# Megawatt Electromagnetic Plasma Propulsion

**Presented at**
***Technology and Systems Options Towards Megawatt Level Electric Propulsion Workshop***
**June 9-10, 2003**
**Lerici, Italy**

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The NASA Glenn Research Center program in megawatt level electric propulsion is centered on electromagnetic acceleration of quasi-neutral plasmas. Specific concepts currently being examined are the Magnetoplasmadynamic (MPD) thruster and the Pulsed Inductive Thruster (PIT). In the case of the MPD thruster, a multifaceted approach of experiments, computational modeling, and systems-level models of self field MPD thrusters is underway. The MPD thruster experimental research consists of a 1-10 MWe, 2 ms pulse-forming-network, a vacuum chamber with two 32" diffusion pumps, and voltage, current, mass flow rate, and thrust stand diagnostics. Current focus is on obtaining repeatable thrust measurements of a Princeton Benchmark type self field thruster operating at 0.5-1 g/s of argon. Operation with hydrogen is the ultimate goal to realize the increased efficiency anticipated using the lighter gas. Computational modeling is done using the MACH2 MHD code, which can include real gas effects for propellants of interest to MPD operation. The MACH2 code has been benchmarked against other MPD thruster data, and has been used to create a point design for a 3000 second specific impulse (Isp) MPD thruster. This design is awaiting testing in the experimental facility. For the PIT, a computational investigation using MACH2 has been initiated, with experiments awaiting further funding. Although the calculated results have been found to be sensitive to the initial ionization assumptions, recent results have agreed well with experimental data. Finally, a systems level self-field MPD thruster model has been developed that allows for a mission planner or system designer to input Isp and power level into the model equations and obtain values for efficiency, mass flow rate, and input current and voltage. This model emphasizes algebraic simplicity to allow its incorporation into larger trajectory or system optimization codes. The systems level approach will be extended to the pulsed inductive thruster and other electrodeless thrusters at a future date.

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# Electromagnetic Thruster Benefits

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## BENEFITS

**MISSION ENHANCING:**

- **More payload/reduced trip times vs. low power EP**
  - significantly higher thrust at comparable Isp
- **Reduced propellant mass vs. chemical rockets**
  - increase payload or reduce launch mass
- **LEO–GEO transfers, Lunar & Mars cargo, Mars piloted**

**MISSION ENABLING:**

- **Continuous thrust levels from 1–N to over 100–N**
  - evolutionary with increasing in-space power
- **Specific impulse values from 2,000 s to 10,000 s**
  - depending on propellant type and power level
- **Electrodeless PIT adds option for in–situ propellant utilization**
- **Outer planet/asteroid sample return, outer planet piloted**

# MAGNETOPLASMADYNAMIC (MPD) THRUSTER

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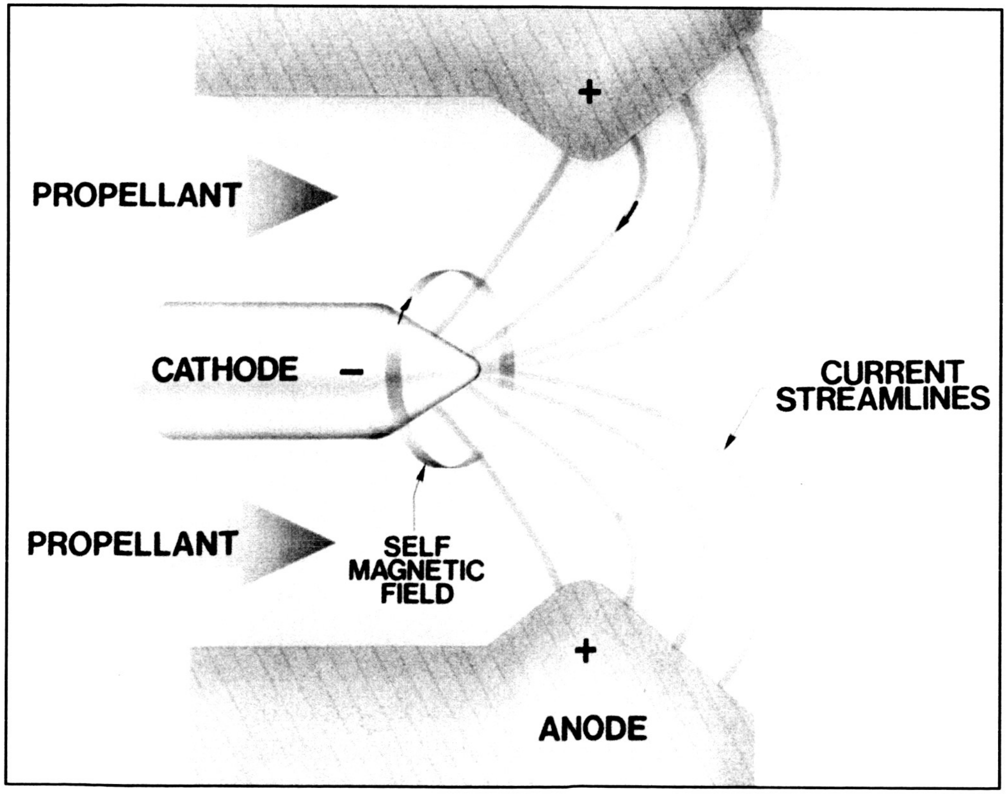
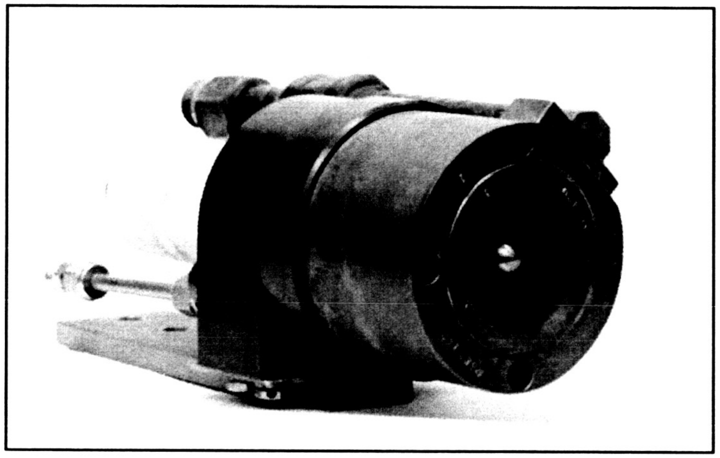
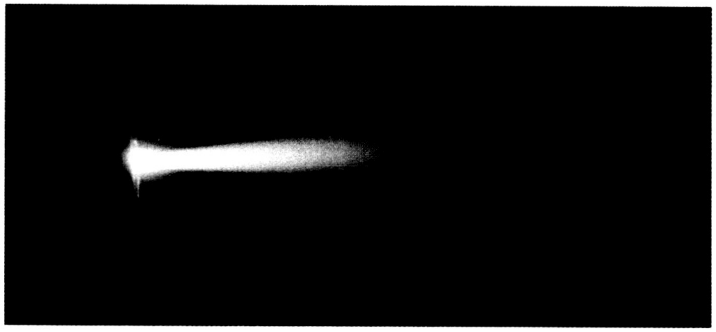
**Electromagnetic (Lorentz) Force Acceleration of Ionized Plasma Propellant**





# MPD THRUSTER RESEARCH

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("MWe Class Thruster Experiments at NASA GRC,"M. Lapointe, 2003 Space Technology and Applications Forum, February 2-5, 2003, Albuquerque, NM.)

## NUMERICAL MODELING AND EXPERIMENTAL VALIDATION

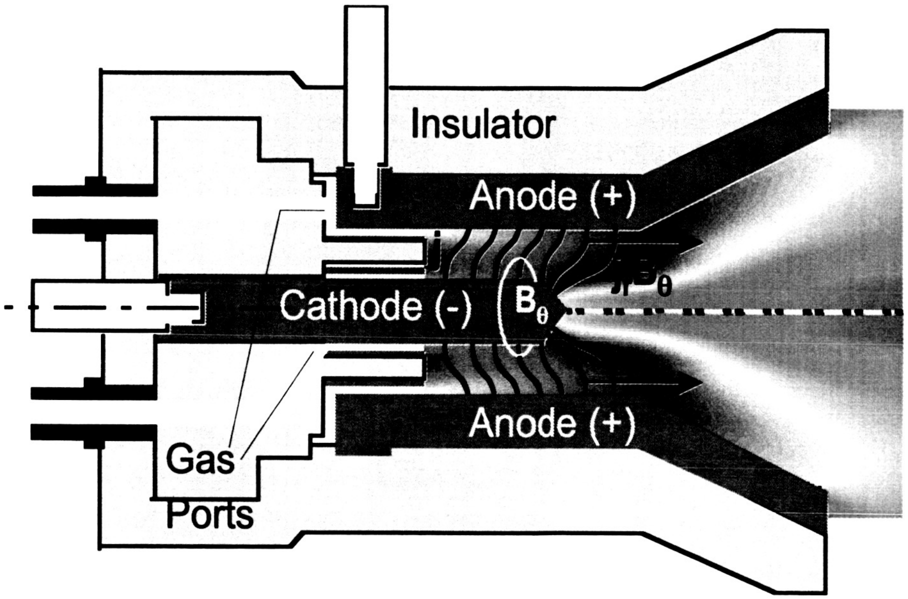
- **MACH2 CODE FOR MPD THRUSTER MODELING**
  - Self-field and applied magnetic field thruster modeling (ASU)
  - Electrode sheath modeling (Kettering U.)
- **PULSED, MW–CLASS THRUSTER EXPERIMENTS (GRC/OAI)**
  - Gas-fed MPD thrusters, non-condensable propellants
  - Moscow Aviation Institute, JPL, Princeton U. are currently investigating lithium propellant (MAI ~ 45% efficiency)
  - Transition most efficient quasi-steady designs to steady-state thruster experiments (required for thruster life demonstration)

# MODELING: MACH2 CODE

- **Time-dependent, 2-dimensional Axisymmetric Simulation**
  - complex planar or cylindrical geometries
- **Quasi-neutral, Viscous Compressible Fluid**
  - ablation models, multi-material capability, elastic-plastic package
- **Multi-Temperature**
  - electron, ion, radiation temperatures
  - various radiation models with real semi-empirical opacities
- **Resistive-Hall-MHD with Braginskii Transport**
  - models for anomalous resistivity, electron-neutral contributions
- **Analytic or Semi-empirical (SESAME) Equations of State**
  - LTE ionization state
- **Multi-ported Circuit Solver**
  - LRC circuits, pulse forming networks

# MACH2 CODE VALIDATION

## MY-II Thruster Self-Field MPD Thruster*




**MEASURED THRUSTER PERFORMANCE:**

- Hydrogen Propellant
- Power: 0.5-MW to 6-MW
- Current: 4-kA to 18-kA
- Thrust: 10N to 80N
- Efficiency: 8% to 36%

* Tahara, H., Kagaya, Y. and Yoshikawa, T. "Quasi-Steady Magnetoplasmadynamic Thrusters with Applied Magnetic Fields for Near-Earth Missions," Journal of Propulsion, 5 (6), 713, Nov.-Dec. 1989.

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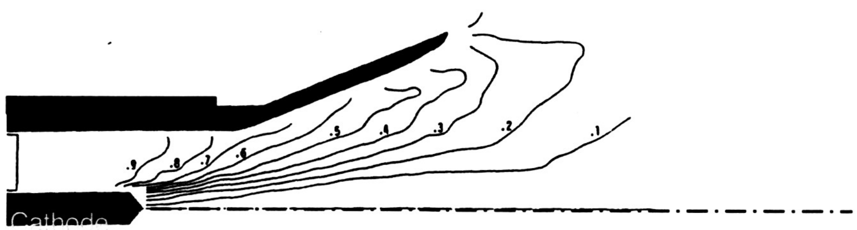
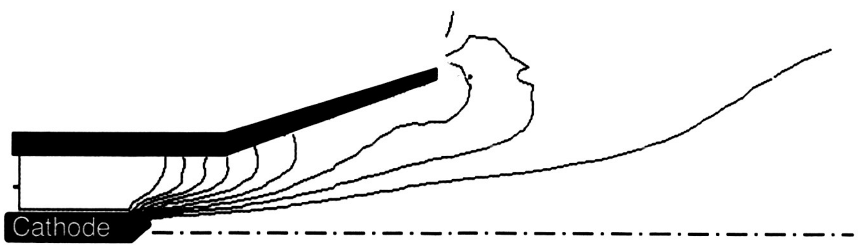
# Preliminary MACH2 Results
# MY-II Current Distribution, Thrust




**Experiment** – 2MW
m=1.37g/s, J=10kA,
V=200V ,Thrust=**34N**
**Efficiency=21%**


**MACH2**
m=1.37g/s, J=10kA,
V=108V,Thrust=**32.4N**
**Classical Resistivity**




**MACH2**
m=1.37g/s, J=10kA,
V=183V,Thrust=**36.9N**
**+Neutral Resistivity**

**Electron-neutral collisions dominate transport at these operating conditions**

# Calculated My-II Power Deposition

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**MY-II: 2-MW POWER DEPOSITION**

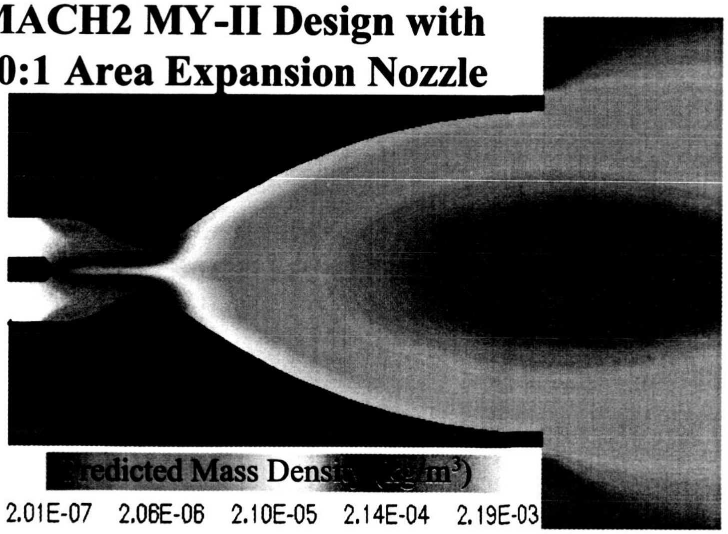
| | |
|---|---|
| Axial Thrust: | 0.5 MW |
| Radial Thrust: | **0.123 MW** |
| Dissociation/Ionization: | 0.608 MW |
| Electrode Conduction: | 0.154 MW |
| Thermal Power: | **0.445 MW** |
| Fall Voltage: | 0.17 MW |

**Computed Power Balance: 0.5-MW of Total Power in Axial Thrust**

**Radial Thrust and Thermal Power Are Recoverable Losses**

**Use Expansion Nozzle To Improve Thruster Efficiency**

**MACH2 MY-II Design with 40:1 Area Expansion Nozzle**



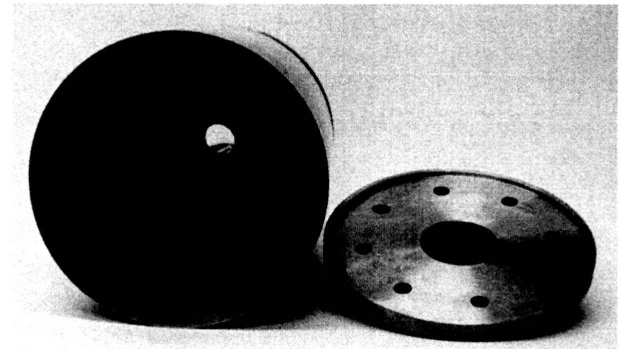

## Predicted Performance:

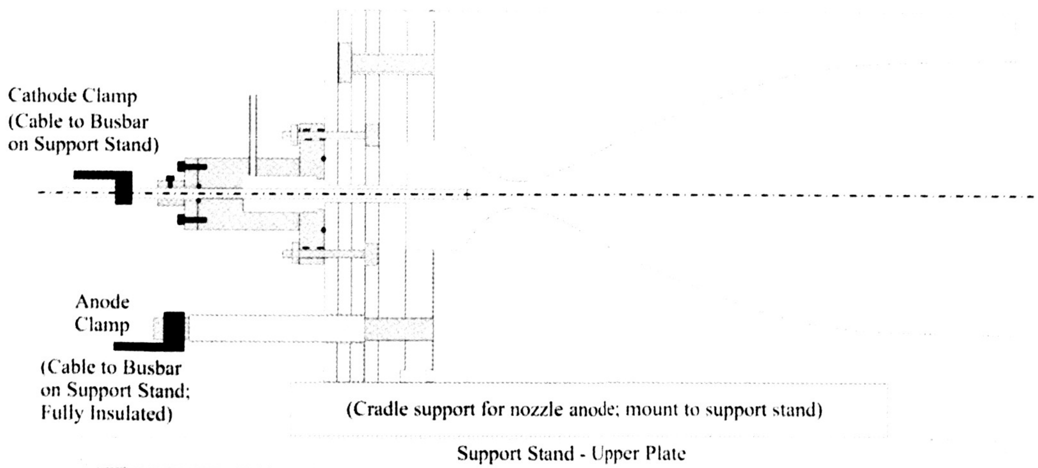
| | |
|---|---|
| Mass Flow ($H_2$): | 1.3 g/s |
| Thruster Current: | 8,000 A |
| Thruster Voltage: | 191 V |
| Total Power: | 1.53 MW |
| Thrust: | 44 N |
| Isp: | 3430 s |
| **Efficiency:** | **48%** |

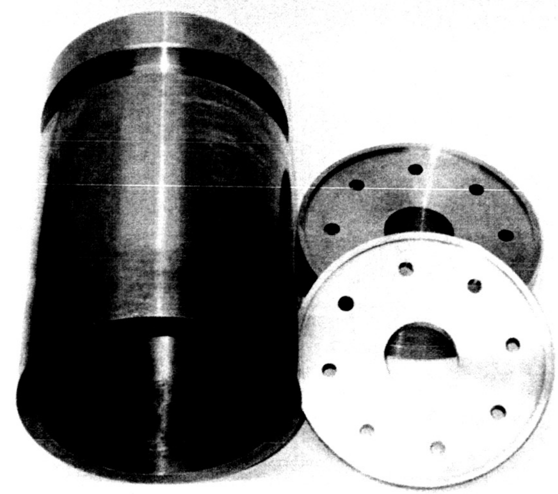
**to be tested...**

# Self-Field MPD Thruster With Nozzle

- **Thruster components fabricated**
  - complete assembly ready for testing
- **Awaiting thrust stand modifications**
  - stronger supports, new electrical cabling
- **Anticipate testing during FY03**
  - validation of MACH2 code predictions





# GRC PULSED THRUSTER TEST FACILITY

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## ECONOMICAL TESTBED FOR MW-CLASS MPD THRUSTER RESEARCH

- **Pulsed test facility allows cost-effective demonstration of**
- **MW-class MPD thruster performance similar to steady-state**
  - quasi-steady (_t ~ 2-ms), high power thruster operation
  - lower thrust, higher voltage, worse efficiency than steady-state
- **Transition only the most efficient MPD thruster designs to more costly steady-state experiments**
  - ground tests require high pumping speeds, significant
  - power, associated facility costs
  - possible testing options at NASA Plum Brook (SPF)
  - existing MW test facilities at the University of Stuttgart

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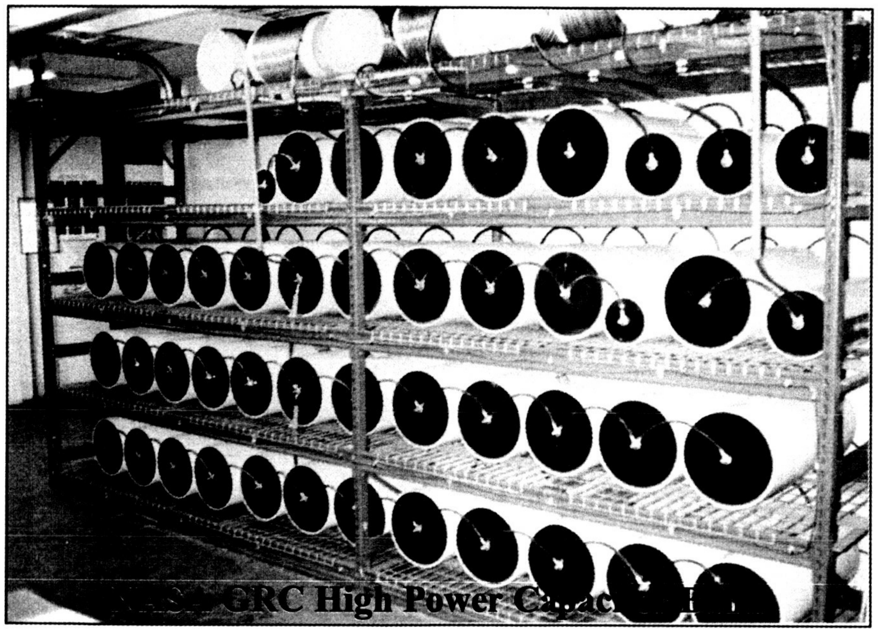
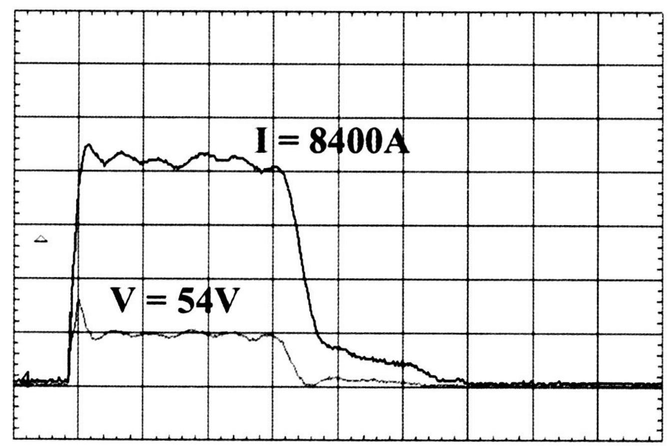
# PULSED POWER BANK AND PFN



## CONSTRUCTION:

- 7-element Guillemin PFN
- 46 Capacitors, 7 Inductors
- 250-kJ Stored Energy
- 10-kV Max Charge Voltage
- Solid State Thyristor Switch
- ~ 2-msec Discharge Period



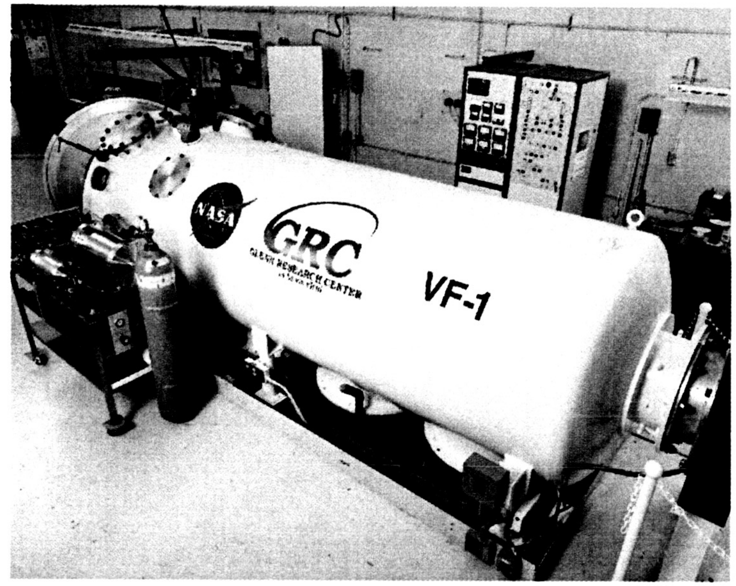

500-_s/division

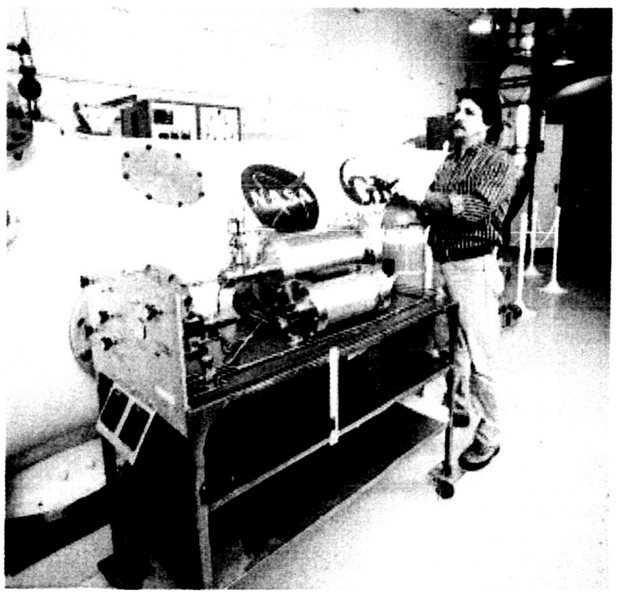
Representative voltage and current waveforms, 0.013-_ resistive load

# TEST CHAMBER

## VACUUM FACILITY 1 (VF-1)

- 1.5-m x 4.5-m cylindrical chamber
- Two 32" ODP, 1 mechanical pump
- Unloaded base pressure ~ $10^{-6}$ Torr
- Access through 1.5-m end cap



## PROPELLANT GAS PLENUM

- Calibrated using known volume
- Set gas pulse: 90-ms to 160-ms
- Argon mass flow rates ≤ 2 g/s

# BASELINE FACILITY OPS

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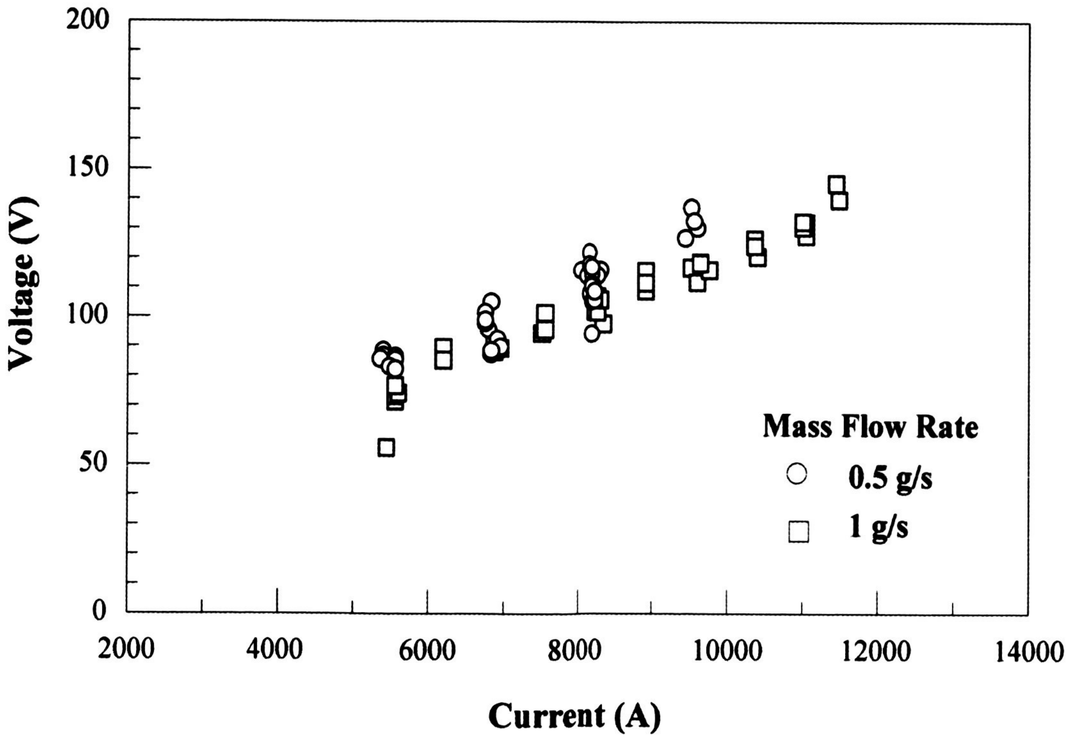
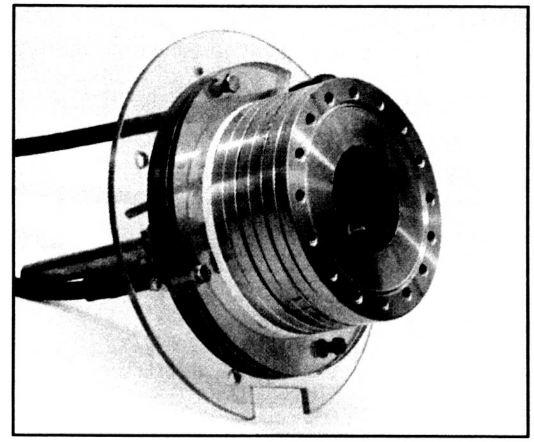
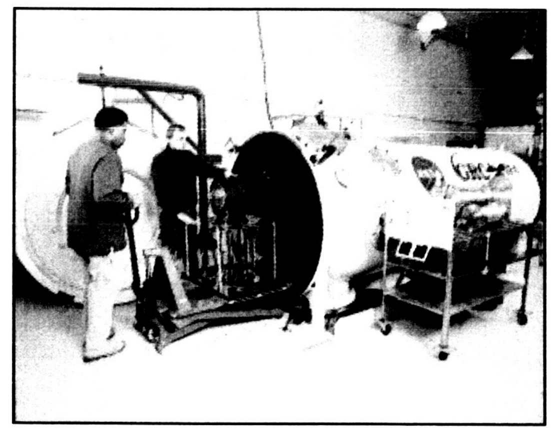
## BASELINE MPD THRUSTER

- Argon; mass flow rate: 0.5-1.0 g/s
- Voltage-current characteristics
- Thrust measurements in FY03



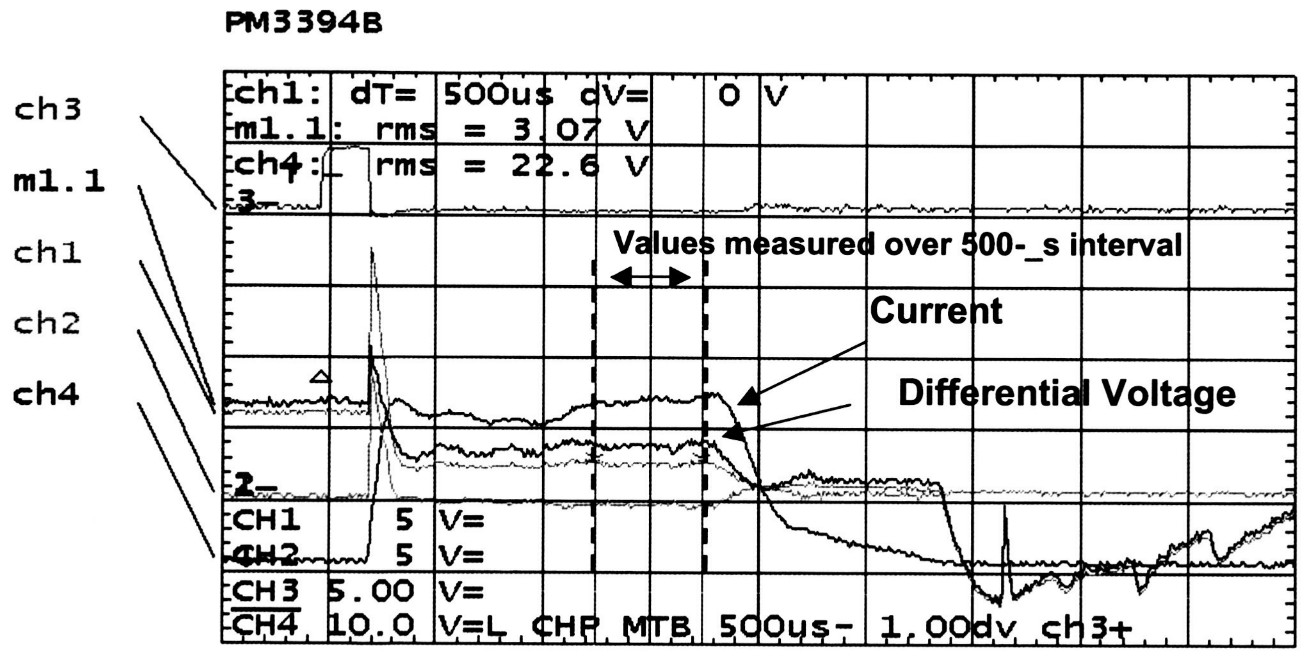
Baseline MPD Thruster



Thruster installation in VF-1

# BASELINE MPD THRUSTER

## Typical discharge voltage and current waveforms




Bank voltage: 3000-V

CH1: V(+), CH2: V(-); M1.1: V(diff) = 88.7 V

CH3: Trigger, CH4: Current = 9040 A (Discharge Power = 0.8-MW)

# NEAR-TERM PLANS

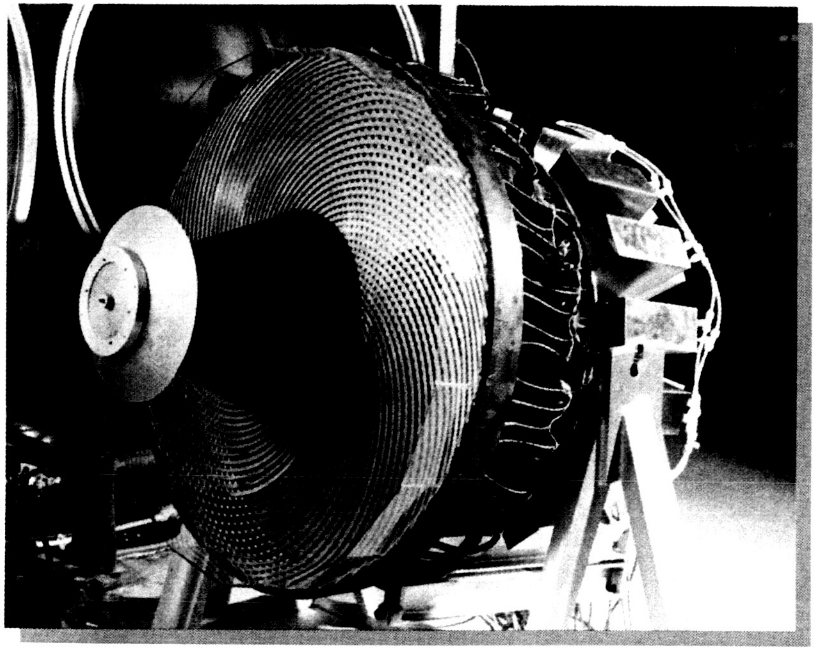
- **QUASI-STEADY MPD THRUSTER RESEARCH, GRC VF-1**
- **MACH2 simulations of applied-field MPD thrusters**
  - ASU: optimize performance from sub-MW to > 1-MW
  - Kettering: electrode fall model (total voltage)
- **Pulsed, MW-class MPD thruster experiments (Ar, H2)**
  - self-field and applied-field; MACH2 code validation
  - additional baseline MPD thruster experiments
  - nozzle anode MPD thruster experiments

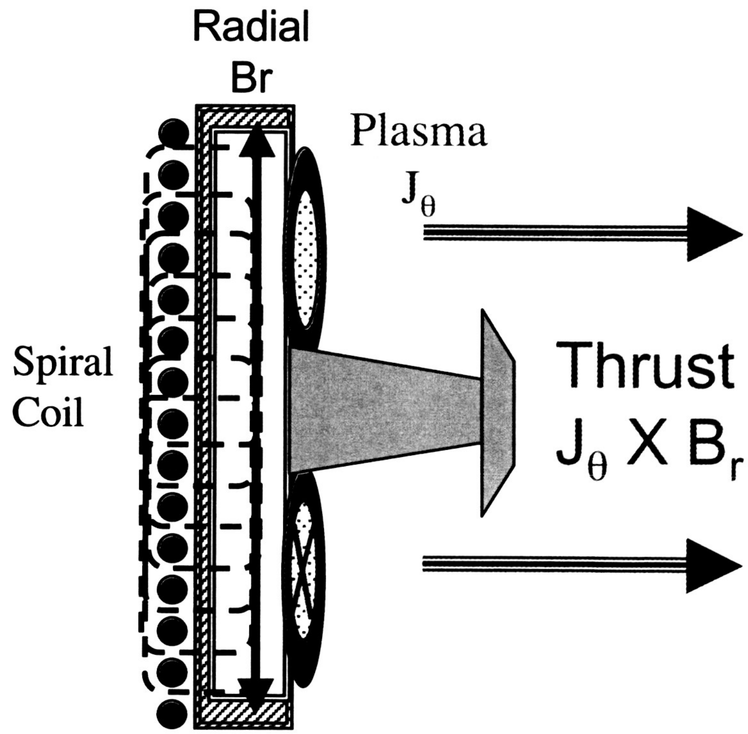
# LONG-RANGE PLANS

## STEADY-STATE MPD THRUSTER DESIGN AND OPERATION

- **TRANSITION DESIGNS TO STEADY–STATE OPERATION**
  - requires cooling, steady-state thrust stand, etc.
- **SUB–MW THRUSTER TESTING AT NASA GRC (VF–5, VF–7)**
  - test steady-state designs to ~ few hundred kW
  - evaluate lower power operation and performance
- **MW–CLASS MPDT TESTS AT NASA GRC, U. STUTTGART**
  - U. Stuttgart in place; GRC planned facility upgrade

# PULSED INDUCTIVE THRUSTER






## History:

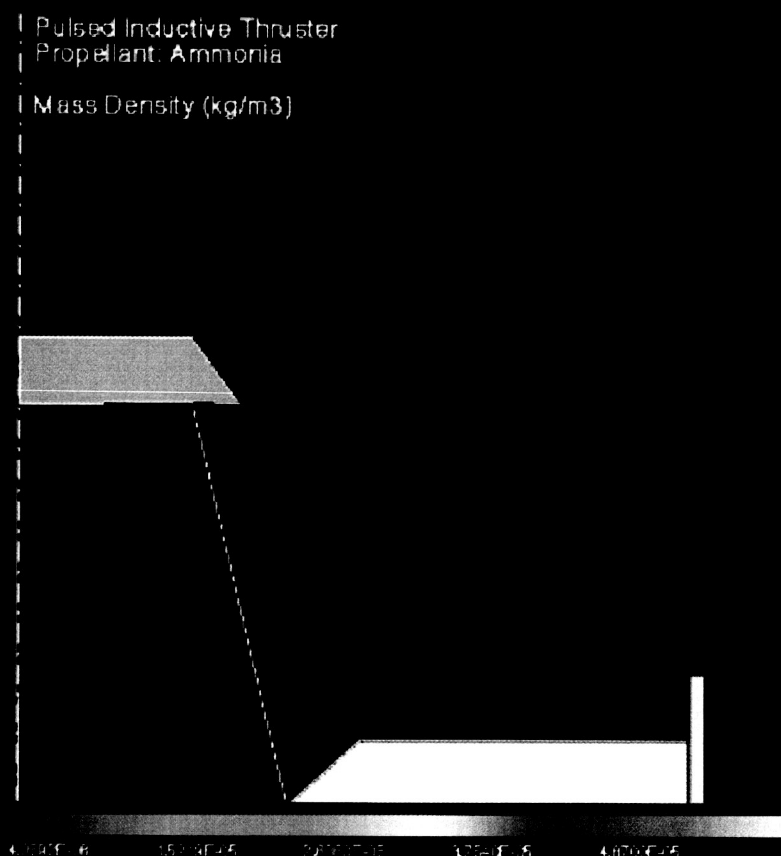
- Developed by TRW, Inc.
  - **1960's – 1990's (intermittent)**
  - **Funded by TRW, DOD, NASA**
- Demonstrated ~ 50% efficiency with NH3 for wide range of specific impulse values (single-shot expts)

# PULSED INDUCTIVE THRUSTER BENEFITS

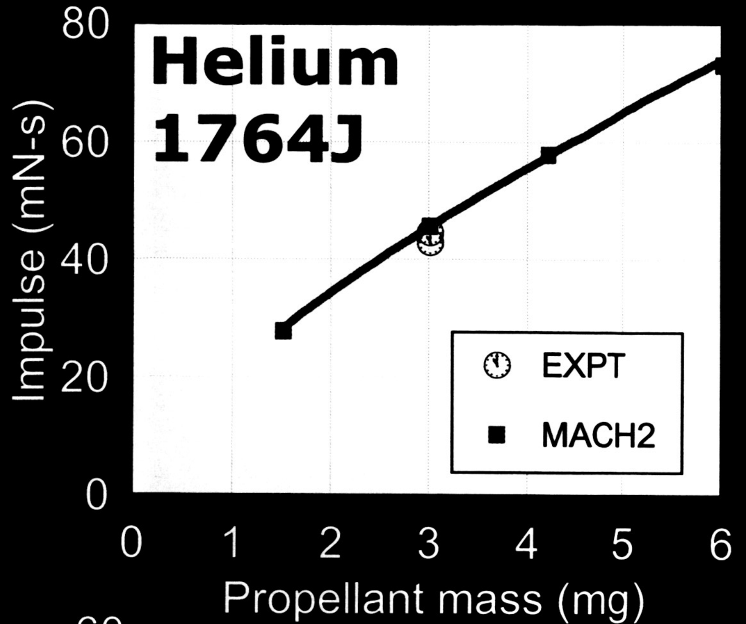
- **MISSION IMPROVEMENTS:**
  - Same enhancing and enabling benefits as MPD plus
  - Pulsed operation allows a wide range of average power levels
  - Electrodeless operation could allow the use of in-situ propellant
- **EXPERIMENTAL STATUS:**
  - Requires fabrication of new test hardware for multiple rep-rate demo
  - Numerical modeling by Mikellides to better understand PIT operation
  - NASA/TRW solid-state switch evaluation to replace spark-gap switches
  - Requires operation at several Hz for ~ $10^9 - 10^{10}$ shots...challenging!

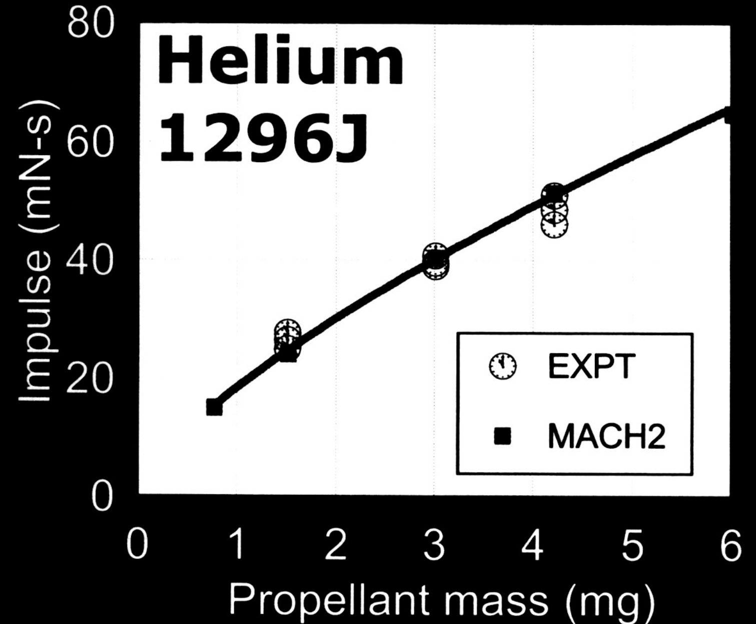
# QUALITATIVE SIMULATIONS WITH AMMONIA PROPELLANT.

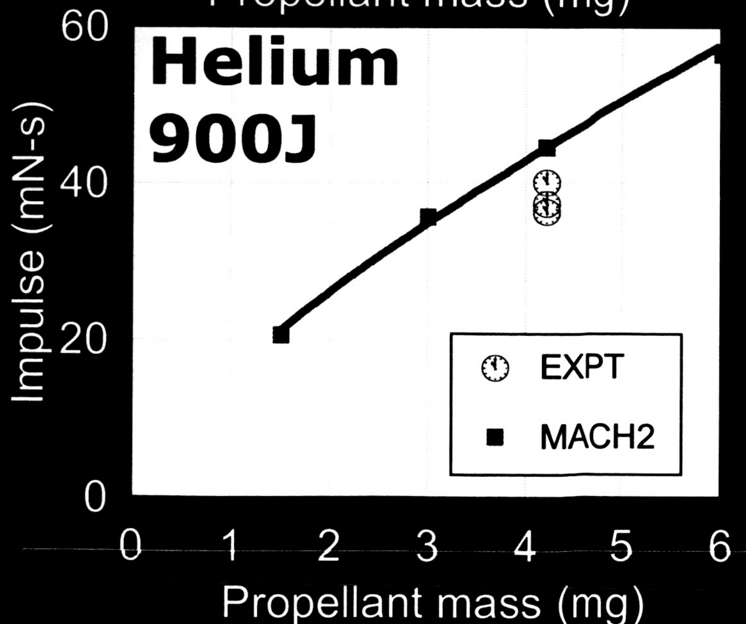
**"Pulsed Inductive Thruster (PIT); Modeling and Validation Using the MACH2 code,"** MIKELLIDES, P., IEPC Paper No. 135-303, Toulouse, France, March 17-21, 2003.

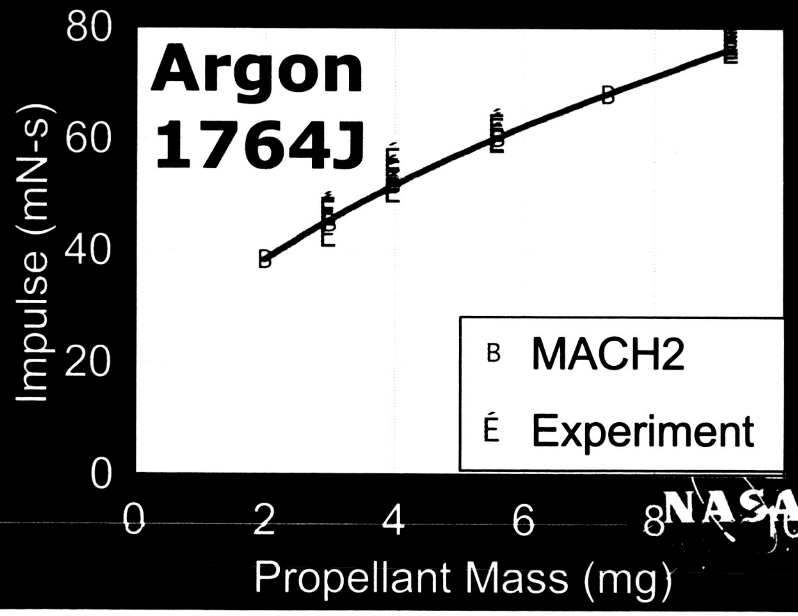


# MACH2 COMPARISONS WITH EXPERIMENT ARE ENCOURAGING.



# THE SIMULATIONS PREDICT THAT THE EFFECTS OF THE RESTRICTIVE VACUUM TANK ARE …

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… INSIGNIFICANT.

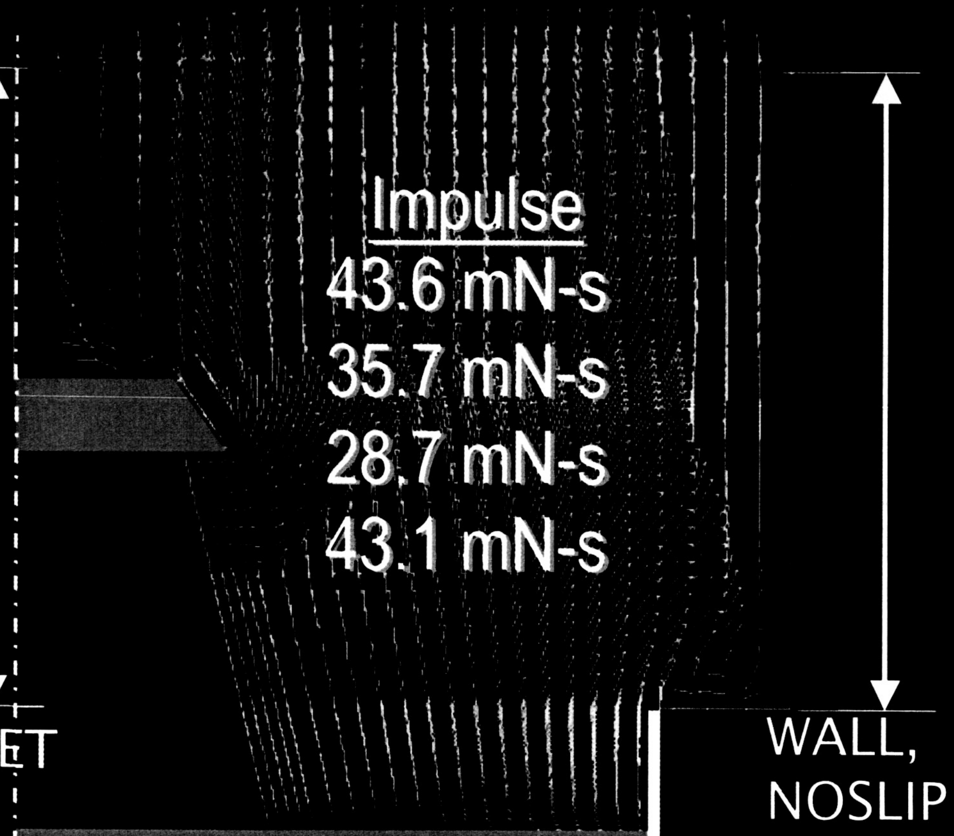
**Energy / Mass**

**900J / 4.2mg**

**1296J / 3mg**

**1296J / 1.5mg**

**1764J / 3mg**

# MPD System Model for Mission Analysis

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("MPD Thruster Performance Analytic Models,"J. Gilland and G. Johnston, 2003 Space Technology and Applications Forum, February 2-5, 2003, Albuquerque, NM.)

- **MPD experiments focus on variables in the "lab frame":**
  - Control mass flow ($\dot{m}$), current (J)
  - Measure thrust (T), voltage (V)
  - Calculate exhaust velocity (c), Power ($P_e$), $\eta$
- **System and trajectory analysis have their own "frame":**
  - Input $P_e$, c
  - Output T, $\eta$, J, V
- **Goal: Find an MPD Thruster physics model that can be converted from "lab" to "system" frame**

# Modified Mäcker Model Structure

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("MPD Thruster Performance Analytic Models,"J. Gilland and G. Johnston, 2003 Space Technology and Applications Forum, February 2-5, 2003, Albuquerque, NM.)

$$T = \begin{cases} \dot{m}\, U_A \dfrac{J}{J_{fi}} & c \le U_A \\ b\, J^2 & c \ge U_A \end{cases}$$

$$V = \frac{T^2}{2\dot{m}J}(1+\delta) + \frac{\dot{m}\,\varepsilon_i}{J} + \frac{J\, f_i}{\sigma} + V_f$$

$$\eta = \frac{T^2/2\dot{m}}{J\,V}$$

$$P_e = J\,V$$

Models are systems oriented

- Analytic MPDT models needed for fast, accurate trajectory computations
- Inputs: Power, c
- Outputs: Current, Voltage, Mass Flow ($\dot{m}$), Efficiency, Thrust

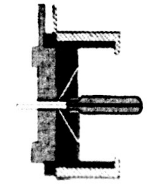
| | | |
|---|---|---|
| J | = | Discharge Current |
| b | = | Thrust Coefficient |
| $V_f$ | = | Fall Voltage |
| $\varepsilon_i$ | = | Ionization energy |
| $U_A$ | = | Alfven Critical Speed |
| V | = | Discharge Voltage |
| $\sigma$ | = | Conductivity |
| $\dot{m}$ | = | Mass Flow |
| $\delta$ | = | Thrust Divergence |
| $f_i$ | = | Geometry factor |

# ASSUMPTIONS INHERENT IN THIS MODEL

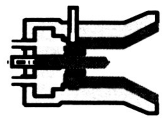
- **Alfven critical speed theory holds**
  - Full ionization point is clearly defined
- **All ionization energy is lost in fully ionized regime (frozen flow)**
  - Neglects possible recovery of recombination energy in nozzle
- **Current attachment does not vary significantly over full range of powers**
  - Assumes b parameter independent of power

("MPD Thruster Performance Analytic Models,"J. Gilland and G. Johnston, 2003 Space Technology and Applications Forum, February 2-5, 2003, Albuquerque, NM.)

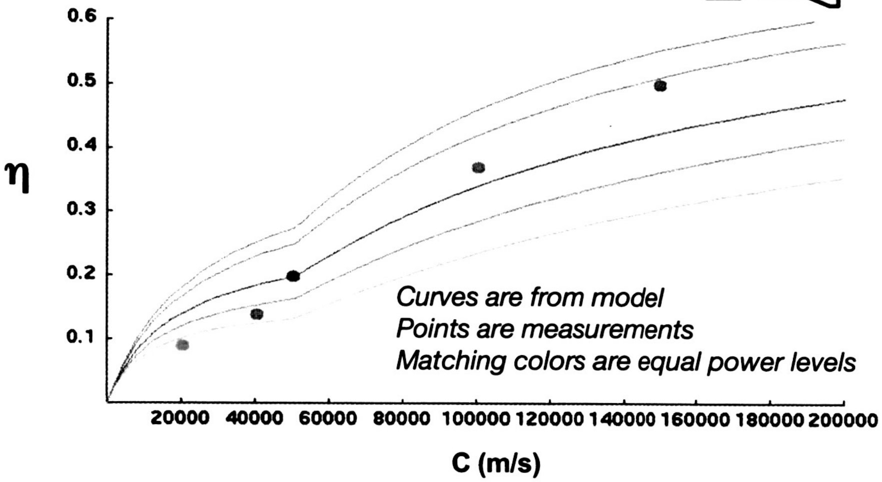
# Comparison to Experiments with Hydrogen
# Top: Princeton Benchmark

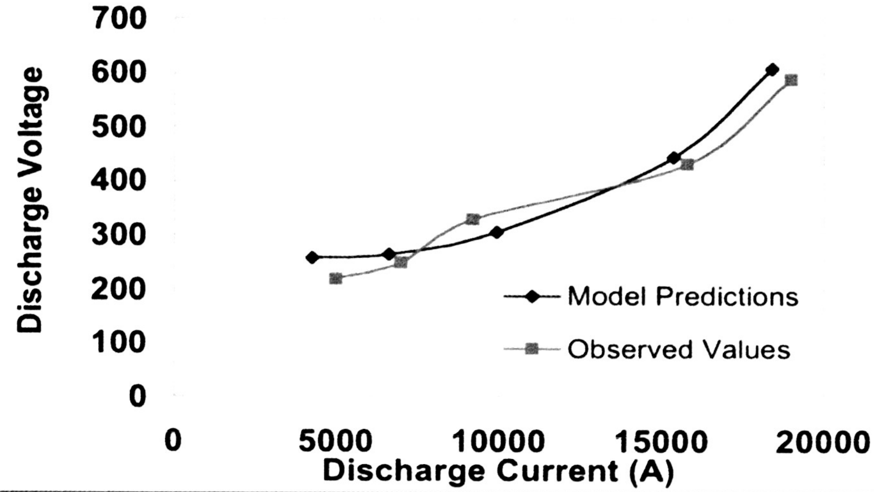


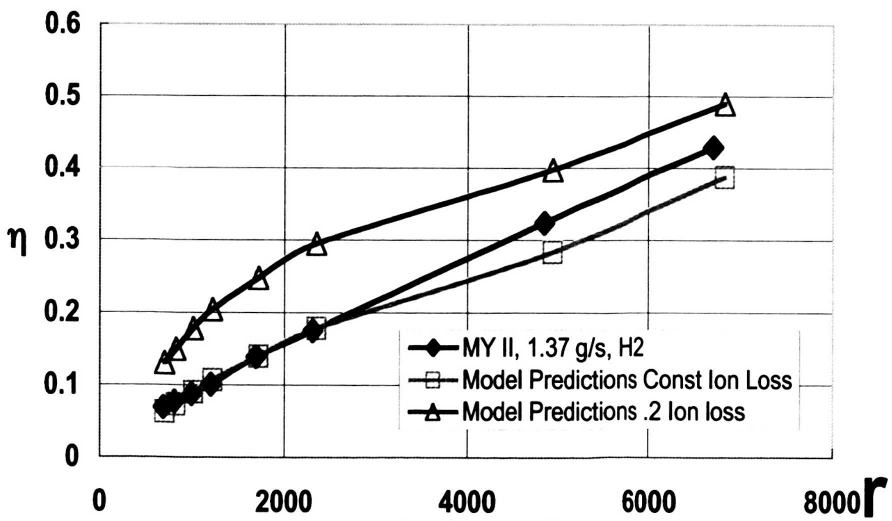
# Bottom: MY-II

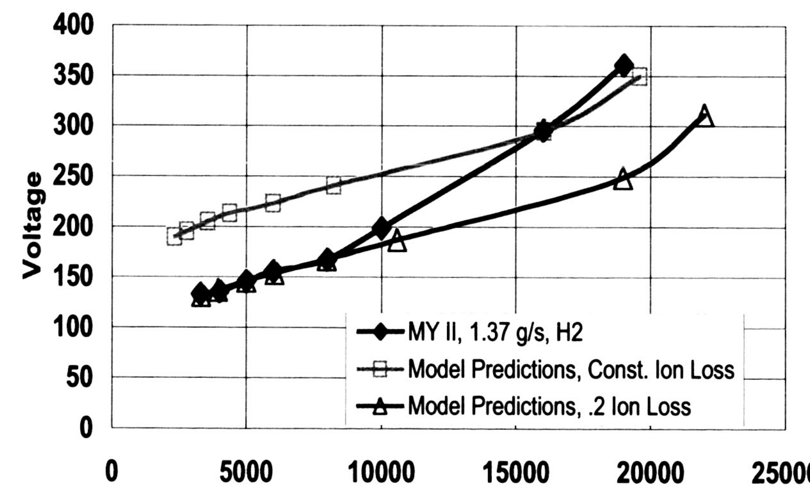







("MPD Thruster Performance Analytic Models," J. Gilland and G. Johnston, 2003 Space Technology and Applications Forum, February 2-5, 2003, Albuquerque, NM.)