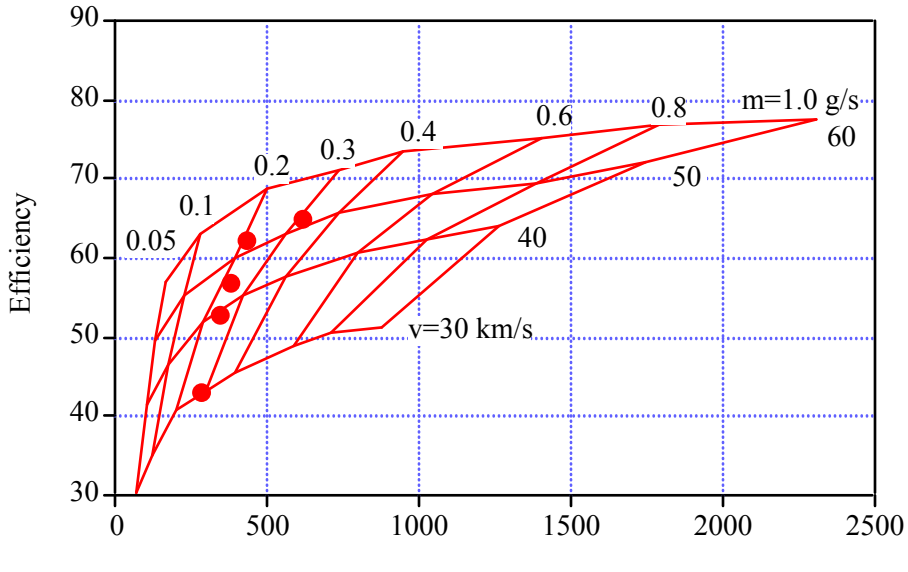
Lorentz Force Accelerators are under investigation because:

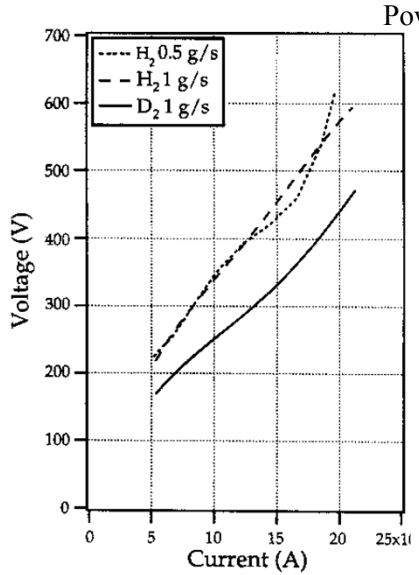
- Physics of operation yield high power processing capability
- Lithium propellant has potential for very high efficiency--low first ionization potential, high second ionization potential, and high first excited state of the ion yield low frozen flow losses

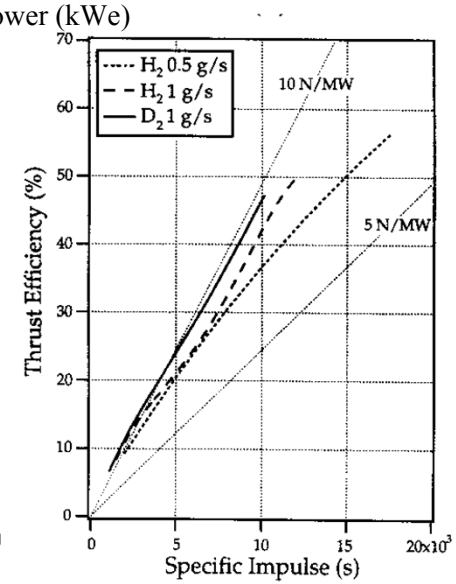
Very high power propulsion systems may enable many far-term missions:

- Orbit-raising heavy payloads in Earth orbit
- Fast robotic outer planet missions
- Lunar and Mars cargo missions
- Piloted Mars missions
- Piloted outer planet missions

Propulsion Niches for High Power Lorentz Force Accelerators Define Evolutionary Path

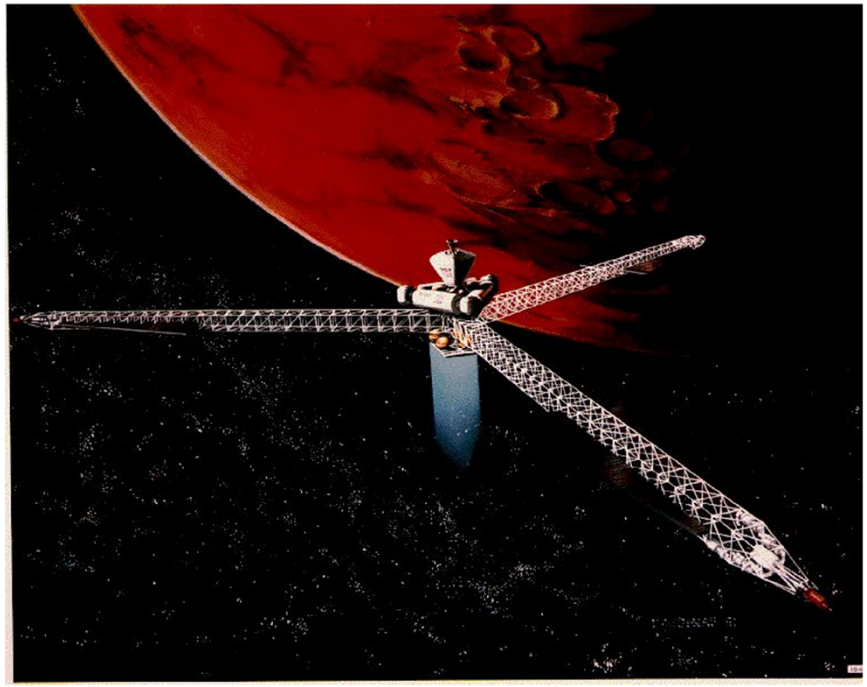


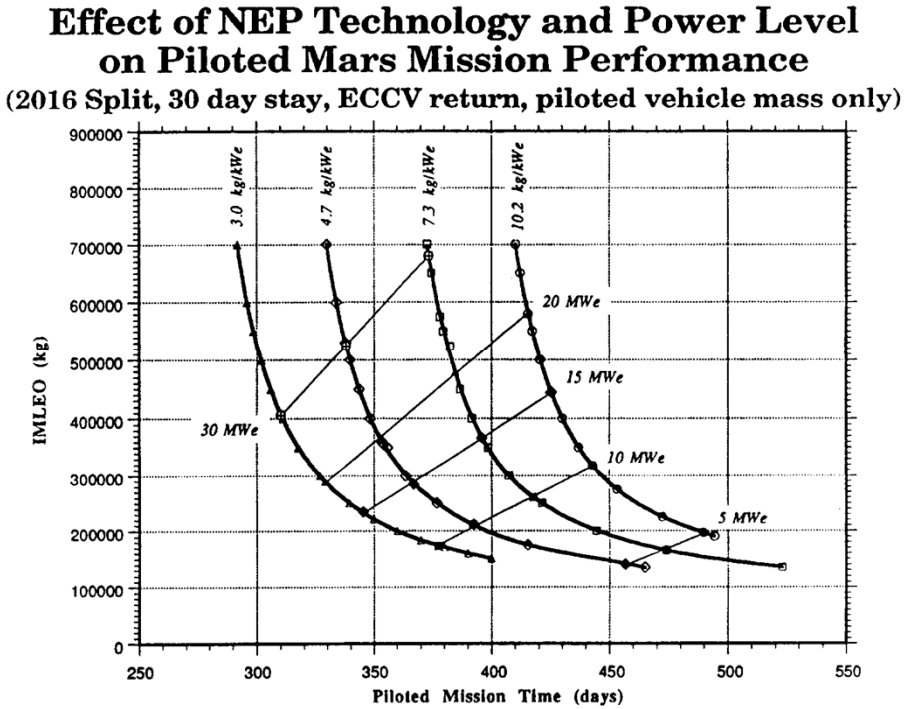




- **250-500 kWe lithium-fed thrusters give large mass savings for cargo missions**
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Lunar and Mars cargo applications
- **1-- 5 MWe lithium thrusters fulfill mid-term propulsion requirements**
  - Second generation power systems at 5 MWe
  - Specific impulse of 4000-6000 s
  - Initial piloted Mars missions
- **5--10 MWe hydrogen or deuterium-fed thrusters open up the solar system**
  - Third generation (very low alpha) power systems at 100's of MWe's
  - Terminal voltage with lithium is too low to process very high power levels; hydrogen appears to provide required efficiency at Isp's of 10000-15000 s
  - Piloted missions to Mars and the outer planets

Second Generation Propulsion and Power Systems Can Enable Fast Piloted Mars Missions

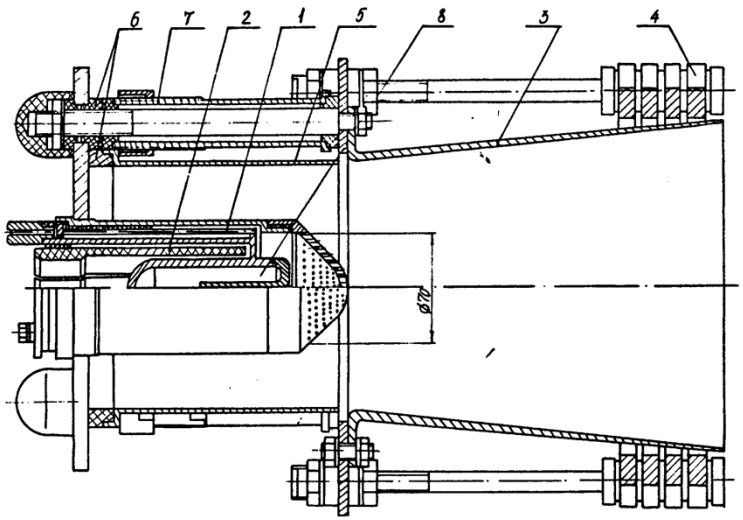




- 1 year round trip time possible with 20-30 MWe system
- All NEP missions consistently show the lowest IMLEO of all options

Large Experience Base For Very High Power Self-Field MPD Thrusters

Organization	Power (kWe)	Current (kA)	Specific Impulse (s)	Efficiency	Typical Operating Period	Notes
NIITP	300-1000	6-15	3500-5000	40-60	5 min	NIITP design
Fakel	300-500	6-9	3500-4500	40-60	30 min	Energiya design
Energiya	300-500	6-9	3500-4500	40-60	30 min	Energiya design
Energiya	500	9	4500	55	500 hours	Endurance test of Energiya design
Energiya	250-500	5-8	3000-4500	35-55	30-60 min	Coaxial thruster with long cathode. Stopped because of cathode failure
MAI	300-500	6-9	3500-4500	40-60	30 min	Energiya design



Energiya 500 kWe thruster design.

- **Development of high power Li-fed thrusters also occurred in Russia.**
- **Capabilities required for human exploration missions largely attained.**
  - High performance verified at 3 different institutions.
  - 500 hour lifetest at 500 kWe successfully completed.
  - Several thousand hour life projected.

Conclusions

- **Electric propulsion is an enabling technology for demanding deep space missions**
- **We are in the transition from an era of technology development to one of flight applications**
- **There are still a number of interesting research problems that require a multi-disciplinary approach**
  - Advanced materials
  - Plasma physics
  - Plasma-surface interactions
  - Plasma chemistry