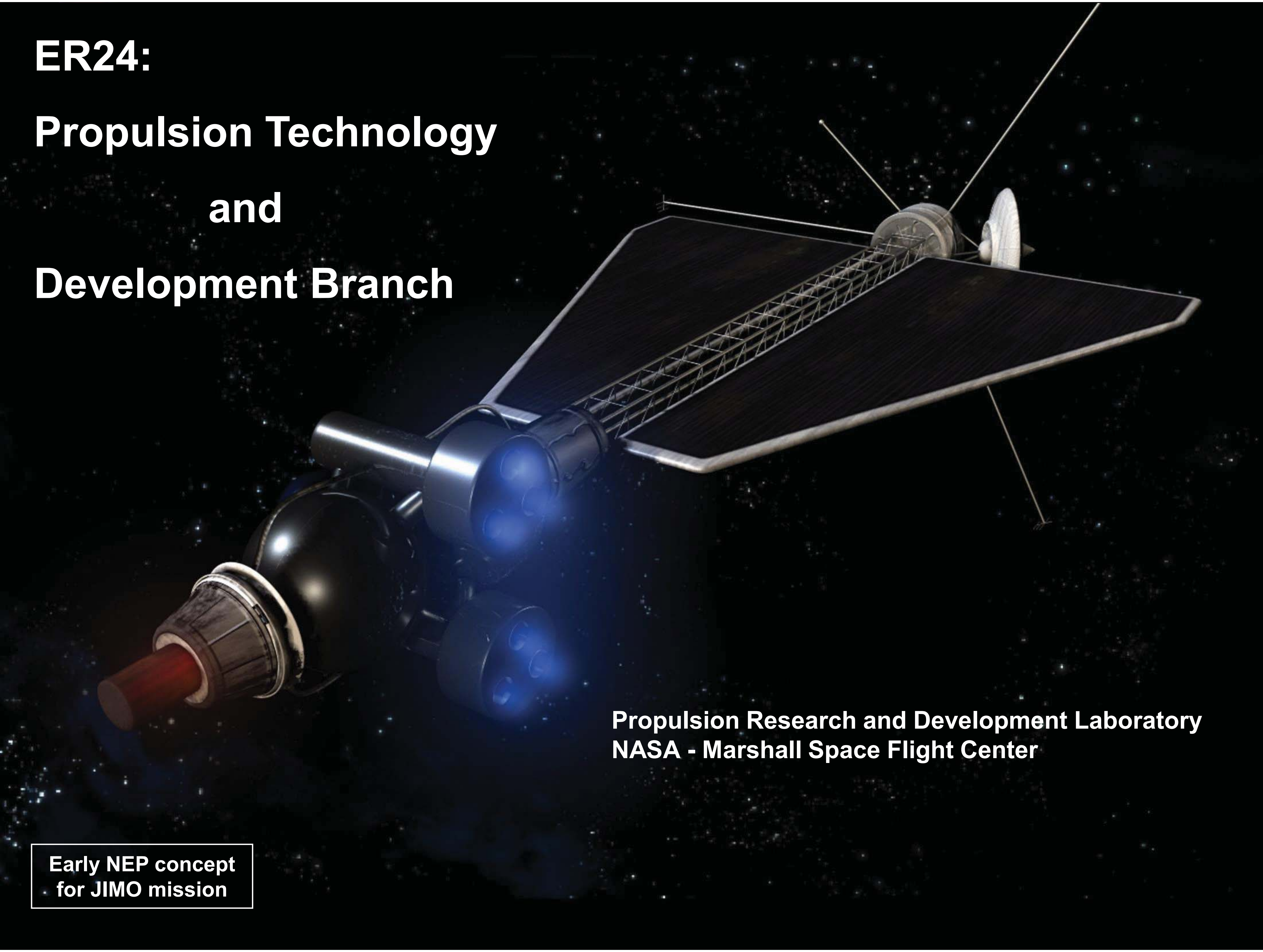
Propulsion Research Work at Marshall Space Flight Center

Amy Sivak

November 5, 2013

ER24:

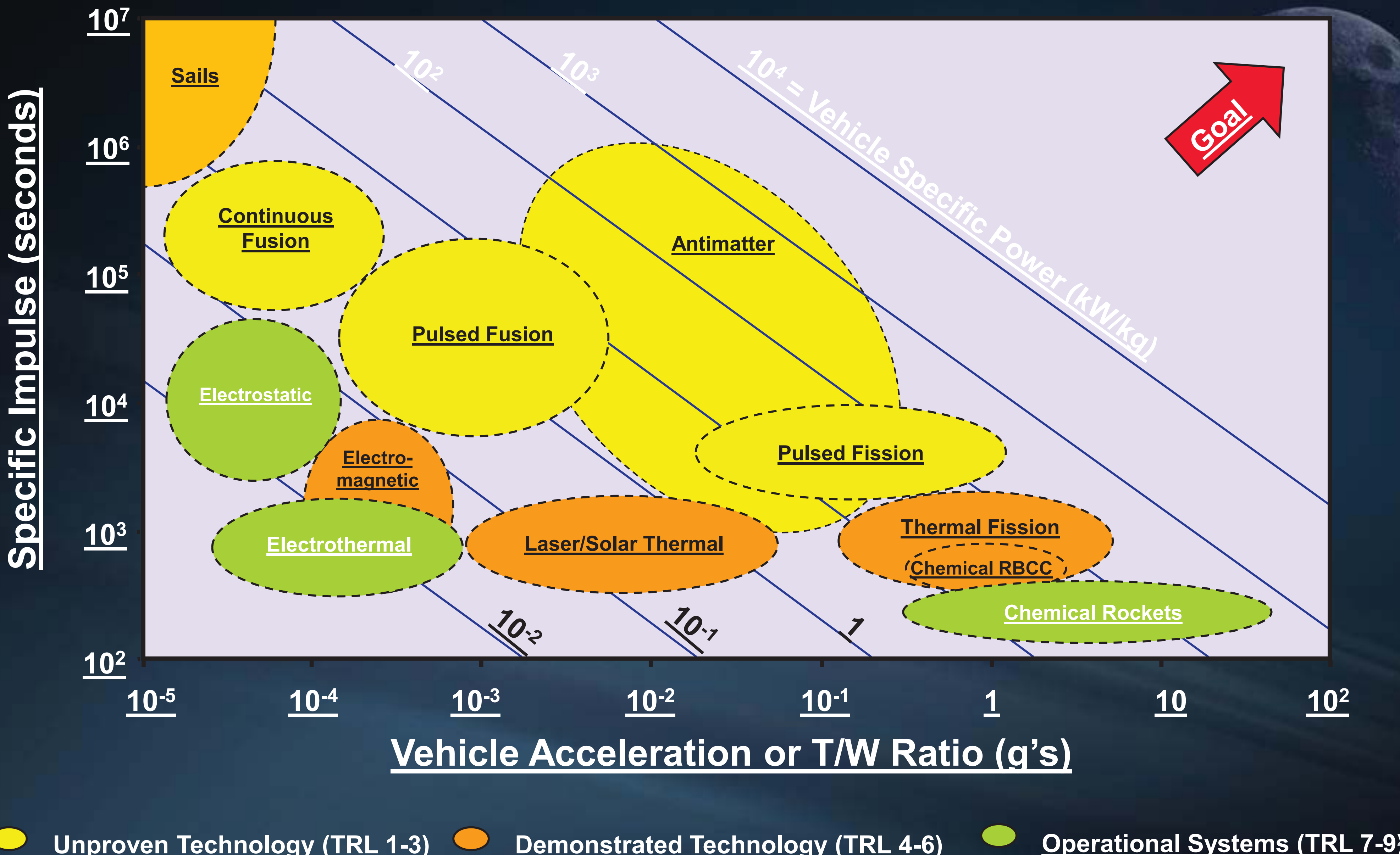
Propulsion Technology and Development Branch



Early NEP concept for JIMO mission

Propulsion Research and Development Laboratory
NASA - Marshall Space Flight Center

Space Propulsion Concepts

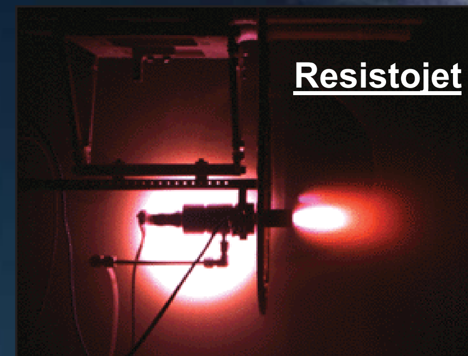


Types of Electric Propulsion

Electric thrusters are generally categorized by their primary acceleration mechanism:

Early → In Use → R&D Area

- **Electrothermal**
  - Electrical energy into thermal energy
  - Large number of all EP systems on-orbit
  - I_{sp} 500-1500 s, thrust medium/high
  - Hot exhaust / high density gas / nozzled expansion



- **Electrostatic**
  - Applied electric field directly accelerates ions
  - Growing fraction of all EP systems in space
  - I_{sp} 1000-10,000 s, thrust low/medium
  - Low density gas / grid or electrodes to apply E-field / low thrust density

- **Electromagnetic (Plasma)**
  - Interacting currents and magnetic fields directly accelerate plasma
  - I_{sp} 1500-6000 s, thrust medium/high
  - High density gas / generally compact

- MSFC R&D on iodine-fed Hall thrusters, high-power arcjets (1 MW) and high-power pulsed inductive thrusters (PIT).

NASA EP Activities – Past & Planned

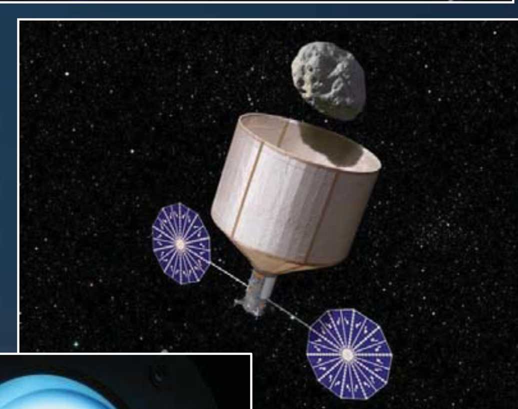
What has been done?

- Deep Space 1 technology demonstrator (NSTAR ion engine)
- Dawn science mission to asteroid belt (ongoing w/NSTAR ion engine)

Planned

Asteroid-Retrieval Mission

- Capture asteroid and return it to cislunar space by ~2025
- 7-m diameter, 500-1000 t object
- ~40 kW (solar) power level



Human Exploration – DRM-5

- Power manned transfer vehicle for trip to NEA
- 300 kW (solar) power level

Solar Electric Propulsion (SEP) Technology Demonstration Mission

- Test and validate key technologies required for future exploration elements (i.e. 300-kW solar electric transfer vehicle) by ~2017/2018
- ~15-30 kW solar power level on demonstrator

Usage Through the Years

As 2010

Recent High-Profile EP Missions

ESA's Smart 1 – PPS1350G Hall thruster (x1)

2003-2006 (Moon)

JAXA's Hayabusa – 10μ microwave ion thruster (x4)

2003-2010 (Itokawa – sample return)

NASA's Dawn – NSTAR ion thruster (x3)

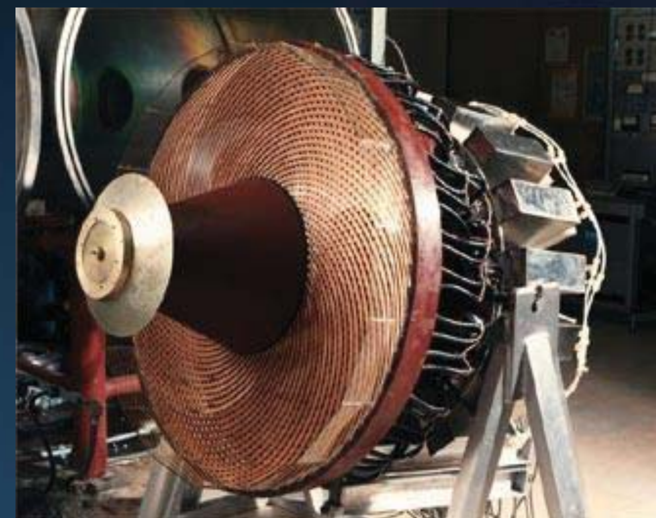
2007-2015 (Vesta and Ceres)

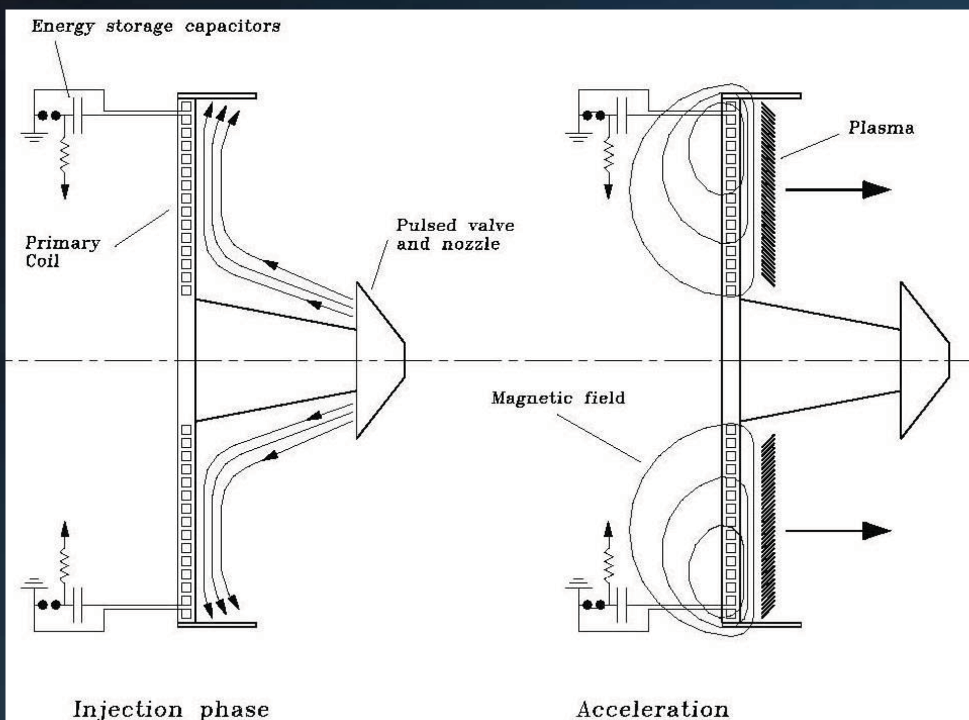
USAF AEHF – BPT-4000 Hall thruster (x4)

2010 (Geo Orbit – boosted system when bi-prop motor failed)

EP at MSFC – Pulsed Inductive Thrusters

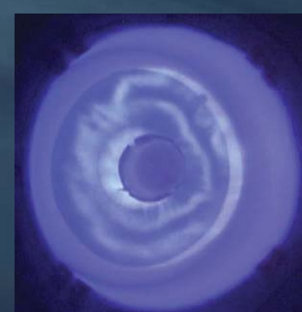
- High power, high thrust density
- Electrodeless (requires high power switches)
- Many propellant options
- Impulse ~ 0.1 N-s, I_{sp} ~ 2000-s to 10000-s
- High impulse maneuvers, primary planetary propulsion
- Research level (single shot, η_t ~ 50% on ammonia)

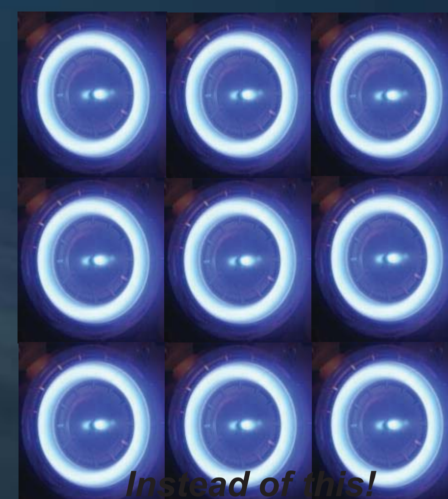




*From NASA CR-191155, by C.L. Dailey and R.H. Lovberg, 1993

Higher thrust density enables this:

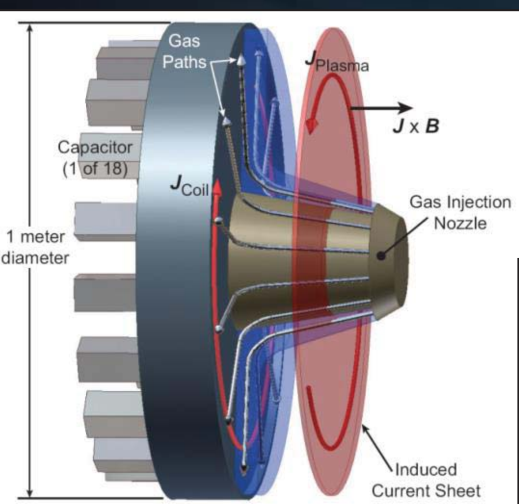




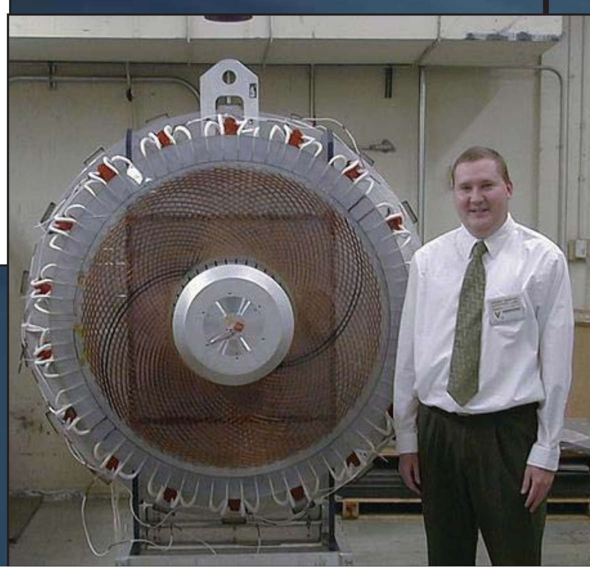
Pulsed Inductive Thruster Characteristics

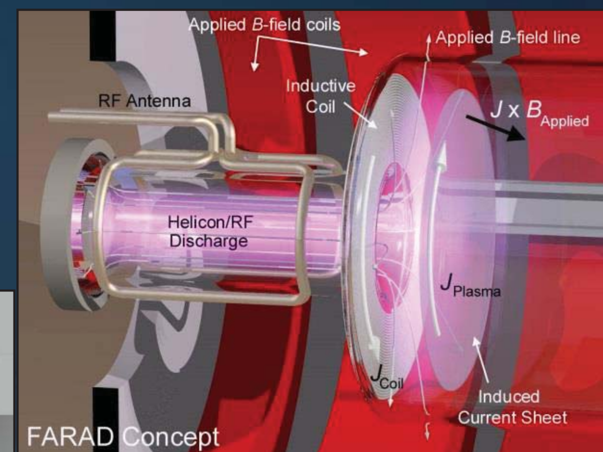
- High voltage (15 kV) and energy (4 kJ/pulse)
- Complexity (18 capacitors, 18 switches)
- Stringent switching requirements
  - Simultaneous closing of 18 switches
  - High voltage holdoff, high current switching
  - Presently spark gap switched

- Separate ionization and acceleration mechanisms
- Preionization lowers energy/voltage required to operate
  - ~100 J/pulse vs. 4 kJ/pulse
- All other advantages of inductive acceleration



Difficult to scale to small size

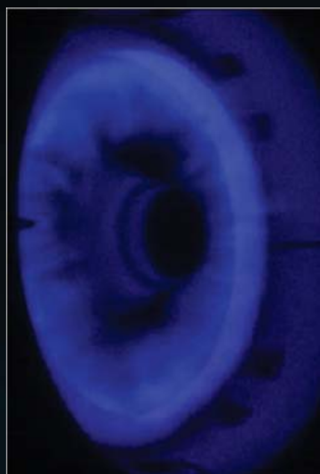


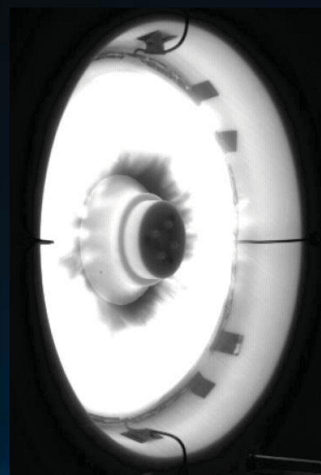


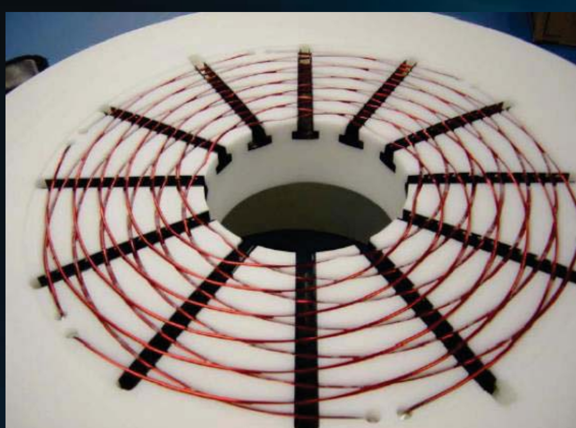
Easier to scale to small size

Thruster Development

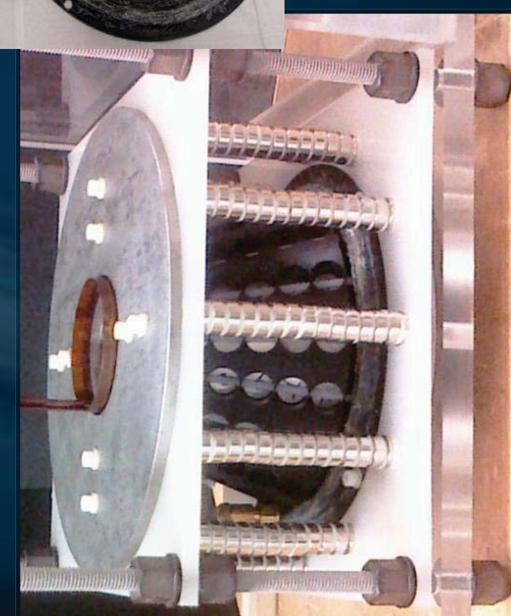
Flat-plate geometry





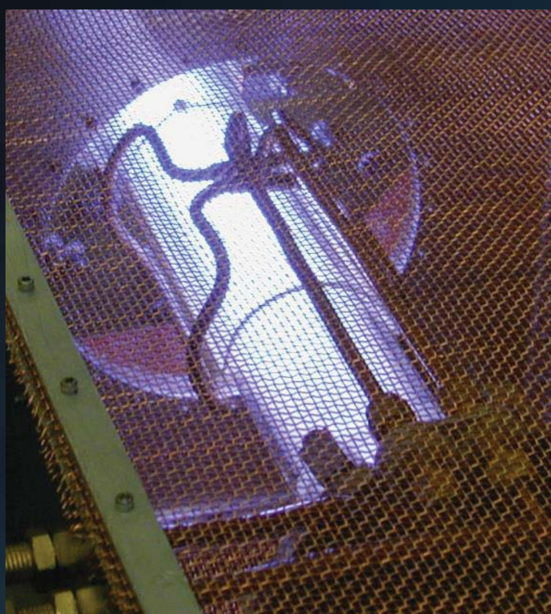


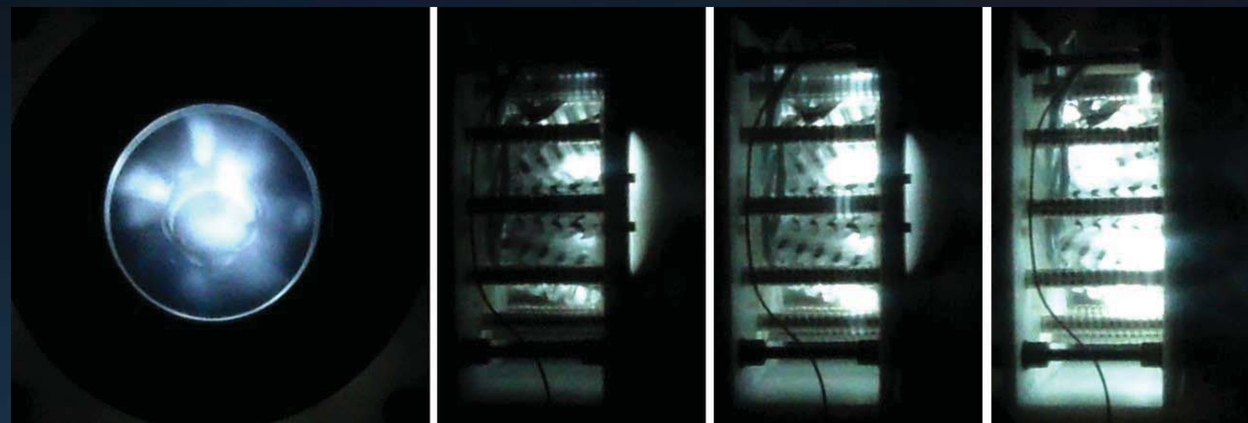
Conical geometry



Critical Issues - Preionization

Helicon discharge
(~1000 W)
13.56 MHz

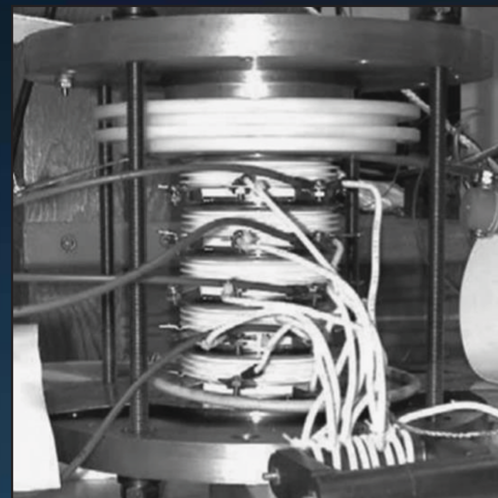


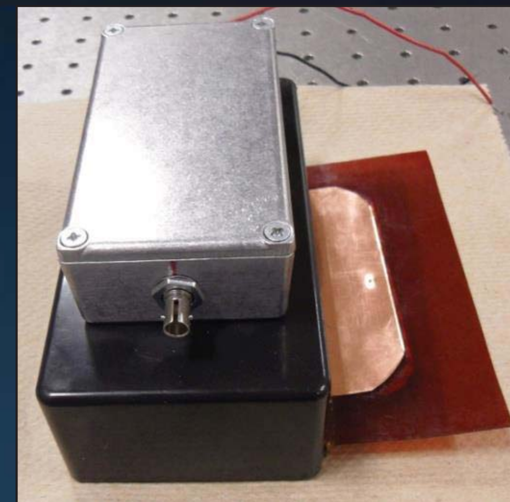


Microwave-driven ECR discharge (~1 kW)
2.45 GHz

Inductively-coupled discharge (35-50 W)
~600-900 MHz

Critical Issues - Continued





Switching
- High voltage holdoff (multiple kV)
- High current conduction (10s of kA)
- Fast (> 100 kA/μs rise time)
- Repetition rate (> 100 Hz for high power)
- Fast turn off / reset for next pulse

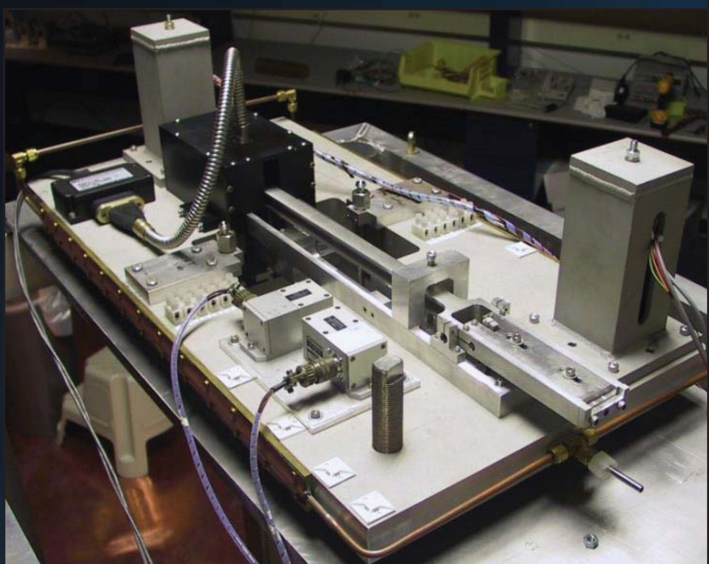
Pulsed Gas Injection
- Fast open and close (1-3 ms total)
- Low latency in propellant lines
- Low leak rate (0.001 sccs GHe)
- Lifetime (10^8-10^9 pulses)

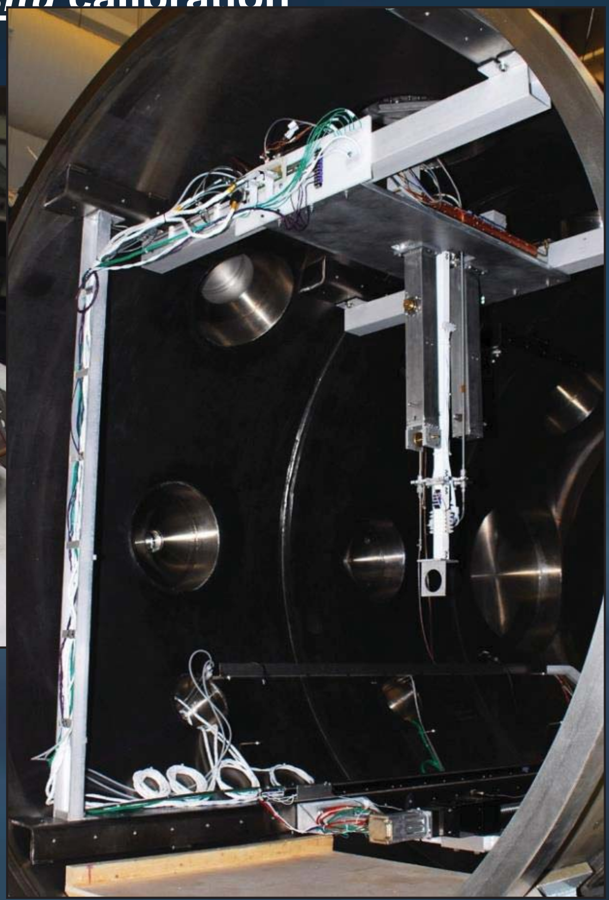
Power systems
- Transform spacecraft bus power to current / voltage needed by thruster
  - DC / AC input power
- Repetitive capacitor charging to multiple kV
- Charging rate commensurate with capacitor switching capabilities
- Operate in environment (vacuum)
  - Remove / dissipate heat in system

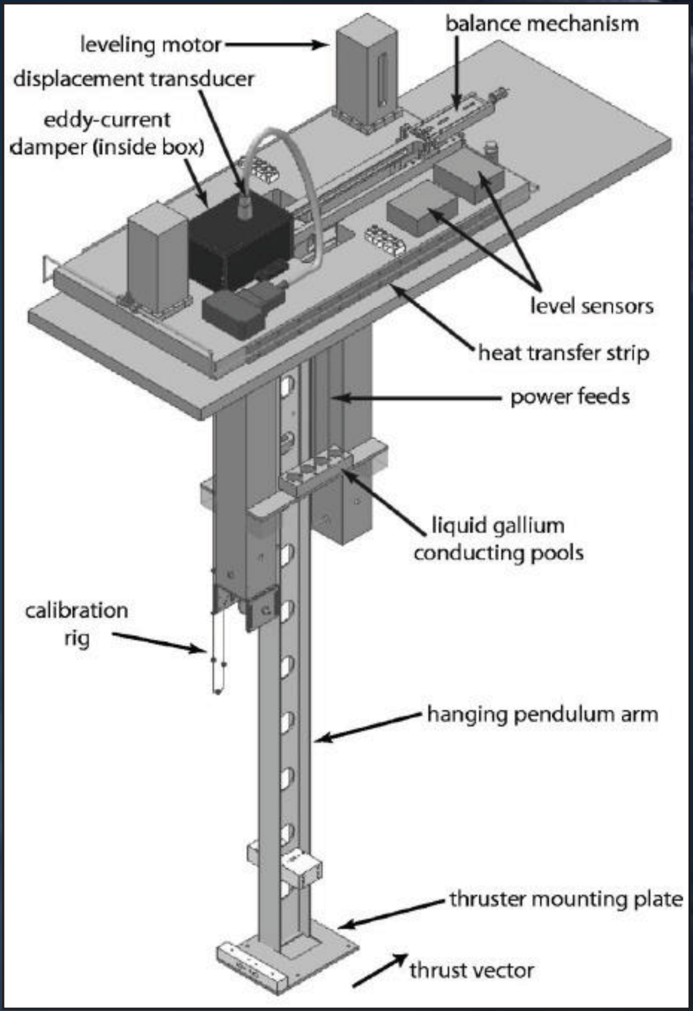
Measurement at MSFC

High-fidelity thrust stand

- **Thrust levels ~1 mN – 1 N (50 μN resolution)**
- **Impulsive resolution below 1 mN-s ***
- **Steady-state or pulsed *in-situ* calibration**







Rev. Sci. Instrum., by Wong, Toftul, Polzin, Pearson, Feb. 2012

Second Capacitor PIT Design

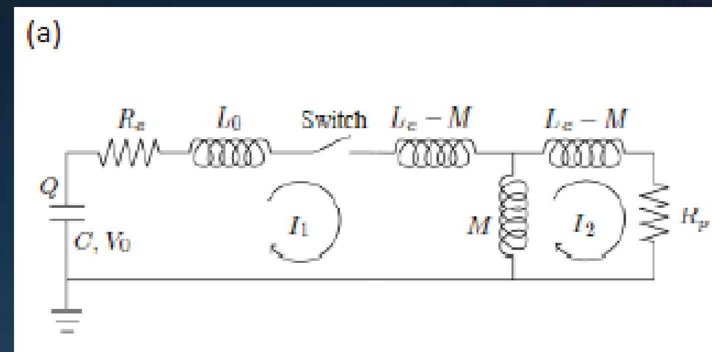
- Traditionally, the PIT uses one capacitor with a switch to send current to the thruster coil.

- Addition of a capacitor
  - Increases current rise rate through the inductive coil
  - Better ionizes the propellant
  - May eliminate the need for pre-ionization

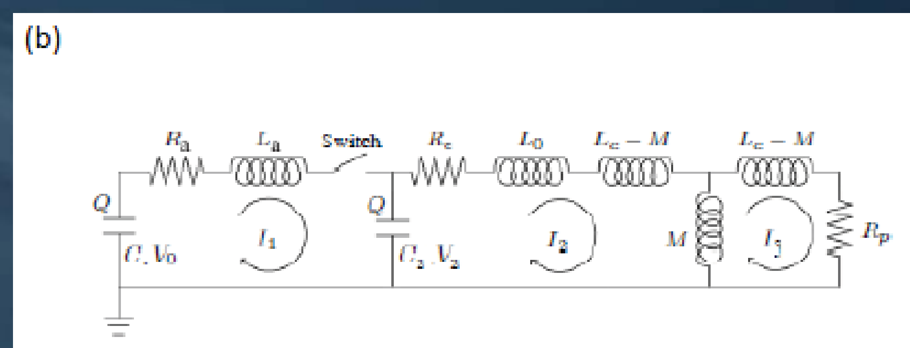
- Numerical Analysis of the two capacitor case was performed.

- Paper on the two capacitor case:

"Pulse Inductive Plasma Accelerator Effect of a Second, Parallel Capacitor on the Performance," Polzin, Sivak, and Balla. 2011.



(a) Schematic of a traditional PIT circuit with one capacitor.



(b) Schematic of the PIT circuit with a second capacitor.

Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

A key technology element in Nuclear Thermal Propulsion is the development of fuel materials and components which can withstand extremely high temperatures while being exposed to flowing hydrogen. NTREES provides a cost effective method for rapidly screening of candidate fuel components with regard to their viability for use in NTR systems

Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

- **The NTREES is designed to mimic the conditions (minus the radiation) to which nuclear rocket fuel elements and other components would be subjected to during reactor operation.**

- **The NTREES consists of a water cooled ASME code stamped pressure vessel and its associated control hardware and instrumentation coupled with inductive heaters to simulate the heat provided by the fission process.**

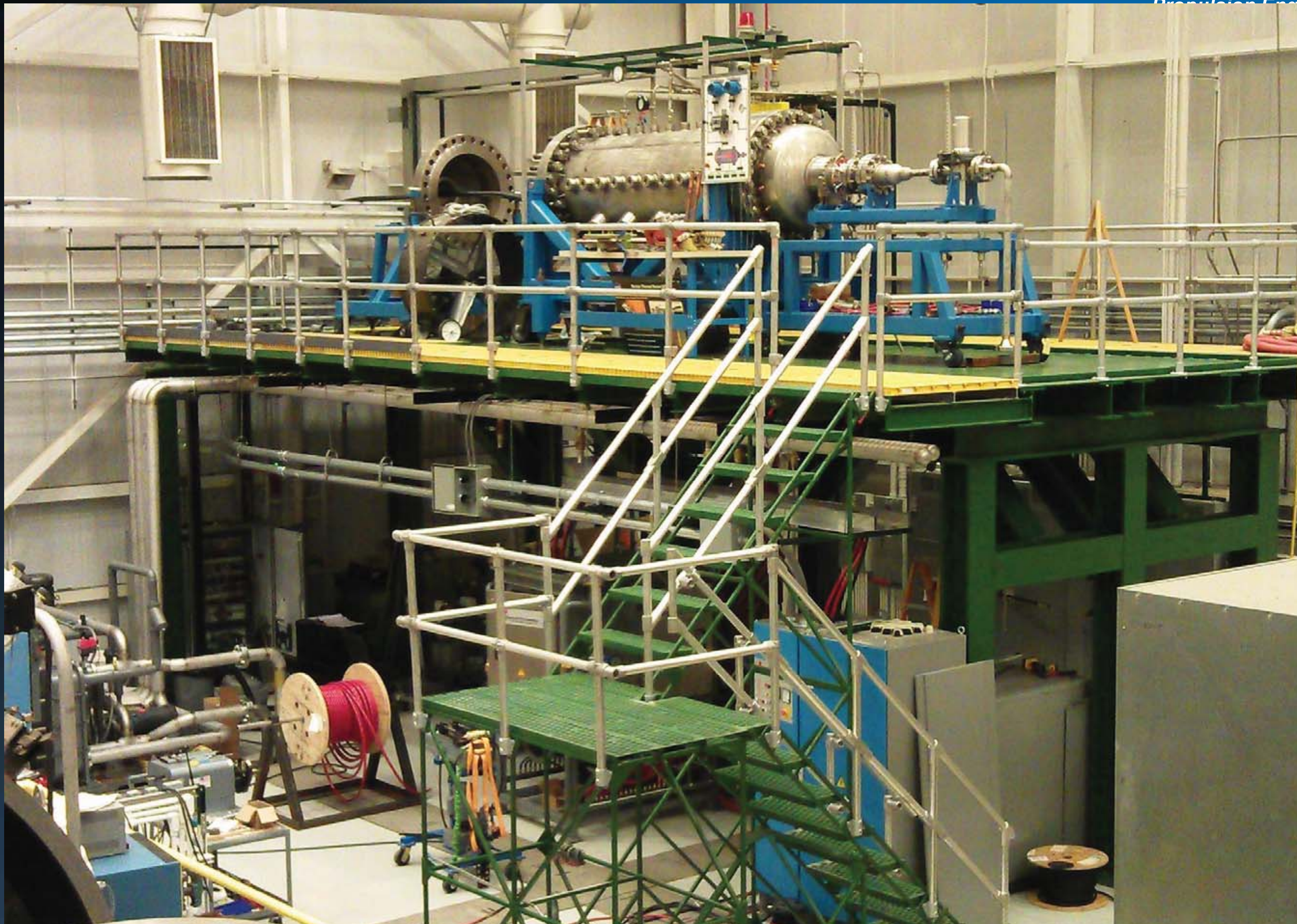
- **The current NTREES upgrade will increase the induction heating capacity by a factor of 30 over the previous configuration (now 1.2 MW)**

- **In addition to the power upgrade, there will be numerous enhancements to the data acquisition and control system**

Description of NTREES Upgrade Activities

- Much of the NTREES system is being relocated on top of a platform to conserve space and increase safety
- NTREES induction power supply is being upgraded to 1.2 MW
- Water cooling system is being upgraded to remove 100% of the heat generated during testing
- Data acquisition system is being upgraded to detect the release of radioactive particles and provide addition system performance data
- The H_2 / N_2 mixer is being upgraded to handle increased heat loads of up to 5 MW

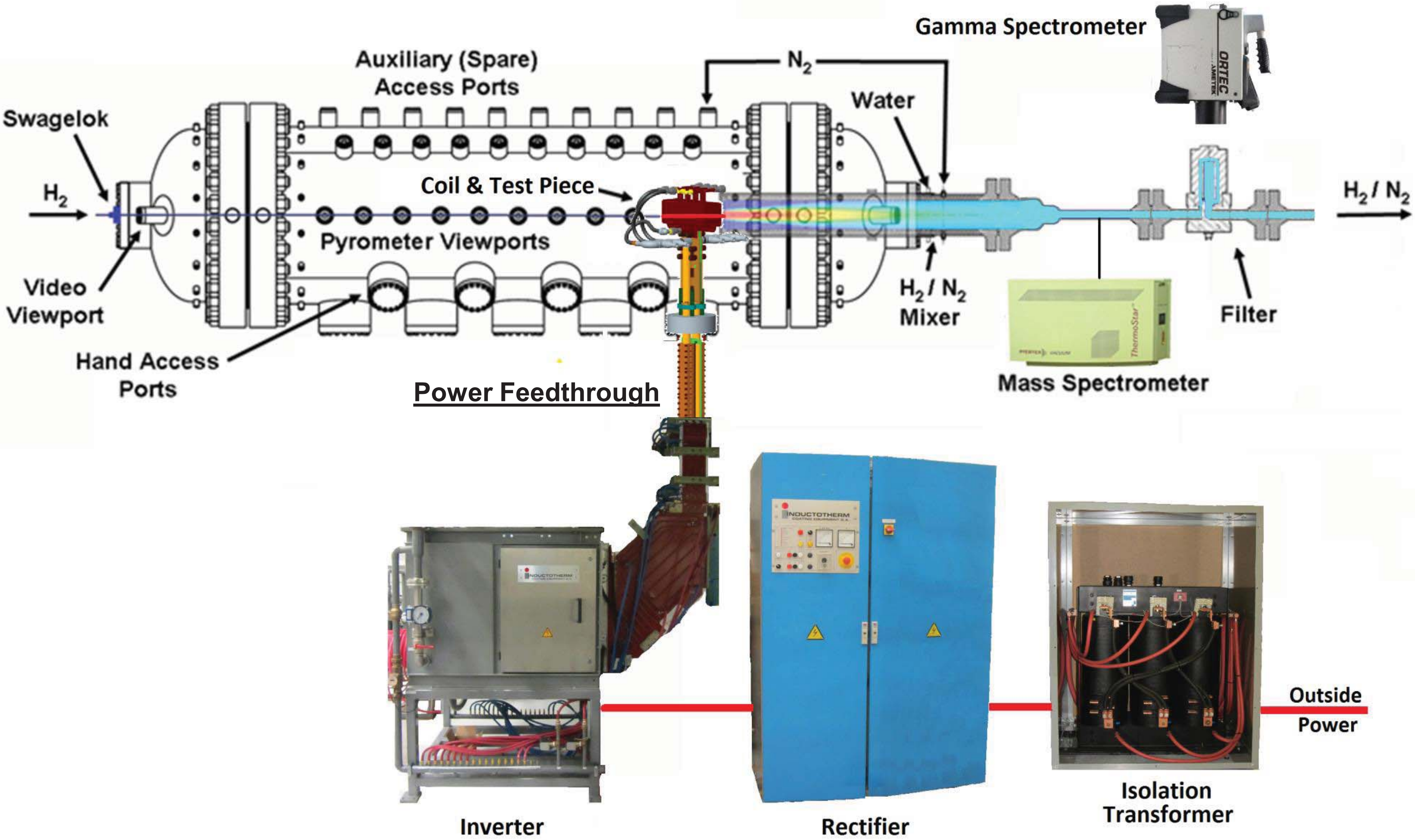
Current View of the NTREES Facility



NTREES Upgrade to 1.2 MW

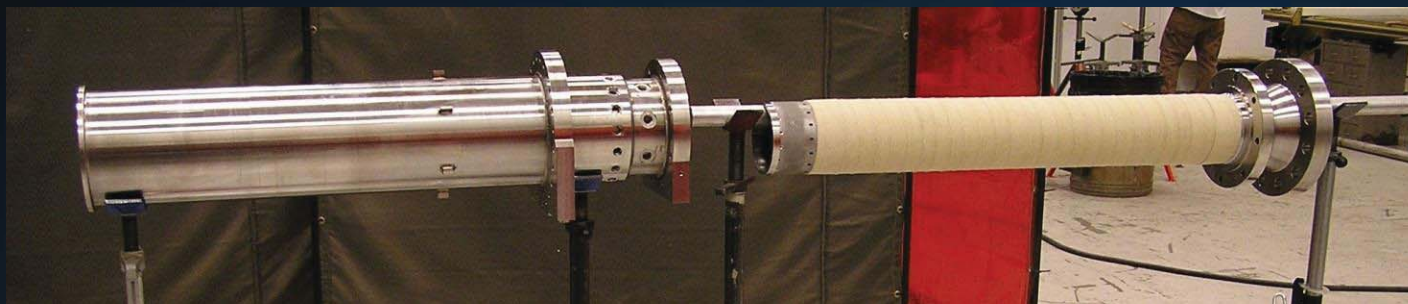
- Water cooling system
- Construction the H_2/N_2 mixer
- Test article induction coil
- Induction heater power bussbar and feedthrough installation
- Installation of the nitrogen line is complete and pressure certification activities
- Exhaust line installation
- Induction heater power connections
- Data acquisition and control system activities

New NTREES System Layout

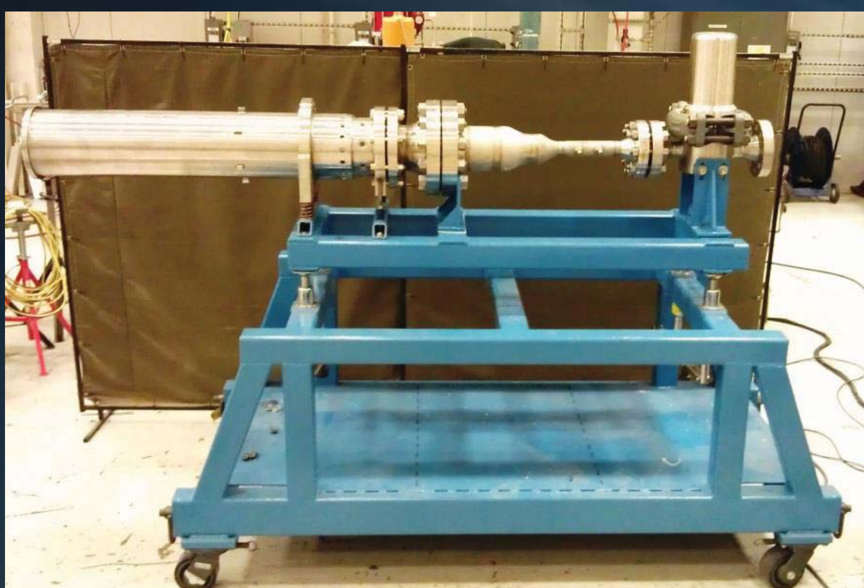


Induction Heater - 1.2 MW, 20 - 60 kHz

NTREES H2 / N2 Mixer Assembly

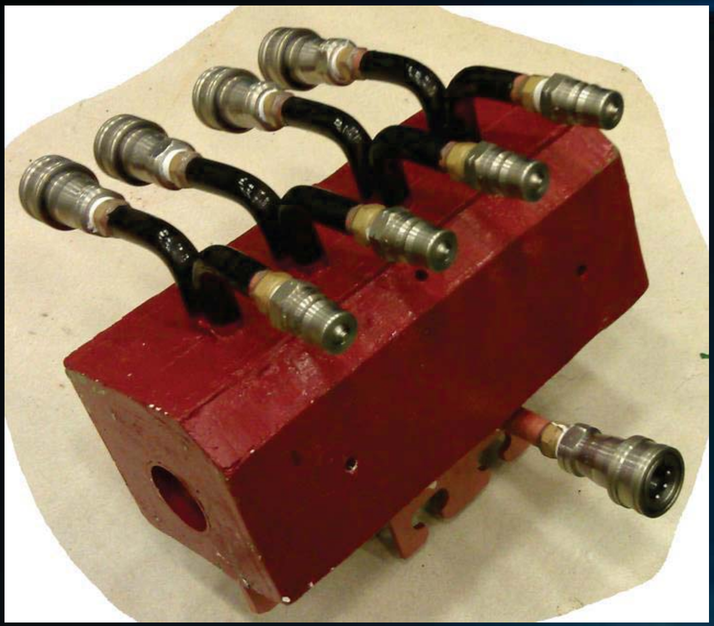


H2 / N2 Mixer Installed on Main Chamber

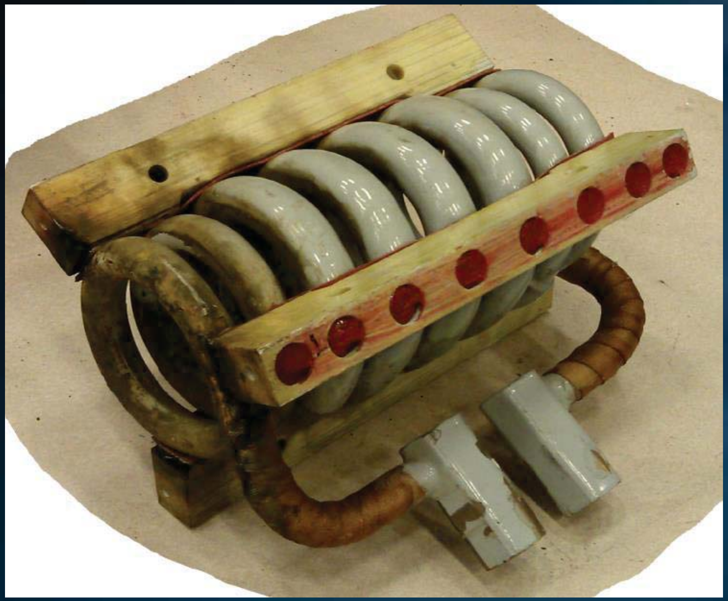


NTREES Coil and Feedthrough

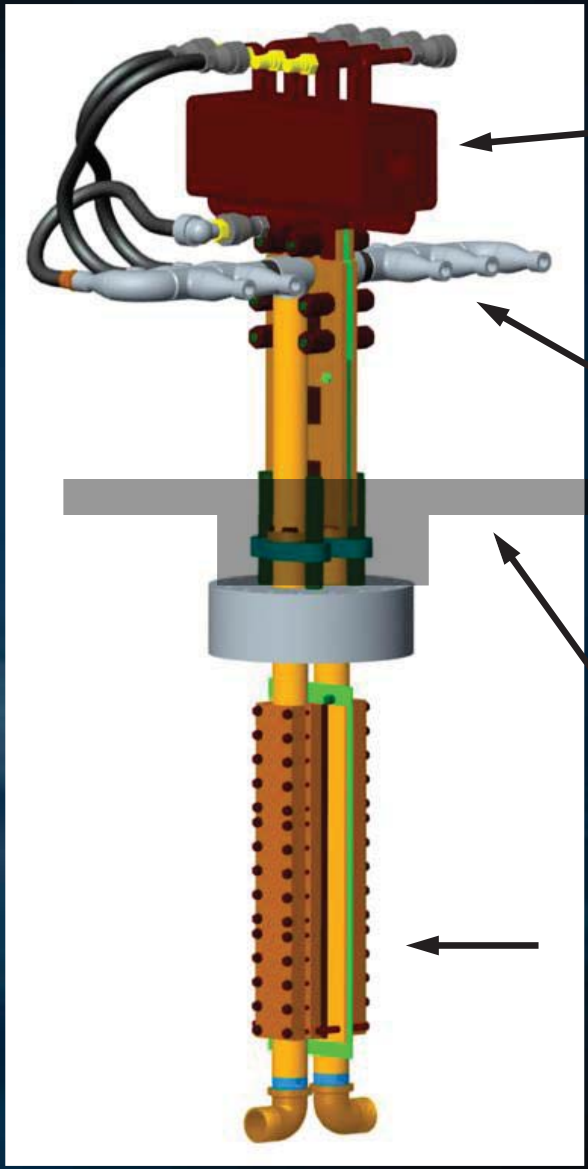
Coil and Feedthrough Assembly



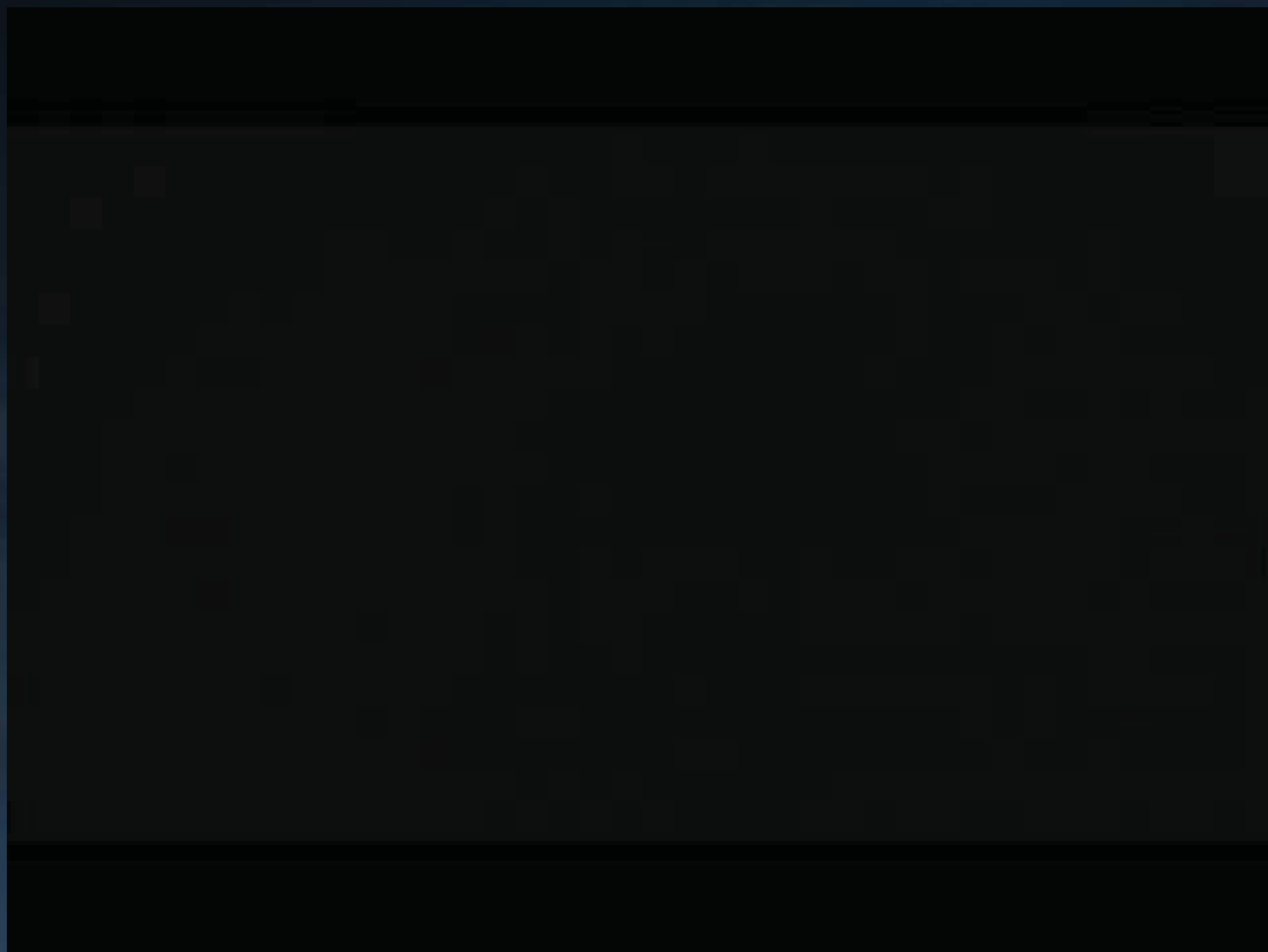
New Coil is Heavily Insulated and Rugged



Old Coil was Uninsulated and Somewhat Fragile



Test Run of NTREES



Pyroelectric Microthruster

Propulsion Engineering

- **Use on microsatellites**
  - **Low thrust technology**
  - **Utilizes solar heating and a Pyroelectric Lithium Tantalate Crystal for power source.**

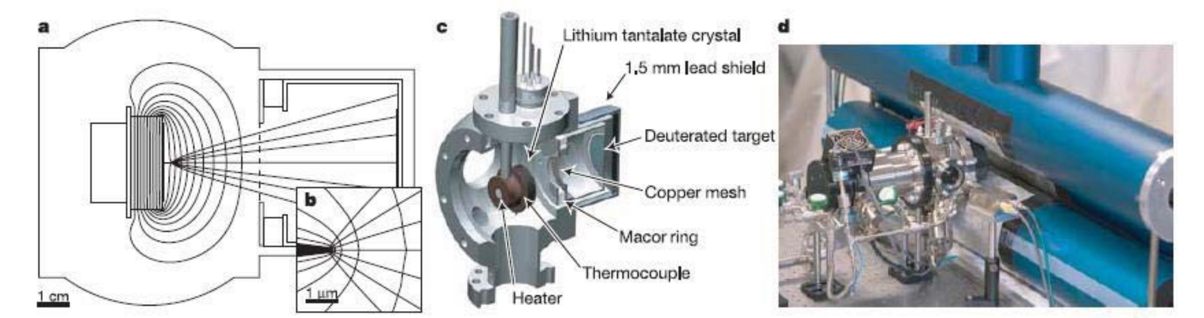


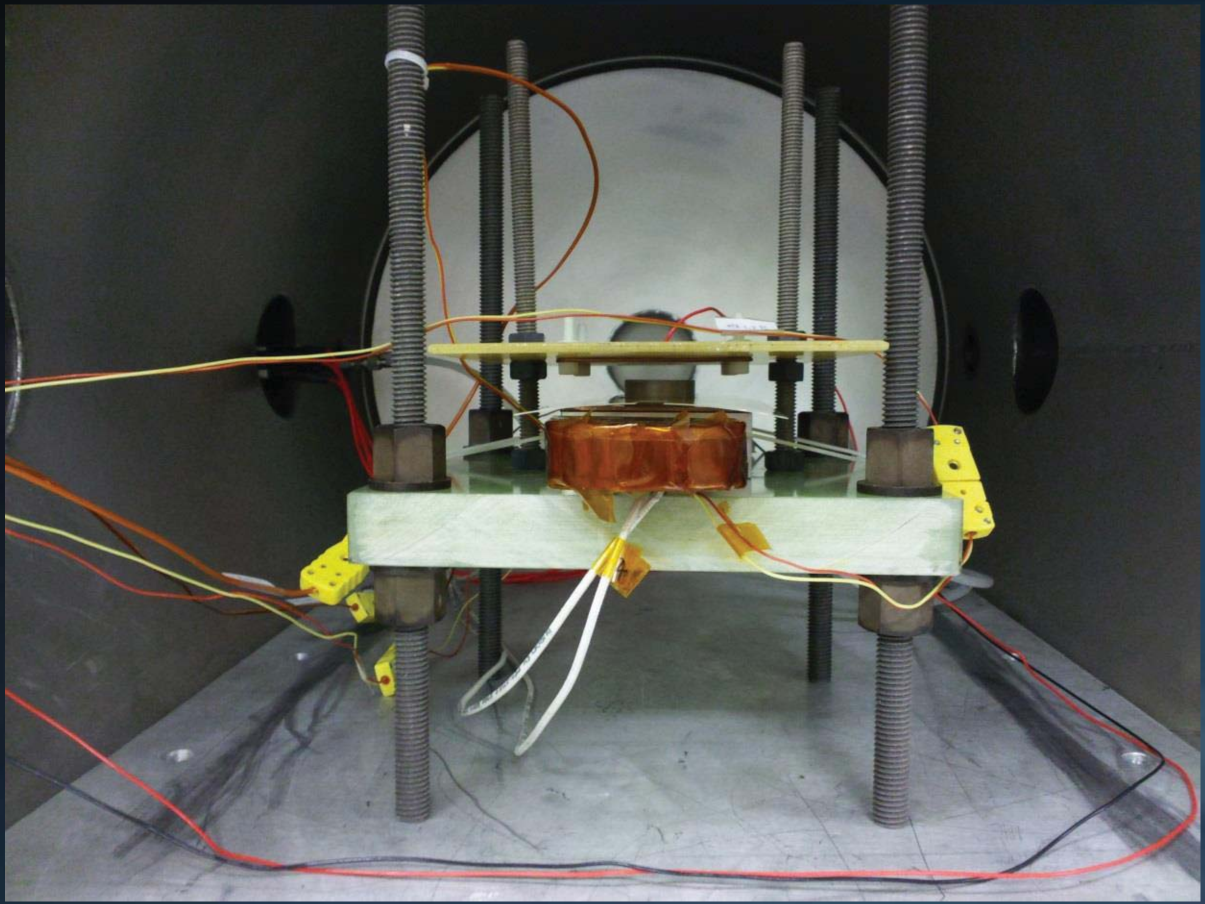
Figure 1 Experiment geometry. **a**, Calculated equipotentials and D^+ trajectories for a crystal charged to 100 kV; calculations were performed using finite-element methods. The grounded copper mesh (85% open area, 19.8-µm wire; vertical dashed line) shields the Faraday cup (right). The cup and target are connected to a Keithley 6485 picoammeter and biased to +40 V to collect secondary electrons and help prevent avalanche discharges. **b**, Same trajectories shown near the tip. Using a shorter tip reduces the beam's angular spread. **c**, Vacuum chamber cut-away view. D_2 pressure was set using a leak valve and monitored with a D_2 compensated Pirani gauge. The target was a molybdenum disc coated with ErD_2. **d**, Arrangement of neutron and X-ray detectors (Amptek XR-100T-CdTe). To better resolve the bremsstrahlung endpoint, a 2.5-cm aluminium filter (not shown) was placed between the X-ray detector and the viewport. The vacuum chamber's thick stainless steel walls and lead sheet shielded the neutron detector from X-rays.

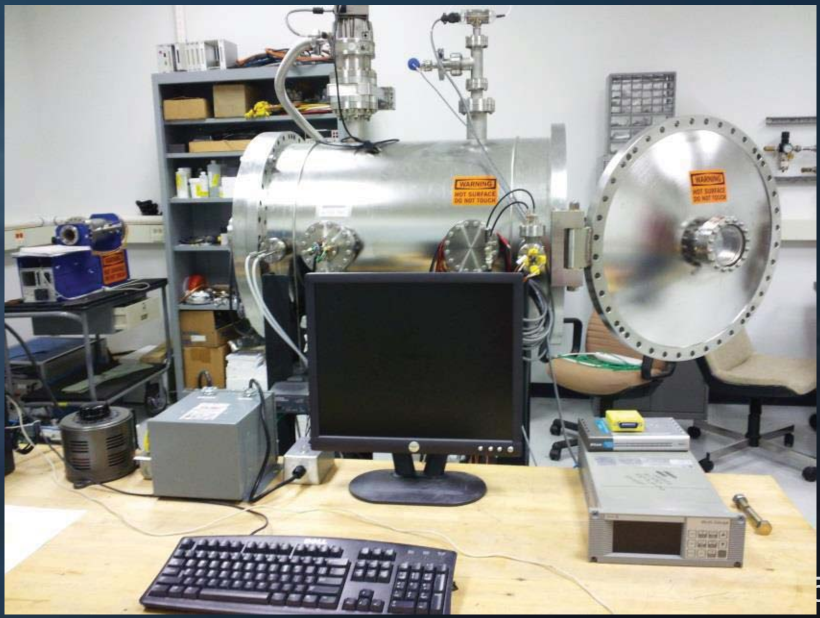
Observation of Nuclear Fusion Driven by a Pyroelectric Crystal. **Naranjo, B., J.K. Gimzewski, and S. Putterman. s.l. : Nature, Apr. 2005, Vol. 434**

- Prior scientific experiment preformed using pyroelectric Lithium Tantalate Crystal
- Design is driven by a pyroelectric crystal, Lithium Tantalate, which produces an electric field when subjected to a temperature cycle.
- Electric field ionizes surrounding deuterium gas which hits an Erbium Dideuteride/ Tritiate Water target to produce a small amount of neutrons.
- Low level neutrons produced, just above background.

D + D -> 3He (820 keV) + n (2.45 MeV)

Pyroelectric Microthruster Test Setup





Results Comparable to Literature

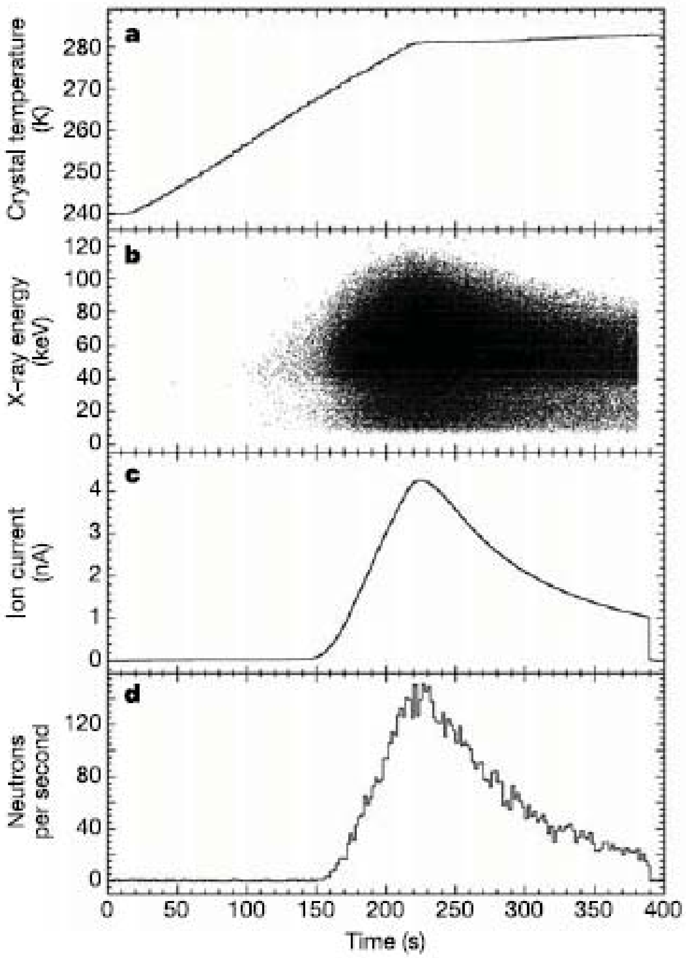


Figure 2 Data from a single run (see also Supplementary Movie 1). **a**, Crystal temperature. The heating rate was 12.4 K min^{-1}, corresponding to a pyroelectric current of 22 nA and a heating power of 2 W. **b**, X-rays detected. **c**, Faraday cup current. **d**, Neutrons detected.

<u>Current and dT/dt During Heating</u>

<u>Observation of Nuclear Fusion Driven by a Pyroelectric Crystal.</u> **<u>Naranjo, B., J.K. Gimzewski, and S. Putterman. s.l. : Nature, Apr. 2005, Vol. 434</u>**

EP Opportunities with ER24

- Full multidimensional MHD modeling of plasma flows in thrusters and magnetic nozzles
  - Code exists, but may need modified for different conditions, boundary types, and to include additional physics.
  - Also, there is no graphical interface to using the code, so a good graphical interface person might be useful in making the code more usable/accessible as development goes forward. (the modeling is actually a good modeling problem and the GUI design/implementation would be a good project for a computer sciences major.)
- Detailed study/modeling of a triple probe for plasma measurements.
- Help with fabrication/testing of ablative z-pinch thruster.
- Design//fabrication of a thrust measurement apparatus that can measure thrust levels from steady-state to (time-resolved) pulsed thrust levels on the microsecond or faster timescales.
- Multiphysics modeling of the interaction between a flowing plasma and a magnetic field probe inserted into the flow, including the release of magnetic field from the plasma into the probe (which permits measurement of the magnetic field)
- Modeling (theoretical and maybe multiphysics) of the issue of current sheet canting (tipping) in pulsed plasma accelerators.
- Multiphysics modeling of a liquid metal electromagnetic induction pump.

Nuclear and Other Opportunities with ER24

- Inertial Electrostatic Confinement (IEC) fusion device at the Marshall would be used to produce fusion neutrons which would be captured in thorium foils mounted on the outside of the IEC. Subsequent neutron energy measurements would help establish concept viability.
- Perform detailed CFD analyses of the new configuration has been proposed called the Grooved Ring Fuel Element that addresses the problem of low thrust to weight in the Rover/NERVA engine design, and then experimentally verify the analysis using a prototypical fuel element in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES).
- Work toward improved performance of NTR systems by augmenting propellant heating resulting from its passage through the nuclear reactor by an after heater consisting of a high power arcjet or MHD system.
- Test the feasibility of operating uranium fuel at the highest possible temperature consistent with maintaining structural integrity, by encasing uranium in a higher melting point material such as Ta_4HfC_5 and operating the uranium above its melting point.
- Help with testing of the Pyroelectric Thruster.
- Multiphysics modeling of the Pyroelectric Thruster.

Contacts

Amy Sivak

amy.sivak@nasa.gov

Dr. Kurt Polzin – Electric Propulsion Lead

kurt.a.polzin@nasa.gov

Dr. Bill Emrich – Nuclear Propulsion Lead

bill.emrich@nasa.gov

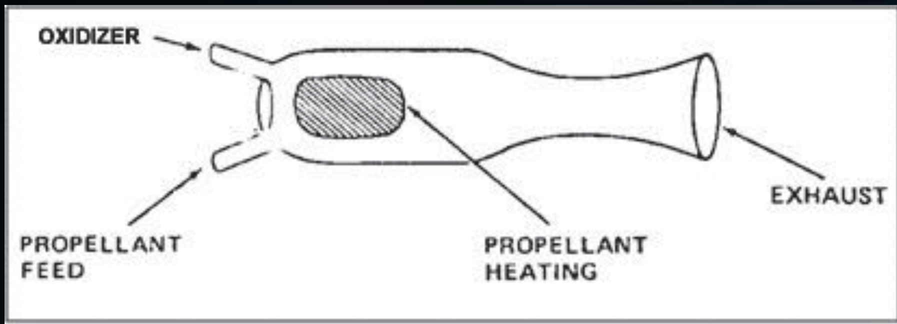
For Information on Co-op / Internship

- Cooperative Education – http://coop.msfc.nasa.gov
- Internships – http://www.nasa.gov/centers/marshall/education
  - Opportunities listed under the links "Higher Education" and "Other Educational Opportunities."
  - Mona Miller (mona.miller@nasa.gov)
  - Tina Haymaker (tina.c.haymaker@nasa.gov)
- To apply for internships – https://intern.nasa.gov
- Student Opportunity PODCASTS available at www.nasa.gov/nso

BACK UP

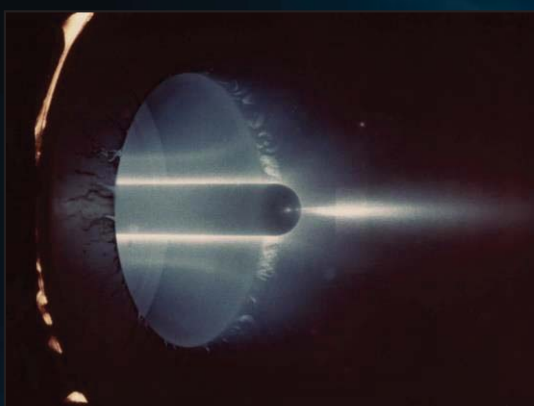
What is Electric Propulsion?

- Chemical Rocket

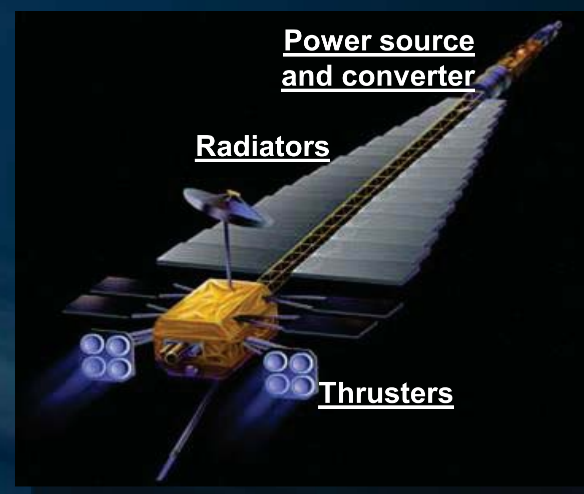


Chemical Energy
↓
Thermal Energy (high entropy)
↓
Directed Kinetic Energy

- "Electric" Rocket



Electrical Energy (refined low entropy)
↙ ↘
Thermal Energy (high entropy) | Electromagnetic Field Energy (low entropy)
↓ | ↓
Directed Kinetic Energy | Directed Kinetic Energy

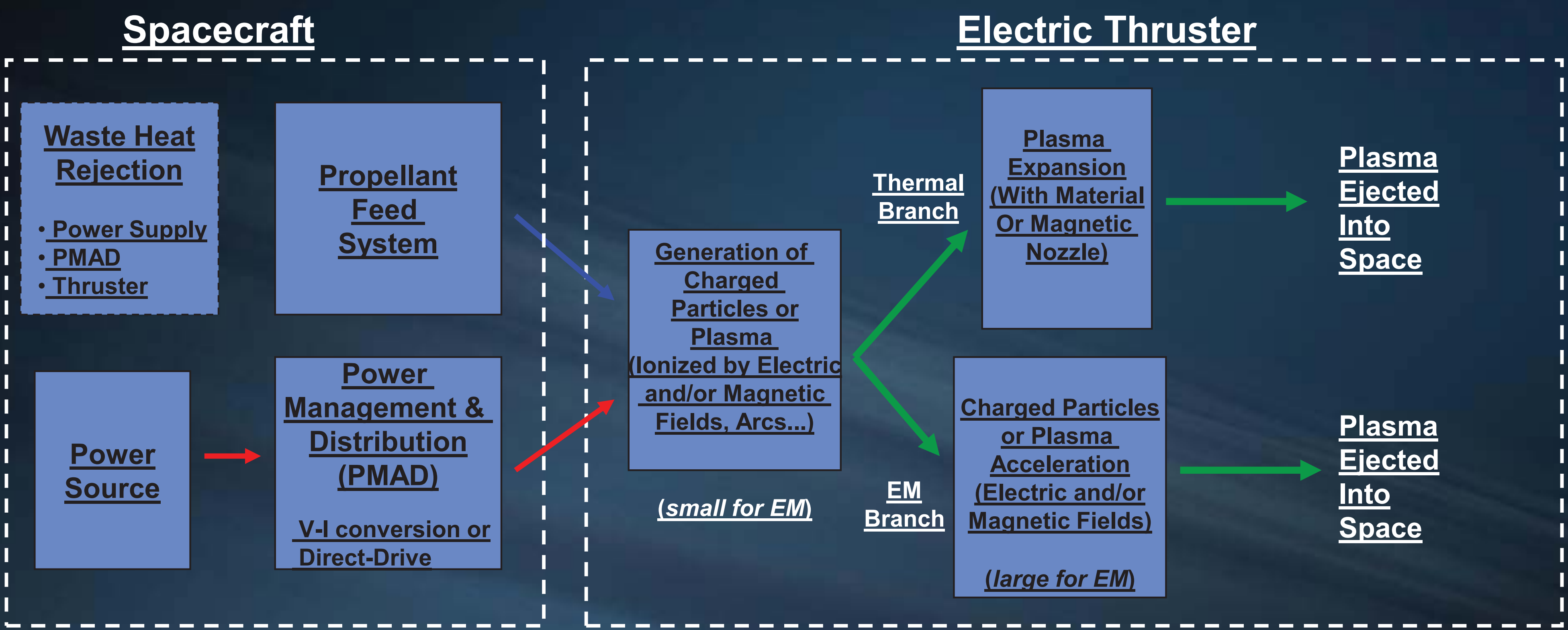


The acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces.

- Uses: Orbit raising, momentum dumping, stationkeeping, primary propulsion
- Power system supplies refined energy enabling high I_{sp}
- Thrust level dependent on available power

Electric Propulsion – Simplified System

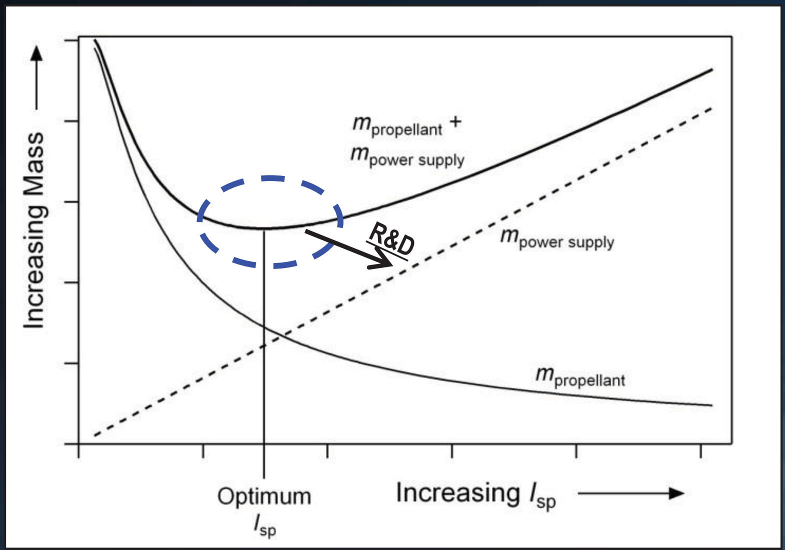
- Spacecraft system: propellant, power, heat rejection, & PMAD systems provide electrical power condition to meet thruster input requirements (flowrate, gas pressure, voltage, current, operating duration (pulsed/steady-state)).
- Thruster system: operates in either a steady-state or pulsed fashion to convert electric power into propellant jet power by creating ions or a plasma and accelerating them into space.



- Direct-drive can simplify the system by eliminating components, but limits power supply choices linking them directly to thruster operating requirements

Electric Propulsion – Power & Mass Relationship

- Power source is decoupled from propellant
  - No longer constrained by the energy available in chemical bonds
  - Electrically accelerate propellants to high velocities ($u_e \approx \Delta v$)
  - Tempered by mass of power supply, conversion efficiency, etc.



- Minimized propulsion system mass at an optimum I_{sp} for a fixed mission duration and power system
- For fixed power system and IMLEO, increasing I_{sp} from optimum lowers payload mass
- Improvements in power conversion (power supply specific mass) pushes optimum I_{sp} higher OR can provide more thrust, decreasing mission duration

- High Efficiency Solar
  - Specific Mass of 10-12.5 kg/kW$_e$
    SOA, 5-6.5 kg/kW$_e$ (goal)
  - ISS – ~250 kW$_e$
  - Typical US Comsat – 15-20 kW$_e$
  - Moderate Potential Growth

- Nuclear (Fission)
  - Uranium 235 fueled
  - Brayton/ Stirling Cycles
  - ~30 kg/kW$_e$ (at 100 kW$_e$ to 1 MW$_e$)
  - ~12 kg/kW$_e$ (at > 1 MW$_e$)
  - Significant Future Growth

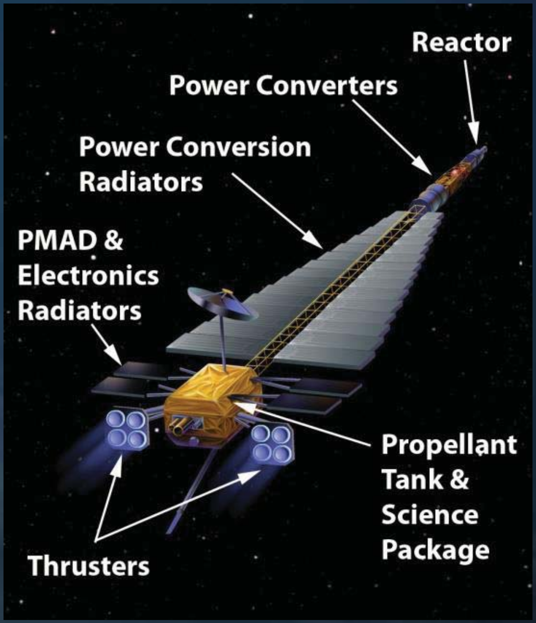
- Nuclear (Radioisotope)
  - Plutonium decay
  - Thermoelectric/Stirling Cycle
  - Specific Mass of ~200 kg/kW$_e$
  - Limited Future Growth

- For up to 500 kW$_e$ photovoltaics are reasonable (up to football-field size), but start to become physically unwieldy and less competitive compared to nuclear above this power level.

EP – Waste Heat Rejection

Propulsion Engineering

- System requires means to reject waste heat generated due to inefficiencies
  - Power Supply – 5-30% efficient – 70+% thermal energy radiated
    - High temperatures reduce radiator size (materials research issue)
  - PMAD/PPU – ~90% efficient – 10% of power supply output radiated
  - Thruster
    - Thermal – ~50% max efficiency – 50% of PMAD output radiated
    - Electromagnetic – 50-75% efficiency – 25-50% of PMAD output radiated

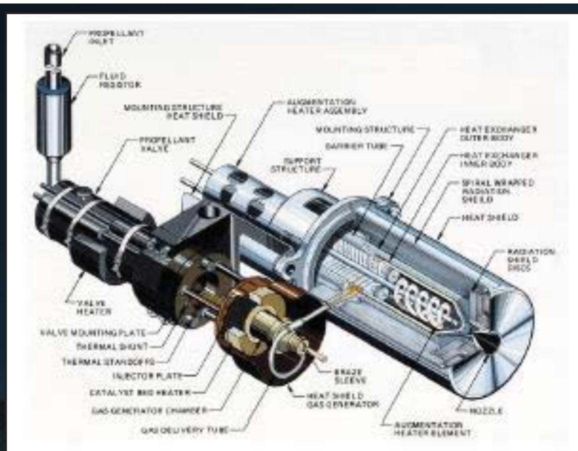


- Each step for an EP power system has a conversion inefficiency
  - Requires large radiators for heat rejection
  - Practical limits to system efficiency even if thruster is 100% efficient
  - Pushes EP to missions with higher Δv increments so gains made using a high I_{sp} system outweigh the inefficiencies (and associated masses) of the power system

- Benefits to direct energy conversion
  - Direct-Drive, coupling power supply to thruster with minimal/no PMAD
  - Nuclear power – direct tapping of low entropy, high energy particles (non-thermal power)

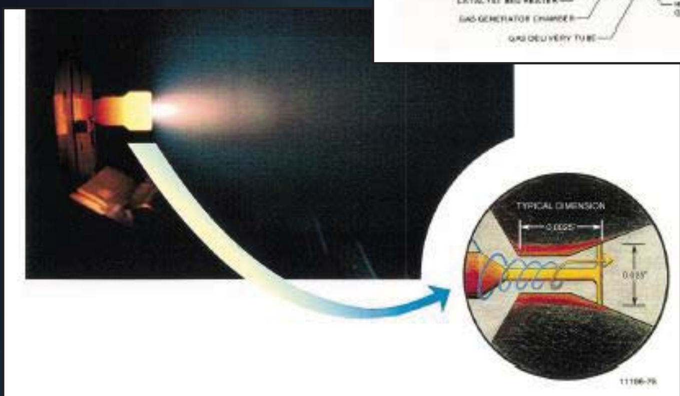
EP Thrusters - Electrothermal

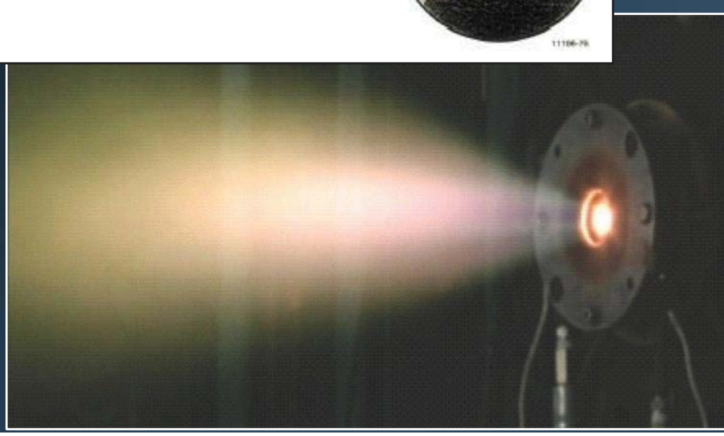
- **Electrothermal Thrusters**
  - **Heat propellant and expand through a nozzle**



Resistojet

- Heating element heats gas flow
- Power typically < 1-kW
- Thrust < 1-N, I_{sp} < 600-s
- Satellite station-keeping
- in-flight (*e.g.* Olin MR-501: 500-W, 300-s)
- Typical Propellants: Hydrazine, Ammonia





Arcjet

- Electric arc heats gas flow
- Power typically < few-kW
- Thrust < 2-N, I_{sp} < 1500-s
- Station-keeping, orbit maneuvers
- in-flight (*e.g.* Olin MR-510: 2-kW, 600-s)
- Typical Propellants: Hydrazine, Ammonia

- MSFC work on research-level high power arcjets (1MW, 1500s, 20 lb_f on H_2 and ammonia)v

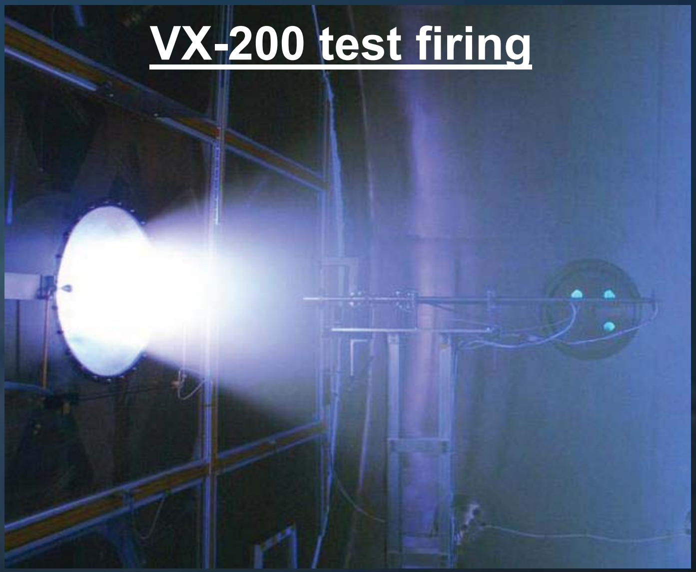
EP Thrusters - Electrothermal

Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

- Operation composed of 3 main subsystems

Neutral Gas →	1. Ionizer	→	2. Booster	→	3. Magnetic Nozzle	→ High Energy Ions
	Turn neutral gas to plasma		Add Energy to Ions		Convert perpendicular energy to thrust	
	↑ Electrical Energy		↑ Electrical Energy			

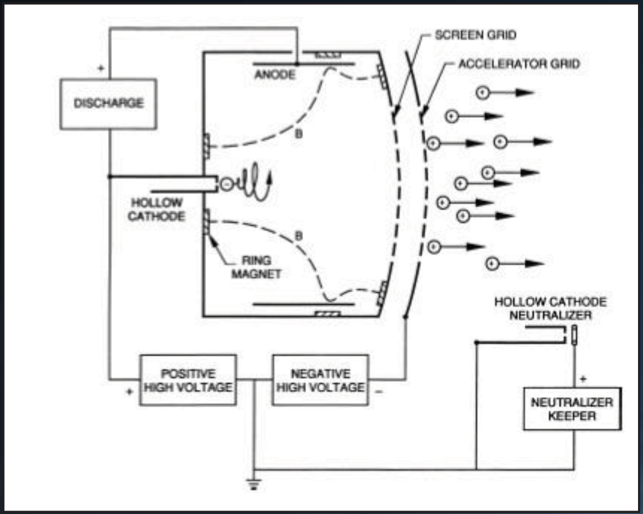
- Electrodeless, quasi-neutral plasma propulsion capable of using various propellants and operating at variable specific impulse at constant power. (thrust inversely proportional to I_{sp})
- research level. Thruster operated in pulsed mode at 200 kW_e in vacuum chamber.
- Issues: overall system efficiency /specific mass, RF power processing for high power operation
- Deep-Space Manned / Cargo missions

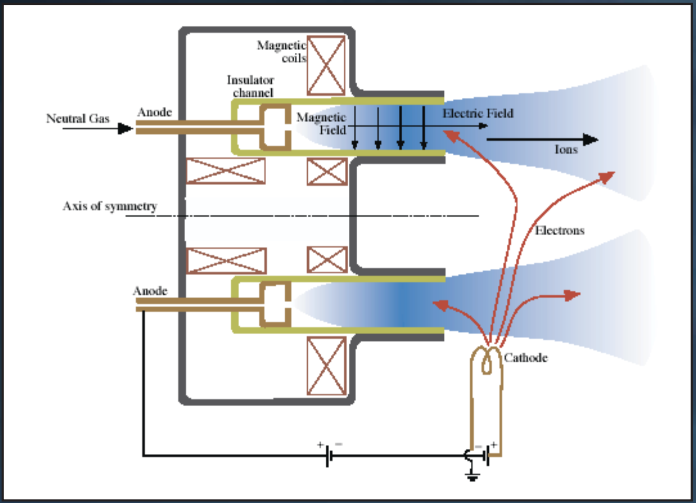


VX-200 test firing

EP Thrusters - Electrostatic

- **Electrostatic Thrusters**
  - High voltages directly accelerate ions





Ion Thruster

- Voltage generated by high voltage grids
- Power typically < 20-kW
- Thrust < 0.5-N, I_{sp} < 5000-s
- Station-keeping; LEO-GEO; deep space
- in-flight (*e.g.* NASA NSTAR: 2.5-kW, 3300-s)
- Typical Propellant: Xenon

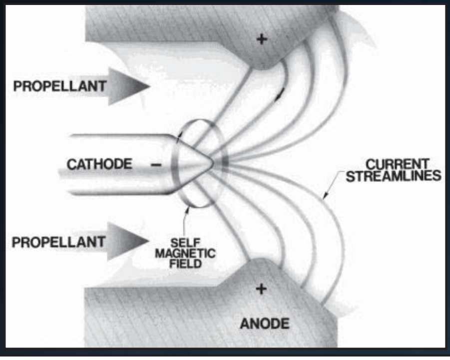
Hall Thruster

- Voltage concentrated by trapped electrons
- Power typically < 50-kW
- Thrust < 1-N, I_{sp} < 3000-s
- Station-keeping, LEO-GEO, LEO-Lunar
- in-flight (*e.g.* BPT-4000: 4.5-kW, 1850-s)
- Typical Propellants: Xenon, Krypton
- Alternate Propellants: Iodine, Bi, Mg

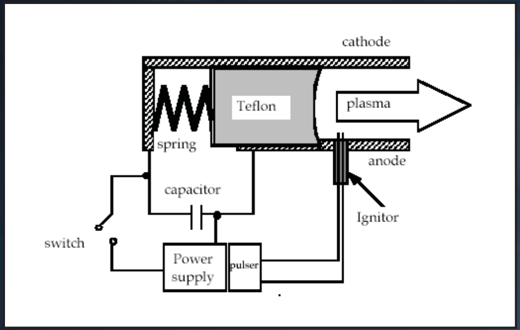
- MSFC examining Iodine Hall (solid propellant substitute) / partners w/Busek, GRC

EP Thrusters - Electromagnetic

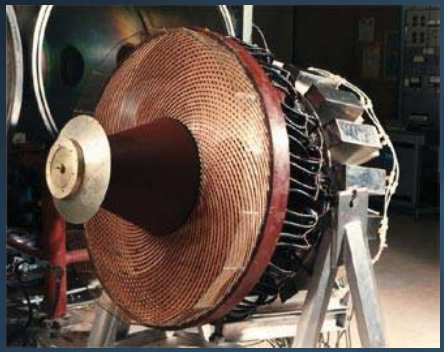
- **Electromagnetic Thrusters**
  - Use Lorentz (jxB) force to accelerate plasma



Magnetoplasmadynamic (MPD)
- High power, high thrust density
- Thrust ~ 1-10's N, I_{sp} ~ 2500-s to >10000-s
- Orbit raising, primary propulsion for planetary
- research level (~ 250-kW steady-state, > 1 MW quasi-steady)
- Propellants: Argon, Hydrogen, Lithium

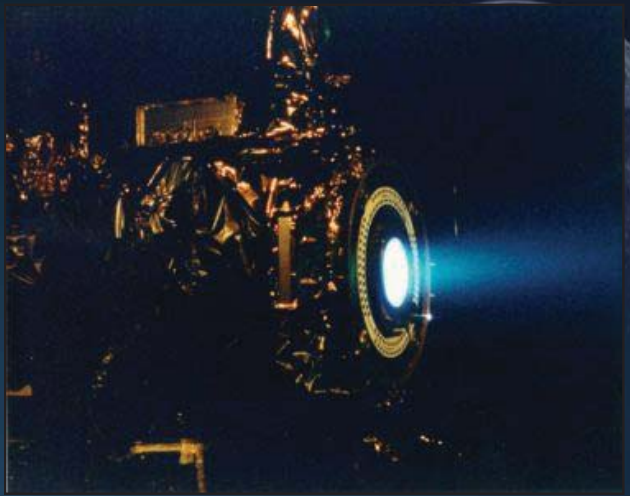


Pulsed Plasma Thruster (PPT)
- Low continuous power, precise impulse bits
- Impulse < 0.3-N-s, I_{sp} ~ 2500-s to >10000-s
- Station-keeping, drag make-up
- in-flight (*e.g.* LES-9: 30-W, 1000-s)
- Typical propellant: Teflon



Pulsed Inductive Thruster (PIT)
- High power, high thrust density
- Electrodeless (needs high power switches)
- Impulse < 0.1-N-s, I_{sp} ~ 2000-s to >10000-s
- Orbit raising, primary propulsion for planetary
- research level (tested in single-shot operation)
- Typical propellants: Ammonia, *In-Situ* propellants

Difficulties with TRL Advancement



- **Limited Number of Test Facilities**
  - With higher power, fewer vacuum facilities suited to host operation /qualification testing (primarily a pumping speed issue)
- **Lifetime Evaluation and Qualification**
  - Qualification by test for a deep-space mission requires tens of thousands of hours of continuous operation
  - Mission start could be sooner than the amount of time needed for full lifetime qualification
- **Component Availability**
  - Components, especially in the power system, are limited in number, especially for high power systems
  - Limited number of EP-powered deep-space flights mean qualified components are deprecated or obsolete for ensuing / follow-on missions (spaceflight community as a whole, including NASA, not the driving customer base for electrical / electronics components) [fewer required components make Direct-Drive relatively attractive]
- **Power**
  - Power availability for testing (available power from the electric grid, lab or PPU supplies capable of converting input grid power to the type needed by the thruster)
  - Relative low power available in space… power system (supply and PPU) lag thruster development [fewer required components in PPU make Direct-Drive relatively attractive]

Circuit Equations

- **One Capacitor Equations**

$$\frac{dI_1}{dt} = \frac{V L_C + (M I_1 + I_2 L_C)\frac{dM}{dt} - I_2 M R_p - I_1 R_e L_C}{L_C(L_0 + L_C) - M^2}$$

$$\frac{dI_2}{dt} = \frac{M\frac{dI_1}{dt} + I_1\frac{dM}{dt} - I_2 R_p}{L_C}$$

$$\frac{dV}{dt} = -\frac{I_1}{C}$$

- **Second Capacitor Equations**

$$\frac{dI_1}{dt} = \frac{V_1 - V_2 - n\mathrm{R_e} I_1}{nL_0},$$

$$\frac{dI_2}{dt} = \left\{L_C V_2 + (L_C I_3 + M I_2)\frac{dM}{dt} - (1-n)\mathrm{R_e}\, L_C I_2 - R_p M I_3\right\}$$
$$/\left\{L_C[(1-n)L_0 + L_C] - M^2\right\}$$

$$\frac{dI_3}{dt} = \frac{I_2\frac{dM}{dt} + M\frac{dI_2}{dt} I_3 R_p}{L_C},$$

$$\frac{dV_1}{dt} = -\frac{I_1}{C_1},$$

$$\frac{dV_2}{dt} = \frac{I_1 - I_2}{C_2},$$

$$M = -\frac{L_C}{2z_0} exp\left({}^{z}/_{2z_0}\right) v_z$$

$$\frac{L_C I_2^2}{2z_0} exp(-z/z_0) = \rho_A v_z^2 + m(t)\frac{dv_z}{dt}$$

Nondimensionalizing the Circuit Equations

- Equations used to nondimensionalize the circuit equations.

$$I_1^* = \frac{1}{V_0}\sqrt{\frac{L_0}{C}}I_1$$

$$I_2^* = \frac{1}{V_0}\sqrt{\frac{L_0}{C}}I_2$$

$$I_3^* = \frac{1}{V_0}\sqrt{\frac{L_0}{C}}I_3$$

$$t^* = \frac{t}{\sqrt{L_0 C}}$$

Scaling Laws

Found Within Equations

$$z^* = \frac{z}{z_0}$$

$$V^* = \frac{V}{V_0}$$

$$M^* = \frac{M}{L_C}$$

$$v_z^* = \frac{\sqrt{L_0 C}}{z_0}v_z$$

Scaling Parameters

$$L^* = \frac{L_0}{L_C}$$

$$\psi_1 = R_e\sqrt{\frac{C}{L_0}}$$

$$\psi_2 = R_p\sqrt{\frac{C}{L_0}}$$

$$\alpha = \frac{C^2 V_0^2 L_C}{2 m_{bit} z_0^2}.$$

- Propellant Mass as a Function of Position, z:

$$m^* = m_0^* + \int_0^{t^*} \rho^* f(z^*) v_z^* dt^*$$

where, $m_0^* = m_0 / m_{bit}$

and $\rho^* = \rho_0 z_0 / m_{bit}.$

Nondimensionalized Equation Set

- **One Capacitor Case Nondimensionalized Equations**

$$\frac{dI_1^*}{dt^*} = [L^*V^* + (M^*I_1^* + I_2^*)(dM^*/dt^*) - I_2^*M^*L^*\psi_2 - I_1^*L^*\psi_1] \,/\, [(L^*+1) - (M^*)^2]$$

$$\frac{dI_2^*}{dt^*} = M^*\frac{dI_1^*}{dt^*} + I_1^*\frac{dM^*}{dt^*} - I_2^*L^*\psi_2$$

$$\frac{dV^*}{dt^*} = -I_1^*$$

$$\frac{dM^*}{dt^*} = -\frac{1}{2}\exp\left(-\frac{z^*}{2}\right)v_z^*$$

$$\frac{dz^*}{dt^*} = v_z^*$$

$$\frac{dv_z^*}{dt^*} = \left[\alpha(I_1^*)^2\exp(-z^*) - \rho^* f(z^*)(v_z^*)^2\right] / m^*$$

$$\frac{dm^*}{dt^*} = \rho^* f(z^*) v_z^*.$$

- **Second Capacitor Case Nondimensionalized Equations**

$$\frac{dI_1^*}{dt^*} = \frac{1}{n}\left[V_1^* - V_2^*\right] - I_1^*\psi_1$$

$$\frac{dI_2^*}{dt^*} = \frac{V_2^*L^* - (1-n)I_2^*\psi_1 L^* + \frac{dM^*}{dt^*}\left[M^*I_2^* + I_3^*\right] - M^*I_3^*\psi_2 L^*}{\left[(1-n)L^* + 1\right] - M^{*2}}$$

$$\frac{dI_3^*}{dt^*} = M^*\frac{dI_2^*}{dt^*} + I_2^*\frac{dM^*}{dt^*} - I_3^*\psi_2 L^*$$

$$\frac{dV_1^*}{dt^*} = -I_1^*$$

$$\frac{dV_2^*}{dt^*} = C^*\left(I_1^* - I_2^*\right)$$

$$\frac{dM^*}{dt^*} = -\frac{1}{2}\exp\left(-\frac{z^*}{2}\right)v_z^*$$

$$\frac{dz^*}{dt^*} = v_z^*$$

$$\frac{dv_z^*}{dt^*} = \left[\alpha\left(I_1^*\right)^2\exp\left(-z^*\right) - \rho^* f(z^*)\left(v_z^*\right)^2\right] / m^*$$

$$\frac{dm^*}{dt^*} = \rho^* f(z^*)\left(v_z^*\right)$$

- **Initial Conditions**

$I_1^*(0) = 0$	$I_2^*(0) = 0$
$I_3^*(0) = 0$	$V_1^*(0) = 1$
$V_2^*(0) = 0$	$M^*(0) = 1$
$z^*(0) = 0$	$v_z^*(0) = 0$
$m^*(0) = \frac{m_0}{m_{bit}}$	

EP Thrusters - VASIMR

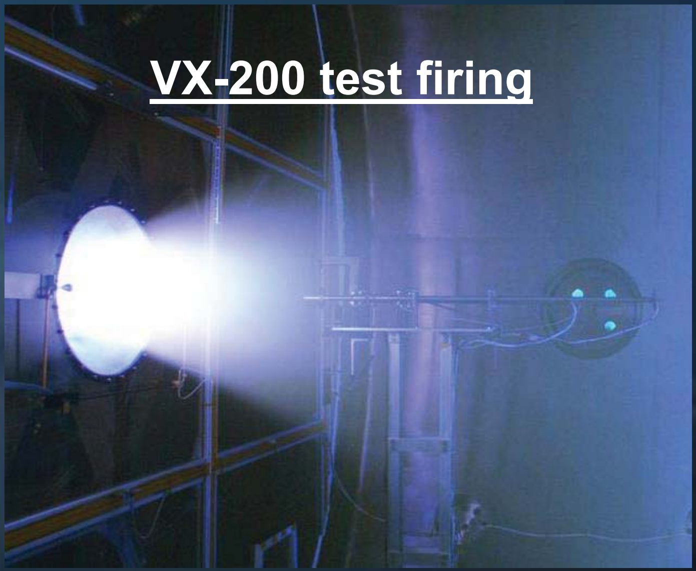
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

- Effort was led at JSC from 1993 to 2005 by Franklin Chang-Diaz. Dr. Chang-Diaz left NASA in 2005 to lead the Ad Astra Rocket Company and continued the development of VASIMR using private funds.
- VASIMR is composed of 3 main subsystems

Neutral Gas → **1.** Turn neutral gas to plasma (← Electrical Energy) → **2.** Add Energy to Ions (← Electrical Energy) → **3.** Convert perpendicular energy to thrust → High Energy Ions

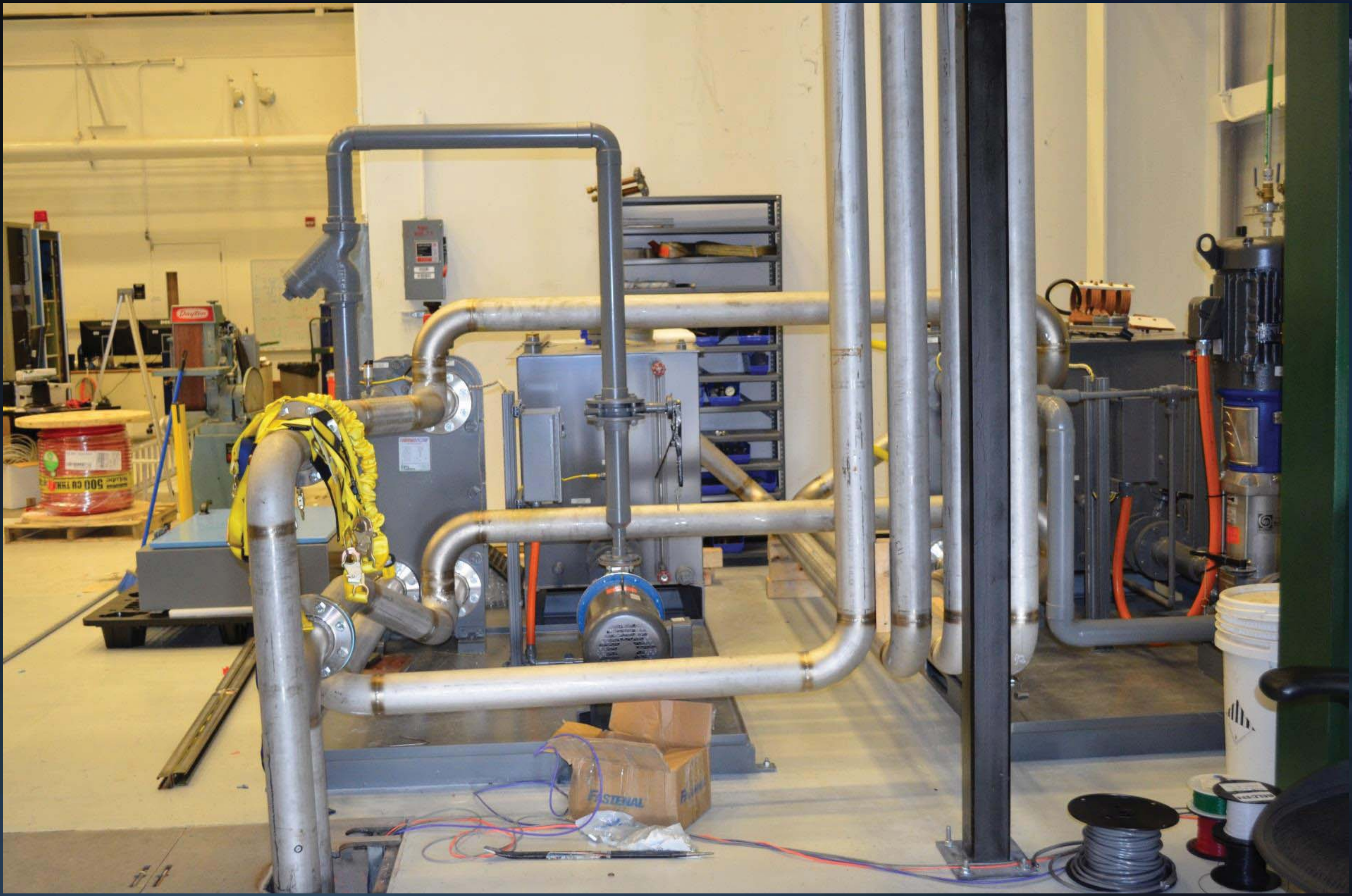
- VASMIR – electrodeless, quasi-neutral plasma propulsion capable of using various propellants and operating at variable specific impulse at constant power.
- TRL is currently 4 – 6. System operated in vacuum chamber.
- Biggest issue is demonstration of system efficiency.

MSFC collaborated on basic research & development from 1999 to 2006. MSFC provided diagnostics and plasma expertise measuring momentum flux (~thrust) and plasma density at the ASPL. MSFC partnered with ASPL / AdAstra and university partners on the Detachment Demonstration Experiment conducted in the PRL/4205. Experimental evidence that plasma can detach at certain conditions. DDEX was abandoned in 2005/2006. Several theses and dissertations.



VX-200 test firing

NTREES Cooling Water System has been Completed



NTREES Induction Heater Power Connections Nearing Completion

NTREES Data Acquisition System Upgrade Well Underway

NTREES Nitrogen System is Complete

Nitrogen Panel

- Inerts and dilutes the hydrogen flow
- Cools the exhaust gases
- Flow rates up to 1.5 lb/sec. Limited by the currently installed building piping
- Building supplies nitrogen at 4500 psi

Nitrogen piping is complete

NTREES Exhaust System is Nearing Completion

Work Remaining to Complete NTREES Upgrade

- **Complete revisions to the Standard Operating Procedures and Safety Assessment**
- **Complete and install the induction heater power bussbar and feedthrough assemblies**
- **Complete pressure certification of the entire NTREES system**
- **Complete installation of the exhaust system**
- **Complete induction heater high power electrical connections**
- **Complete wiring and checkout of the data acquisition and control system**