Solar Electric Propulsion: Introduction, Applications and Status

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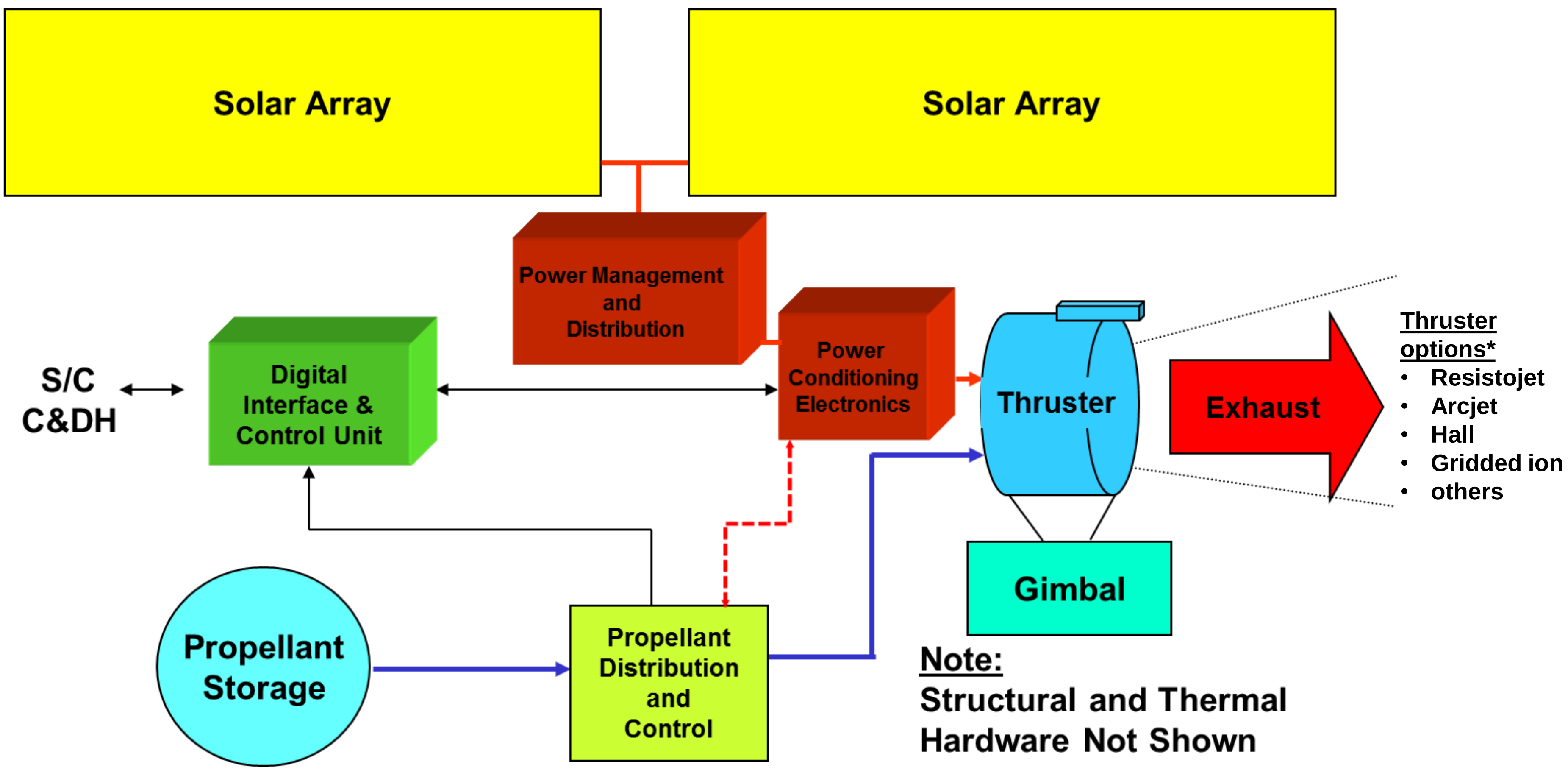
Agenda

- Solar Electric Propulsion Overview
- Benefits and Applications
- Power Level Trends and Mission Drivers
- System Challenges
- Summary

What is Solar Electric Propulsion?

Use of solar electric power to create and accelerate ions to exhaust velocities >5x chemical rockets

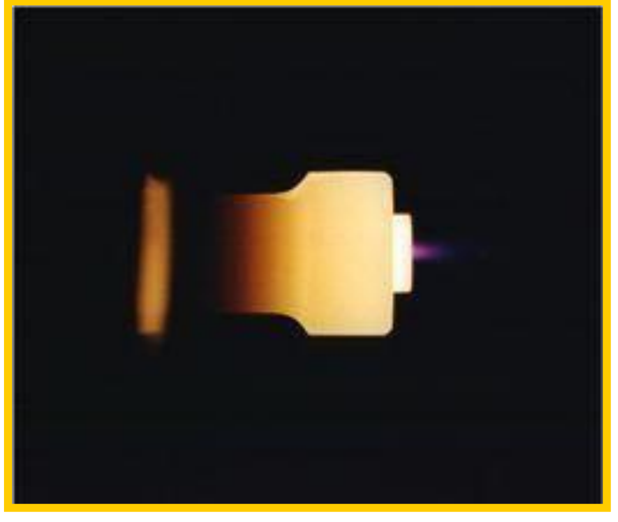


*Each thruster option has different capabilities and system requirements

Three Classes of Electric Propulsion

Electrothermal

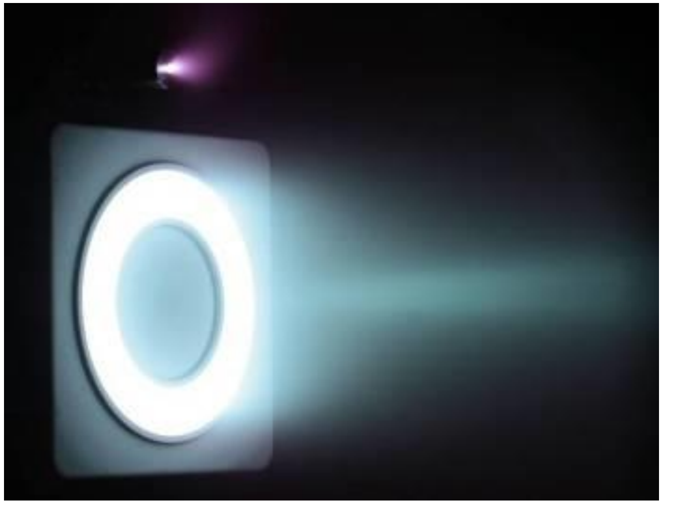
Gas heated via resistance Element, discharge, or RF interactions and expanded through nozzle



- Resistojets
- Arcjets
- Microwave, ICR, Helicon

Electrostatic

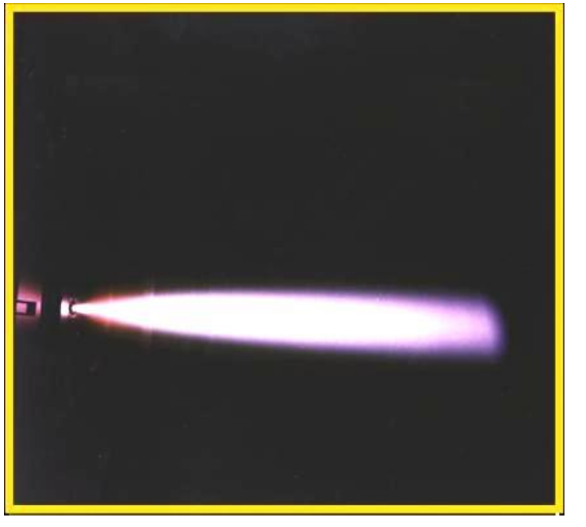
Ions created and accelerated in an electrostatic field



- Hall Thrusters
- Gridded Ion Engines
- Colloid Thrusters

Electromagnetic

Plasma accelerated via interaction of current and magnetic field



- Pulsed Plasma
- MPD/LFA
- Pulsed Inductive

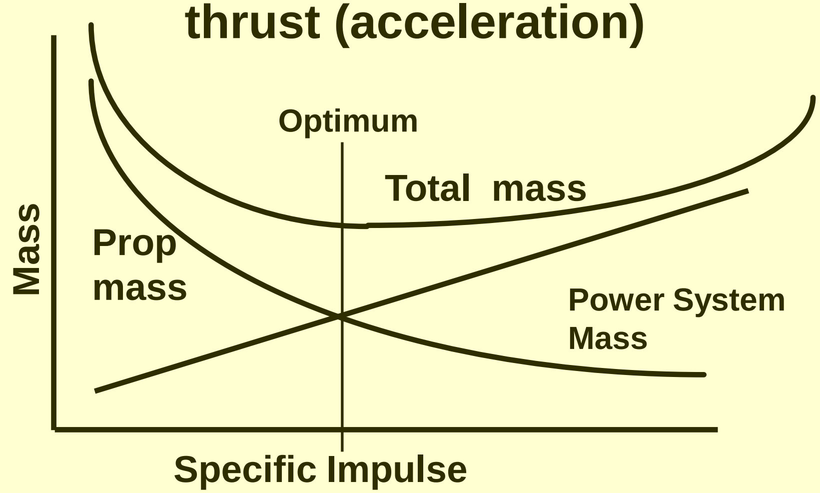
Primary Systems Today are Resistojet, Arcjet, Hall, and Gridded Ion Systems

Electric Propulsion Options and Trades

- **Benefits:**
  - Much higher specific impulse
    - Arcjets – 600s
    - Hall Thrusters – 1500 – 3000s
    - Ion thrusters – 2500 – 10,000s
    - Other concepts (VASIMIR, MPD, PIT) in same range
  - Higher Isp results in much lower propellant mass

- **Trades:**
  - Need external source of power and electronics to match to the thruster
  - Thrust increases linearly with power
  - Trip time decreases as thrust increases
  - Power increases quadratically with Isp for a given thrust
  - Propellant mass decreases exponentially with Isp for a given ΔV

Optimum Isp for a given thrust (acceleration)



Typical Earth-space missions optimize between 1500 – 3000s Isp

Why Consider Solar Electric Propulsion?

Typical Spacecraft Mass Fractions

In-Space Propulsion Dominates Spacecraft Mass
Impact increases for Deep Space Missions

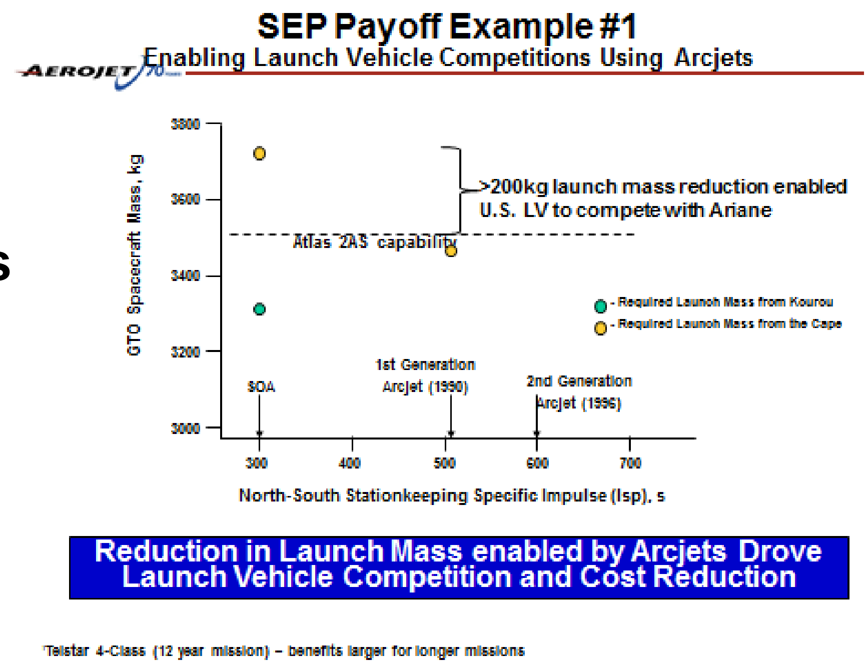
Some Factors Influencing Spacecraft Mass Allocations:

- **Mission: ΔV, duration, environments**
- **Technology changes: launcher size/capability, payload mass/volume, power system**
- **Policy changes: deorbit requirements, debris removal, insurance rates**

***About one-half of Everything* Launched is In-Space Propulsion**
It is a Major Opportunity for Mission Affordability Improvement

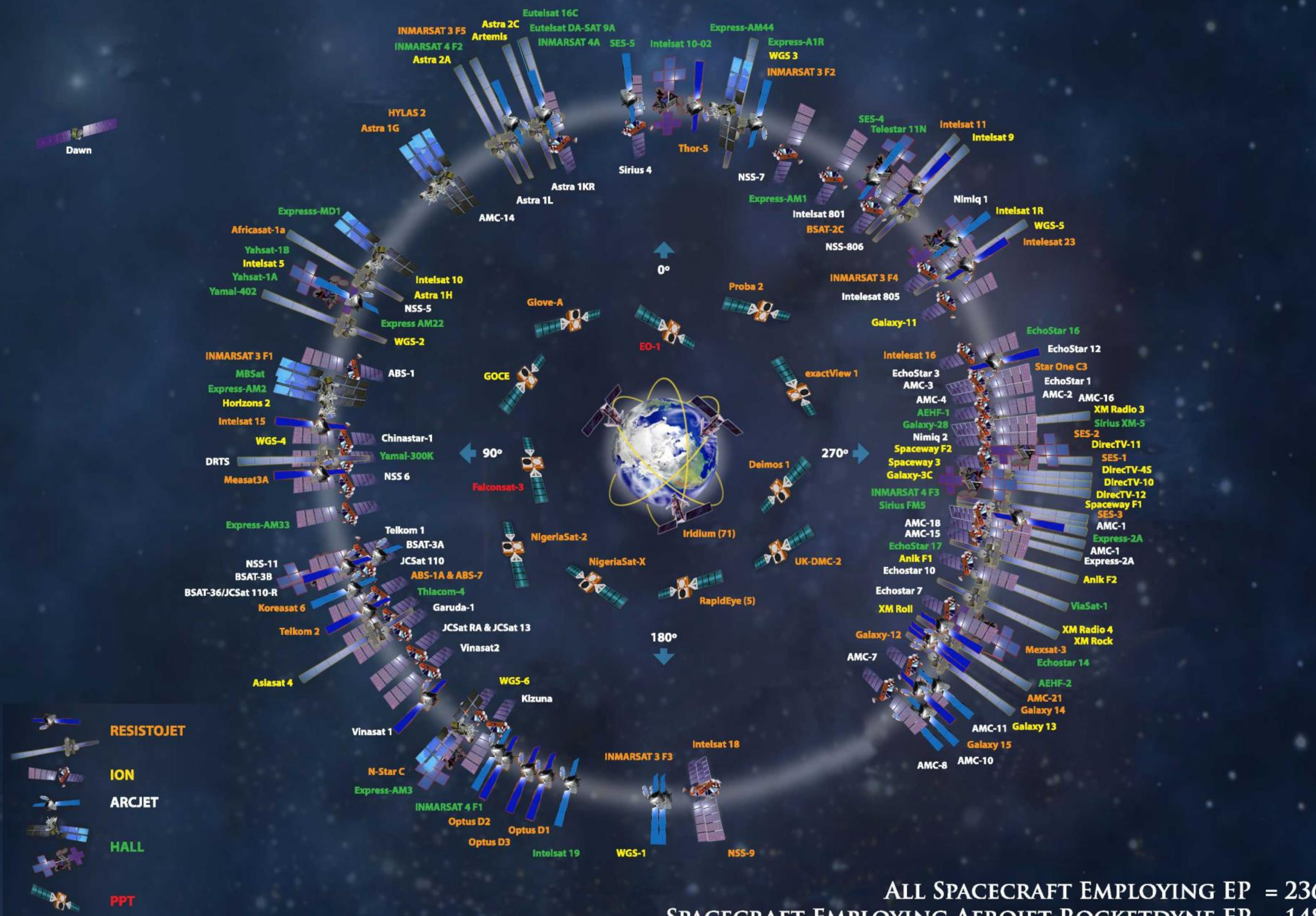
SEP Adoption Driven by Competitive Advantage

- **General use started for station keeping**
  - **Vehicle power levels 5 - 10kW**
    - **EP thruster powers 0.5 – 2kW**
  - **First commercial use in 1980s**
- **Enabled launch vehicle competitions**
- **Reduced launch costs by reducing size of required launcher**
- **Low power SEP used on:**
  - **>250 satellites in Earth Orbit**
  - **Deep Space-1**
  - **Smart-1**
  - **Dawn**
  - **Hayabusa**



Operational Satellites with Electric Propulsion

Aerojet Rocketdyne



All Spacecraft Employing EP = 236

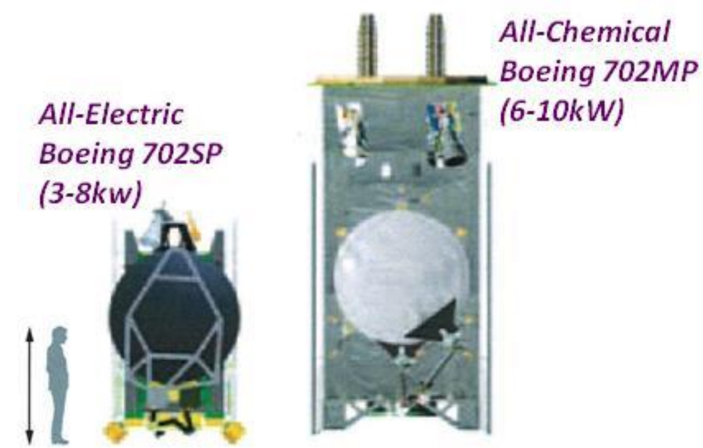
Spacecraft Employing Aerojet Rocketdyne EP = 148

9/18/2013

Recent Events Driving Acceptance of High-Power SEP

- **Launch Costs Continue to Increase**
- **Successful Rescue of DoD AEHF SV1 using Hall Thruster System for Orbit Raising**
  - **Baseline mission saves >2000lbf by doing ~50% of orbit raising using EP**
  - **SV-2 launched and operational**
  - **SV-3 launched and orbit raising now**
- **Boeing's Announcement of <u>All-Electric</u> 702-SP**
  - **Use gridded ion engines (L-3)**
  - **Enables dual-launch on Falcon-9**
- **Emergence of New Exploration Missions Requiring Efficient High-Mass Payload Delivery Within Constrained Budgets**

LM's AEHF



Source: Space News

Critical Trends for Future SEP Systems

- **Mission Parameters**

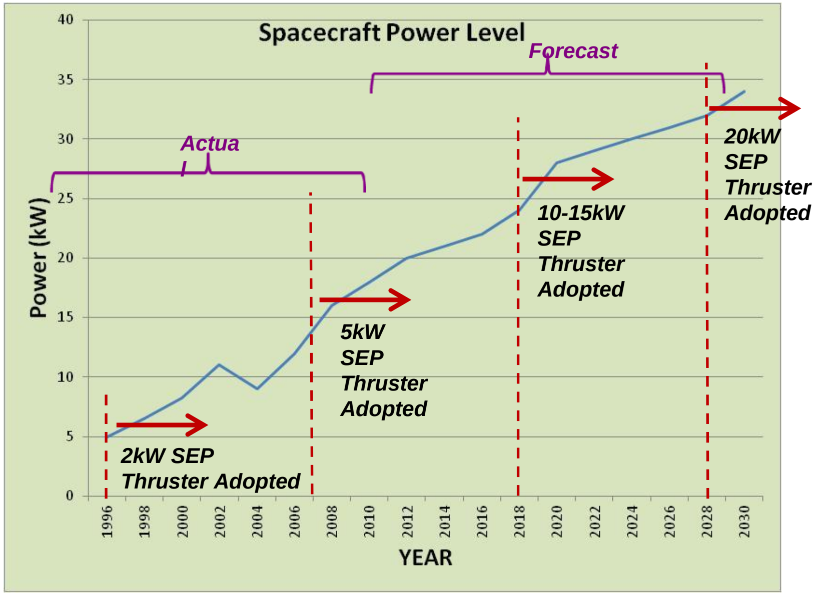
Thrust ~ Power*Efficiency / Isp

$$\text{Thrust} \sim \frac{\text{Power*Efficiency}}{\text{Isp}}$$

  - **Trip time ~ Mass/Thrust ~Mass/Power**

- **So, Faster SEP Trip Times Require Higher Power/Mass Ratios and Power Conversion Efficiency**
  - **Need lighter weight, high power solar arrays**
  - **Need lightweight, efficient power management and processing**

- **Trip times through radiation belts are long**
  - **Radiation tolerance critical**



Spacecraft Power Level Increasing

Near-Term Higher Power SEP Benefits & Trades Analysis

AEROJET ROCKETDYNE

Example: Payload delivered to Earth-Moon L2

Total Delivered Mass = LV Launch Mass – Fuel Req'd to get to destination

Think of this as the max mass that can be divided up into S/C and Payload

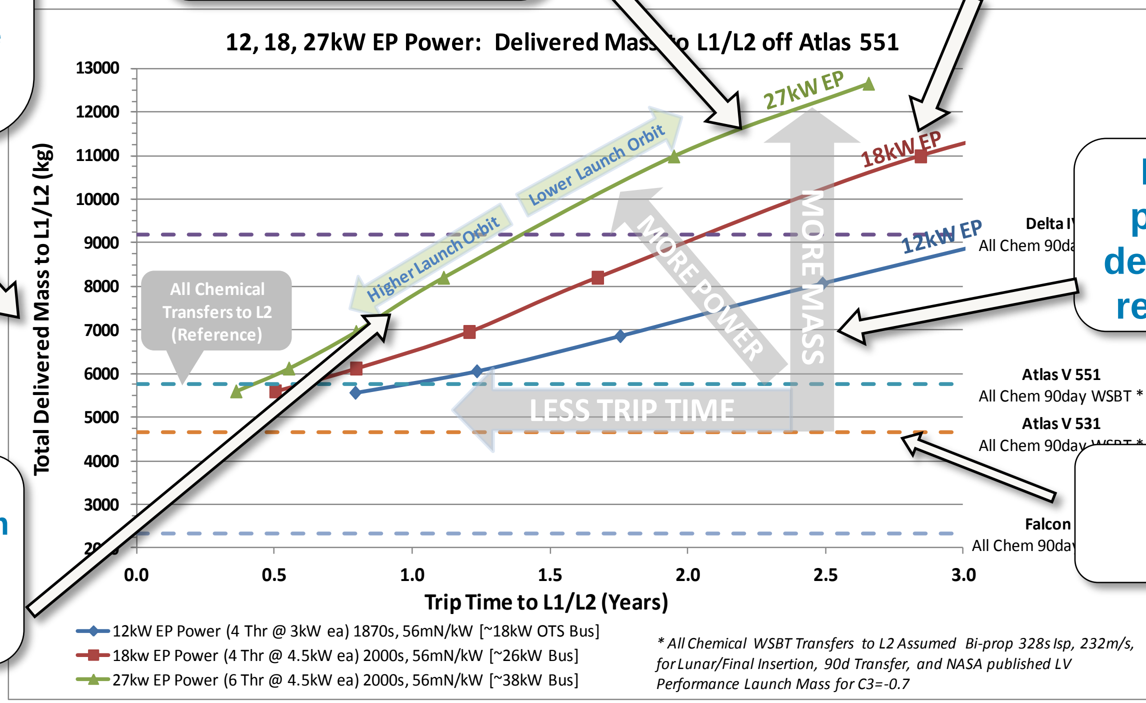
SEP curves of total delivered mass are independent of S/C design.

SEP curves are at fixed EP power and thruster performance

Increasing SEP power increases delivered mass and reduces trip times

All chemical transfers for comparison

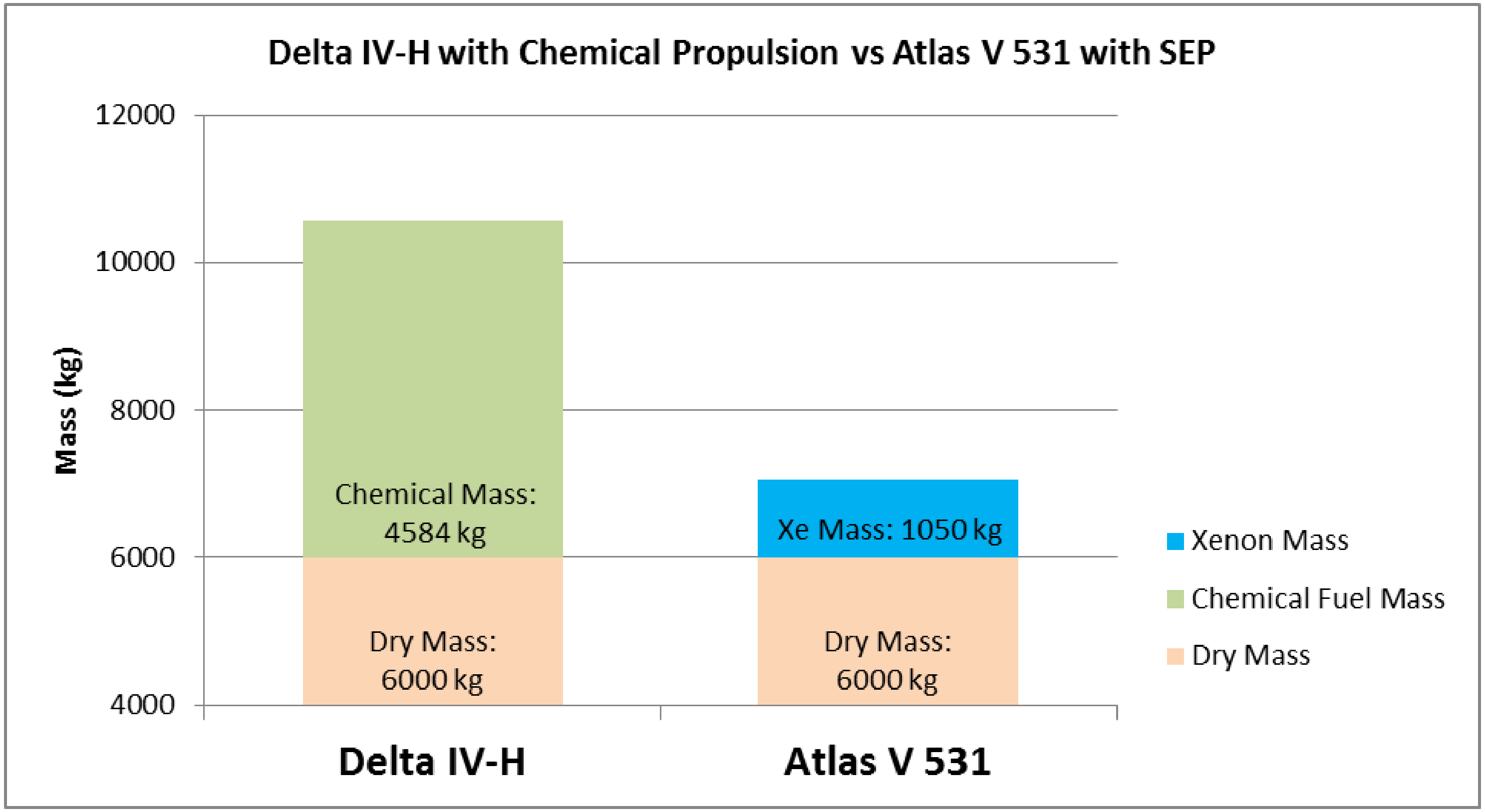
SEP curves are based on LV launch mass from very highly eccentric (bot. left) to LEO (top right) orbits



Performance Curves Show Trades between Power, Trip Time, and Delivered Mass for a Given Launch Vehicle and Destination

Ex #1: High Power SEP Application Example: Delta IV-H and Atlas

6000kg Space Vehicle: GTO → GEO Mission



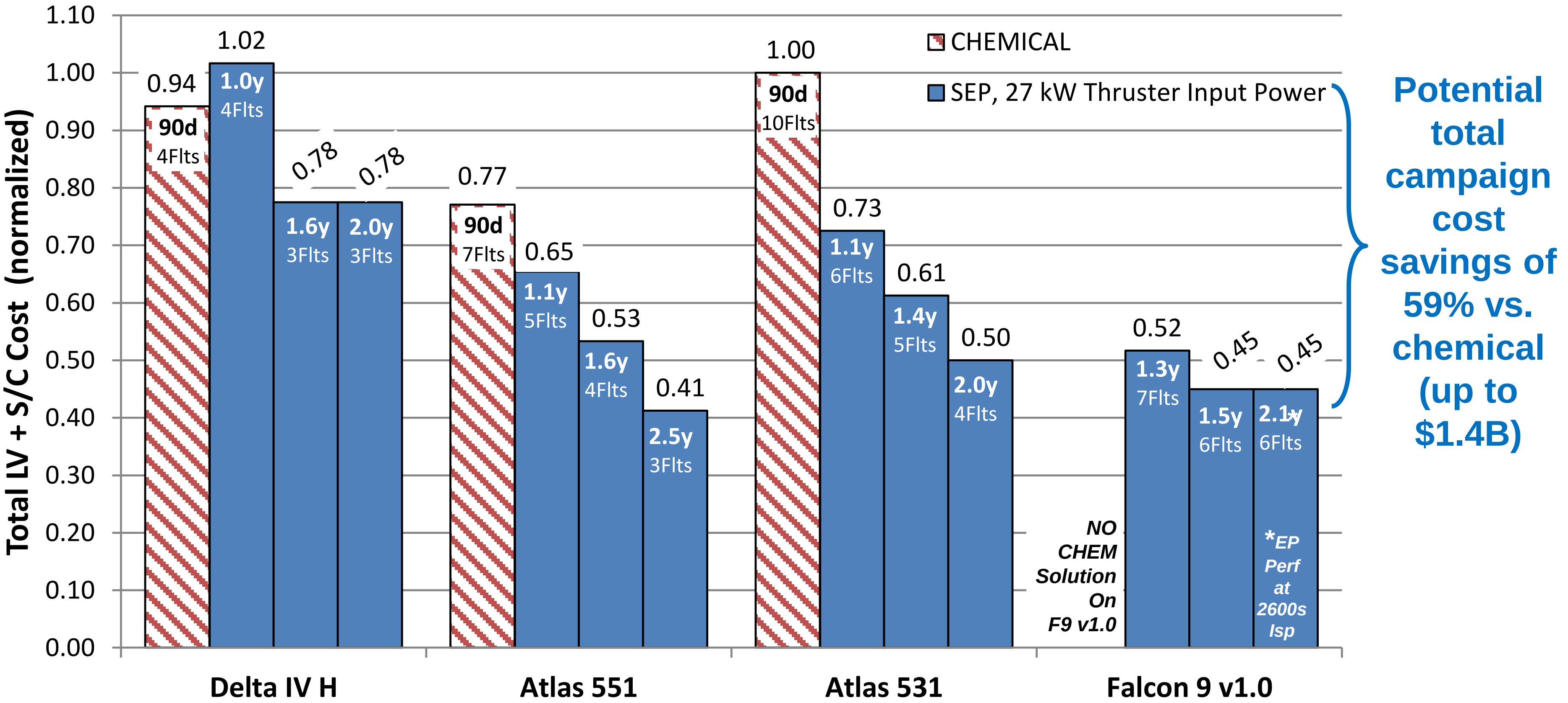
- Using a S/C with 27 kW EP to thruster gives a transfer time of 4.5 months
- Using a S/C with 18 kW EP to thruster gives a transfer time of 6.7 months

Switching to SEP allows for a ~65% reduction in launch vehicle costs

XR-5 Isp of 1816 s and T/P of 62.22 mN/kW. GTO is 185x35786 km (28.5°). GEO is 35786x35786 km (0°)

Example #2: EML-2 Habitat Logistics Supply

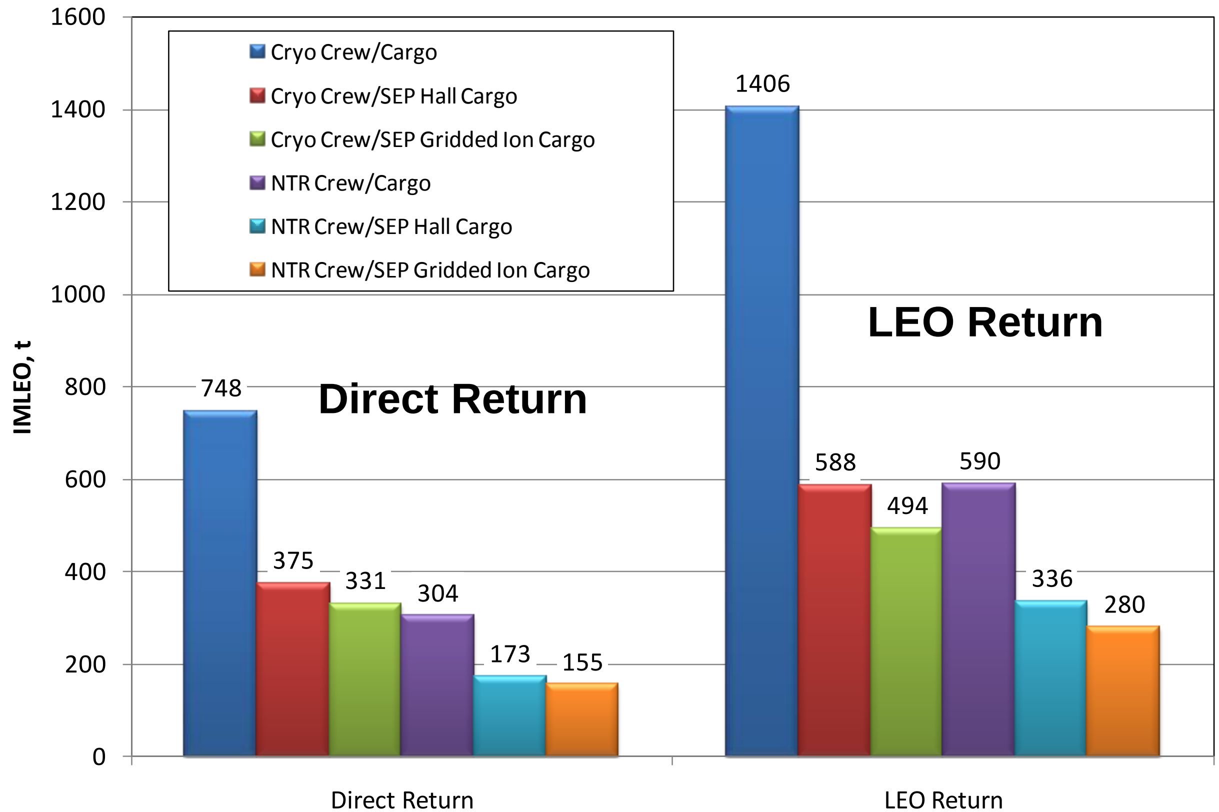
Deliver 20mt over 5 yrs using the TRL-9 Hall Systems



SEP solutions enabled significant total campaign cost savings of up to ~$1.4 BILLION for this notional campaign

Example #3: Impact of In-Space Propulsion Technology on Launcher Requirements for Mars

Crew of 4 to Low Mars Orbit and back



Separating Cargo and Crew, and using SEP for Cargo and High Thrust Chemical or NTR for Crew, <u>decreases launcher requirements by 2X</u>

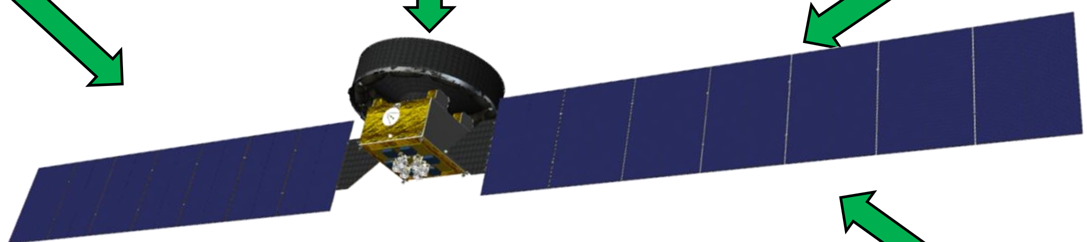
High-Power SEP Dramatically Improves the Affordability of Space Missions for Multiple Customers

Aerojet Rocketdyne

Large Payload Delivery
DoD/NASA HEOMD/SMD/ Commercial

Robotic Missions
NEOs/Phobos/ Moon/other
NASA SMD/HEOMD

Validate Technologies for Higher Power SEP
NASA HEOMD



30-50kW-class SEP Space Vehicle

Space Situational Awareness
DoD

Satellite & Depot Servicing
DoD/NASA/ Commercial

Orbital Debris Removal

Space Environments Mapping
DoD/NASA

30-50 kW SEP Vehicles Reduces Cost for Many User Communities

Exploration Mission Needs

It's All About Affordability

- **Establish an efficient in-space transportation system to reduce mission cost**
  - **Use SLS and other launch vehicles along with efficient in-space transportation to reduce cost and increase science mission and exploration capability**
- **Near Term (next 5 years): 30 – 50kW SEP Vehicles for**
  - **Logistics in cis-lunar space**
  - **Larger scale robotic precursors (Asteroid Re-Direct Mission)**
  - ***NOTE: These systems have broad applicability to DoD and other civil missions***
- **Mid-Term (5 – 15 years): 100 – 200kW SEP Vehicles for**
  - **Cargo pre-placement at destinations (Martian Moons, Lunar Orbit, etc.)**
- **Long-term (15- 20 years): 200 – 600kW SEP Vehicles for**
  - **Large cargo pre-placement (habitats, landers, Earth Return stages, etc.)**
  - **NOTE: "Vision System" includes reusability – multiple trips through belts**

Evolutionary Growth of SEP Systems will Keep Missions Affordable

Aerojet Rocketdyne
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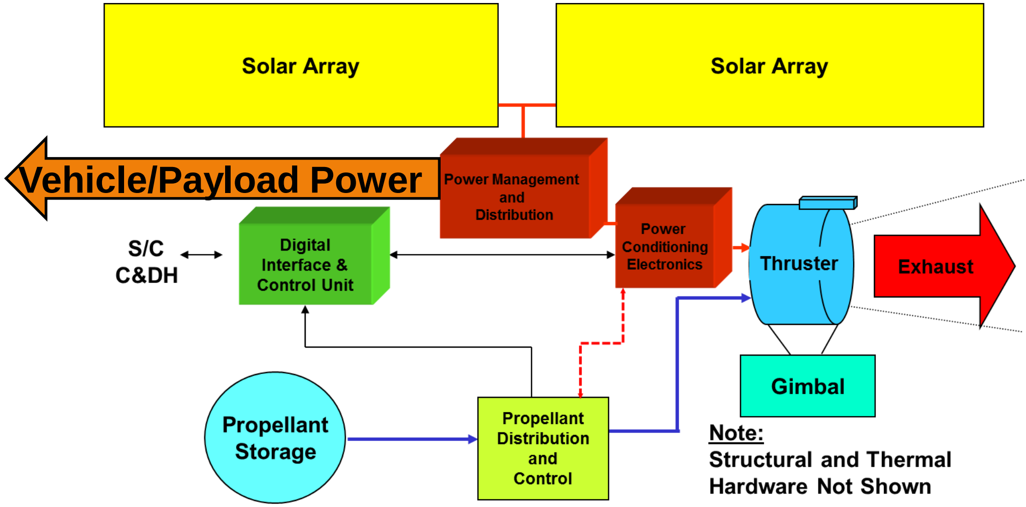
SEP Subsystem Options and Trends

Power and Propulsion

Power System Architecture Options

To date, vehicle power systems are dominated by payload power:



For Vehicles where SEP Power is Dominant:

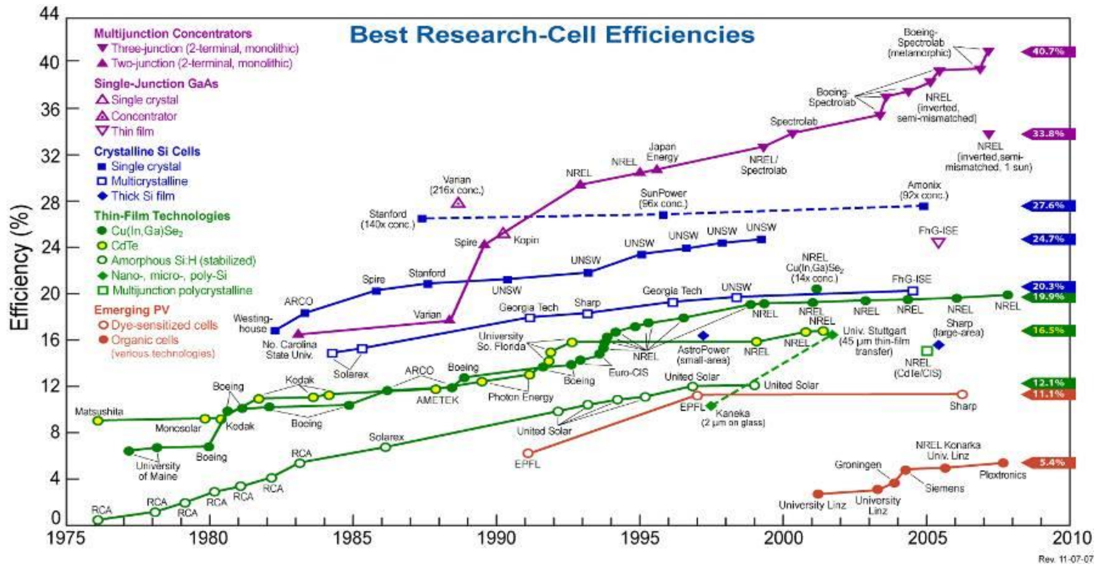
1) Combine PMAD & PPU?
2) "Direct Drive" EP from arrays?

SEP Vehicle Power System Architecture May Need Re-evaluation When SEP is Dominant Power Consumer

SEP Power System Technology Challenges (1/3)

High Power Arrays

- **Cell Efficiency**
  - Currently ~40% in lab
  - Target is ~50% BOL



- **Lightweight Structures**
  - Current array P/M is ~ 70W/kg
  - Target is 200 – 400W/kg

- **Launch Vehicle Packaging and Deployment Mechanisms**
  - Current Stowed Volume is <20kW/m^3
  - Target is 60 – 80 kW/m^3

- **Radiation tolerance**
  - Capability and affordability will be enhanced if degradation can be reduced from current ~15% per trip to ~5% per trip without a large mass penalty

SEP Power System Technology Challenges (2/3)

Power Management and Distribution Systems

- **Efficiency**
  - Currently ~92%
  - Target is ~95%
- **Lightweight Thermal Management and Rejection**
  - Current PMAD systems reject <2kW
  - Near-term target requires rejecting ~4kW
  - Mid-term target: 8 – 16kW
  - Long-term target: 20 – 30kW
  - Potential for high temperature electronics?
- **Power transient handling**
  - How to Handle eclipse transients with 50 – 100kW SEP System?
- **Lightweight Energy Storage**
  - May just turn off SEP system in eclipse to limit battery requirements
- **Radiation tolerance – rad hard parts availability and cost**

SEP Power System Technology Challenges (3/3)

EP Power Processing

- **Efficiency**
  - Today flight PPUs are 92 – 93% efficient
  - Must maintain performance over wide range of input voltages
    - 70 or 100V regulated in Earth Space
    - ~70 – ~160V for deep space
- **Thermal Management**
  - Today's systems reject 400W/PPU, or ~ 800W during firing 2 at a time
  - Near term will need to handle 3 – 4kW
  - Long term will need to handle 20 – 40kW
- **NOTE: Combination of PMAD and PPU can be a 10 – 15% hit on overall efficiency – may drive power system architecture if we can reduce the hit.**
- **Radiation tolerance: rad hard parts availability and cost**
- **Traditional vs. "Direct-Drive" power system architectures**

Some Other Power System Challenges

- **High Reliability/Rad Hard parts availability**
  - **Availability and Lead time on parts drives design**
  - **Is it easier to change packaging for radiation tolerance?**

- **Qualified power system designers and electronics parts experts**
  - **Too many university EE departments went digital!**
  - **Program uncertainties lead to retention issues**

Propulsion: Thruster Options for Discovery

Jet Propulsion Laboratory
California Institute of Technology

	NSTAR	NEXT	NEXT+XIPS PPU	BPT-4000	25-cm XIPS	SPT-100	SPT-140	T6
Performance	**ION**	**ION**	**ION**	**HALL**	**ION**	**HALL**	**HALL**	**ION**
Power: Max: Min:	2.3 kW 450 W	6.9 kW ~500 W	4.5 kW ~500 W	4.5 kW ~225 W	4.5 kW ~225 W	1.5 kW ~600 W	4.5 kW < 2.0 kW	4.6 kW 2.4 kW
Isp	3200	4200 s	3600 s	2000 s	3600 s	1600 s	1800 s	4075-4300 s
Thruster Mass	8.9 kg	13.5 kg	13.5 kg	12.5 kg	13.5 kg	3.5 kg	8.5 kg	7.5 kg
Total Impulse, demonstrated	7 MN-s	**34.3 MN-s**	< 29.4 MN-s	8.7 MN-s	6.7 MN-s	2.7 MN-s	3 MN-s†	3.7 MN-s
Total Impulse, theory	10 MN-s	> 34.4 MN-s	< 19 MN-s	**19 MN-s**	11.4 MN-s	not determined	8.2 MN-s††	11.5 MN-s
Heritage:								
Manufacturer	L3	Aerojet-Rocketdyne	Aerojet-Rocketdyne	Aerojet-Rocketdyne	L3	Fakel	Fakel	QinetiQ
Flight Missions (previous or planned)	**DS1, Dawn**	None	None	AEHF (x6)	HS702 (many)	SS/L (many) European (many) Russian (many)	Future Commerical	BepiColombo (2015)
Heritage for Deep Space	**Full**	**None*****	**None*****	**Full**	**Full**	**Full**	**Full***	**Full/Partial**
Comments	No longer manufactured	Offered with cost credit in Discovery 2010						

* Full Heritage anticipated after qualification for Earth orbiting applications is complete.

*** Flight-like model has passed performance & environmental testing. A full flight qual model needs to be built & tested prior to first flight.

† estimated as of Aug 2013

†† planned duration 8.2 MN-s, throughput estimated

Credit: David Oh, JPL

PPU Options for Discovery

Jet Propulsion Laboratory
California Institute of Technology

	NSTAR	NEXT	NEXT+XIPS PPU	BPT-4000	25-cm XIPS	SPT-100	SPT-140	T6
Performance								
Max Power	2.3 kW	6.9 kW	4.5 kW	4.5 kW	4.5 kW	1.5 kW	4.5 kW	4.6 kW
PPU Mass	14.5 kg	33.9 kg	Same as XIPS	12.5 kg	21.3 kg	7.5 kg	15 kg	23 kg
PPU Efficiency	92% at 2.4 kW	95% at 7.1 kW	92% at 4.5 kW	92% at 4.5 kW	91%-93%	94% at 1.35 kW thruster power	not available	92%-95%
Redundancy/ Cross Strapping	1 PPU - 2 thrusters	1 PPU–2 thrusters	1 PPU-2 thrusters	1 PPU–1 thruster	1 PPU–2 thrusters	1 PPU–2 thrusters	1 PPU–4 thrusters	1 PPU–2 thrusters
Heritage:								
Manufacturer	L3	L3	L3	Aerojet-Rocketdyne	L3	SSL	SSL	Astrium Crisa
PPU Input Voltage	**80V-145V**	**80V-160V**	**Same as XIPS**	**OTS: 68V-74V OTS*: 55V-85V**	**OTS: 95V-100V OTS*: 90V-110V Tested: 80V-120V**	**OTS: 95V-105V OTS*: 80V-120V**	**OTS: 95V-105V**	**OTS: 95-100V**
Flight Missions (previous or planned)	**DS 1 / Dawn**	None	None	AEHF (x6)	HS702 (x many)	SS/L (many)	Future Commerical	BepiColombo (2015)
Heritage for Deep Space	**Full**	**None**	**Partial**	**Full/Partial****	**Full/Partial****	**Full/Partial****	**Full/Partial**,†**	**Full/Partial****
Comments	No longer manufactured	Offered with cost credit in Discovery 2010						

OTS = "Off-the-Shelf"

* Off-the-shelf w/minimal modifications (requires delta or requal)

** Heritage application dependent.

† Full Heritage anticipated for some applications after qualification for Earth orbiting applications is complete.

Off-the-Shelf PPU fully qualified to support unregulated voltage range would greatly benefit deep space missions

Credit: David Oh, JPL

Hall Thruster Family

- **Aerojet Rocketdyne has developed a family of Zero Erosion™ Hall thrusters**
  - **Semi-empirical life-model and design rules developed and validated in 1998-2000, applied to all thrusters since then**
  - **Provides capability for very high total impulse missions as insulators stop eroding**
    - **Beginning of life configuration dictated by launch and IOC environments**
  - **JPL has developed "Magnetic Shielding" model which provides detailed understanding of physics**
- **Power level selection based on market demand**

XR-5 (5kW system, formerly called BPT-4000)

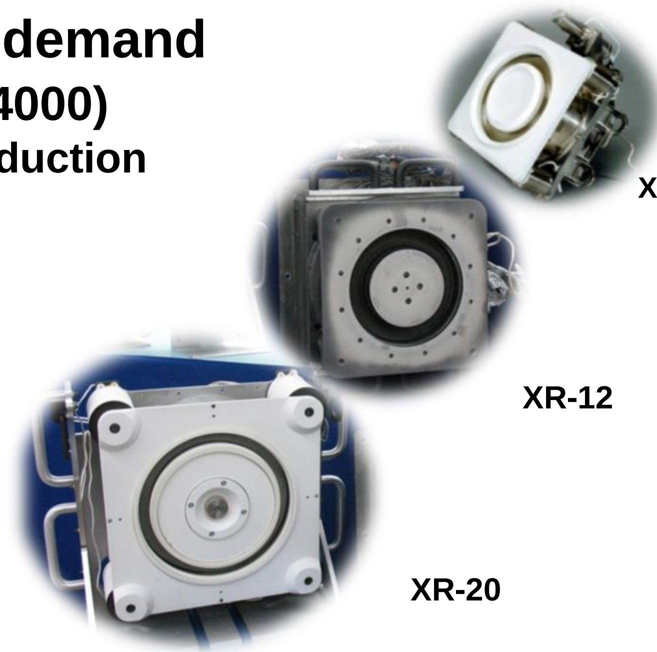
Flying on 3 DoD AEHF spacecraft, in production

XR-12 (12kW system)

Ready for qualification, PPU at BB level

XR-20 (20kW system)

Engineering thruster in development



XR-5

XR-12

XR-20

Zero Erosion design rules enable very long-life, high energy missions

Summary

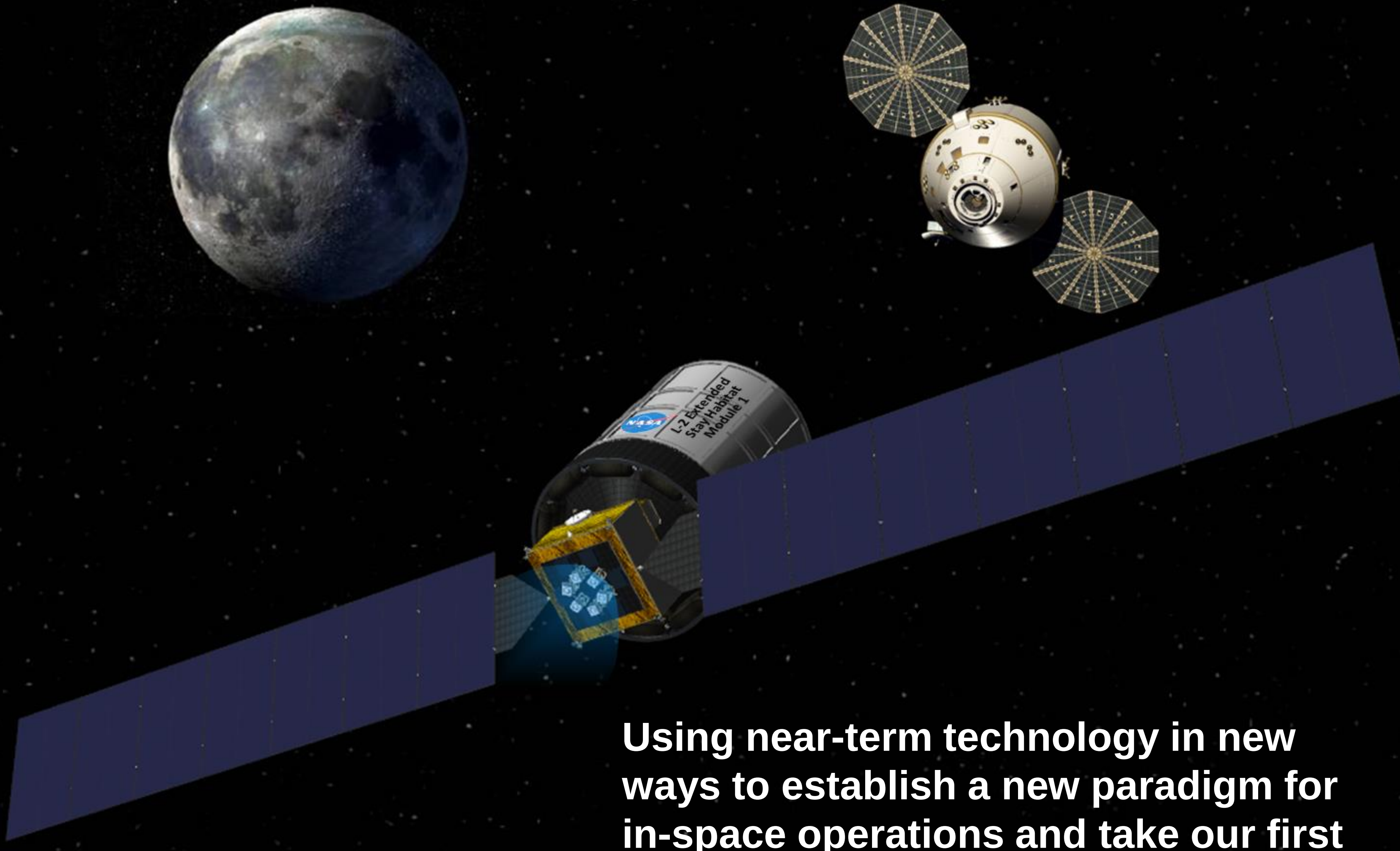
- **SEP Can Enable a 2X Reduction in Launch Mass for a Given Mission *If* Longer Trip Times can be Accepted**
  - **Where affordability is critical, SEP is enabling**

- **Increasing Space Vehicle Power/Mass Ratio is Critical to Reducing Trip time!**

- **SEP Power Levels are increasing from the current 5 – 10kW to:**
  - **Near-term: 30 – 50kW**
  - **Mid-term: 100 – 200kW**
  - **Long-term: 200 – 600kW**

- **Critical SEP Challenges include:**
  - **Ground life testing of higher power systems (fidelity, cost and schedule)**
  - **Solar Array efficiency, structure mass, and storage volume**
  - **PMAD Efficiency, thermal control, and radiation tolerance**
  - **Power Processor voltage range, performance, and radiation tolerance**

A First Step: Demonstrate SEP Cargo Transportation



Using near-term technology in new ways to establish a new paradigm for in-space operations and take our first steps in deep space exploration

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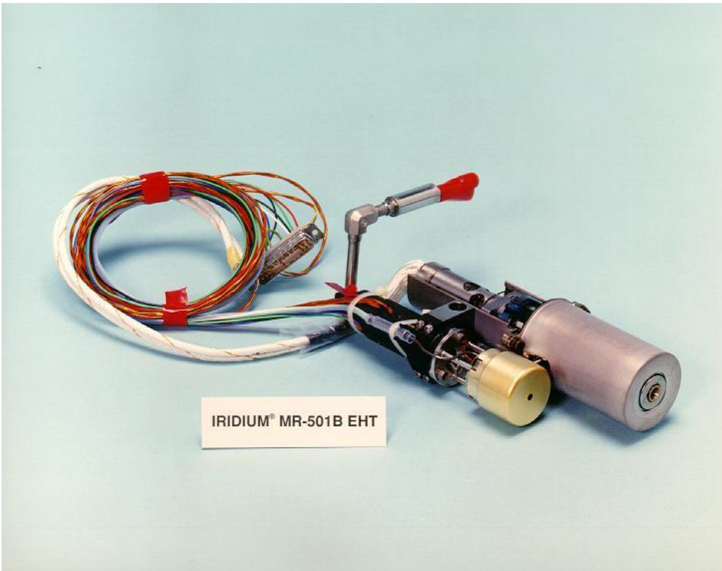
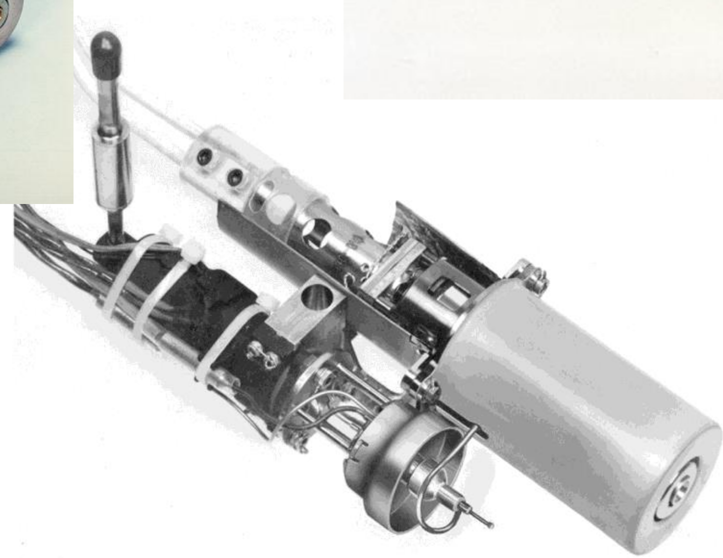
BACKUP SLIDES

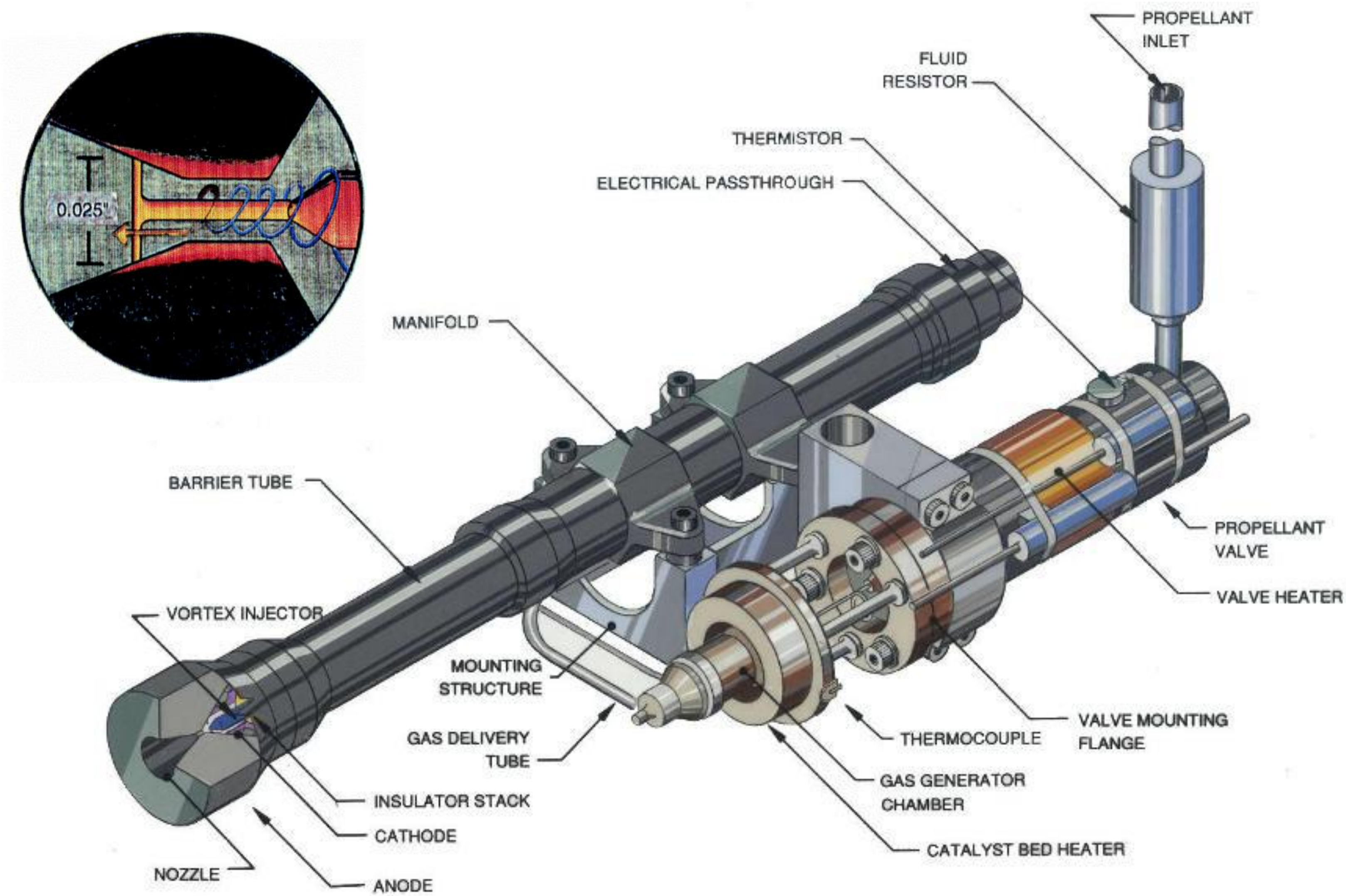
Resistojets: EHTs and IMPEHTs





High Temperature resistive coil adds energy to hydrazine decomposition products

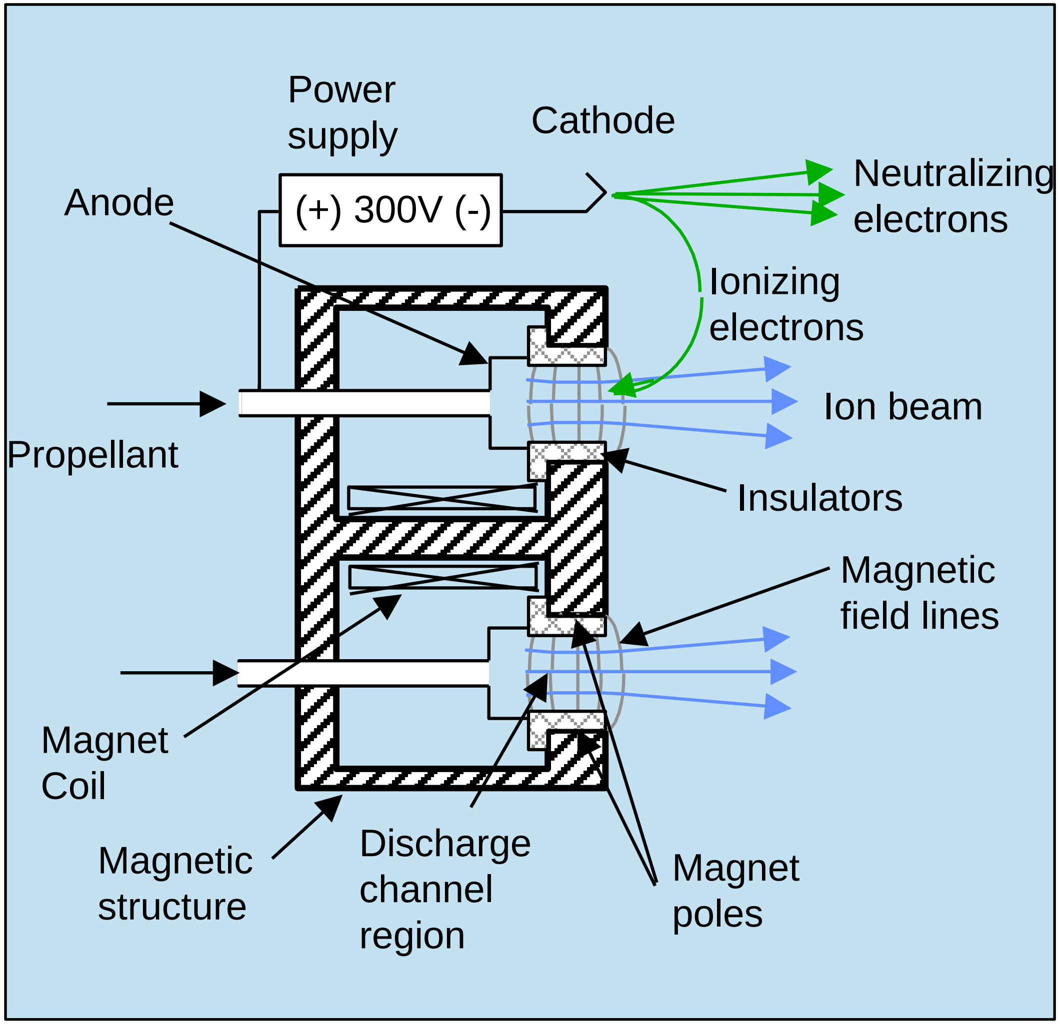
Arcjet Cross-section

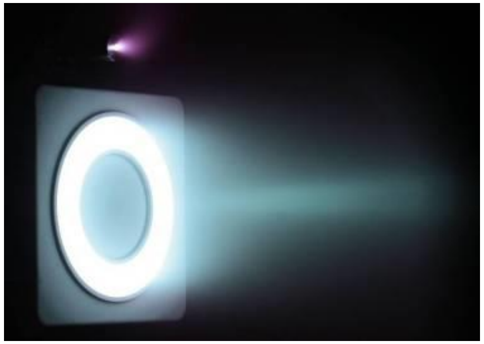


Arcjet Systems are Flying on Over 50 spacecraft today

How Does a Hall Thruster Work?

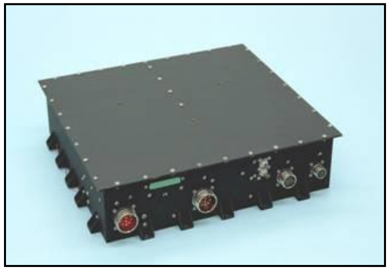
- Neutral gas, typically xenon, is injected into discharge channel
- Electrons emitted by the cathode are attracted towards anode
- These electrons collide with and ionize (charge) gas atoms
- Ionized atoms are accelerated by electric and magnetic fields to >20 km/second
- The beam of these ions create the thrust





Flight Hall Thruster Propulsion Subsystem

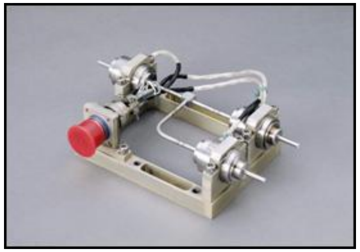
System Elements



Power Processor Unit

Hall Thruster

Cable Harness Assemblies



Xenon Flow Controller

BPT-4000

- Hall Thruster - Multi-mode:
  - 3-4.5 kW 300 - 400 V
  - Isp: 1730 - 2060 sec,
  - Thrust: 176 - 300 mN
- PPU: 1.5 - 4.5 kW power processing
- Xenon Feed Controller - provides propellant to both anode and cathode
- Flying on Advanced EHF for orbit raising and north-south station-keeping

Higher Power Systems

- 10 – 100kW Hall thrusters have been demonstrated in the laboratory

Hall thrusters are flying on a wide range of U.S. and international spacecraft today

Gridded Ion Engine Operation

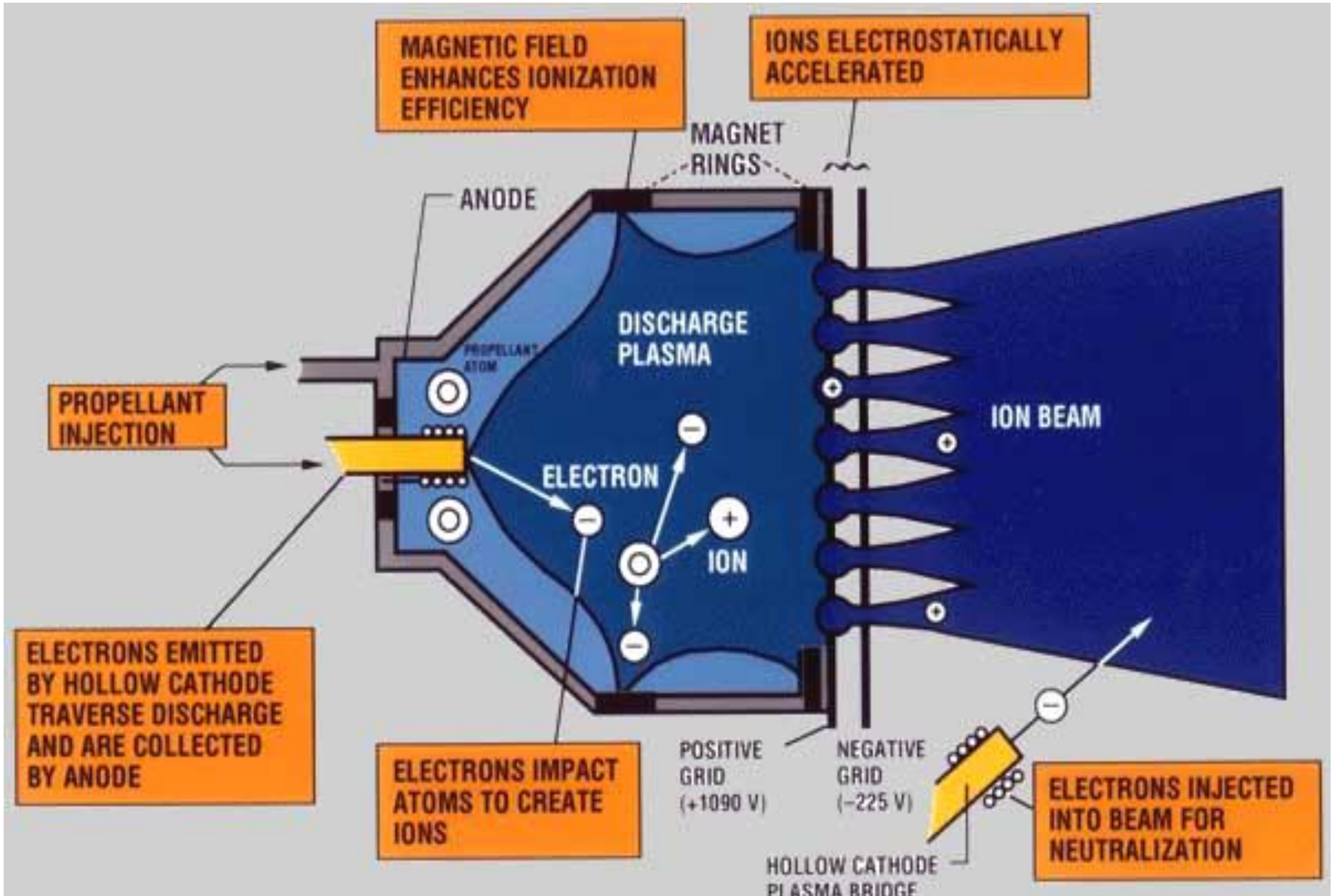
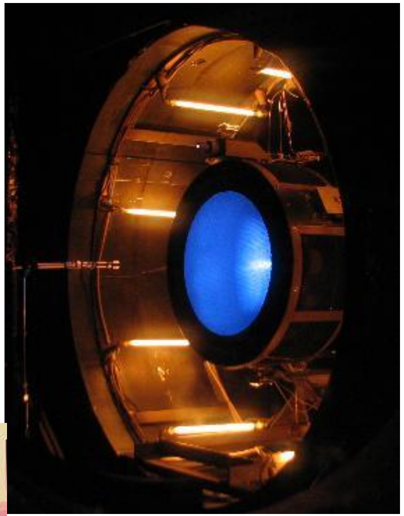


*Chart provided by NASA GRC

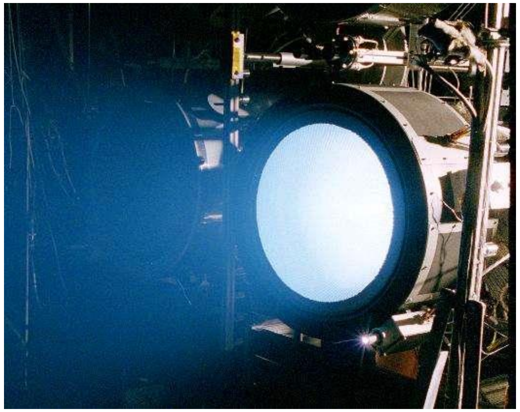
NEXT Gridded Ion Thruster



- <u>**NEXT Ion Thruster**</u>
- **7 kW Max Power**
- **>4100 s Spec. Impulse**
- **Xenon propellant**
- **Recently passed 30khrs of operation in ground test**

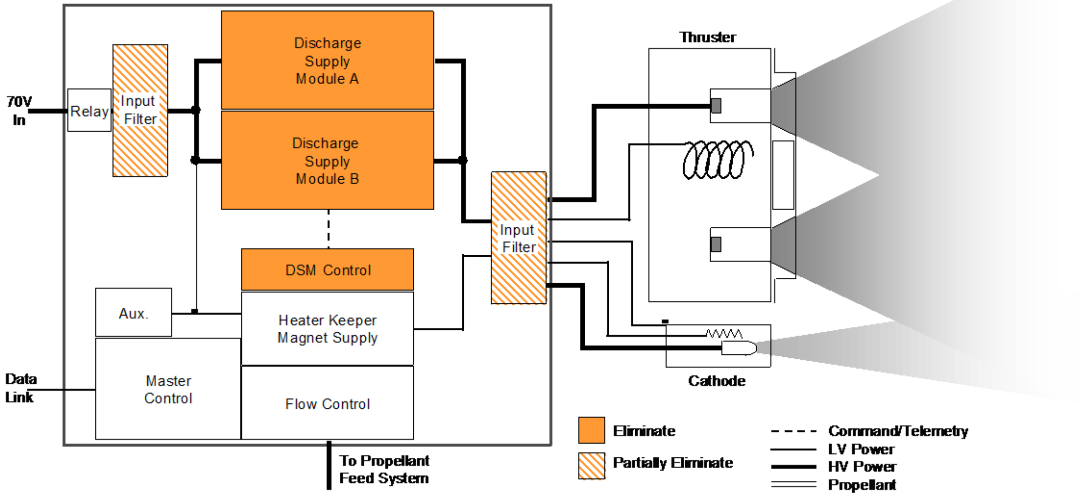
<u>Others</u>

- **Lower power ion thrusters flying on Boeing 702 and NASA's DAWN spacecraft**

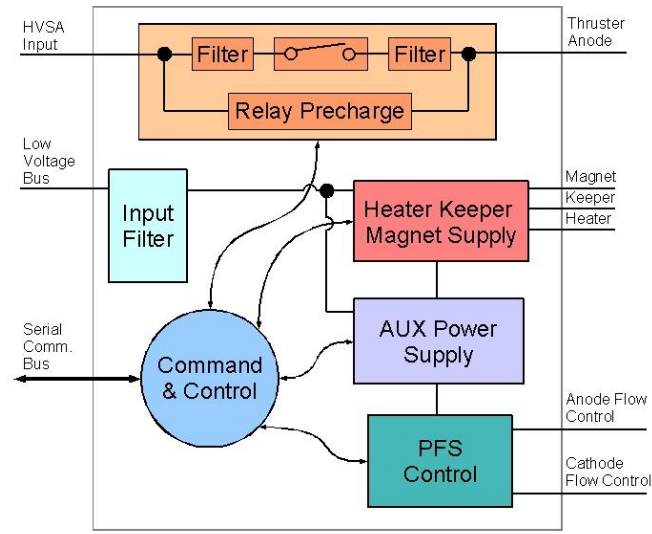


Direct Drive Architecture Option

Today's Power Processors



Direct Drive Option



Direct Drive eliminates high power converter by connecting thruster "directly" to the array

- **Requires high voltage array that matches thruster input requirements**
- **Uncertainties include :**
  - **System stability – plasma can close circuit to solar array**
    - **May need to redesign array or ensure thruster plume does not close the circuit**
  - **Array survivability and dynamic response to thruster transients – filter design and power losses**