Candidate Thruster Technologies for NEP

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Introduction

- **Near- to Mid-Term**
  - Thruster Input Power: 20 to 50 kW
  - Specific Impulse: 6000 to 9000 s
  - Propellant Throughput: 1000 to 2500 kg/thruster

- **Far-Term**
  - Thruster Input Power: 100 to 1000 kW
  - Specific Impulse: 6000 to 15,000 s
  - Propellant Throughput: 50 kg/kW per thruster

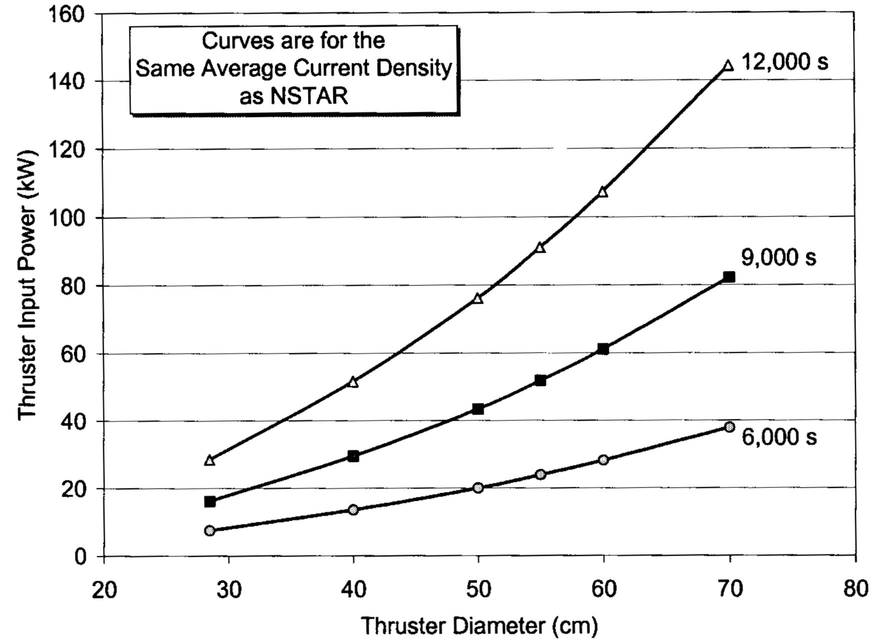
Candidate Thruster Technologies

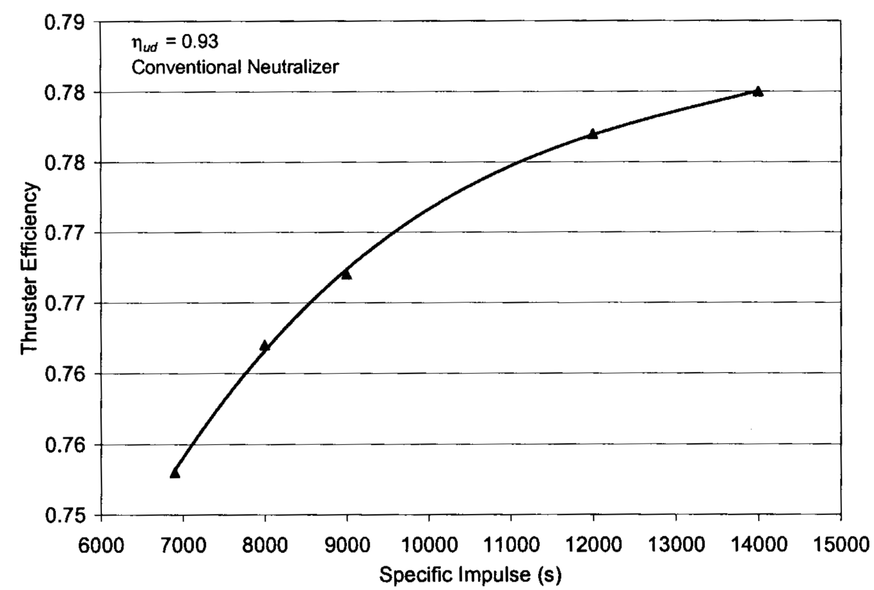
Thrusters	Propellants	Specific Impulse Range (s)	Power Range (kW)
Electrothermal			
Resistojets	N2H4	300 to 400	< 1
Arcjets	NH3, N2H4, H2	500 to 1200	< 100
Microwave Electrothermal Thruster (MET)	NH3, N2	400 to 500	< 10
Pulsed Electrothermal (PET)	H2O	< 2000	< 10
Electrostatic			
Gridded Ion Thrusters			
DC Ion Thrusters	**Ar, Kr, Xe**	**2000 to 15,000**	**0.01 to 100's**
RF/ECR Ion Thrusters	**Ar, Kr, Xe**	**2000 to 15,000**	**0.1 to 100's**
Hall Thrusters			
SPT	**Ar, Kr, Xe**	**1000 to 3000**	**0.05 to 100's**
TAL	**Ar, Bi, Kr, Xe**	**1000 to 8000**	**0.05 to 100's**
Electromagnetic			
Magnetoplasmadynamic (MPD)			
Pulsed	**H2**	**3000 to 10,000**	**0.1 to 5000**
MPD-PET	LH2, LN2	4000	1000
Steady State	**Li, H2**	**4000 to 8000**	**500 to 10,000**
Pulsed Inductive Thruster (PIT)	**Ar, NH3, N2H4, CO2**	**2000 to 8000**	**100 to 1000**
Electron Cyclotron Resonance (ECR)	**Ar, Kr, O2, Xe**	**TBD**	**TBD**
Ion Cyclotron Resonance (ICR)	**H2**	**TBD**	**TBD**
Pulsed Plasmoid Thruster	**N2, O2, CO2**	**5000 to 20,000**	**Not specified**
Field Reversed Configuration (FRC) Thruster	**N2, O2, CO2**	**5000 to 15,000**	**10 to 1000**
Variable Specific Impulse Magnetoplasma Rocket	**H2**	**1000 to 30,000**	**1000 to 10,000**
Deflagration Gun	H2	3000 to 300,000	Not specified
Rail Gun			
Mass Driver			
Dense Plasma Focus			

High Power Ion Engines

JPL

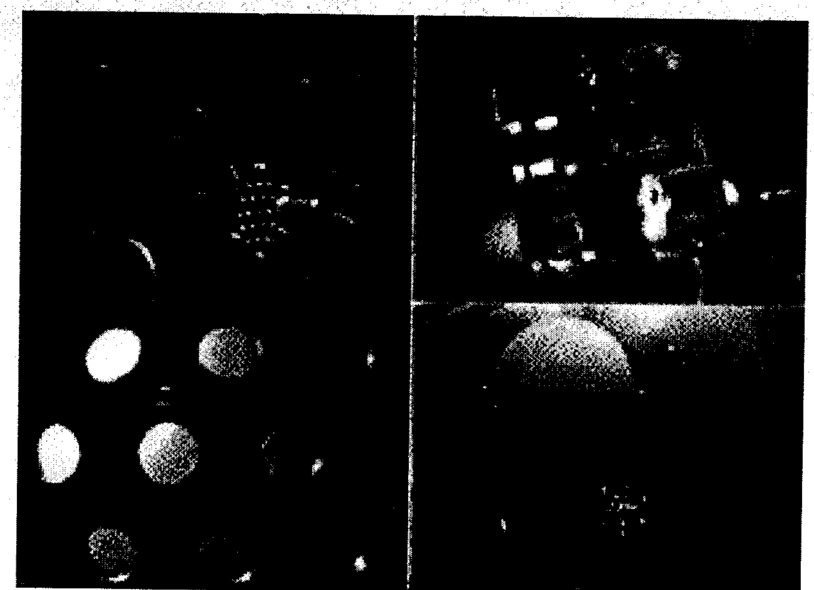
- ➢Ion thrusters scale well to high power at high *Isp*
- ➢High *Isp* is readily achievable with gridded ion thrusters
- ➢High efficiency comes naturally as the *Isp* is increased
- ➢Key challenge is achieving the required thruster life
  - ➢Grid and Cathode designs are the keys to long life





High-Power (Interstellar) Ion Propulsion System

- 30 kW High-Power (Interstellar) Ion Propulsion System (NEP)
- 10-30 kW Power range per engine
- High specific impulse, > 10,000 Sec
- Design and fabrication of large-area discharge chamber completed
- Discharge operation characterized on krypton and xenon propellants
- Performance characterized up to 4 kW input power



- Lessons learned from this engine being applied to current NEP NRA
- Leading team with GD, Boeing EDD, Boeing Phantom Works, NRL, Colo.St., U.Mich, U.Wisc., JHU/APL

NASA 50kW Hall Development

Expected performance

Isp = 2500 sec

Thrust = 2.5 N @500V & 100A

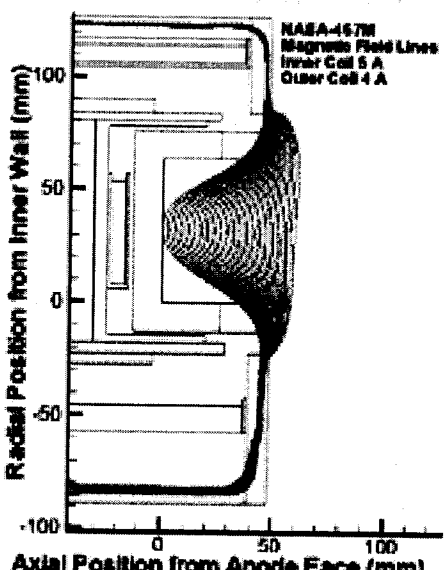
Eff = 63%

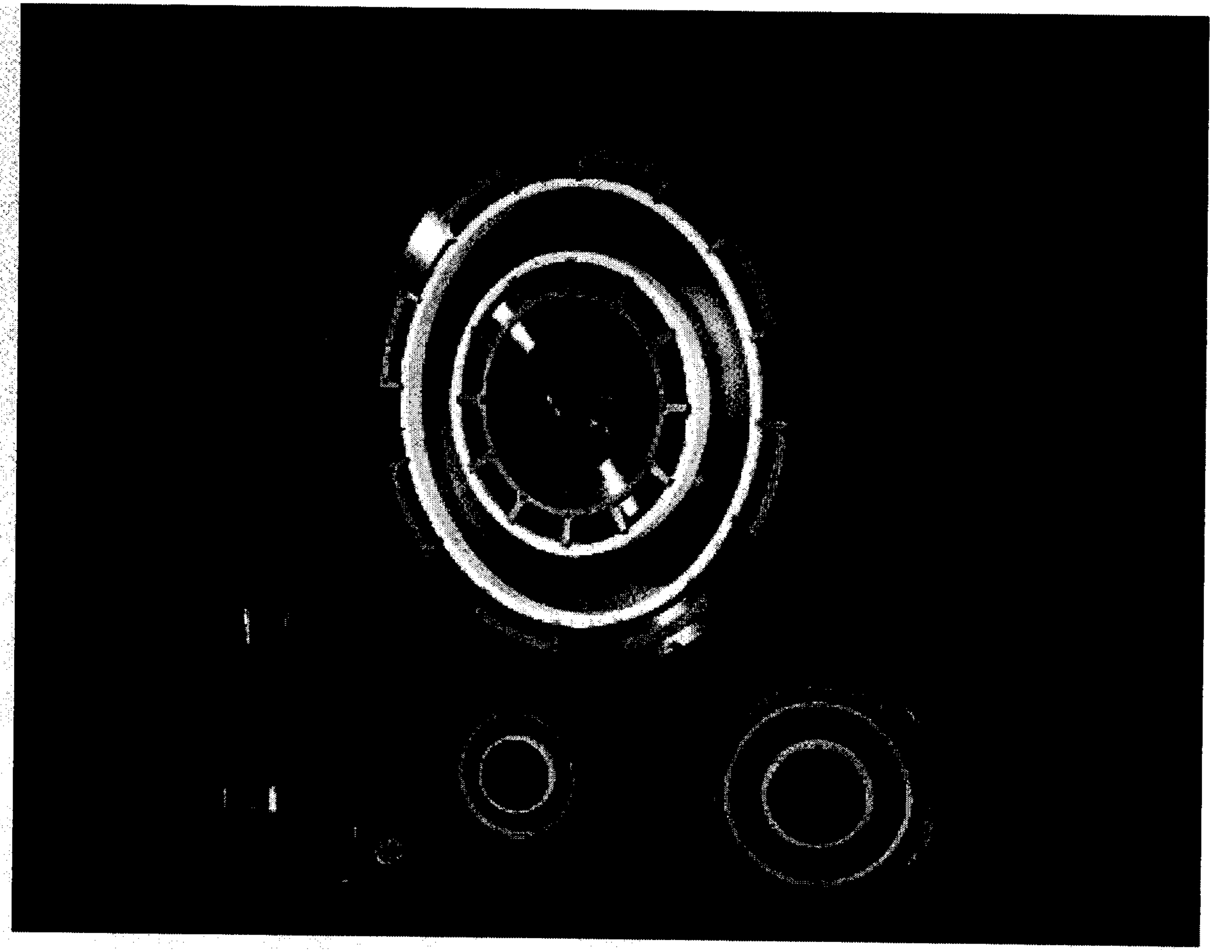
10x SOA

Developed new heat treat process

Developed magnetic field mapping

Developed 100A cathode





Performance Testing Started in March

Similar Activities at General Dynamics Under Contract to GRC

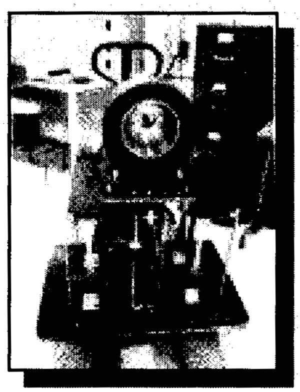
Glenn Research Center
At Lewis Field

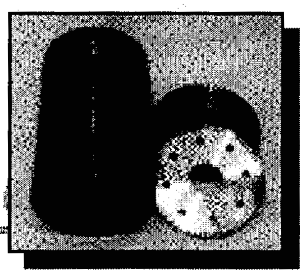
Pulsed MPD Thrusters

HIGH POWER MPD THRUSTER

PROGRAM STATUS AND PLANS

- **MPD Program Status:**
  - Pulsed test facility operational
  - Baseline thruster tested to 2-MW
  - Minor facility bugs corrected





- **FY02 Program Plans**
  - **2nd/3rd Quarter:**
    Baseline self-field & applied-field thruster tests
    Goal: 40% self-field, >50% applied-field
  - **3rd/4th Quarter:**
    Nozzle-anode self-field thruster tests
    Goal: 50% self-field efficiency

ЦНИИМАШ
TSNIIMASH

Bismuth-fueled Anode Layer Thrusters are a Viable Alternative to Ion Engines for NEP Missions

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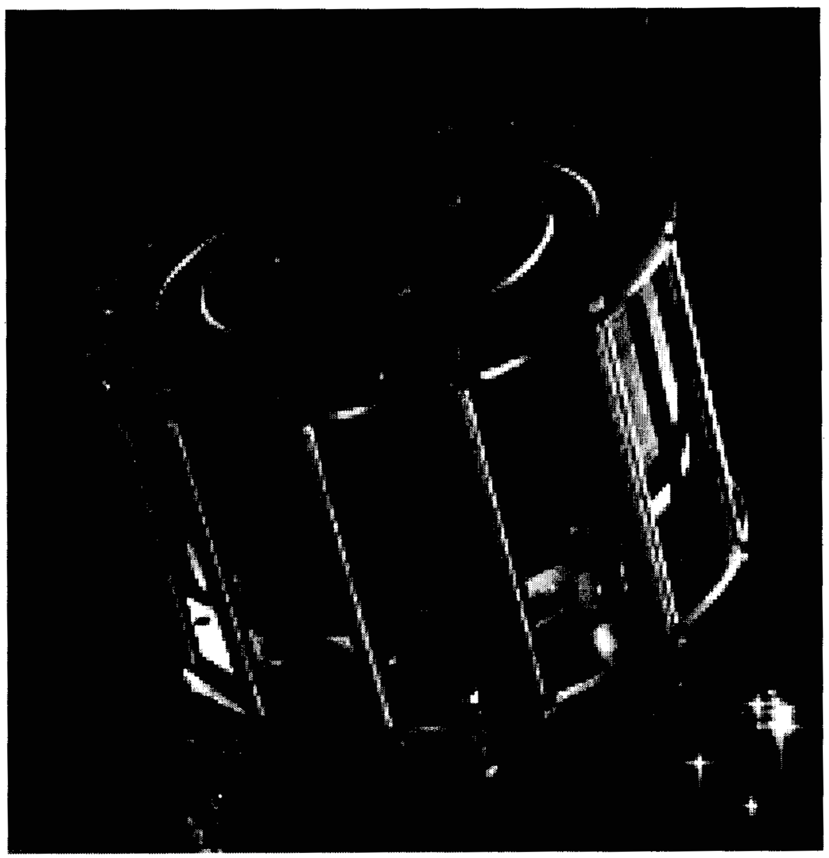
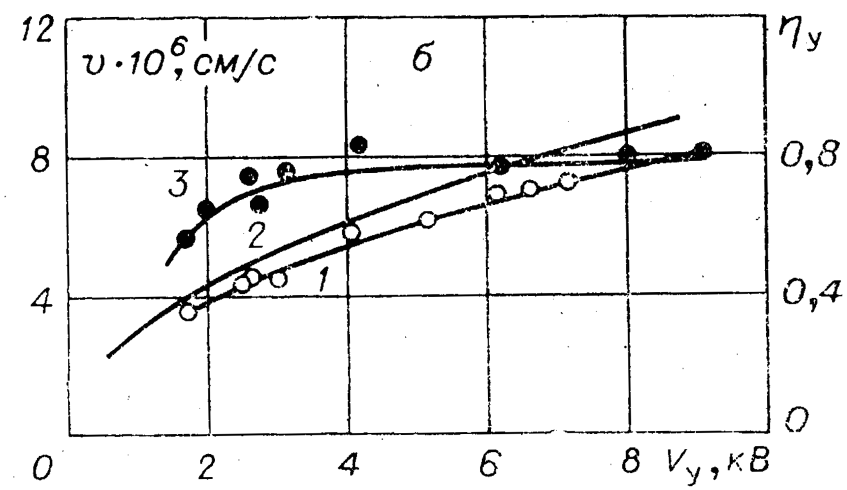
Near-term NEP Performance Objectives Have Already Been Demonstrated With Bismuth-fed TAL's

Isp up to 8000 s, efficiency up to 70% and power per engine as high as 140 kWe



25 kWe, radiation-cooled Bi TAL

Average Ion velocity &Efficiency vs Accelerating Voltage



1. Exp. $\langle \upsilon_i \rangle \cong 2{,}7 \cdot 10^6 \sqrt{U_{ac}}\, cm/s$

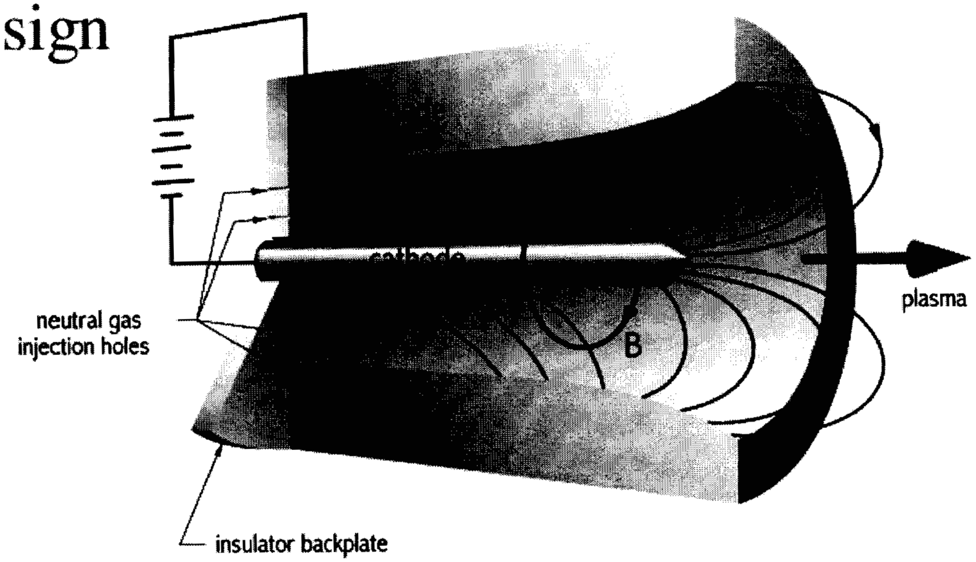
2. Theor. $\langle \upsilon_i \rangle = 3{,}05 \cdot 10^6 \sqrt{U_{ac}}\, cm/s$

3. Efficiency

Steady-State MPD Thrusters

The Self-Field MPDT

- Lorentz force (***j x B***) acceleration
- High *exhaust velocity*, 5-50 km/s
- High *thrust density*, 10^4 - 10^5 N/m^2
- Robust and simple design
- Solid cathode
- Gaseous propellant injected at backplate
- Current attachment along entire cathode



Recent Experimental and Theoretical Results Show Path to MWe Plasma Thrusters

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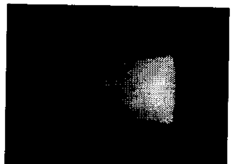


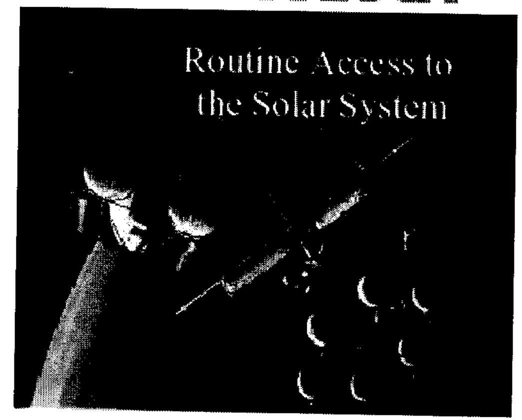
POWER

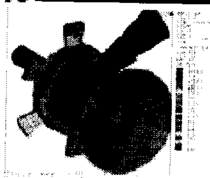
200 kWe Steady State

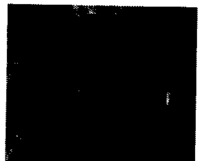
• Anode Texturing
• Heat Pipes

1 - 5 MWe Steady State

MULTIMEGAWATT TECHNOLOGY





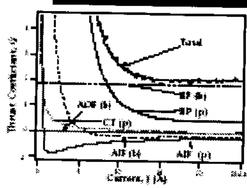


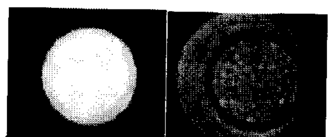
PERFORMANCE

η = 50%
Isp = 4000 s

• Lithium Propellant
• Active Turbulence Suppression

η = 60%
Isp 8000 s



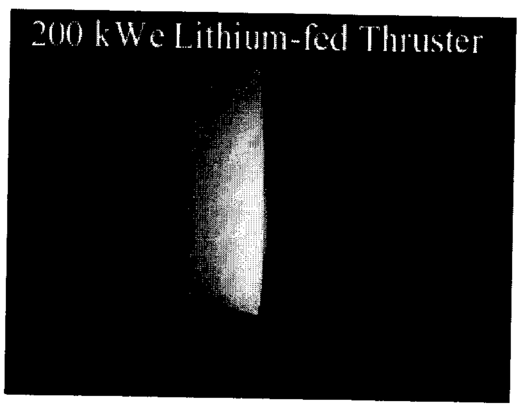


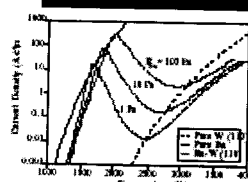
LIFETIME

100's of Hrs
At 3000 A

• Multi-Channel Hollow Cathodes
• Barium Addition

10000 Hrs
At 20000 A



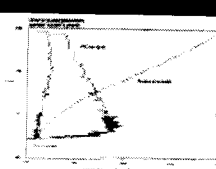


PLUME CONTAMINATION

10^{-8} g/cm²s
at 0.3 m

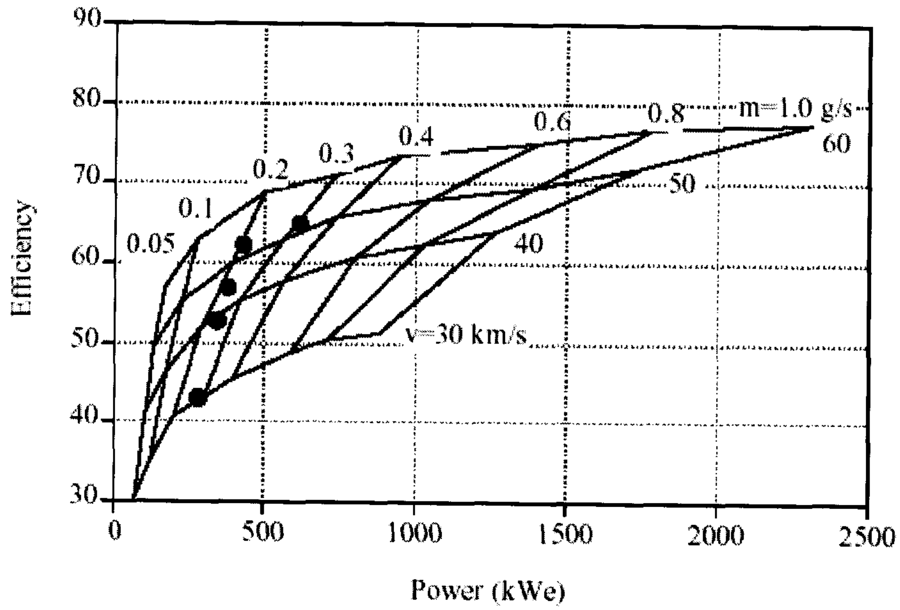
• Plume Shields
• Booms

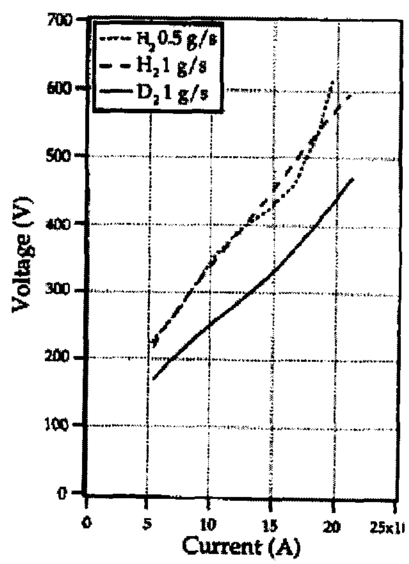
10^{-10} g/cm²s
at 30 m

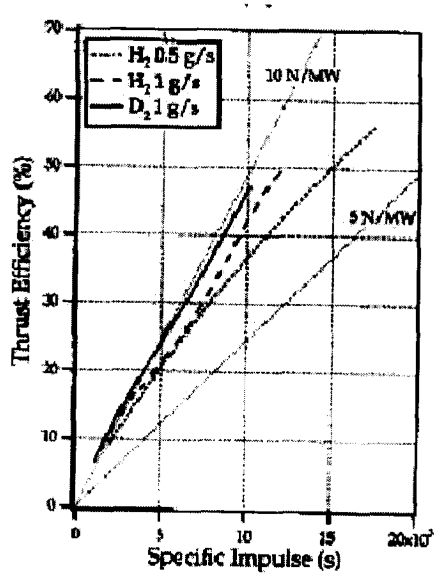


STATE OF THE ART

Steady-State MPD Thrusters
Propulsion Niches for High Power Lorentz Force Accelerators Define Evolutionary Path

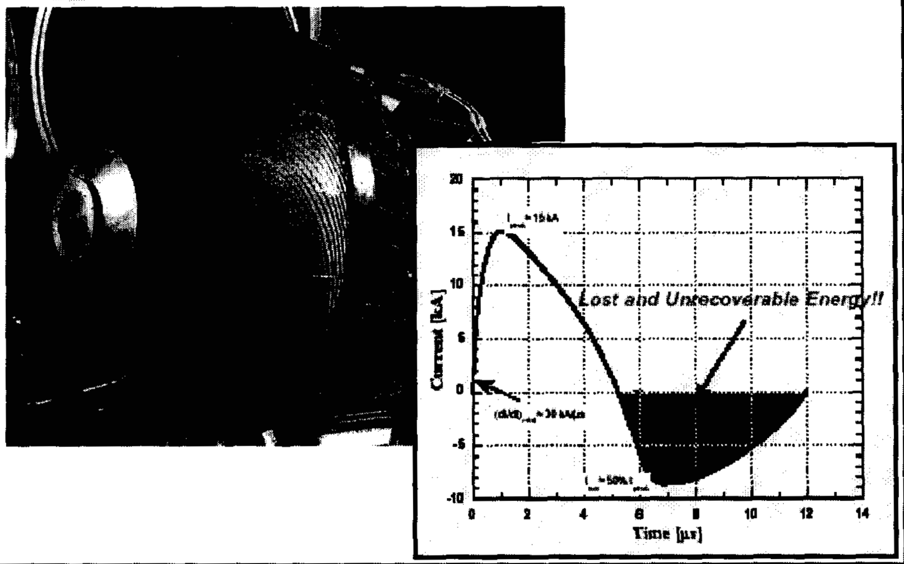






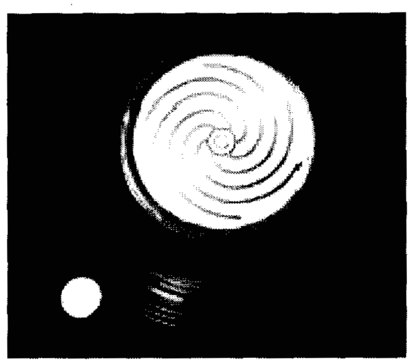
- **0.5 -- 1 MWe lithium-fed thrusters are ideal for near-term applications**
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Orbit transfer and Mars cargo applications
- **1-- 5 MWe lithium thrusters fulfill mid-term propulsion requirements**
  - Second generation power systems at 10--30 MWe
  - Specific impulse of 4000-6000 s
  - Initial piloted Mars missions
- **5--10 MWe hydrogen or deuterium-fed thrusters open up the solar system**
  - Third generation (very low alpha) power systems at 100's of MWe's
  - Terminal voltage with lithium is too low to process very high power levels; hydrogen appears to provide required efficiency at Isp's of 10000-15000 s
  - Piloted missions to Mars and the outer planets

Pulsed Inductive Thruster

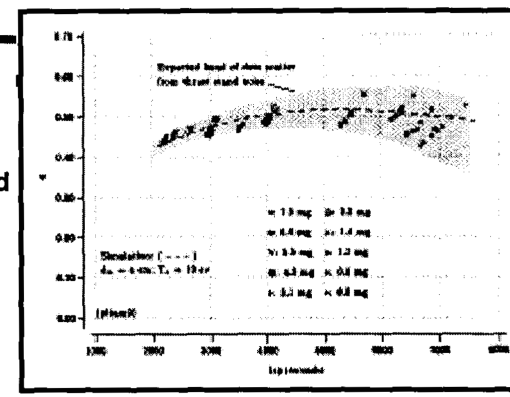


- **Operation:**
  The Pulsed Inductive Thruster (PIT) is characterized by μ-second, MW-power pulsed operation. Thrust is generated by the cross-product interaction of the azimuthal current in the plasma and the magnetic field in the coil generating a Lorentz force, which in turn accelerates the plasma axially away from the coil.
- **Benefit:**
  PIT provides high thrust efficiency over a wide range of specific impulse values.
- **Single Shot Performance:**
  - **Specific Impulse:** 2,000 - 8,000 s
  - **Efficiency:** 20 - 50 %
  - **Discharge Voltage:** 20 - 30 kV
  - **Propellant:** Ar, NH_3, NH_4, CO_2

- **Current On-Going Effort:**
  - **NASA MSFC Work:**
    - **Design and evaluation of innovative powertrain design reducing PIT circuit requirements.**
    - **Explore innovative switch and capacitor technology for short-pulse, high power applications.**
  - **Evaluation of Solid-State Switches for High Rep-Rate PIT Operation by TRW.**
  - **MACH2 Modeling of the Pulsed Inductive Thruster by Dr. Pavlos Mikellides, Arizona State University, AZ.**
  - **Development of 2-D nonlinear MHD code at NASA GRC.**



- **Technical Challenges:**
  - **Switch Technology**
    - **High repetition rate and extreme long lifetime**
    - **High peak currents**
    - **High and rapid initial**
    - b **current rise**
  - **High Power Capacitors**
    - **Extreme long lifetime**
    - **Requires space qualification under extreme operating conditions**
  - **Pulse Driver Network and Architecture**
    - **Recovery of reflected energy**
    - **Pulse shape control for optimum pulse waveform**



Ivana Hrbud, MSFC/TD40

Jim Gilland, GRC 4/4/2001

Helicon wave thruster concepts

- Compact ion or plasma source
  - **1cm radius to replace hollow cathode**
  - **Small radius -> high density**
    - 10^{20} m^{-3} achieved at 1 kG, kW of power in <u>long</u> tube, radius 1 cm
    - Short tube for thruster applications is a departure from long laboratory sources
- ECR thruster
  - **Generate helicon wave in chamber**
    - $T_{\perp} = T_{\parallel} \sim 3$ eV, high ionization
    - Isotropic T_e reduces plasma losses due to Bohm diffusion ($D \sim T_{(\perp ?)}/B$)
  - **Expand magnetic field outside of chamber to ECR region**
    - Continued magnetic expansion past ECR region to accelerate exhaust

FAST
(FRC Acceleration Space Thruster)

Objective: Investigate the use of a Field Reversed Configuration (FRC) for use as an in-space electric thruster. Thrust is produced by inductively accelerating a magnetized plasmoid.

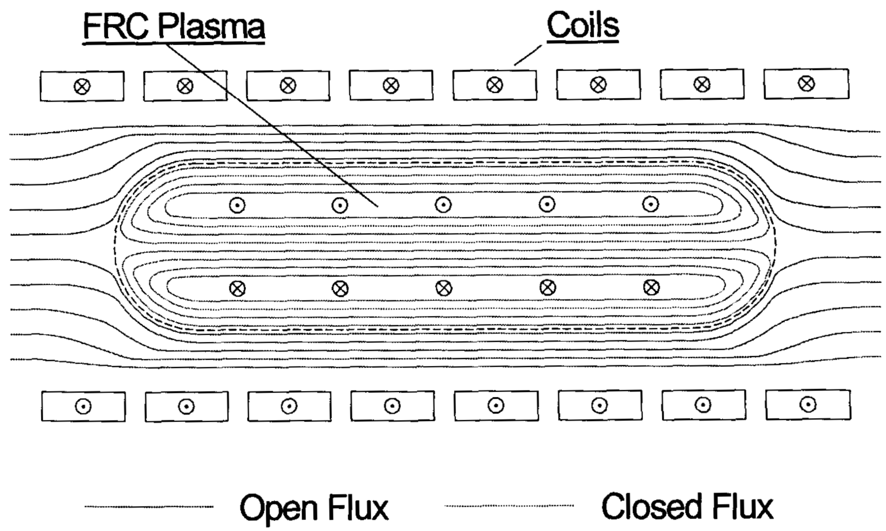
Payoff: A high specific-impulse, high efficiency, inductive (electrode-less) electric thruster

Potential Performance:

- P_{Jet} = 10 KW - 1 MW
- I_{sp} = 5,000 - 15,000 s
- ε = 60 - 80 %

Milestones:

- FRC formation experiments FY02
- Translation experiments FY03
- Design/Construction of acceleration stage FY03



Status:

- Facilities in PRC Lab C (Bldg. 4655) complete
- Major components have been bought
- Vacuum system under construction
- Final design of coils / bus-plates / mechanical structure
- Final design of capacitor banks and triggering circuits
- Procurement of Control / DAQ system

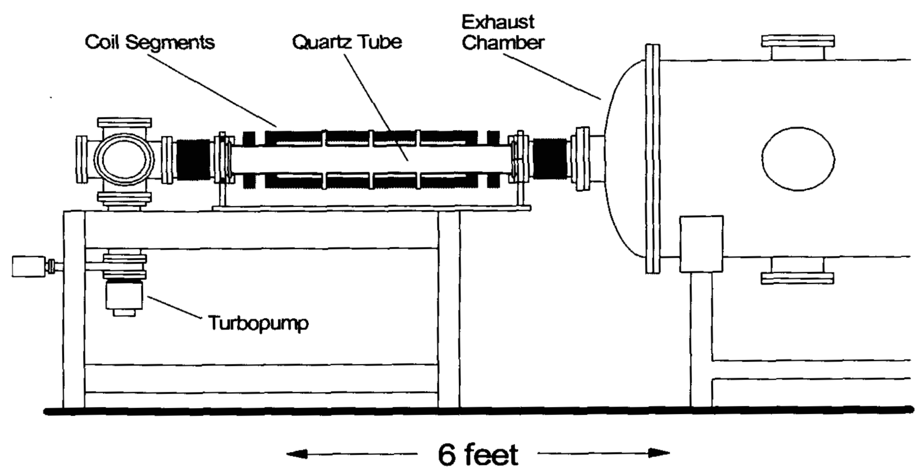
Collaborations:

University of Washington

Points of Contact:

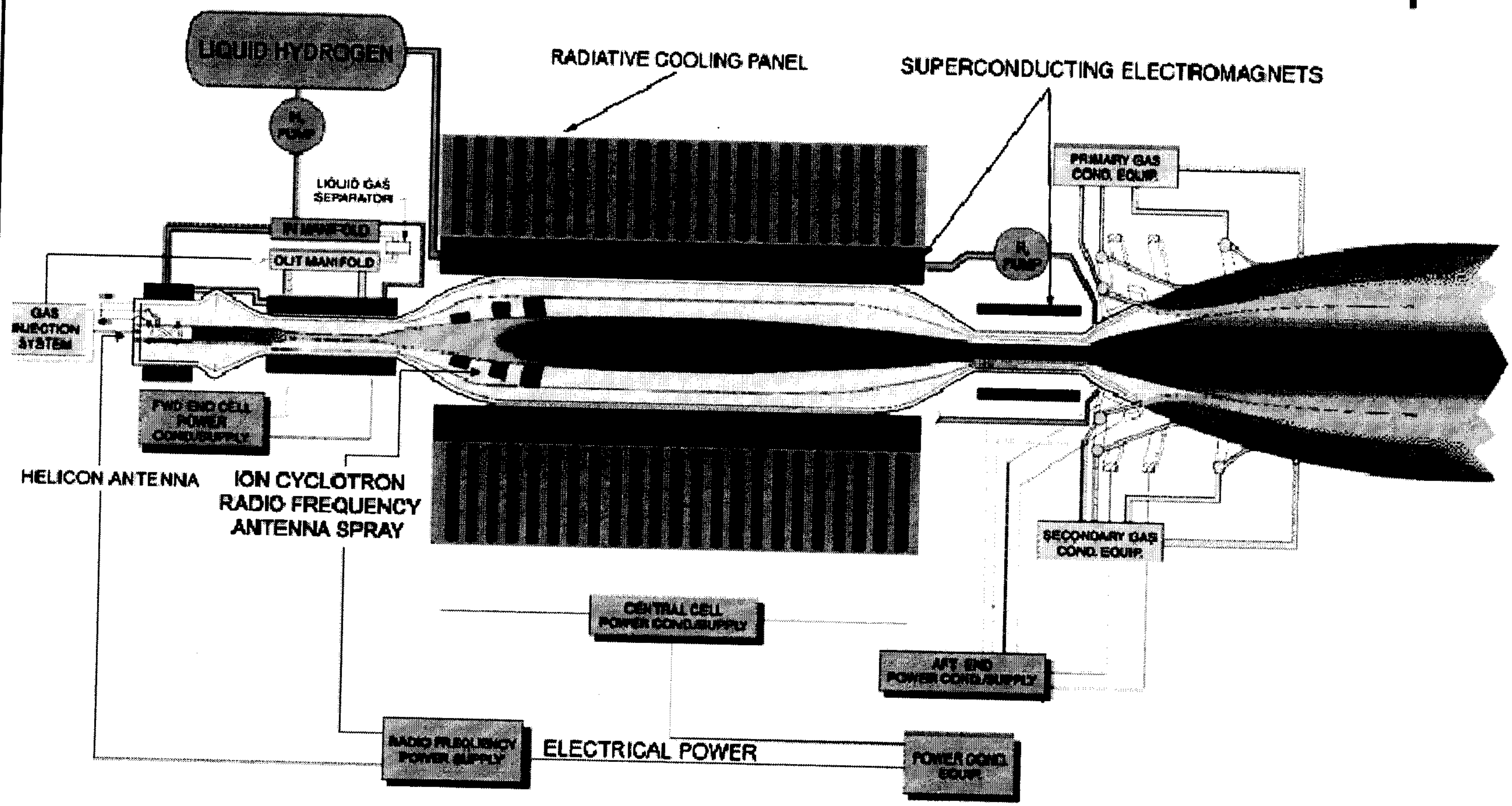
- Adam Martin, MSFC TD40 256-544-5296
- Richard Eskridge, MSFC TD40 256-544-7119

FAST - Formation Stage



Quick Review of VASIMR System

Variable Specific Impulse Magnetoplasma Rocket Concept



Summary

- There are lots of candidate thruster types
  - Many are called, but only a few will be chosen

- For thruster power levels of 20 to 50 kW Ion and 2-Stage Hall Thrusters will be hard to beat

- The field is wide open for thrusters in the 100's to 1000's of kW input power range