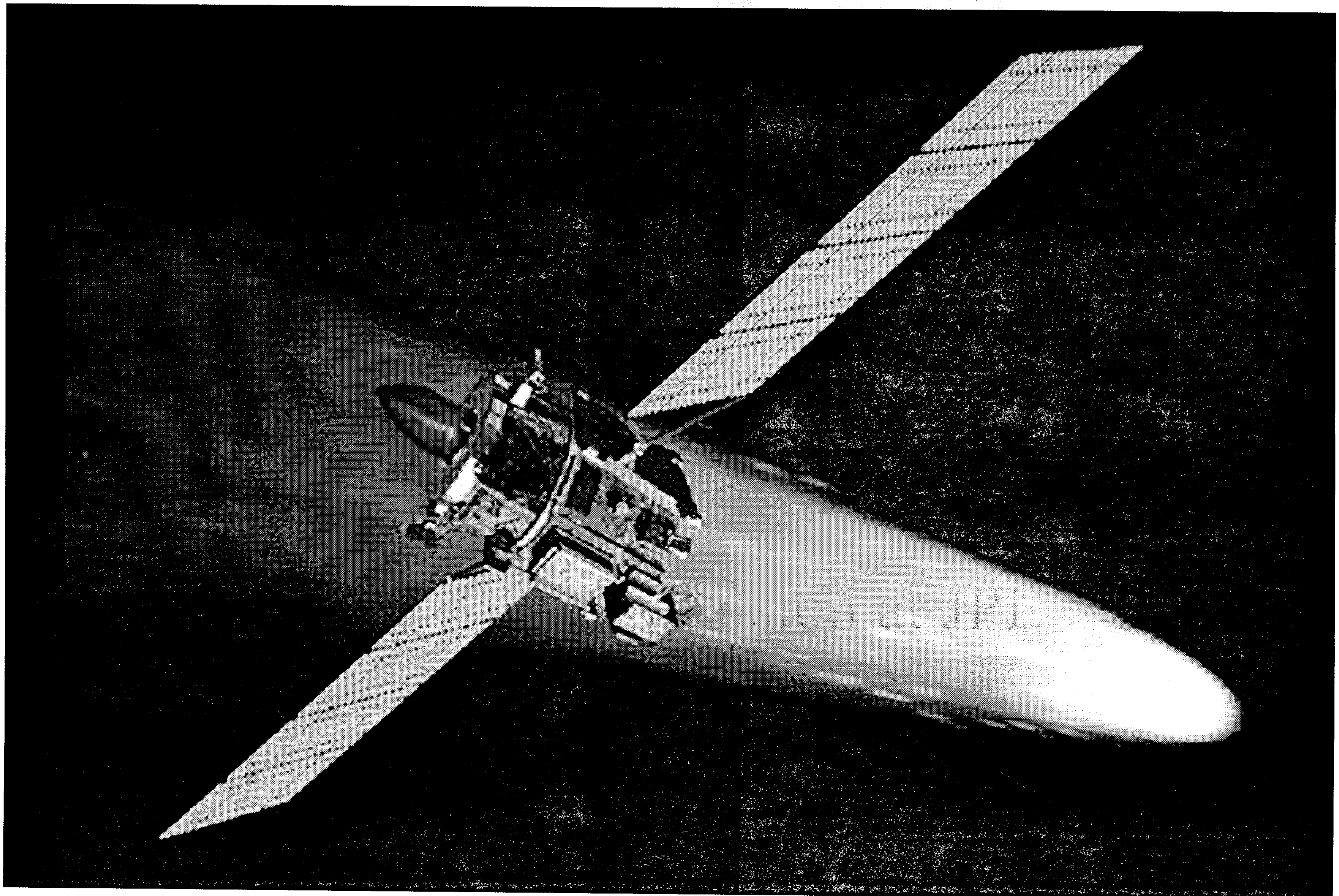
Electric Propulsion at JPL



NASA Science Missions are the Foundation of Electric Propulsion at JPL

Our Vision: "***Advanced Electric Propulsion for NASA's Science Spacecraft***"

- Derived from the Science & Missions Flow Down
  - NASA Strategic Goals
    - To understand and protect our home planet
    - To explore the Universe and search for life
    - To inspire the next generation of explorers
    - ...as only NASA can
  - Space Science Enterprise Strategic Goals
    - Explore the Solar System and the universe beyond
    - Understand the origin and evolution of life
    - Search for evidence of life elsewhere.
  - JPL Strategic Goals
    - Explore our Solar System,
    - Detect "other earths" in neighboring planetary systems,
    - Search for life beyond the confines of Earth
- Electric Propulsion Enables Many of These Missions

Electric Propulsion at JPL: Roles & Resources

JPL Roles in Electric Propulsion

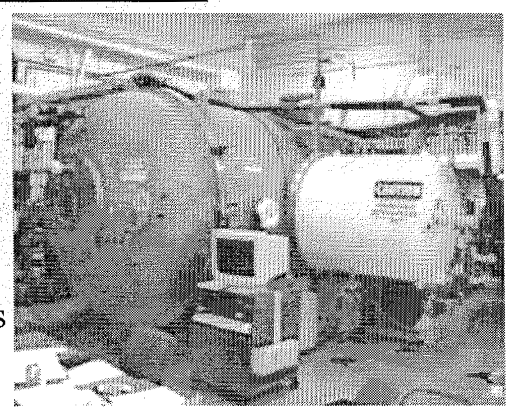
- **Experienced discipline experts, program element & contract technical managers for flight projects**
  - JIMO – High Power Electric Propulsion System
  - Dawn – Ion Propulsion System
  - ST-7 – Disturbance Reduction System Thrusters
  - Road Runner – Hall Thruster Plasma Diagnostics (AFRL)
- **Pre-Project planning technology support**
  - LISA – Thrusters for Precision Formation Flying
  - Prometheus – Electric Propulsion Technology
  - Team-X – Electric Propulsion
- **Electric propulsion system mission assurance**
  - Failure mode analysis
  - Engine qualification tests & life models
  - Electric thruster integration issues: plumes, contamination, etc.; tests & models
- **Technology development to meet mission requirements**
  - Carbon Based Ion Optics (CBIO)
  - NASA Evolutionary Xenon Thruster (NEXT)
  - Nuclear Electric Xenon Ion System Technologies (NEXIS)
  - JIMO Propulsion System Technologies

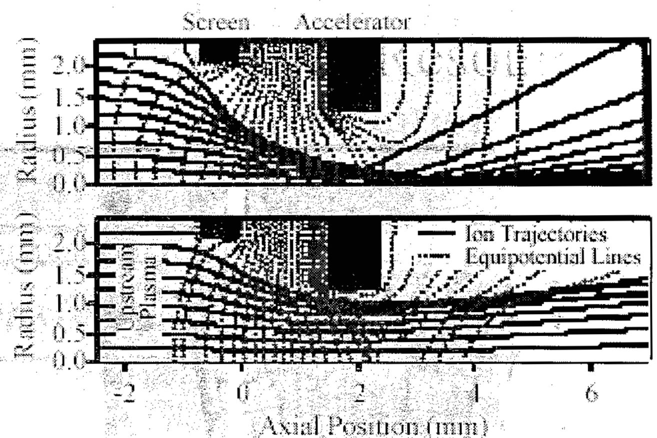
[redacted]

  - Thrusters for Precision Formation Flying
  - Propulsion for Micro-Spacecraft
  - Lithium Lorentz force thrusters
  - Bismuth – Anode Layer Thrusters (TAL) for NEP

World-Class Workforce:
20 Engineers (18 PhD's, 2 MS's) 3 Technicians and Access to a Wealth of Expertise at JPL

Excellent Facilities:
6 Large Vacuum Facilities
Several Smaller Chambers with Advanced Diagnostics

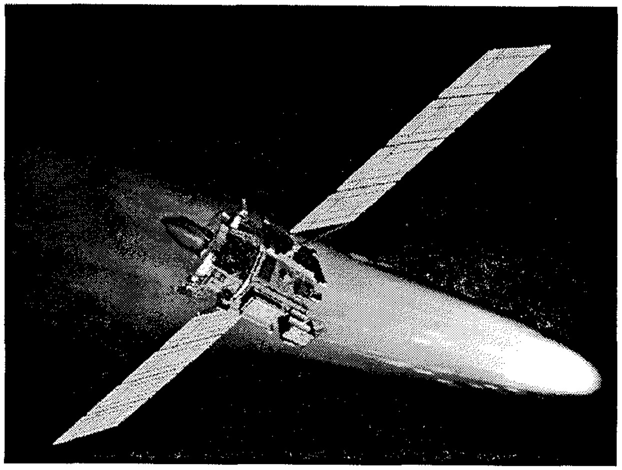




Unique Analytical Capabilities:
A strong tradition of combining analysis and experiment in technology development

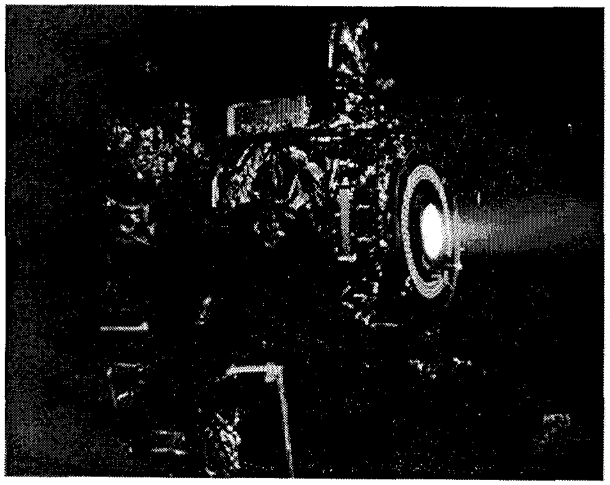
Deep Space 1 Was the First Spacecraft To Use Ion Propulsion for an Interplanetary Mission

JPL GRC flight project

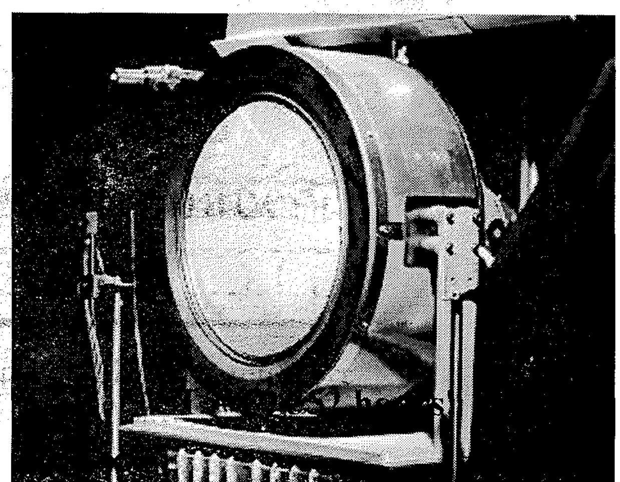


Deep Space 1 flew by the comet Borrelly in 2001, collecting valuable science data.

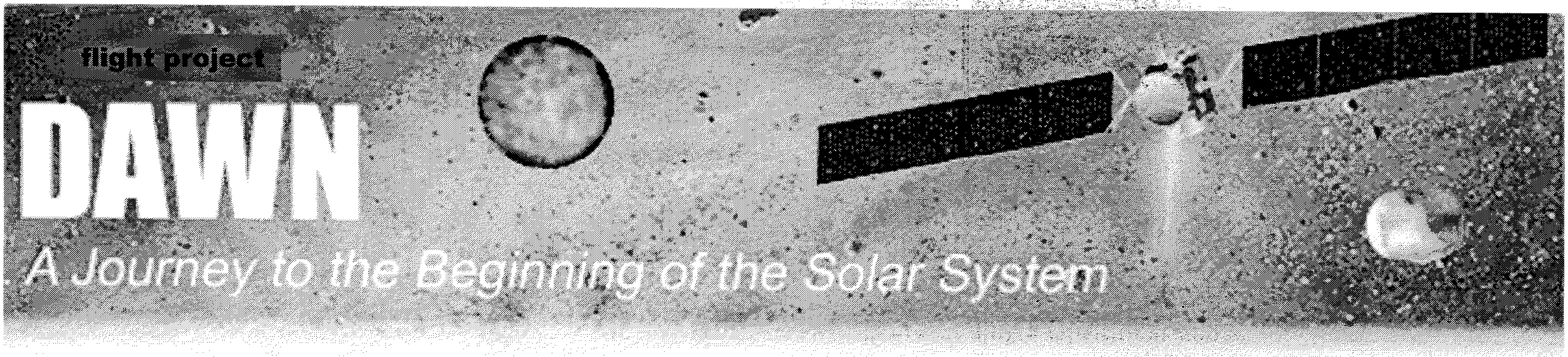
- **Deep Space 1 Flight Engine Developed by JPL Managed Team**
  - NSTAR Project (JPL, GRC, industry, universities and international partners)
- **Deep Space 1 Ion Engine Life Testing Performed by JPL**
  - 1000 hour validation test
  - 8200 hour Life Demonstration Test
  - NSTAR Extended Life Test (30,352 hours)
- **Deep Space 1 Flight System Integration and Functional Tests**
  - End-to-end system demonstration in thermal-vacuum test
- **Deep Space 1 NSTAR Flight Diagnostics Package**
- **Deep Space 1 Flight Operations and Successful Mission**
  - 16,265 hours of operation in space
  - Hyper-Extended Mission – NSTAR thruster tests



Flight ion engine firing on Deep Space 1 spacecraft during solar thermal vacuum test.



World's longest ion engine endurance test was conducted at JPL.



- GOAL

  Characterize the conditions and processes of the solar system's earliest epoch by investigating in detail two of the largest protoplanets remaining intact since their formations.

  Ceres and Vesta reside in the zone between Mars and Jupiter called the asteroid belt.

- MISSION OVERVIEW:

  Delta 7925H launch; 3 NSTAR Xenon (Xe) thrusters

  Cruise: one thruster at a time

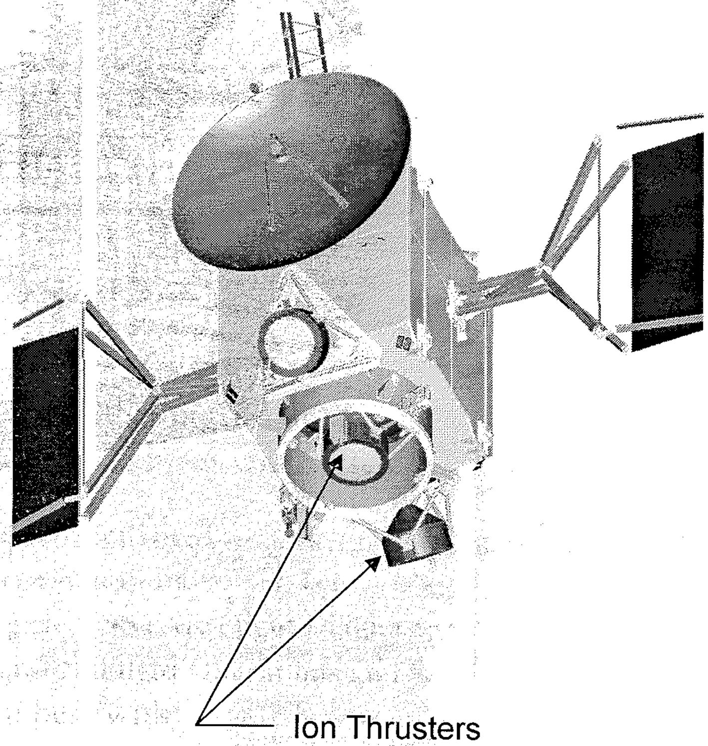
  Vesta: orbit at 2450, 700 and 200 km alt. 7 months incl. orbit changes

  Ceres: orbit at 5900, 1300 and 700 km alt. 5 months incl. orbit changes

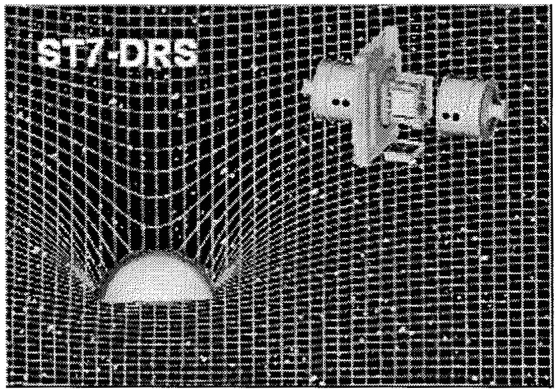
  288 kg Xe to Vesta; 89 kg to Ceres for maximum injected mass

  Orbit capture with xenon

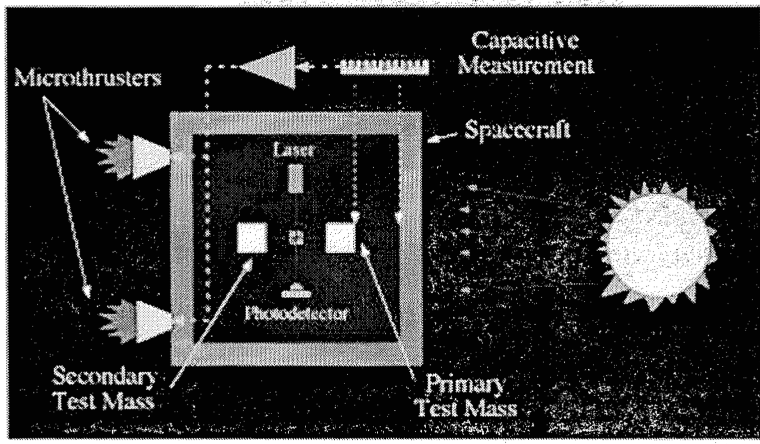
Dawn Spacecraft Configuration
(3 ion thrusters, 2 PPUs, 2 DCIUs)

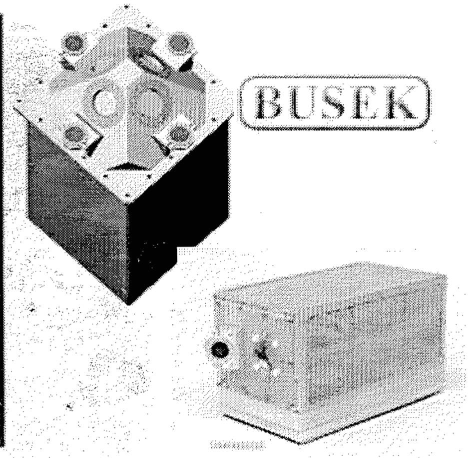


ST7-Disturbance Reduction System

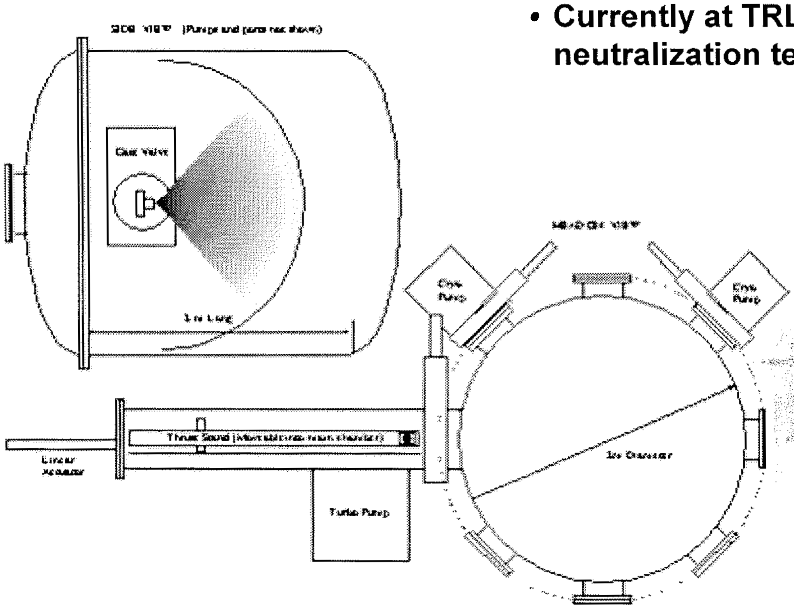


- Demonstrate drag-free operation
- Launch: August, 2006



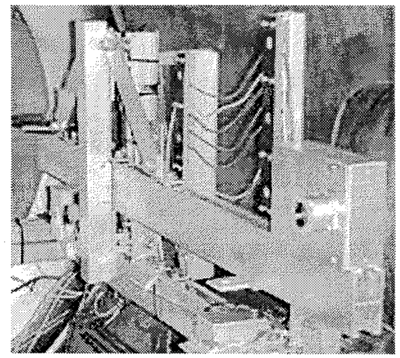


- **Busek Colloid Microthrusters will offset solar pressure for gravitational sensor**
- **Each Microthruster provides between 2-20 μN with 0.1 μN precision**
- **Currently at TRL 4--Requires performance, contamination, beam profile and neutralization testing to move to TRL 6 before launch**

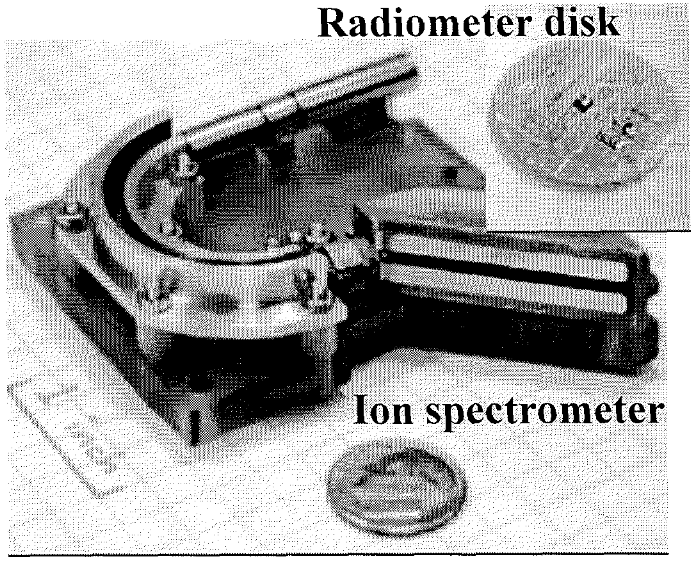


- Advanced Propulsion Technology Group supporting ST7 as technology advisor with thruster testing in FY03-04

- **Developing world-leading test facilities for Microthrusters:**
- **Nano-Newton Thrust Stand**
- **2 m diam. ultra-high vacuum chamber with beam profile and contamination diagnostics**



Road Runner: Flight Instrumentation for Hall Thruster Integration

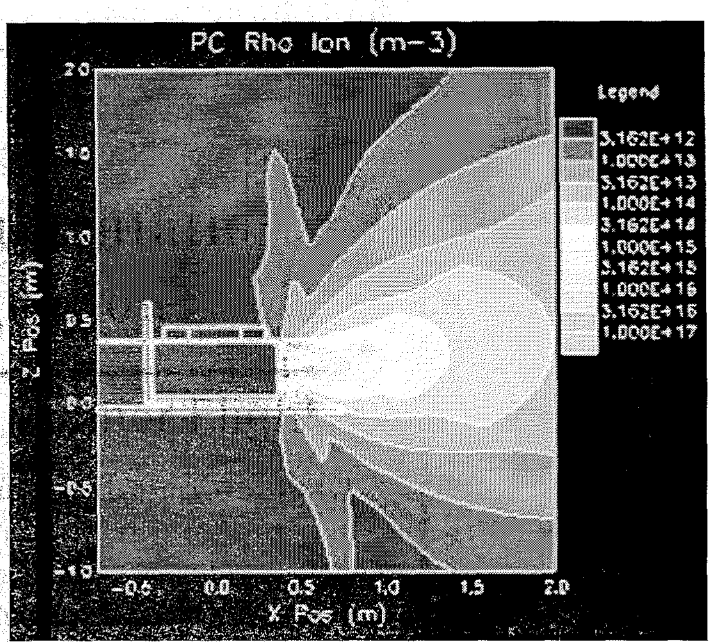


AFRL Road Runner Flight Project

- **JPL/AFRL Propulsion Measurements Program**
  Combined flight instrument, ground measurement, and modeling program.
  Objective: integration handbook for 200 W class Hall Thruster.
- **Design and systems engineering for flight instruments**
  2 plume probes, 3 contamination instruments: 2 kg overall.
  Team: JPL, AFRL, Broadreach Engineering, Spaceworks.
- **Activities**
  Ground plume characterization - 2001-2005
  Flight systems delivery (AFRL to AFRL) – late 2004
  Launch – Early 2005

Instruments/Modeling

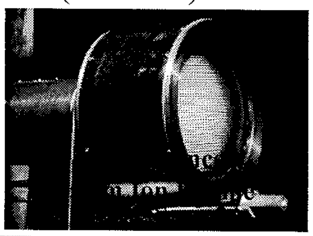
- **Validated model required to extend flight results to operational missions**
  Modeling efforts SAIC, AFRL, U. Mich.
- **Path to validated model**
  Plume instruments directly measure ion, electron content of plume, providing validation of thruster internal and plume expansion code.
  Contamination instruments assess degradation, provide validation of more complex plume/spacecraft 3D interaction codes.
- **Plume Instruments take snapshot of thruster operational conditions**
  Ion energy spectrometer: ion flux energy distribution
  Electron probes: Plume electron density and SC current return/balance.
- **Contamination Instruments determine changes over thruster operational life**
  Radiometer: assesses change thermal control material α and ε.
  Photometer: measures optical transmission changes.
  Solar cell: determine I-V characteristic of triple junction cells.

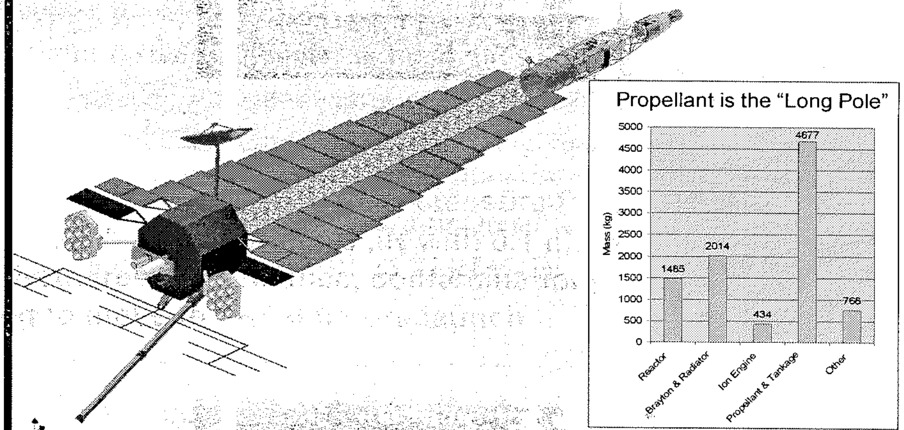


Ion Thrusters for the Prometheus JIMO Project

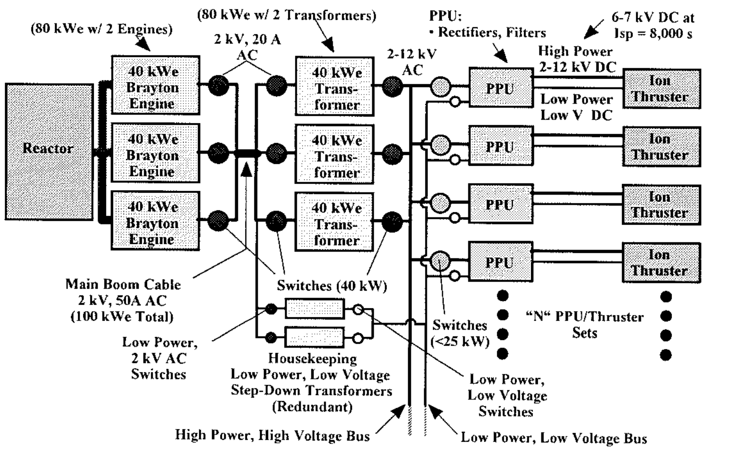
JPL flight project

- **Nuclear Electric Propulsion Systems Engineering**
- **Thruster Development – Competitively Selected**
  - Nuclear Electric Xenon Ion System Technologies (NEXIS)
  - Two Stage Bismuth – Anode Layer Thrusters (TAL)
- **NEP System End-to-End Test at JPL**
  - Joint MSFC – JPL effort
  - Demonstrated 11/01 at low-power (< 200We)





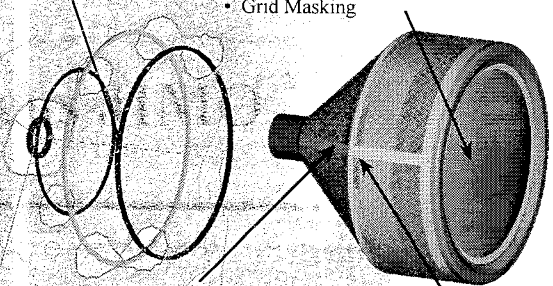
Jovian Icy Moon Orbiter requires 6500s *Isp* thrusters, enabled by JPL carbon grid and service life assessment technologies



NEP Electric Propulsion System Block Diagram

- Large Discharge Chamber
- Advanced Ring Cusp Magnetic Field Configuration

- Beam Voltage > 4860 V
- New Grid Design Using Advanced SimulationTools
- Erosion-resistant Carbon Carbon Grids
- High Perveance Margin Operation
- Accelerator Grid Hole Size Tailoring
- Grid Masking



- Reservoir Hollow Cathode Incorporating:
  - -Advanced Emitter Material
  - -High Capacity Activator Supply Reservoir
  - -Improved Activator Transport
  - -Decoupled Emitter and Activator Source
- One Neutralizer Shared By Multiple Engines

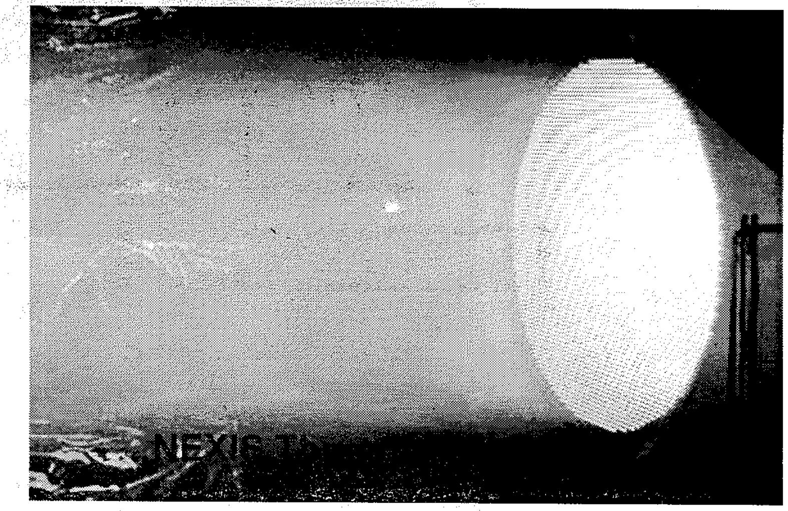
- Erosion-resistant Carbon Keeper Electrode
- Operational Control of High Energy Ion Production

NEXIS long life and high efficiency thruster for JIMO

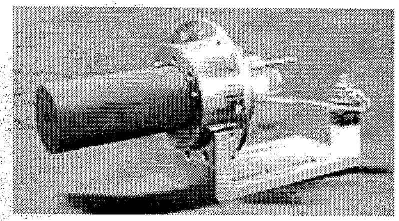
JIMO-NEXIS Ion Thruster Development

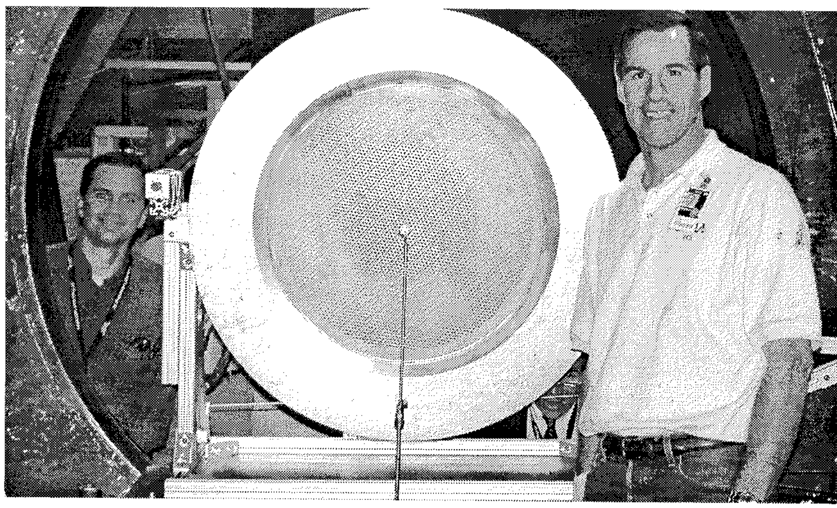
JPL flight project

- NEXIS Lab Model Thruster demonstrated performance in agreement with JIMO mission analysis model
- NEXIS designed for extraordinary life using revolutionary Carbon-Carbon grids, graphite keeper, long life hollow cathodes
- The thruster demonstrated the NRA performance objectives of 22.5 kWe, 7500 s and 3.9 A,
- Peak performance achieved 27 kWe at 8700 s, 4 A with an efficiency of 81%.
- Beam flatness measured at 80-82%

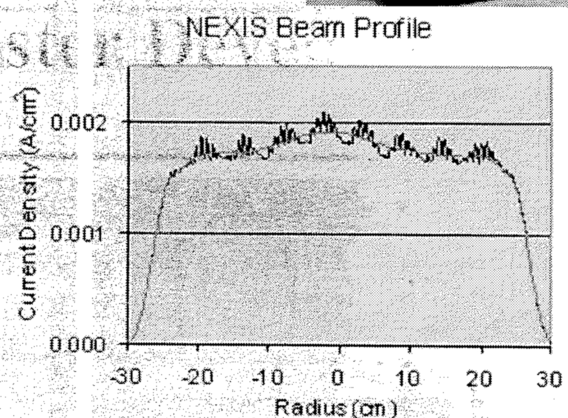


Graphite discharge cathode keeper



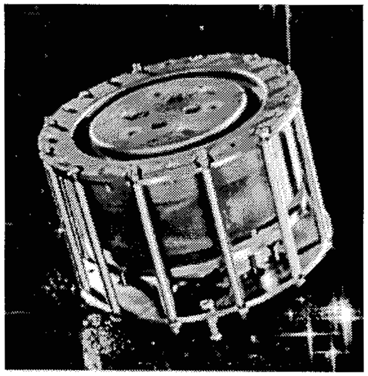


NEXIS thruster prior to installation in the vacuum test chamber

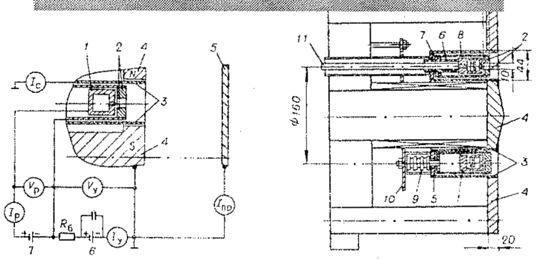


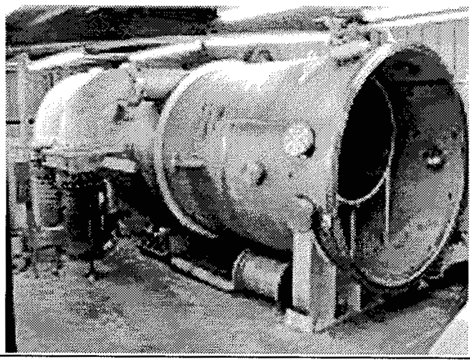
Very High *Isp* Anode Layer Thruster (VHITAL)

project planning



TAL-160 -TsNIIMASH





JPL vacuum facility for high power and liquid metal-fueled thrusters

Motivation:

2-Stage Thruster with Anode Layer (TAL) 160 developed more than 20 years ago and demonstrated excellent performance on Bi at TsNIIMASH with a specific impulse up to 8000 s, efficiency greater than 70% at 100 kW and 8000 s and power up to 140 kW. This high power and high efficiency performance is optimal for NEP missions to the outer planets.

Objective:

Validate the TAL-160 thruster performance at 25 kW (6000 s) and 36 kW (8000s) on Bi at JPL.

JPL Roles/Capabilities:

Mission analysis to identify the thruster operating regimes which are optimal for the missions of interest.

Thruster performance evaluations in vacuum facility for high power liquid metal-fueled electric thrusters.

Development of Bi-fed cathode, propellant isolator, and feed system.

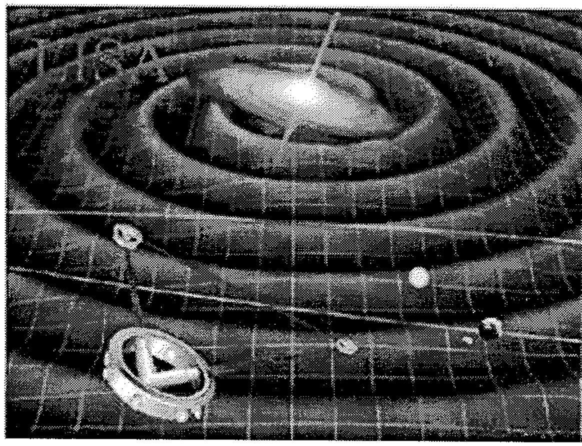
Thruster lifetime assessment with surface layer activation diagnostic.

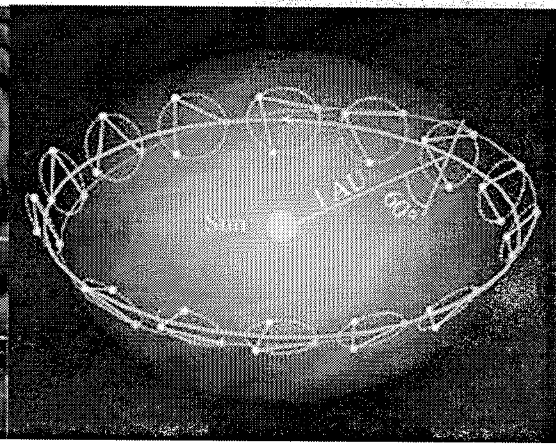
Thruster plume characterization with Faraday, emissive, and ion energy and QCM probes.

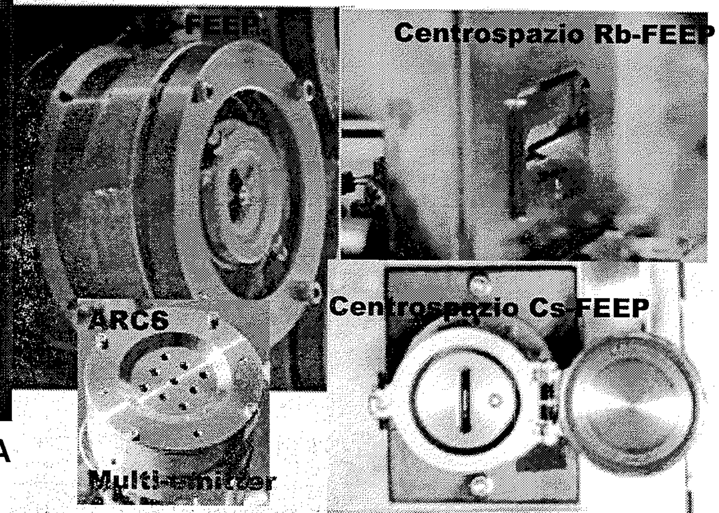
Assessment of spacecraft contamination with experimental and theoretical approaches.

VHITAL Project Selected – Start April 1, 2004

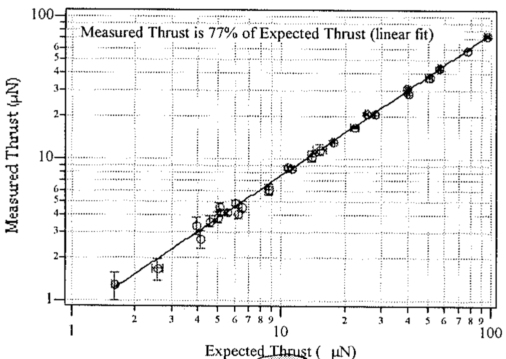
LISA Project Technology Support

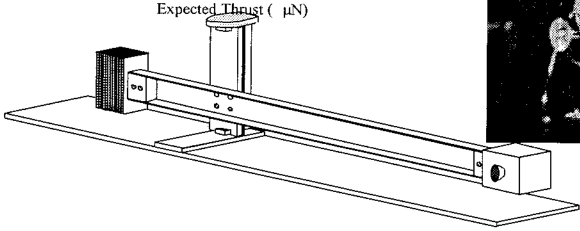




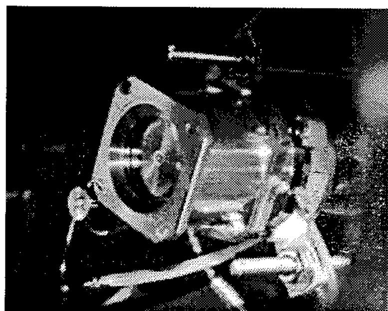


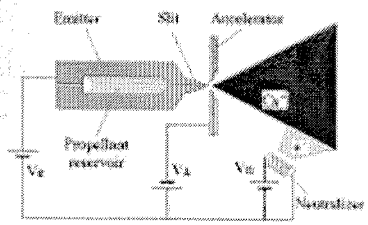
- LISA is an Interferometric Gravity Wave Detector currently in pre-phase A
- Precision Formation Flying requirement: 5 million km within 10 nm
- Thrust requirements: 1-25 μN within 0.1 μN for 3 years continuously





Advanced Propulsion Technology Group supporting LISA as technology advisor with thruster and neutralizer testing and modeling efforts in FY02-04

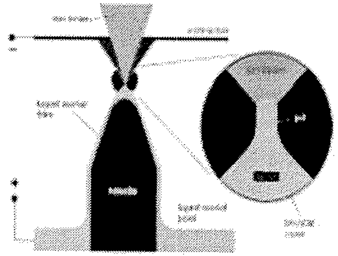




- JPL was first US institution to test FEEP Technology in June 01

<u>APT Group Developing:</u>

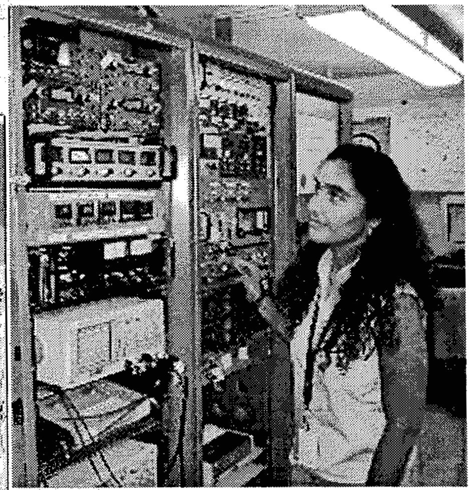
- Nano Newton Thrust Stand
- UHV chambers for beam profile and field emission cathode neutralization experiments
- Computational plume expansion and droplet production models



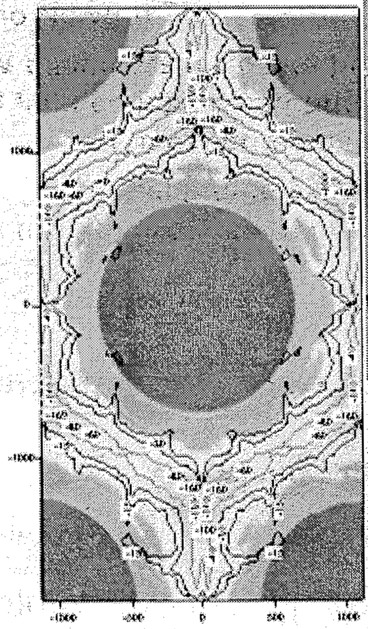
Ion Thuster Service Life Validation: Quantitatively Assessing Engine Service Life Capability

EP mission assurance

- **Long Duration Tests to Identify and Characterize Failure Modes**
  - 10 kWe test (1988)
  - 5 kWe test (1990)
  - Test-to-Failure Test (1993)
  - NSTAR Testing
    - 2000 Hour Test (1994)
    - 1000 Hour Test (1995)
    - 8200 Hour Test (1998)
    - 30,0352 Hour Test (1998-2003)
- **In-Space Data from the Deep Space 1 Spacecraft to Characterize Failure Modes and Validate Ground Measurements**
- **Probabilistic Analysis to Assess Service Life**
  - Relatively simple analytical models of failure process embedded in Monte Carlo simulation
  - Experimental data and additional modeling to characterize parameter distributions
- **Modeling of Plasma and Surface Processes**
  - Particle-in-Cell code simulations of ion acceleration and charge exchange process
  - Hollow cathode physics models
  - Surface kinetics modeling of simultaneous sputtering and deposition
- **Critical part of JIMO and NEXT programs**

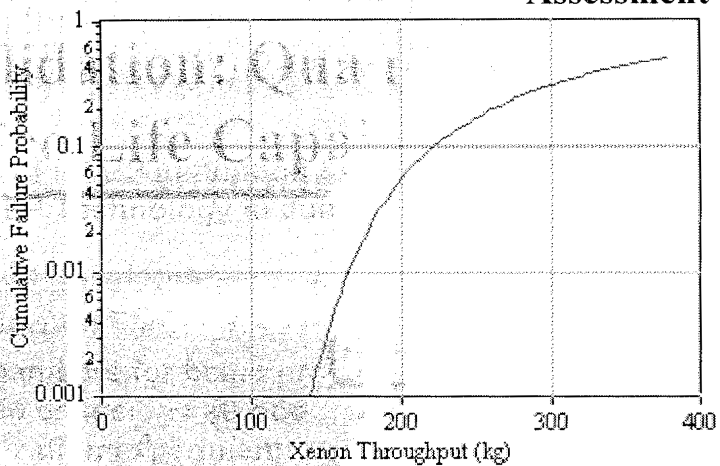


Testing



Modeling and Analysis

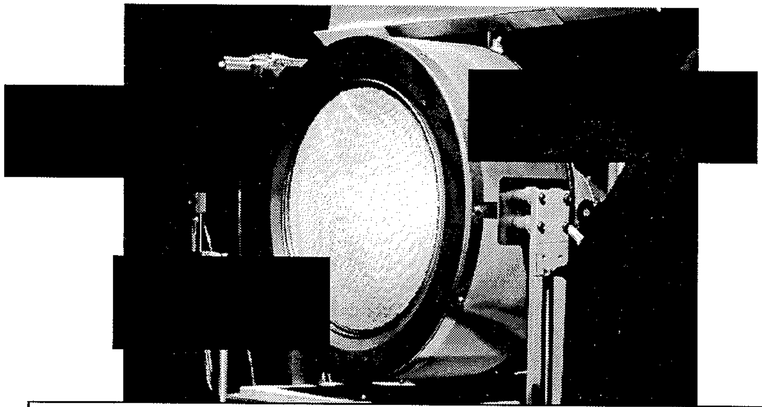
Probabilistic Failure Assessment



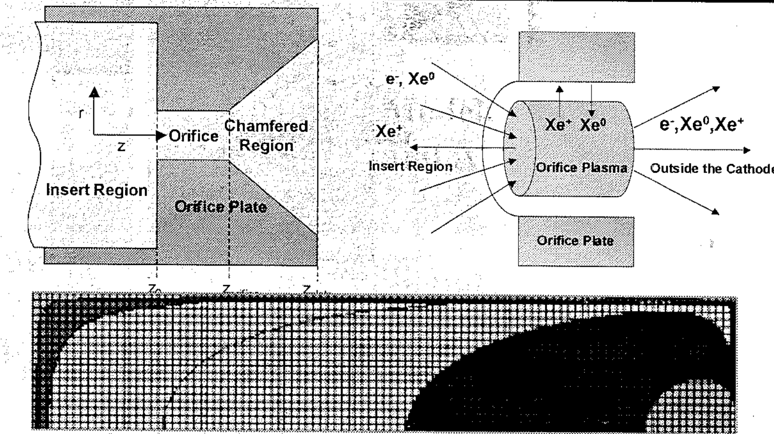
JPL

EP mission assurance

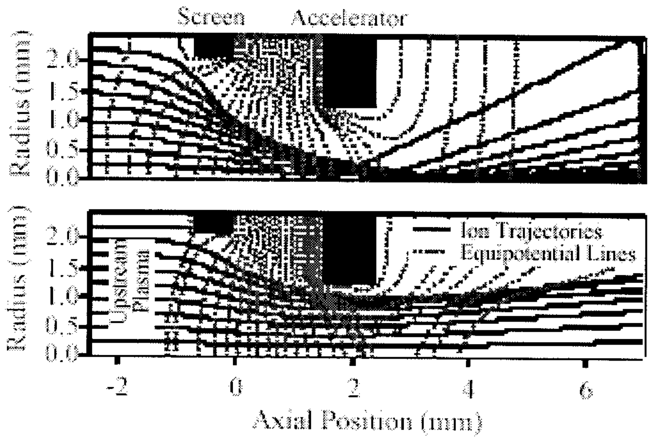
JPL Computer Models of Ion Thruster Performance & Life



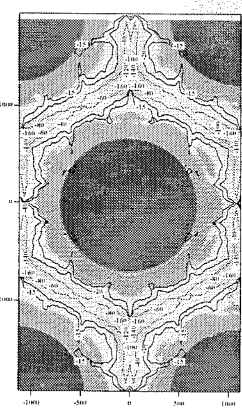
Computer models are used to guide design, correlate test data & predict engine life
Validated with lab & flight performance & wear data



Hollow cathode orifice and discharge chamber models include ionization physics

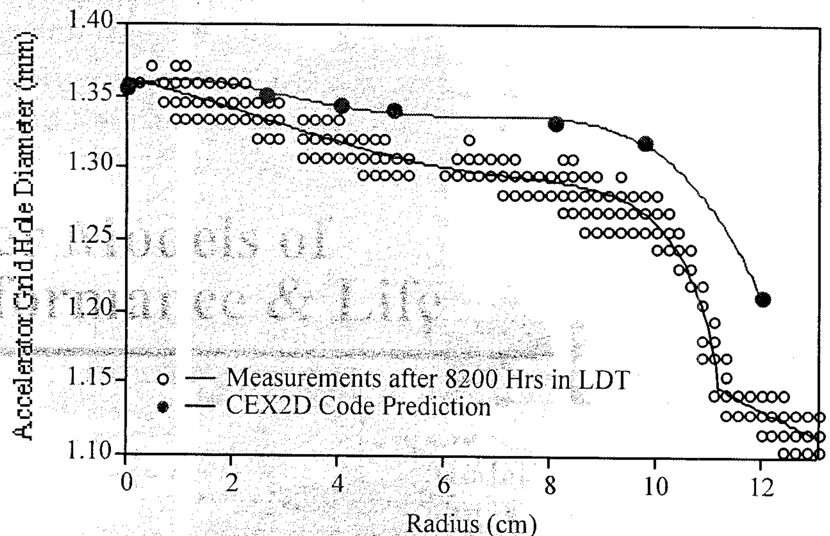


ion trajectories



erosion pattern

Codes model ion trajectories and erosion of a single grid aperture



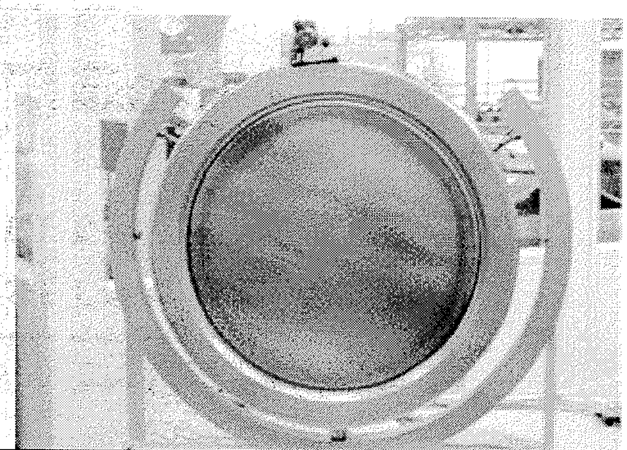
Calculated accelerator grid hole compared with data from the NSTAR Life Demonstration Test

JPL Roles in the GRC Led NASA Evolutionary Xenon Thruster (NEXT)

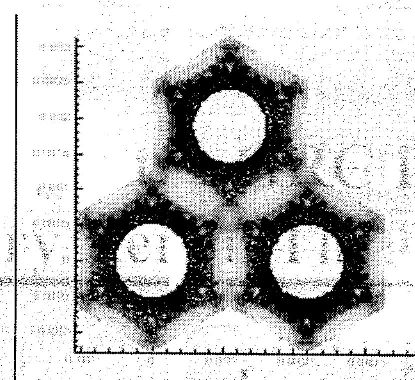
technology for missions

JPL Tasks

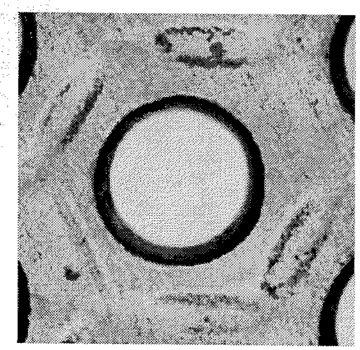
- Leadership of the project's definition and review of the System Technical Requirements and Verification (TRV) document
- Support to the Deep Space Design Reference Mission (DSDRM) analysis, and leadership of the mission analysis of NEXT application to other Code S missions
- Leadership of the initial integrated breadboard system testing
- Leadership of the service life validation activity, and development of the project's service life validation plan.
- Support to the NEXT project manager in the review of component design efforts and system integration test planning activities



The 40cm NEXT thruster will be more than twice as powerful as today's NSTAR thruster.



CEX3D Calculation

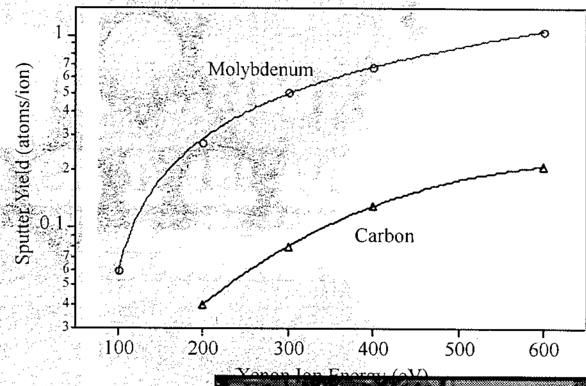


NEXT 2000 Hour Wear Test

JPL leading the service life validation activity

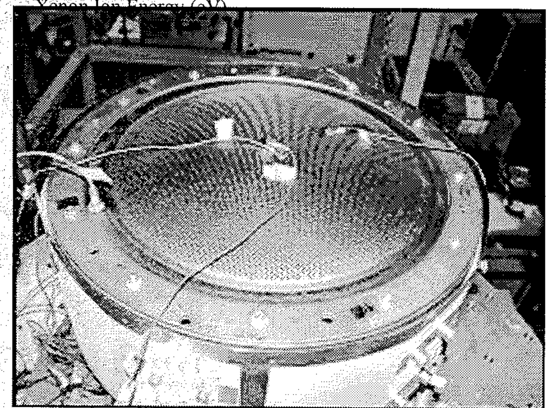
Carbon Based Ion Optics (CBIO) for the Next Generation Ion Technology

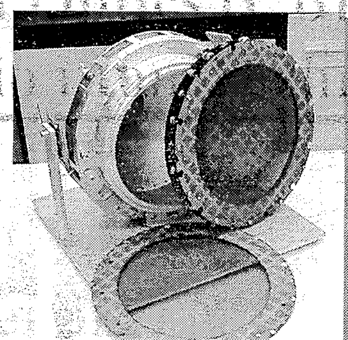
- **Advanced carbon grid materials offer dramatic improvements in ion engine technology**
    - Carbon erosion resistance essentially eliminates grid wearout failure modes
    - Light weight carbon materials yield factor of 3 savings
- **Goals and Objectives**
    - Develop 30-cm carbon-carbon grids
    - Validate the performance and life of the carbon-carbon grids
    - Develop and deliver grid life modeling software
- **Major Products**
    - 30-cm CC grids for long life operation at Isp's between 4000 and 5000 s.
    - "User friendly" grid life modeling software
    - Establish the feasibility of developing 40-cm CC Grids
- **Key Challenges**
    - Achieving required beam extraction characteristics
    - Demonstrate ability to survive launch loads
    - Demonstrate ability to provide sustained operation with acceptable arcing at the required electric field
- **Accomplishements**
    - **30cm Carbon – Carbon Grids Running at 5000s**
    - **Grids on thruster passed vibe**

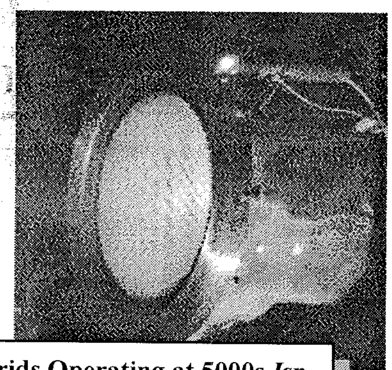


Carbon erosion rates the lowest

Modeling and testing used to demonstrate ability to survive launch loads







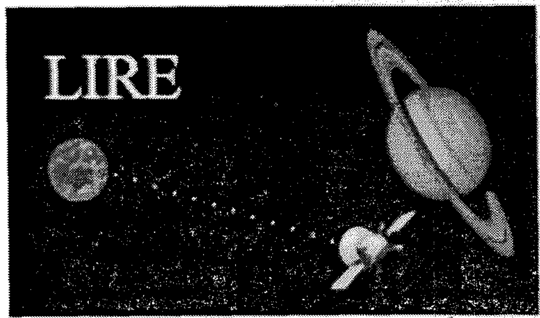
30 cm Carbon-Carbon Grids Operating at 5000s *Isp*

Emerging NASA Missions Require Extremely High Precision, Low Noise Thrusters

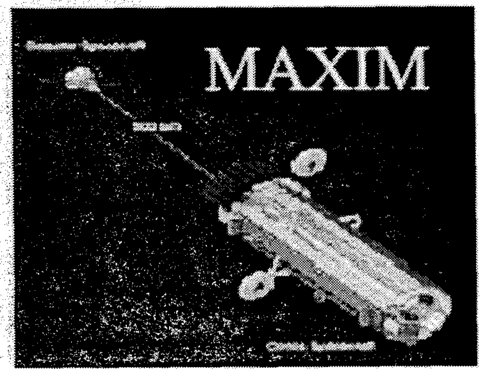
technology for missions

NASA roadmaps show many missions requiring precision thrusters for drag make-up and constellation maintenance besides LISA and ST-7:

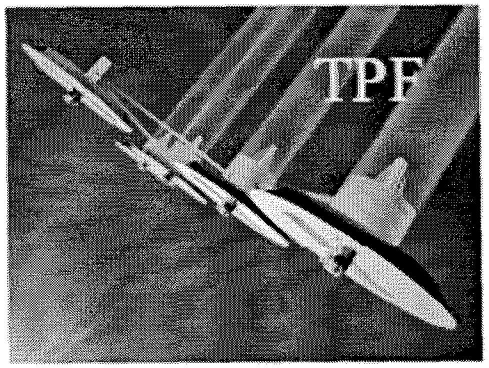
EX5 (Earth Science)
- Time varying Earth Gravity
- Code Y Strategic Plan



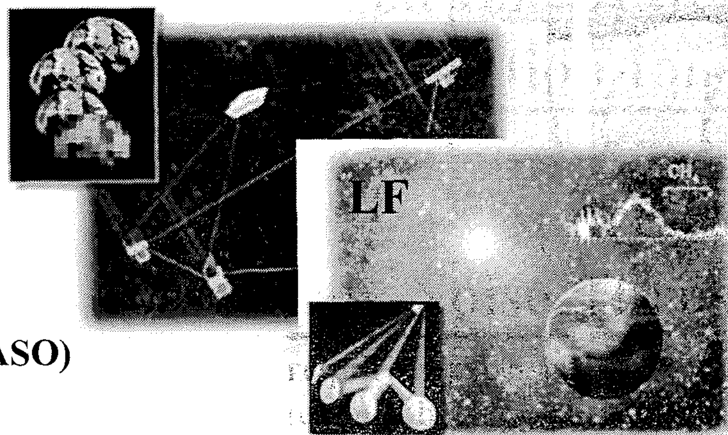
LIRE (Code U)
- Solar System Test of General Relativity
- On Fundamental Physics in Space Roadmap



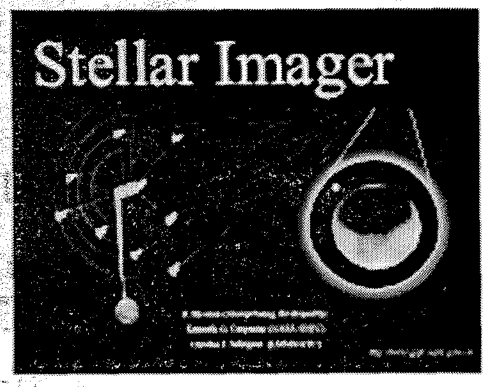
MAXIM (SEU)
- X-ray imaging of black holes
- On SEU roadmap



Terrestrial Planet Finder (TPF) (ASO)
- IR Imaging of planetary Systems
- Positioning control < 30μm



Planet Imager (PI) and Life Finder (LF)
- TPF follow-on



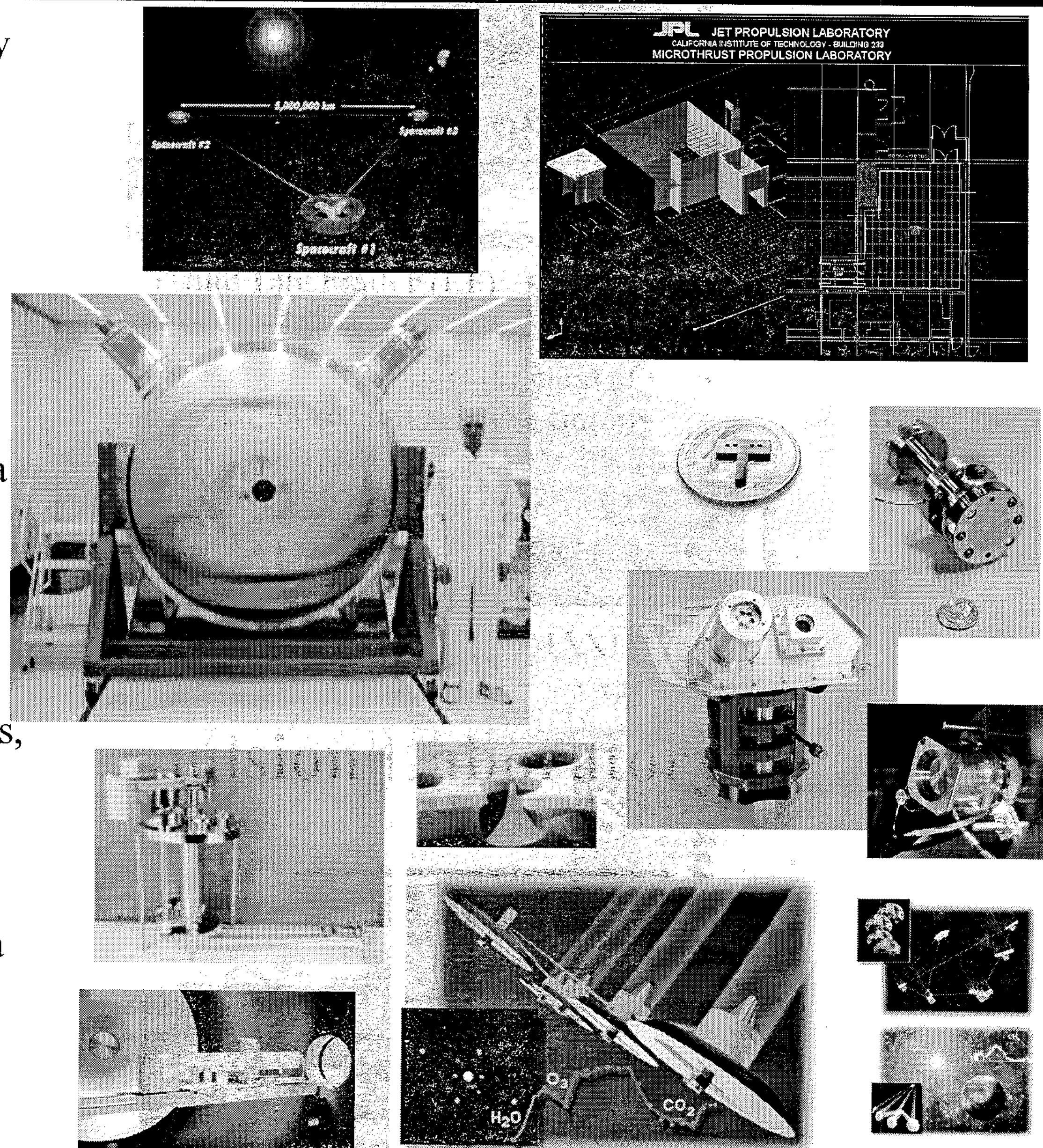
Stellar Imager (SEC)
- UV Imaging of other stars
- On SEC Roadmap

In-Space Propulsion should address the needs of this important class of missions (Typical: μN thrust levels, <0.1 μN thrust noise, and < 1 μNs Impulse bit)

Microthrust Propulsion Laboratory

technology for missions

- The Microthrust Propulsion Laboratory (MPL) is a world-class facility for developing and testing microthrust propulsion systems
- Capable of a Class-10 cleanroom environment, MPL has 1000 sq. ft. of floor space for multiple projects
- A 2 m diam., 2 m long ultra-high vacuum (UHV) chamber will provide a unique environment for testing microthrusters
- Chamber is equipped with a Nano-Newton Thrust Stand, exhaust beam profiling and contamination diagnostics, and a load-lock system for rapid turn around
- This facility is the only one of its kind in the world, allowing JPL to become a leader in microthruster technology development and evaluation



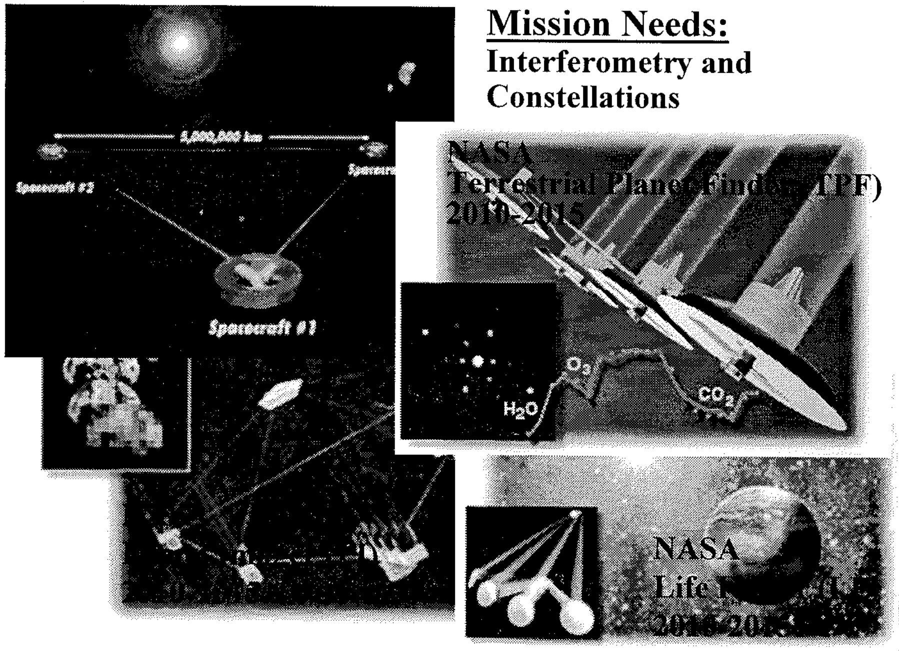
JPL

technology for missions

Thrusters for Precision Formation Flying

NASA

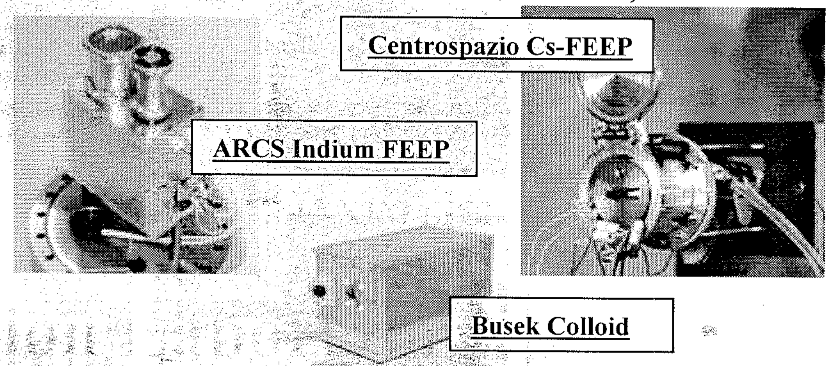
Mission Needs:
Interferometry and Constellations

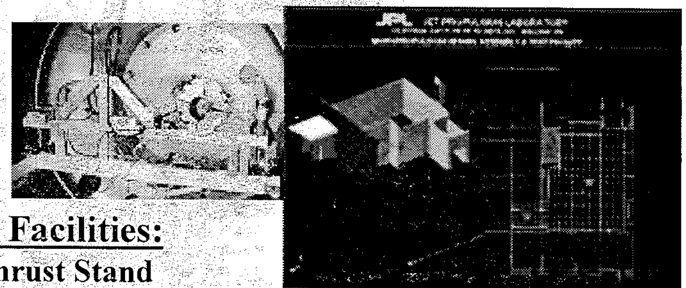


Many NASA missions are planned for interferometry and gravity wave detection, as well as DOD missions. Constellation attitude maintenance and control poses stringent propulsion requirements:

LISA: (NASA/ESA)	Thrust: Control Accuracy:	1 - 20 μN 0.1 μN
ST-7 (NASA):	Thrust: Thrust Noise:	1-20 μN 0.1 μN
TechSat 21: (Air Force)	Min. Thrust: Impulse Bit:	2 mN (2003), 40 - 200 μN 2 mNs (2003), 2 μNs (est.)
TPF: (NASA)	Thrust:	0.1 N (re-formation) ~ μN (pointing)
PI, LF (NASA):	unknown, presumed similar to TPF	

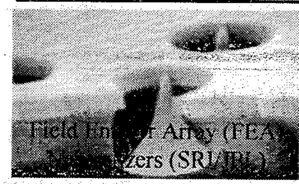
Technology Needs: Evaluate FEEP and Colloid Thrusters (Performance, Contamination, Plume, Lifetime)



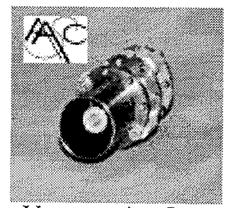


Key JPL Facilities:
- Micro-Thrust Stand
- Micropropulsion Test Facility with UHV Chamber

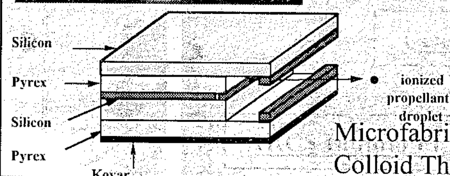
Advanced Technology Development:



Field Emitter Array (FEA) Cathodes as neutralizers for FEEPs /Colloids. Collab. Development with Industry

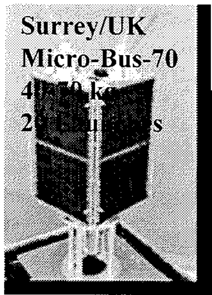


Vacuum Arc Ion Thruster (SBIR)

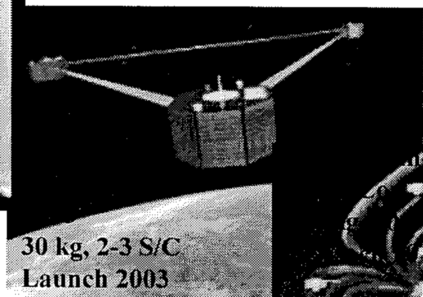


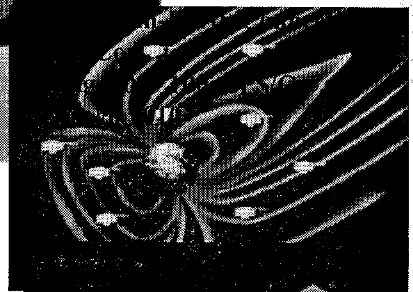
Microfabricated FEEP/ Colloid Thruster (DRDF)

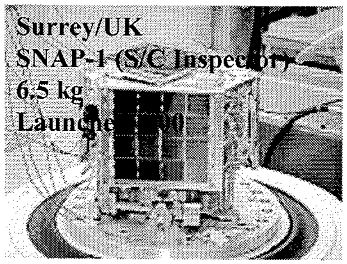
Propulsion for Micro Spacecraft



Mission Needs: Micro Spacecraft propulsion and attitude control



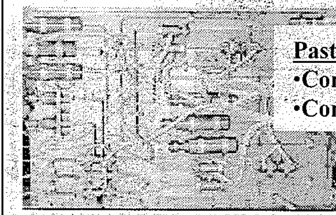




Due to the small mass of micro spacecraft, pointing and deadband control will require extremely small impulse bits and thrust values depending on mass of the spacecraft:

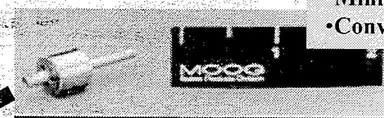
S/C Mass (kg)	Required Impulse Bit (Ns)			
	17 mrad (1°)		0.02 mrad (5 arcsec)	
	20 s	100 s	20 s	100 s
1	1.4×10^{-4}	2.9×10^{-5}	1.7×10^{-7}	3.4×10^{-8}
10	4.3×10^{-4}	8.5×10^{-5}	1.0×10^{-6}	1.0×10^{-7}
20	1.1×10^{-3}	2.3×10^{-4}	1.3×10^{-6}	2.7×10^{-7}

Technology Needs: Highly integrated, modular, miniature, ultra-low impulse bit attitude control thrusters. Utilize novel microfabrication (MEMS) methods in their realization.

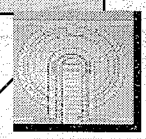


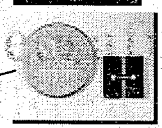
Past:
- Conventional Components
- Conventionally Integrated

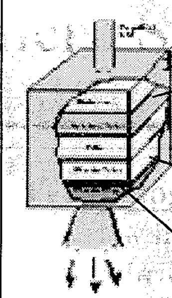
State-of-the-Art:
- Miniature Components
- Conventionally Integrated

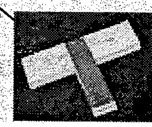


Goal:
- Micromachined Components
- Highly Integrated Modules
- Minimal External Interfaces







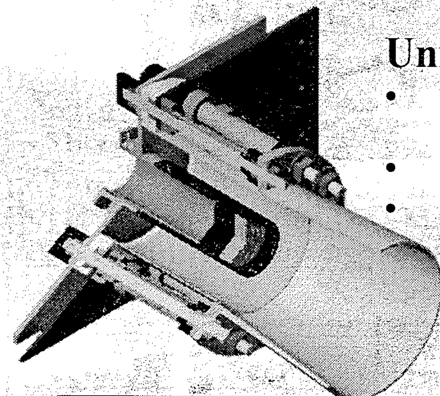


Component	Specifications
Integrated High Voltage Interface	Drivers for MIV, MMV, VLM on single chip
Micro-Isolation Valve (MIV)	Energy: 10 - 60 mJ Response: 0.1 - 0.3 ms Pressure: 3000 psi burst
MOOG Micro-Thruster Valve (MMV)	Power: 0.5 W (holdi) Voltage: 5 Vdc Response: 1.5 ms open, 0.5 ms close Pressure: 300 psi Life: 1M cycles
Vaporizing Liquid Micro-Thruster (VLM)	Thrust: 32 µN Power: 0.8 W Ibit: <10^{-6} Ns

Lithium Lorentz Force Accelerators are Ideal for Very High Power Applications

[redacted]

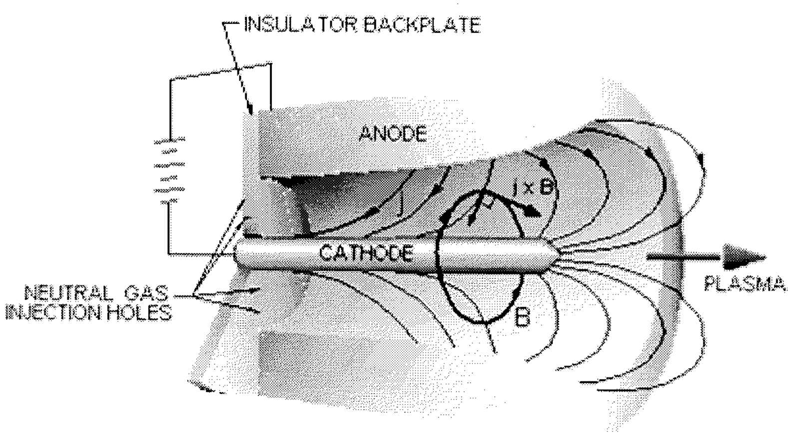
- Lithium-fed Lorentz Force Accelerators (LFA's)
  - High power processing capability
  - Lithium propellant has potential for very high efficiency
- 0.5 -- 1 Mwe Ideal for near-term applications
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Orbit transfer and Mars cargo applications
- 1-- 5 MWe Mid-term propulsion requirements
  - Second generation power systems at 10--30 MWe
  - Specific impulse of 4000-6000 s
  - Initial piloted Mars missions



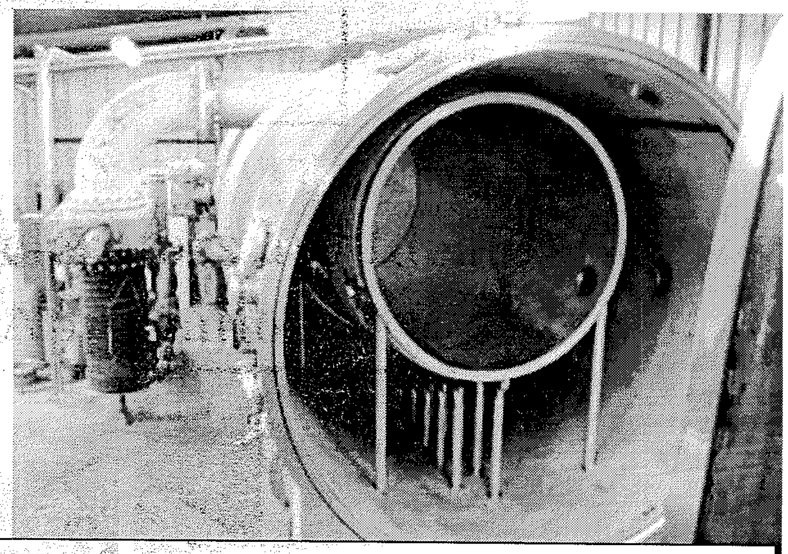
Unique Attributes:

- Steady state operation up to 500 kWe
- Radiation-cooled
- All refractory metal construction

JPL's 500 kWe Thruster: A Testbed for High Power LFA Technology Development



J X B forces accelerate plasma axially and radially

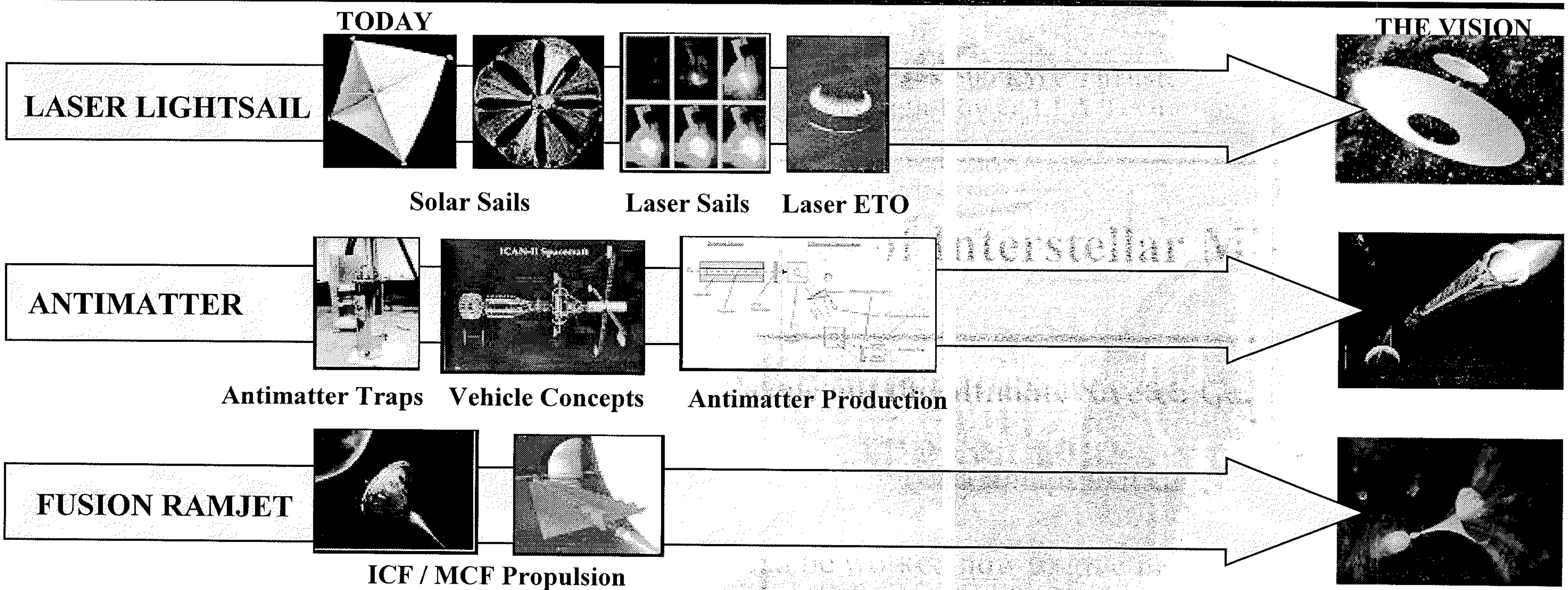


The JPL High Power Test Facility: A Unique Asset for MWe-Class Thruster Development

Advanced Propulsion Studies of Interstellar Missions

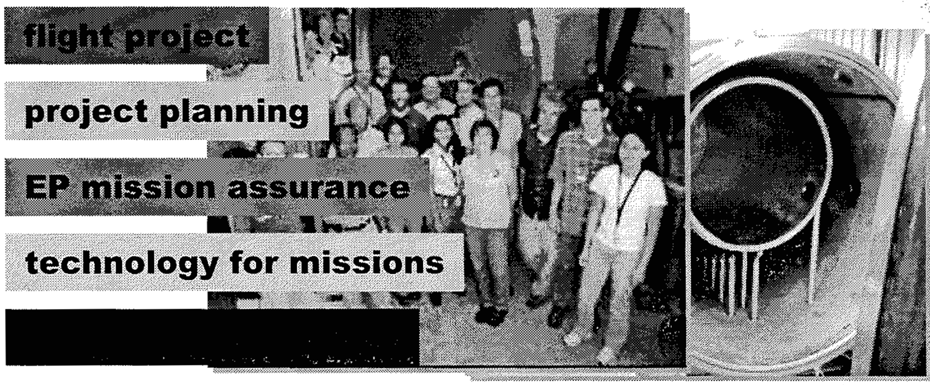
[redacted]

- **Mission/technology studies to identify and scope out the ultimate Stretch Goal for propulsion: Interstellar Missions**
  - Goal is to identify candidate technologies and technology roadmaps that can provide required performance
  - Identify current/near-term technologies that can be worked now to give mid-term benefits for ambitious missions within the solar system, and eventually provide the performance required for Interstellar capabilities
- **Mission requirements based on assumption that the Interstellar Mission will be a follow-on to Origins Program: Need FAST (0.5c cruise), RENDEZVOUS (not flyby) mission**

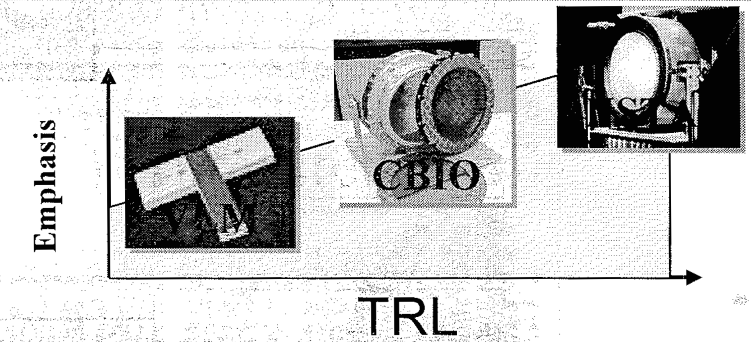


Electric Propulsion at JPL

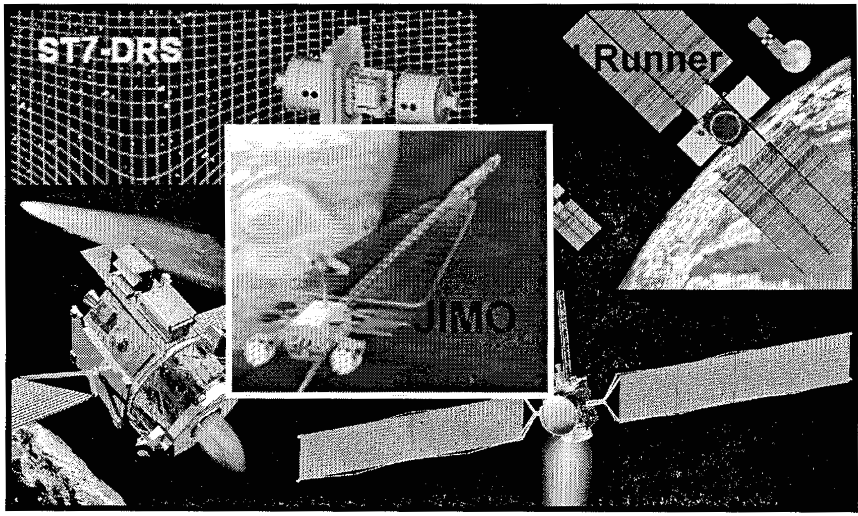
Vision: "*Advanced Electric Propulsion for NASA's Science Spacecraft*"



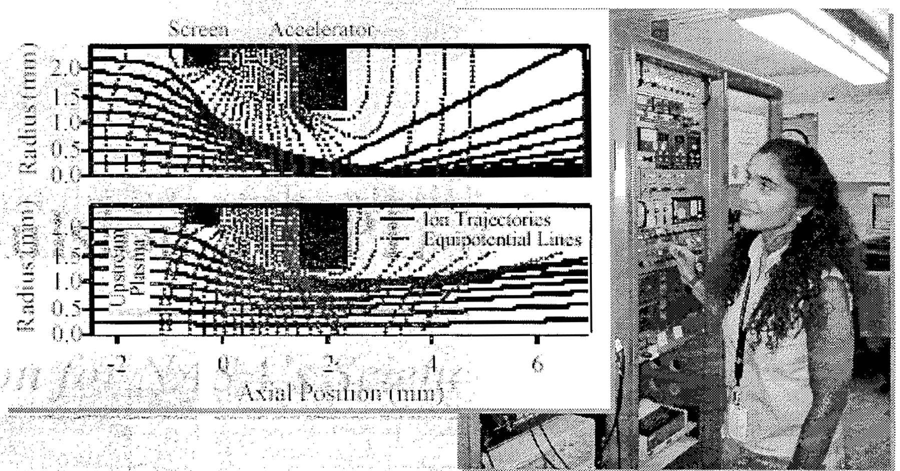
Roles and Resources



Wide Range of Technology Development Guided by Flight Project Needs



Flight Project Experience



Focus on Understanding Basic Processes: Coordinated Modeling & Experiment