Opportunities and Challenges for High Power Electric Propulsion Power Processing Units

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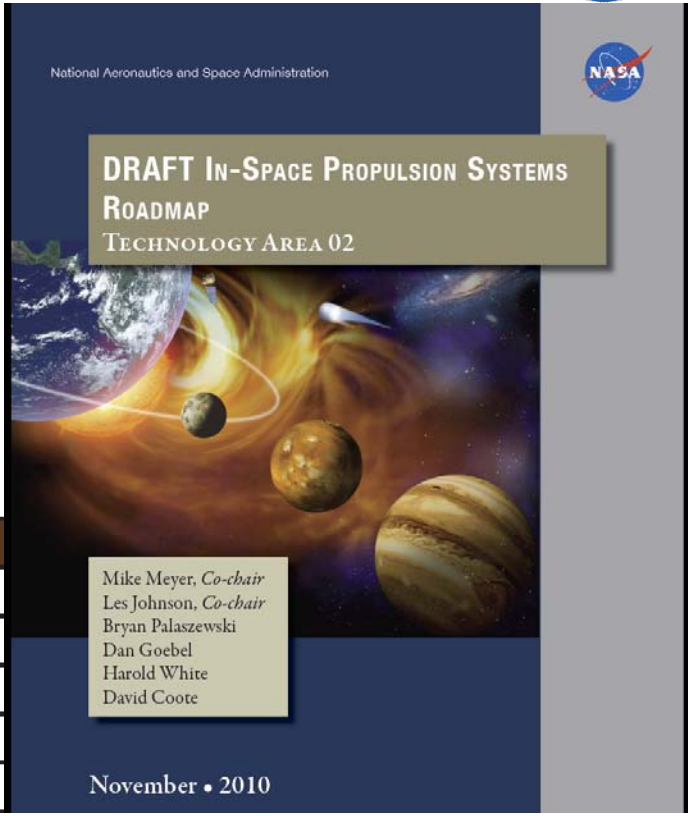
Motivation

- New NASA and Air Force programs that are developing high power electric propulsion systems
- NASA's In-Space Propulsion Systems Roadmap Identified the development of power processing units for EP thrusters as presenting the top technical challenge

Rank	Description
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems
2	Long-term in-space cryogenic propellant storage and transfer
3	High power (e.g. 50–300 kW) class Solar Electric Propulsion scalable to MW class
4	Advanced in-space cryogenic engines and supporting components
5	Developing and demonstrating MEMS-fabricated electrospray thrusters



- In a special electric propulsion panel session held during the 57th Joint Army Navy NASA Air Force (JANNAF) meeting, one of the main recommendations of the panel was engaging the power electronics community in order to familiarize the electronics and high voltage power supply communities about the EP community needs and issues as they relate to PPUs and their interactions with thrusters

What is Electric Propulsion?

Electric propulsion uses electrical power to provide kinetic energy to a gas propellant

- Decouples kinetic energy from the limitations of chemical energy
- Provides higher exhaust velocities than chemical engines
  - Reduces propellant mass needed to provide a given impulse
  - Allows reduction in launch mass or increase in payload; can provide substantial benefits in mission cost

$$\frac{Final \quad Mass}{Initial \quad Mass} \equiv \frac{m_f}{m_0} = \exp\left(-\frac{\Delta V}{g\, I_{sp}}\right)$$

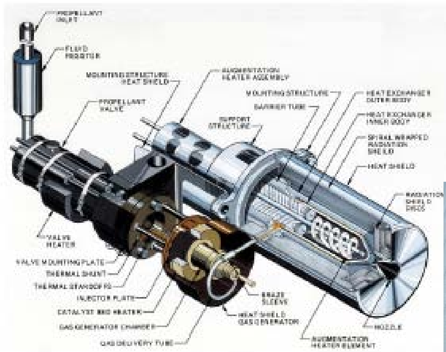
Mission specified

Increasing I_{sp} reduces fuel mass required to accomplish mission

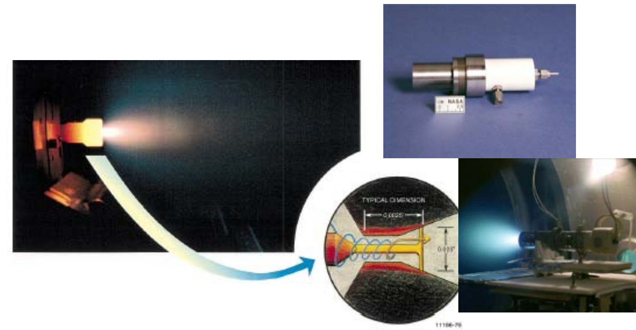
- Opens launch window over chemical systems in certain scenarios
- Electric propulsion primarily benefits large total impulse missions
  - Orbit raising, repositioning, long-term station keeping
  - Robotic planetary and deep space science missions
  - Precise impulse bits for formation flying (pulsed EP systems)
- Electric propulsion (including arcjets, Hall, ion, and pulsed plasma thrusters) employed in over 250 spacecraft

Electrothermal and Electromagnetic Thrusters

Electrothermal Heat gas and expand through a nozzle, Isp Range of = 300-1500 s

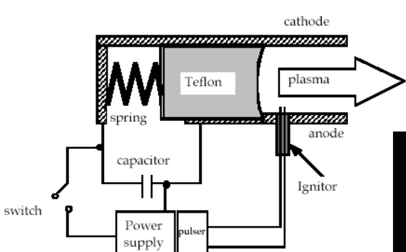


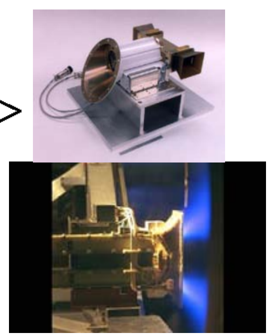
Resistojet

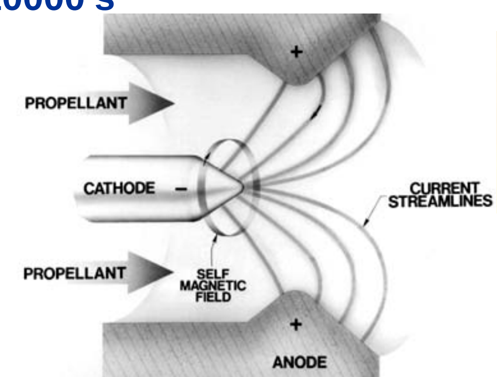


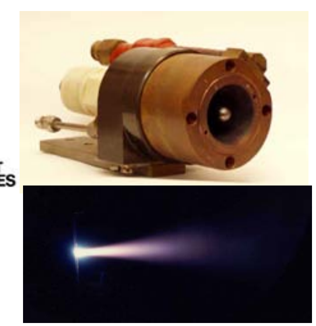
Arcjet

Electromagnetic Apply a Lorentz Force (JXB) for plasma acceleration, Isp Range of =1000-10000 s



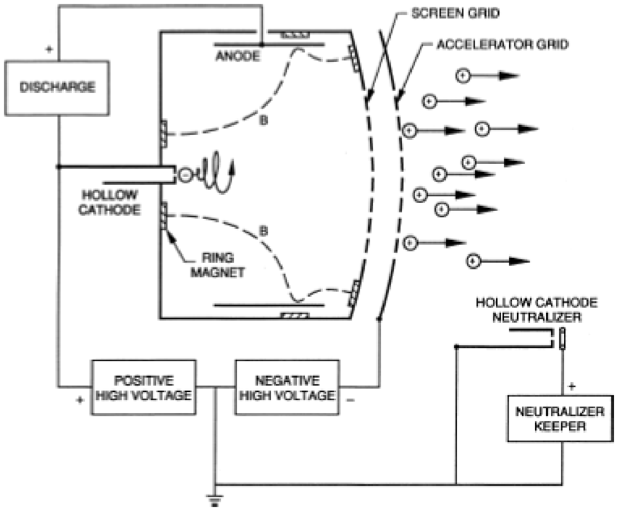




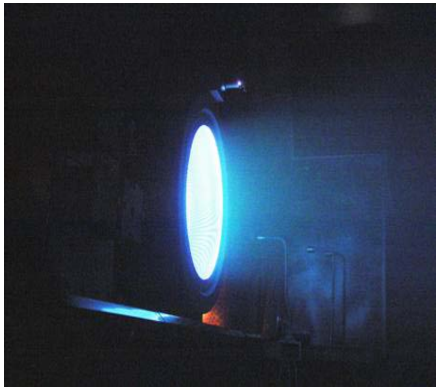


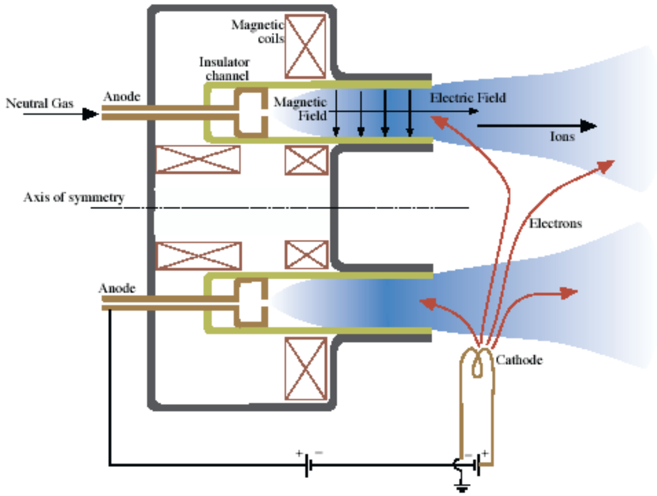
Electrostatic Thrusters

Generate high voltages for ion (plasma) acceleration, Isp Range of 1000-10000+ s

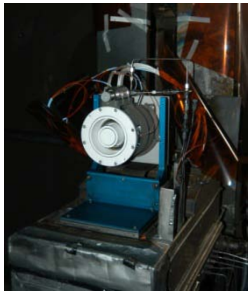


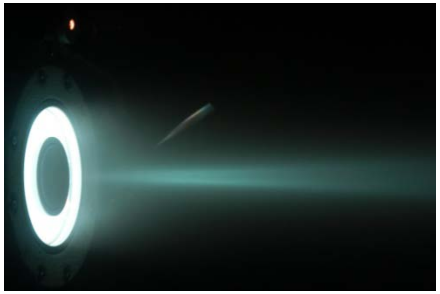
Ion thrusters use closely spaced high voltage grids to create an electrostatic field





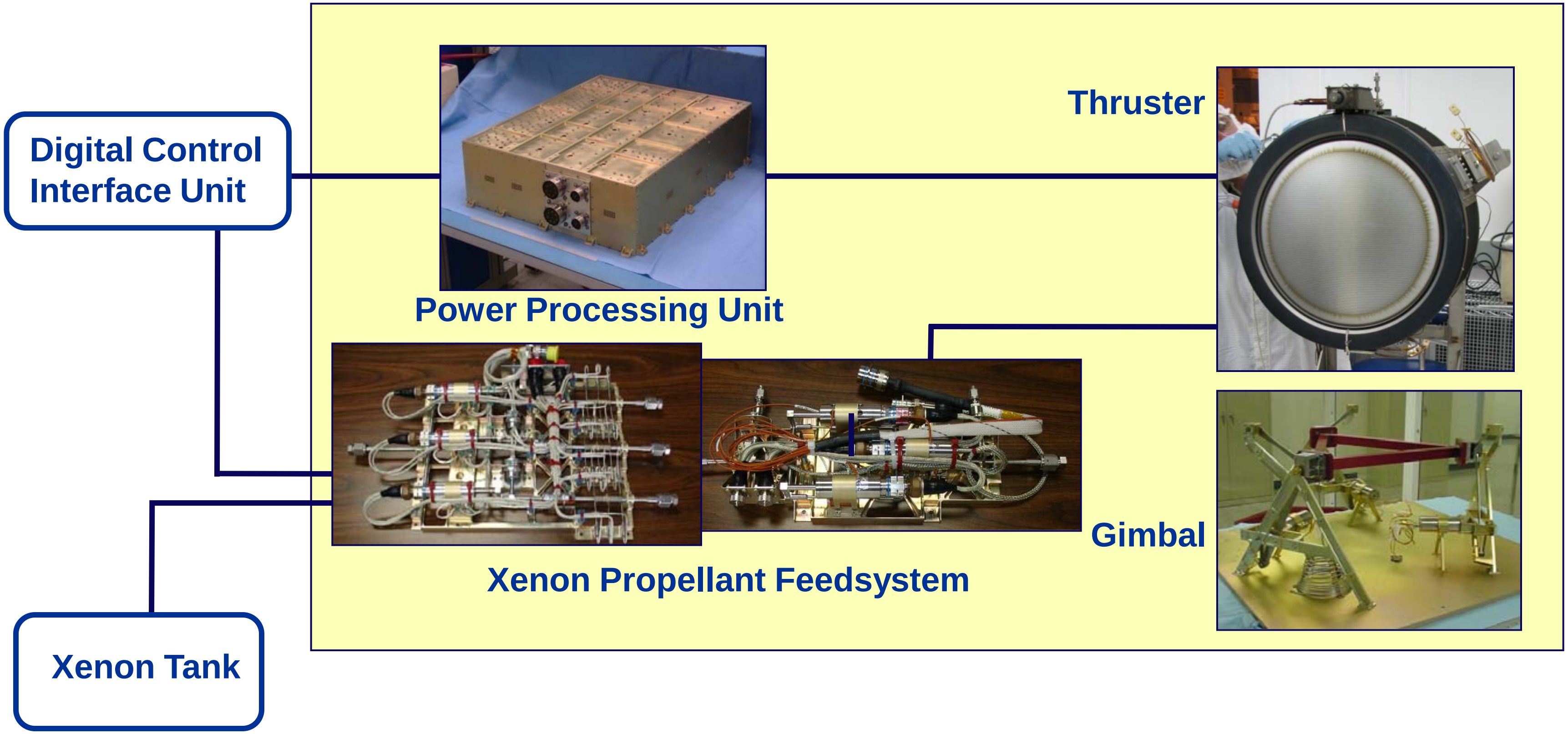
Hall thrusters use magnetically trapped electrons to create an electrostatic field





Electric Propulsion System Elements Include: Thruster, PPU, Propellant Feedsystem, Digital Control Interface, and Gimbal

Example: NEXT Thruster String



NASA, Air Force, and Industry Have Developed Electric Propulsion Thrusters Have Demonstrated Operation to Power Levels up to 72 kW

HiVHAC 3.5 kW
EM Thruster

NSTAR 2.3 kW
Ion Engine

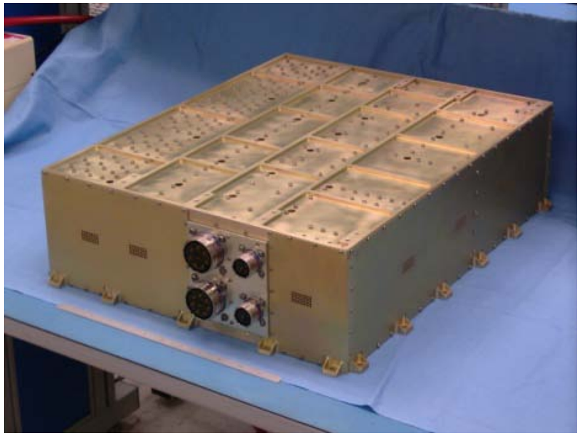
NASA-457M-v1
50 kW (72 kW)

NEXT 6.9 kW
Ion Engine

Flight Electric Propulsion Power Processing Unit Development Focused on Power levels < 10 kW

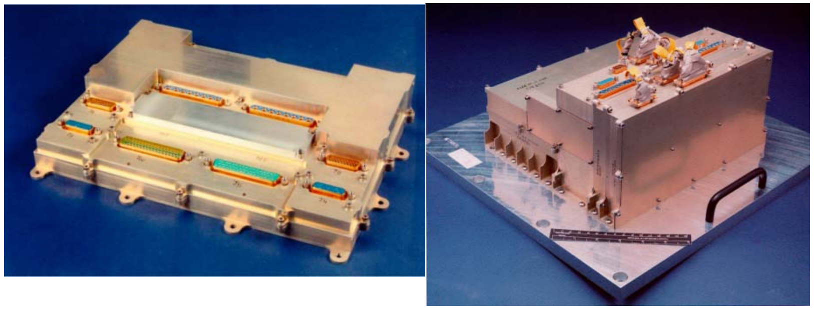
NASA Solar electric propulsion Technology Application Readiness (NSTAR) 2.5 kW Hughes manufactured PPU

- Mass = 13.7 kg , Efficiency ≤ 93%
- Input Voltage 80-160 Vdc, Output Voltage 650-1100 Vdc



NASA Evolutionary Xenon Thruster (NEXT) 6.9 kW L3 designed and manufactured PPU

- Mass = 33.8 kg, Efficiency ≤ 95%
- Input Voltage 80-160 Vdc, output Voltage 200-1800 Vdc



Loral 1.35 kW Hall Thruster Flight PPU

- Mass = 8.2 kg, Efficiency = 93%
- Input Voltage 100 Vdc, output Voltage 300 Vdc

Aerojet 4.5 kW Hall Thruster Flight PPU

- Mass = 12.5 kg, Efficiency > 92% (average)
- Input Voltage 70 Vdc, output voltage 150-400 Vdc

NASA ESMD/OCT Investment in High Power Electric Propulsion

- Enabling Technology Development & Demonstration - ETDD

  Develop, mature, and test enabling human exploration technology – Develop long-range, critical technologies to provide the foundation for a broad set of future exploration capabilities

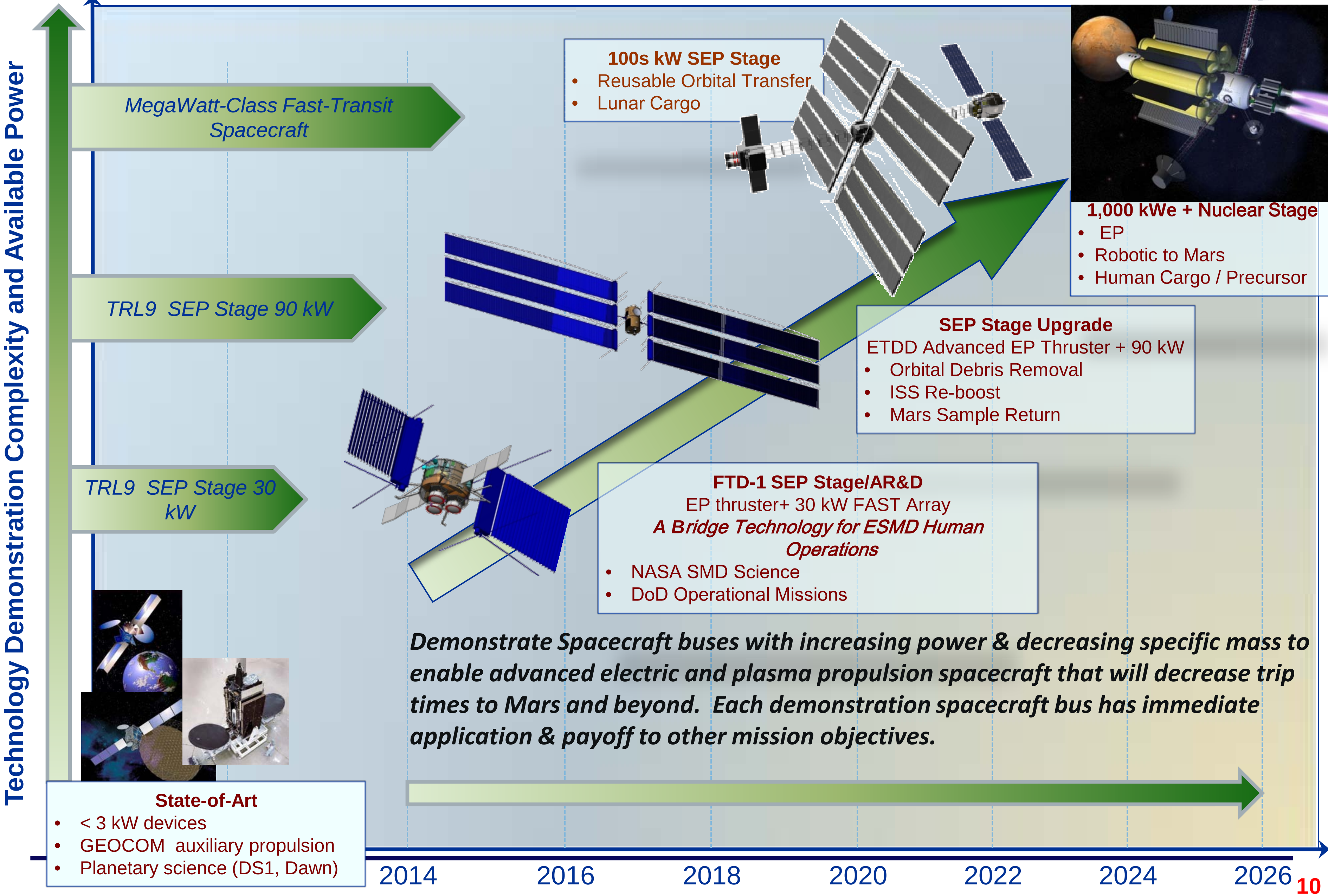
  <u>Advanced In-Space Propulsion</u> NASA will conduct foundational research and study the requirements and potential designs for advanced high-energy, in-space propulsion systems to support deep-space human exploration and reduce travel time between Earth's orbit and future destinations for human activity. These technologies could include nuclear thermal propulsion, solar and nuclear electric propulsion, plasma propulsion, and other high-energy and/or high-efficiency propulsion concepts.

- Flagship Technology Demonstrations – FTD

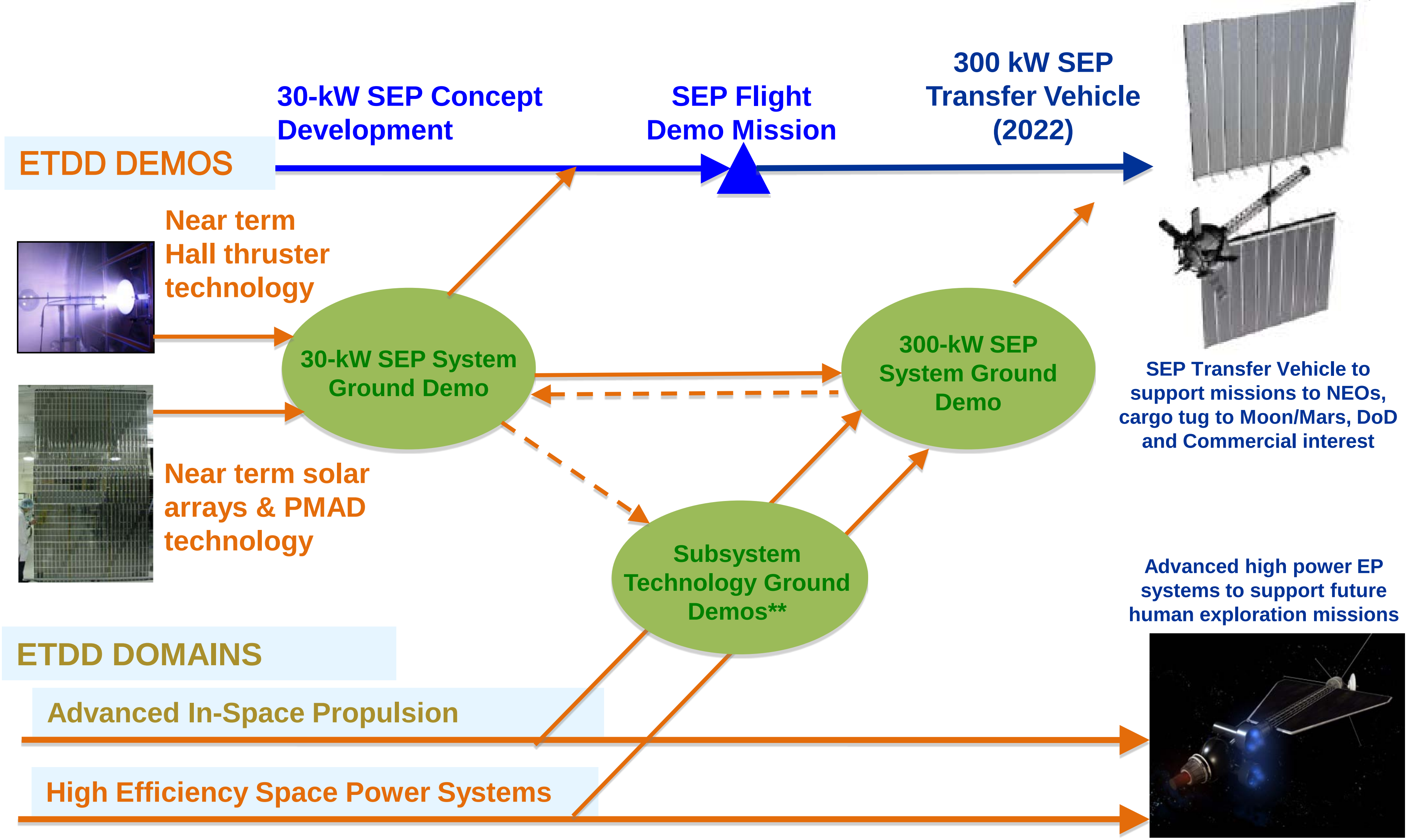
  Demonstrates the technologies needed to reduce the cost and expand the capability of future space exploration activities

  <u>Advanced In-Space Propulsion</u> Integrate emerging complementary technologies into an operational spacecraft & rapidly demonstrate system viability enabling a new space transportation capability via Solar Electric Propulsion (SEP) Stage. SEP Stage enables cost effective missions within Earth orbit, Cis-lunar, NEOs, and deep space robotic science missions – and – *Builds a new national capability that will dramatically enhance the competitiveness of existing U.S. launchers by minimizing the requirement for on-orbit propellant*

NASA's Roadmap For High Power EP System Development



Roadmap to SEP Transfer Vehicle



** Frequent subsystem demonstrations occur as technologies mature
(e.g. deployable solar array mechanism, PPU-PMAD integration test, etc.)

NASA OCT Opportunities in High Power Electric Propulsion

- Early-Stage Innovation program includes:
  - NASA Innovative Advanced Concepts (NIAC)
  - Space Technology Research Grants
  - Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR)
  - Centennial Challenges
  - Center Innovation Fund
- Game Changing Technology
- Crosscutting Capability Demonstrations program includes:
  - Technology Demonstration Missions Program
  - Edison Small Satellite Demonstration Missions Program
  - Flight Opportunities Program

EP Power Processing Unit (PPU) Requirements

- DC Input Voltage: Present ~100 V, Future ≥ 300 V
- Output Voltage: 200 V to 5kV depending on the application
- Output Power: Present 1 kW to 7 kW, Future 30 kW to 1 MW
- Efficiency: Present ~94% max, Future ~96% to 98% max
- Specific Mass:
  - Hall: present ~3 kg/kW, Future < 1 kg/kW
  - Ion: present ~ 5kg/kW, Future < 3 kg/kW
- Input/Output Isolation
- Electrostatic thrusters (Hall and ion) also require supplies for heaters, keepers, magnets, etc. in addition to the main screen or discharge supplies

PPU Thermal Considerations

- Baseplate temperature range -40°C to 70°C
- Conductively cooled
- Maximum PPU baseplate heat flux to the spacecraft ~0.15 W/cm^2 (limited by heat rejection system constraints)
- Low heat flux limit leads to “pizza box” chassis designs
- Largest space-qualified discrete FET IRHMS67264 is in TO-254 package (similar to TO-220, but hermetically sealed)
- TO-254 rated maximum heat flux ~ 60 W/cm^2
- TO-254 practical maximum heat flux ~ 0.8 W/cm^2 (PCB mount with inner-layer cooling planes coupled to chassis)
- Multi-chip modules provide heat spreading

PPU Power Semiconductor Requirements

- Component radiation ratings: 100 kRad (Si) to 300 kRad (Si)
- NASA Deratings, EEE-INST-002
  - T_j = maximum of 125 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.
  - Diode Voltage 0.7
  - Transistor Voltage 0.75
- Rad-hard Power MOSFET voltage: Present 250 V, Future 300V to 600 V for Si and GaN, 600 V to 1200 V for SiC
- Diodes: Present up to 600 V, Future > 1 kV (SiC)

How will Power be Increased by 10X?

- Modular construction
- Higher-efficiency circuit topologies (Soft-switching, Resonant)
- Multi-phase converters
- Improved semiconductors (Si, GaN, SiC)
- Improved semiconductor packaging (multi-chip modules)
- Improved thermal design and internal active cooling (heat spreaders, heat pipes)

Improved Power Semiconductors for Space Applications

- Rad-Hard Si MOSFETs (IR, Microsemi)
  - 300 V to 600 V under development
  - Larger die sizes (260 mil by 360 mil present maximum)
- SiC MOSFETs targeted for 600 V to 1200 V (Cree, Microsemi, Powerex)
  - SiC inherently more rad hard than Si
  - May be useful for pulsed applications
  - High switching speed
- GaN MOSFETs (EPC, IR, Microsemi)
  - GaN inherently more rad hard than Si
  - Low Rds-on
  - Very high switching speed
  - Presently only for low voltages, but parts up to 600 V under development
- IGBTs (some parts have limited radiation tolerance capabilities, but this may be improved in the future)

Improved High-Power Semiconductor Packaging

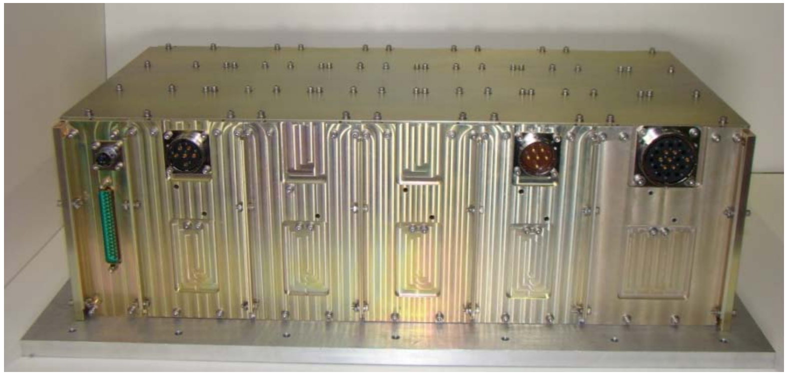
- Multi-chip module vendors
  - Semiconductor/module manufacturers: IR, Microsemi
  - Module manufacturers: Powerex, Semelab
- Improved module construction
  - Heatsink: Aluminum composite or copper composite/laminate
  - Substrate: Metalized or direct bonded copper on CTE matched ceramic
  - Better layouts that address high-frequency effects and current sharing (electromagnetic CAD tools used in design process)
  - Elimination of series gate resistors to improve drive efficiency (ferrite chips used instead of resistors to prevent oscillations)

Comparison of Various Converter Topologies

Ratio of switched voltage to input bus voltage for various topologies

Topology	Vswitch/Vbus
Voltage-fed push-pull	2
Voltage-fed full & half bridge	1
Clarke (D = 0.75)	4
Weinberg (improved version) D=0.5	2
Current-fed sine-wave full & half bridge (D=0.5)	1.6
Current-fed sine-wave push-pull (D=0.5)	3.2

CPE Three-phase Resonant Brassboard PPUs

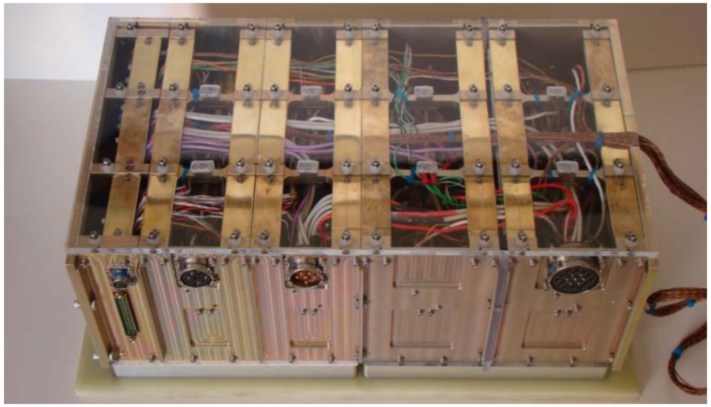


For Ion Engines (2 kW screen supply)

DC Input voltage: 90 V to 110 V

Full-power screen voltage: 800 V to 1600 V

Maximum Efficiency: 94%



For Hall Effect Thrusters (4 kW discharge supply)

DC Input voltage: 80 V to 160 V

Full-power discharge voltage: 200 V to 700 V

Maximum Efficiency: 96%

Multi-Phase Resonant Converter Advantages

- High efficiency—97.9% demonstrated at 10kW
- High Specific Power—0.91 kW/kg for 10kW unit
- Low input and output ripple—Output ripple ~5% rms without filtering
- Low stored energy—1mJ/kW typical
- Low voltage stress on components (Vswitch = Vbus)
- Reduced probability of single-event burnout
- High output impedance

Multi-Phase Resonant Converter Disadvantages

- Control laws are more complex than square-wave power conversion (New numerical analysis method helpful)

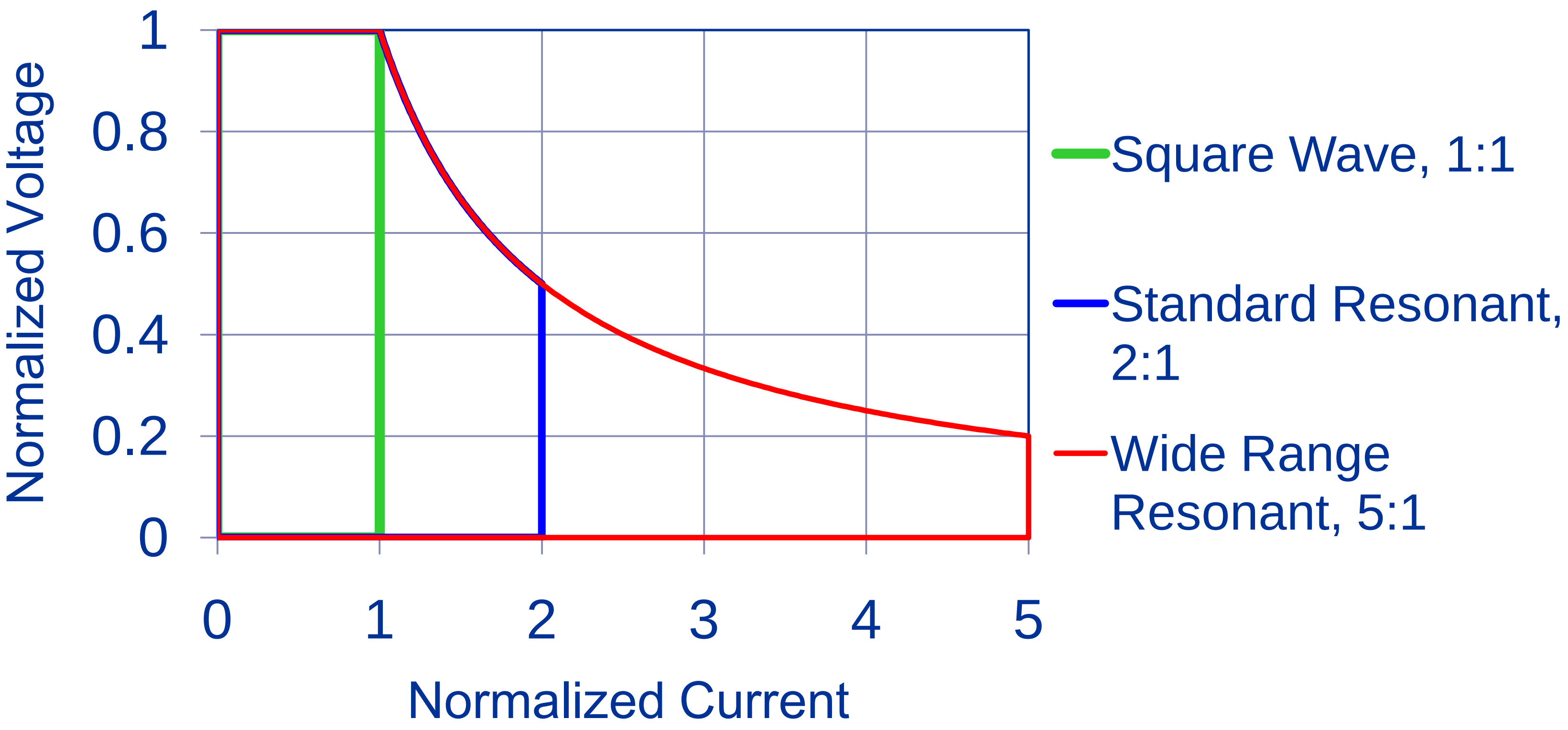
  A novel frequency-domain small-signal analysis of resonant power converters

- No-load losses are greater than with square-wave power conversion

CPE Resonant Inverters & Single-Event Effects

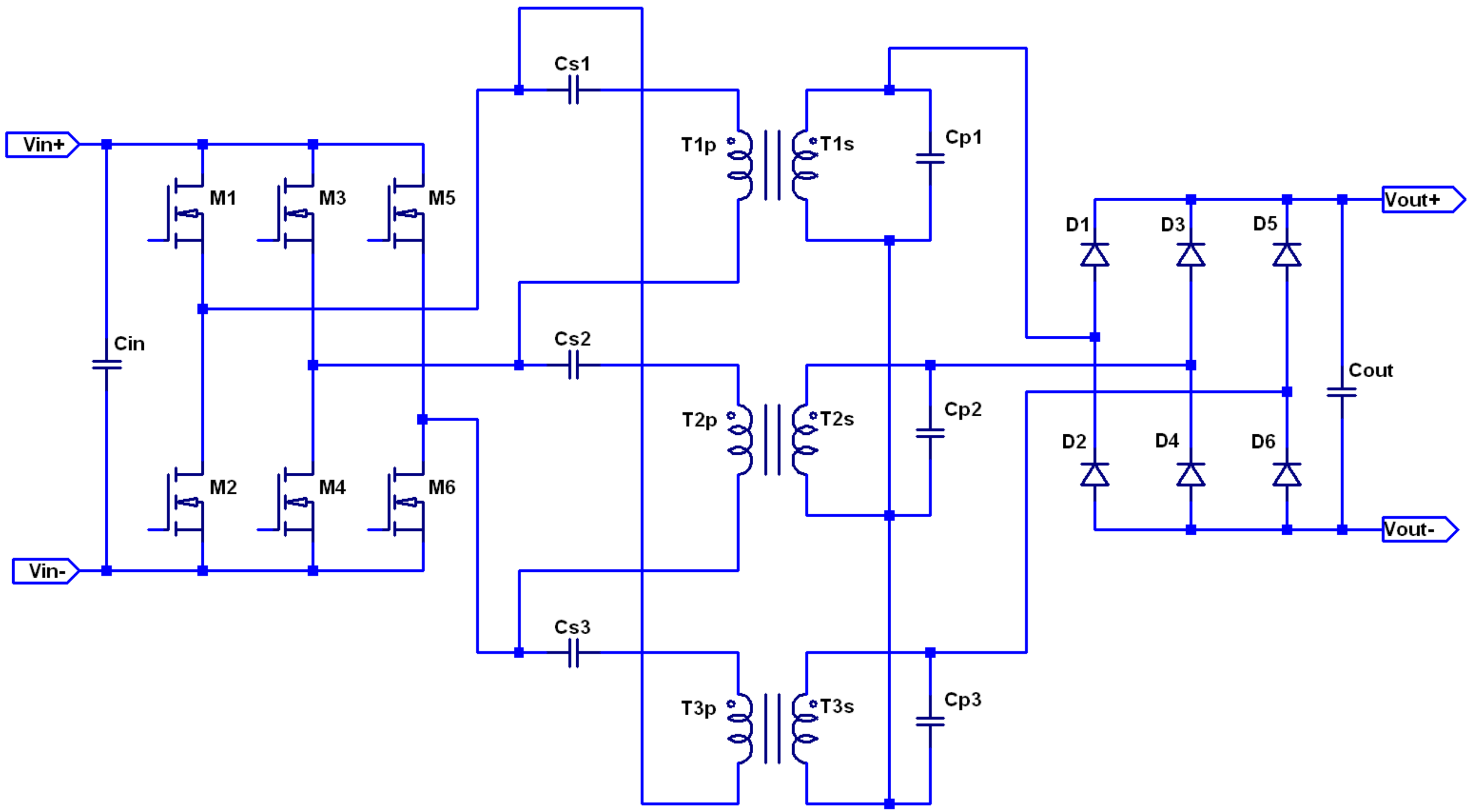
- Voltage-fed bridges are used so the voltage stress is low (improves single-event robustness)
- Low input ripple currents allow the use of small bus capacitors (may help prompt radiation survivability)
- If a MOSFET failure does occur, current sensing circuits can be used to prevent series-connected MOSFETs from failing and shorting the bus
- Output rectifier diodes are typically rated for 600 V or less, and single event effects are only a problem for diodes rated at higher voltages

Typical Full-Power Output Operating Ranges

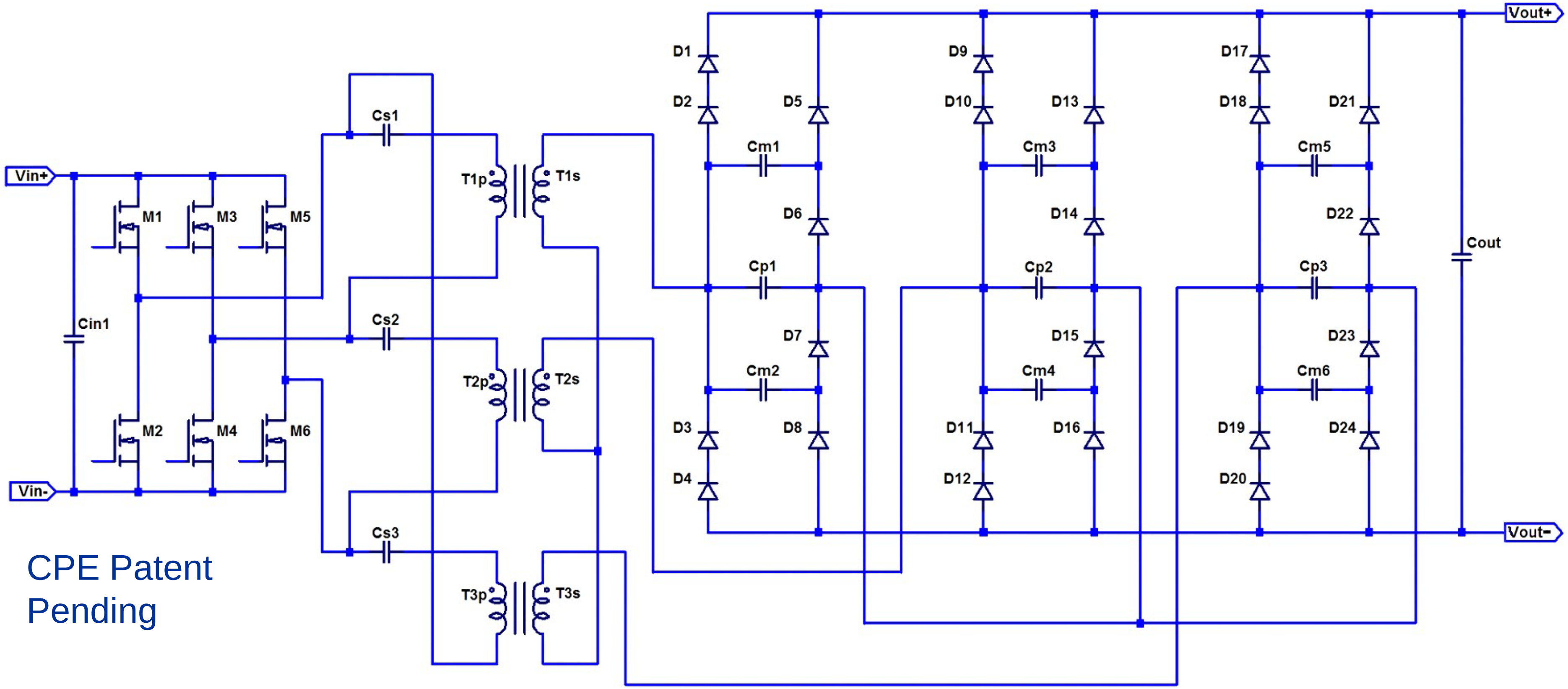


- Typical square-wave power supplies achieve their maximum output power only at their maximum output voltage
- Resonant converters typically have wider operating ranges

Standard Three-Phase Resonant Converter



Wide-Range Three-Phase Resonant Converter



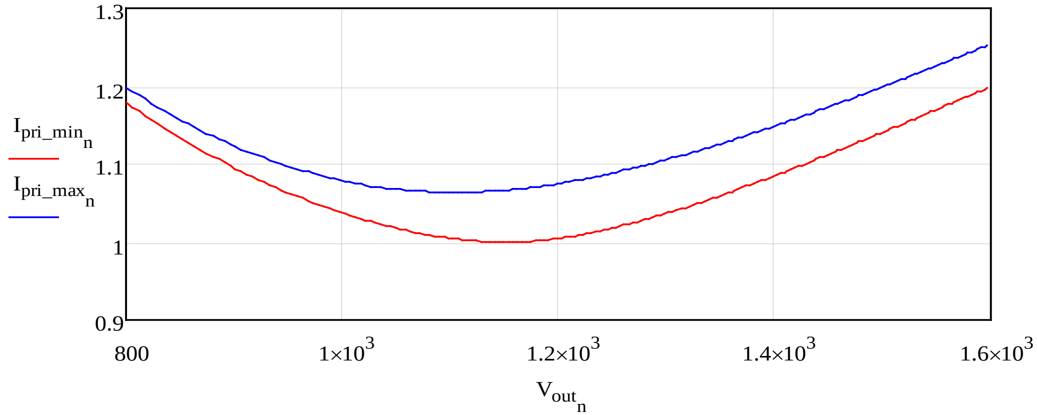
CPE Patent Pending

- A novel output rectifier circuit enables wide-range operation

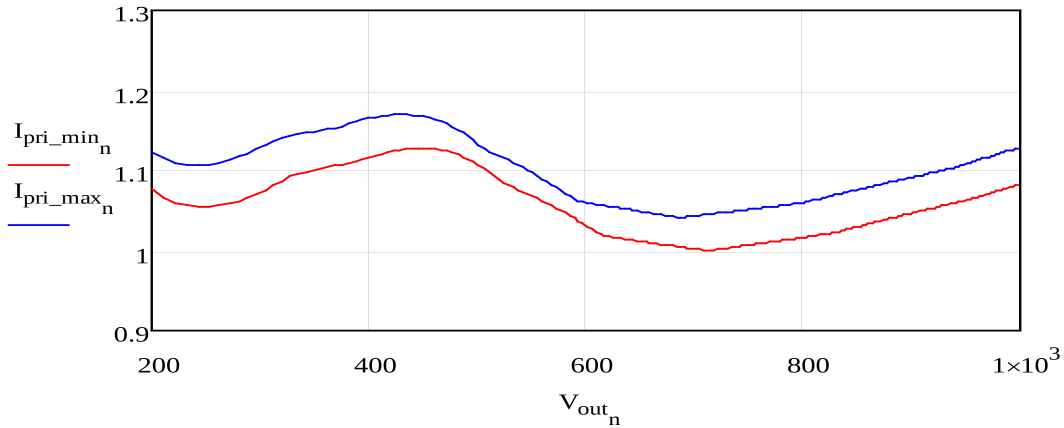
Normalized RMS Primary Currents

(Full output power with maximum and minimum bus voltages)

Standard Three-Phase Resonant Converter, 2:1



Wide-range Three-Phase Resonant Converter, 5:1



- The wide-range converter compresses the variation of the primary current as the output voltage is varied