Advanced Electric Propulsion For Outer Planet Exploration

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May 13, 2002
Overview of Presentation

- High Priority Future Missions
- Propulsion Requirements for the Advanced Mission Set
- Solar Electric Propulsion (SEP) for Near-Term Missions
  - Overview of Ion Propulsion
  - The NSTAR/DS1 Ion Propulsion System
  - Challenges for Future SEP Missions
  - Critical Technologies and Approaches
- Nuclear Electric Propulsion (NEP) for More Demanding Missions
  - NEP Vehicle Overview
  - Technology Requirements
  - Challenges for High Isp, High Power Systems
- Lorentz Force Accelerators (MPD Thrusters) for Very High Power Missions
Detailed Mission and Systems Analysis Show that Higher *I*_{sp} is the Key to Future Mission Capabilities

- Future missions have dramatically higher ΔV requirements
- Optimum *I*_{sp}’s for future missions are considerably higher than NSTAR *I*_{sp}
Ion Engines Accelerate Plasmas Using Electrostatic Forces

Three Major Engine Components

- **Discharge Chamber**
  - Creates ions by electron bombardment of xenon propellant
- **Ion Optics**
  - Two closely spaced grids which create a high electric field that accelerates ions that drift into gap between grids
- **Neutralizer Cathode**
  - Emits electrons to neutralize charge on spacecraft and positive charge in the ion beam

Engineering Model 30 cm Thruster in 8200 Hour Wear Test at JPL
SEP System Elements

Solar Array

Power Conditioning

Exhaust

Propellant Distribution and Control

Note:
Structural and Thermal Hardware Not Shown
NSTAR and Deep Space 1: Paving the Way for the Use of Electric Propulsion in Deep Space Exploration

- The ion propulsion system on the Deep Space 1 spacecraft has achieved:
  - Flawless operation for over 16,265 hours of operation at power levels up to 1.9 kWe and Isp’s up to 3150 s
  - Over 65 kg of xenon throughput
  - Autonomous navigation, attitude control and propulsion system operation
    - Low mission operations costs
    - Compatibility with the spacecraft and science instruments
- Ground testing of the flight spare ion engine has demonstrated:
  - Over 23,000 hours of operation at up to 2.3 kWe
  - Over 188 kg of xenon throughput
DS1 Flight Validation of NSTAR Ion Propulsion

- **16,265 hours of operation in space**
  - By far the longest operation of a rocket engine in the history of the space program

- **Risks Retired by DS1**
  - Guidance, Navigation and Control
  - Mission Operations Costs
  - Contamination
  - Science Measurements
  - Communications
  - Electromagnetic compatibility

- **Hyper-Extended Mission**
  - Designed to take advantage of the unique opportunity to determine if thruster wear in space is consistent with ground life tests
  - Extensive data collected on grid erosion, discharge chamber operation and neutralizer operation
  - Preliminary analyses indicate that ground tests are a good indicator of thruster wear in space

DS1 and the ongoing life test have resulted in NSTAR ion propulsion being considered low risk by the Discovery Program for deep space science missions
DS1/NSTAR Lessons Learned

- It is relatively easy to demonstrate the required engine performance
- Demonstrating the required throughput capability is much more difficult
  - NSTAR required 6 long duration tests (≥ 800 hours) and 31 additional development and characterization tests starting in 1993, even though 30 cm engine technology had been under development since 1981!
  - Even now we are still finding new or under-appreciated potential failure modes
- Long operating times are required to identify new failure modes
  - This is no mystery: most unknown failure mechanisms are unknown because they tend to surface when you go beyond operating experience!
- Full power is not necessarily the most stressful operating point; some processes are accelerated by extended operation at throttled conditions
- NSTAR technology has proven to be remarkably robust
  - Over 50,000 hours of operating experience in ground and flight testing
  - A total of 16,265 hours of operation achieved in space
  - Propellant throughput capability greater than 188 kg demonstrated in ongoing Extended Life Test

• Validating the required throughput capability is the most important issue for future ion propulsion technology development programs
• The growth capability of the NSTAR thruster should be exploited to capitalize on $45M investment and extensive ground and flight heritage
Discharge Chamber Performance is Not a Critical Technology Issue for Future High Isp Systems

- The amount of thrust produced for a given amount of power depends on the specific impulse and the efficiency with which the engine ionizes the propellant.

- At low specific impulses (below about 1800 seconds) the ionization power dominates.

- Above about 1800 seconds the beam power dominates.

- Above about 5000 seconds the discharge chamber performance (represented by the ion production cost in eV/ion) becomes unimportant and all engines approach the ideal performance.

-- Engine Life is the Key Issue
Future Missions Benefit Significantly from Increased Propellant Throughput Capability

**Graph:**
- **Y-axis:** Number of Engines Required
- **X-axis:** Engine Throughput Capability (kg)
- **Lines:**
  - MSR
  - Neptune
  - Saturn
  - CNSR

**Legend:**
- Desired Throughput is between 170 kg and 195 kg
- Original NSTAR Throughput Capability is 87 kg
Understanding Engine Wearout Processes Is a Major Focus of JPL Activities

Source of Ions and Major Erosion Sites
- Discharge Plasma
  - Discharge Cathode Keeper Electrode
  - Discharge Cathode Orifice Plate
  - Screen Grid
- Beam Ions and Charge Exchange Plasma
  - Accelerator Grid
- Neutralizer Plasma
  - Neutralizer Orifice Plate

Deposition of Eroded Material inside Engine Can Also Lead to Formation of Flakes that Can Cause Failures by Shorting the Grids

Engineering Model 30 cm Thruster in 8200 Hour Wear Test at JPL
Tools Being Used to Study Ion Engine Wear Processes

- **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)
    - 23000+ Hour Test (Ongoing)

- **In-Space Data from the Deep Space 1 Spacecraft to Characterize Failure Mode Drivers and Validate Ground Measurements**

- **Probabilistic Analysis to Assess Service Life Capability**
  - 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
  - Surface kinetics modeling of simultaneous sputtering and deposition

- **Supporting Experiments**
  - Low-energy sputter yield measurements
  - Ion-induced desorption cross-section measurements
Accelerator Grid Wear Due to Beam and Charge Exchange Ion Impingement

Electrostatic Potential [V]

Centerline Axial Potential Distribution

Equipotentials and Charge Exchange Ion Velocity Vectors
Status of Modeling: State-of-the-Art Plasma Simulation Tools Have Been Developed

- A 3-dimensional electrostatic Particle-In-Cell model follows ion particles in the self-consistent electric field and resolves the shape of the upstream sheath, the current extraction capability of the optics, as well as ion accelerating characteristics
- A Monte Carlo collision code is used to model charge exchange reactions
- Simulations generate the distribution of ion impingement current density, energy and incident angle on the upstream and downstream faces and hole walls

Domain is fully 3-dimensional and allows multiple holes

Sub-gridscale grids used to match optics boundary

Potential distribution downstream of grid

Ion current density vectors and energy contours
3D Particle-In-Cell Code Very Accurately Reproduces Grid Erosion Pattern

Photo showing wear pattern from 8200 hour NSTAR test with erosion pattern from simulation overlaid.

Detailed comparison of measured and predicted erosion pattern shows excellent agreement.
NSTAR Service Life Validation: Quantitatively Assessing Engine Service Life Capability

- Validating ion propulsion technology for use in deep space missions:
  - Help interpret and apply endurance test data
  - Guide flight system design
  - Help prioritize technology improvements
  - Reduce reliance on expensive testing
  - More rapidly infuse new technologies

- A combination of testing and analysis is required to establish service life
  - Testing:
    - Identify new failure modes
    - Characterize drivers of failure modes
    - Validate models of failure processes
  - Analysis:
    - Develop models of dominant failure modes
    - Characterize uncertainty in model input parameters
    - Calculate failure risk using Monte Carlo techniques

- Results are in use for risk reduction and system design
  - Validated design changes early in program
  - Completed 8200 hour endurance test; results used to support DS1 risk review
  - Risk assessment used by DS4 for system design
  - Risk assessment guided Discovery SEP proposals
Carbon Grids Represent a Major Advance In Ion Propulsion 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 in grid assembly mass
- Carbon grids are a mature technology
  - JPL invented carbon-carbon grids in 1991 and was awarded a patent in 1995
  - Pyrolytic graphite grids are routinely used in ground-based ion sources
  - JPL has verified erosion rates in over 3200 hours of testing
  - The Japanese Space Agency will be the first to fly carbon-carbon grids
    - 18000 hour lifetest of 10 cm grids shows very low erosion
    - MUSES-C asteroid rendezvous mission will fly 10 cm carbon-carbon grids in November, 2002
    - 20 cm diameter grids are now under development
  - Boeing is committed to carbon grids for commercial engines
    - Currently performing accelerated lifetest of 13 cm grids
    - Fabricating 25 cm grids as upgrade to 25 cm XIPS engine
    - Performing vibe tests of JPL 30 cm carbon-carbon grids
- JPL has a vigorous carbon grid development program
  - Currently building and testing 5000 s Isp grids as upgrade to NSTAR
  - Fabricating 75 cm grids for 13,000 s Isp interstellar ion thruster
  - Developing robust carbon-carbon grid technologies for the AF
  - Designing carbon-carbon grids for 6000-9000 s NEP thruster
  - Designing 1 m diameter grids for modules in megawatt-class ion engines

Carbon yields the lowest erosion rates

Advanced carbon-carbon grids on 15 cm ion engine

30 cm Carbon-Carbon Grids
Plasma-Surface Interactions are a Rich and Important Area of Study in Ion Propulsion

- Most significant failure modes are ultimately caused by plasma interactions with thruster surfaces
  - Erosion of cathode potential surfaces due to low energy discharge plasma ions
  - Erosion of accelerator grid surfaces by beam and charge exchange ions
  - Protection of engine surfaces by contaminants
- Because testing to establish reliability is prohibitively expensive, analysis and modeling must be used to assess service life capability
  - Wearout phenomena must be thoroughly understood to predict robustness of design and effect of design changes
  - Intrinsic variability and uncertainty in failure mode drivers must be determined and quantitatively incorporated in risk assessment
  - Differences between ground test environment and space environment must be understood to avoid unpleasant surprises
- Experimental and simulation tools have reached a high level of sophistication

We are close to understanding why and when ion thrusters fail
Nuclear Electric Propulsion Systems

- Muriel--add plot of system masses here...
NEP Mission Performance is Driven by System Power and Engine Efficiency

- System mass scaling (primarily reactor and power conversion system) results in lower system specific mass for higher power levels--this yields lower trip times.
- Total engine efficiency is a strong driver. Higher efficiency results in greater jet power, which reduces trip time.
- Discharge chamber efficiency is not critical at high Isp--propellant utilization efficiency is the key to improved engine performance.
NEP Missions Demand Extremely Long Engine Life

- For missions of interest, burn times are 5-10 years
- To maintain a reasonable specific mass, individual engines must operate for a significant fraction of the total burn time while processing very high power levels at high Isp
- Critical technologies include:
  - Large discharge chambers to reduce beam current density
  - Advanced, erosion-resistant grid materials and careful optics design
  - Revolutionary advances in cathode technology

Muriel--need representative plot here of required burn times
Lithium Lorentz Force Accelerators are Ideal for Very High Power Applications

J X B forces accelerate plasma axially and radially

Lithium-fed Lorentz Force Accelerators (LFA’s) are under investigation because:
- Physics of operation yield high power processing capability
- Lithium propellant has potential for very high efficiency--low first ionization potential, high second ionization potential, and high first excited state of the ion yield low frozen flow losses

Very high power propulsion systems enable many far-term missions:
- Orbit-raising heavy payloads in Earth orbit
- Piloted Mars and Mars cargo missions
- Fast robotic and piloted outer planet missions
- Interstellar precursor missions

Electromagnetic acceleration allows >200 times the power of the NSTAR ion engine to be processed in the same volume
Review of Recent Experience with Gaseous Propellants

- Matrix of geometries used with Ar and H\textsubscript{2} to determine scaling of 100 kWe-class applied field thrusters.
  - Highest power levels achieved: 220 kWe on Ar, 100 kWe on H\textsubscript{2}
  - Highest performance achieved: 24% efficiency at 1800 s and 64 kWe with Ar, 20% at 3700 s and 82 kWe with H\textsubscript{2}
- Endurance test at 60 kWe with Ar (about 18% efficiency at 1300 s) terminated after 33 hours by failure of water-cooled copper anode due to ion sputter damage.
- Temperature and near-cathode plasma property measurements on high current cathodes performed to validate cathode thermal models.
- High power pulsed experiments with H\textsubscript{2} showed efficiency >50% at Isp's over 10,000 s.

Performance with gaseous propellants has been disappointing. Hydrogen may yield high efficiency at very high power levels and high Isp’s.
Large Russian Experience Base Demonstrates Technology Potential for HEDS

<table>
<thead>
<tr>
<th>Organization</th>
<th>Power (kWe)</th>
<th>Current (kA)</th>
<th>Specific Impulse (s)</th>
<th>Efficiency</th>
<th>Typical Operating Period</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIITP</td>
<td>300-1000</td>
<td>6-15</td>
<td>3500-5000</td>
<td>40-60</td>
<td>5 min</td>
<td>NIITP design</td>
</tr>
<tr>
<td>Fakel</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>500</td>
<td>9</td>
<td>4500</td>
<td>55</td>
<td>500 hours</td>
<td>Endurance test of Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>250-500</td>
<td>5-8</td>
<td>3000-4500</td>
<td>35-55</td>
<td>30-60 min</td>
<td>Coaxial thruster with long cathode. Stopped because of cathode failure</td>
</tr>
<tr>
<td>MAI</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
</tbody>
</table>

- Development of high power Li-fed thrusters continued in Russia.
- Capabilities required for HEDS largely attained.
  - High performance verified at 3 different institutions.
  - 500 hour lifetest at 500 kWe successfully completed. Several thousand hour life projected.

Energiya 500 kWe thruster design.
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
Recent Experimental and Theoretical Results Show Path to MWe Plasma Thrusters

**POWER**
- Anode Texturing
- Heat Pipes

200 kWe Steady State

**PERFORMANCE**
- Lithium Propellant
- Active Turbulence Suppression

η = 50%
Isp = 4000 s

100’s of Hrs
At 3000 A

**LIFETIME**
- Multi-Channel Hollow Cathodes
- Barium Addition

10000 Hrs
At 20000 A

**MULTIMEGAWATT TECHNOLOGY**
Rapid Access to the Solar System

η = 60%
Isp ≤ 8000 s

200 kWe Lithium-fed Thruster

**PLUME CONTAMINATION**
- Plume Shields
- Booms

10^{-8} g/cm^2s
at 0.3 m

10^{-10} g/cm^2s
at 30 m

**STATE OF THE ART**
Conclusion

“The future of solar system exploration is in the hands of the propulsion technologists”

-- 4/1/99: Bob Gershman (JPL Advanced Mission Study Lead)
An Overview of JPL’s Advanced Propulsion Concepts Research Program
The Advanced Propulsion Technology Group Fulfills Two Roles

17 Engineers
- 14 with or completing PhD’s
- 3 with or completing MS’s
- 222 years total experience

3 Technicians
- 105 years total experience

Near-Term Electric Propulsion Program
Goal: Implement advanced propulsion in JPL missions
- Primary and auxiliary solar electric propulsion systems
- Mission/systems analysis
- Technology validation
- Advanced technologies

Advanced Propulsion Concepts Program
Goal: Assess feasibility of new technologies which might enable exciting new missions
- Micropropulsion
- Solar sails
- High power plasma propulsion
- Fusion propulsion
- Antimatter propulsion
- Mission/systems analysis
- Computer simulations

Unique Facilities
4 Large Vacuum Facilities and a Number of Smaller Chambers

Advanced Analytical Capabilities
Plasma Simulation Tools Using High Performance Supercomputers
JPL Has a Long and Rich History of Advanced Propulsion Research and Development

- Solar Electric Propulsion Studies Group Formed in 1959
- Electric Propulsion Laboratory Established in 1961
- Advanced Propulsion Concepts Group Formed in 1980
Deep Space Electric Propulsion Activities are Guided by Extensive Mission/Systems Analysis

Mission needs drive technology focus; innovative ideas enable new missions and mission architectures

**Primary propulsion focus**
- NEP Initiative Support Studies (Noca et al., FY 01-02)
- Next Generation Ion Propulsion Trades Study (Noca et al., FY 01)
- IISTP Outer Planet Mission Studies (Noca et al., FY 01)
- Evolutionary NEP Study (Noca et al., FY 00-01)
- Pluto/Kuiper Fast Flyby Trades and Mission Design (Brophy et al., FY 00-01)
- DAWN Mission Design (Brophy et al., FY00-01)
- Mars Sample Return Trades Study (Brophy et al., FY 00-01)
- CNSR Pre-project Trades Studies (Brophy et al., FY 99-00)
- DS4 Mission/System Design (Tan Wang et al., FY 97-98)
- Interstellar Probe Study (Johnson and Leifer, FY 99)
- Propulsion Trades Study (Gershman et al., FY 97)
- Negative C3 Launch Study (Noca et al., FY 98)
- Overpowering the Solar System (Noca et al., FY 97)
- Common SEP Module Study (Sabahi et al., FY 97)
- X2000 SEP Study (Brophy et. al., FY97)
- Small Spacecraft Study (Kakuda, FY96)

**Auxiliary propulsion studies**
- LISA Requirements Studies (Ziemer, FY01-02)
- ST7 Disturbance Reduction Proposal Support (Ziemer, FY01-02)
- IISTP Phase II Auxiliary Propulsion Study (Shotwell, FY 01)
- Micropropulsion Requirements Study (Shotwell, FY 01)
- ST3 Precision Positioning Trades Study (Blandino, FY 97-98)
- JPL Micropropulsion Workshop (Mueller, FY 97)
- LISA Pre-project Trades Studies (Blandino, FY 97-98)
- ARISE Pre-project Trade Studies (Noca, FY 98-99)
- Pluto Fast Flyby PPT Study (Ziemer, FY95)
Personnel, Facilities and Analytical Capabilities
Give JPL Competence in Many Areas

- Mission/Systems Analysis
  - NSTAR and DS
    - Xenon Feed System Development
    - Endurance Testing
    - Service Life Assessment
    - Integration Testing
    - Flight System Development Support
    - Mission Operations

- DS4/CNSR/DSST and Mars Technology Programs
  - Advanced Ion Propulsion System Architecture
  - Advanced Xenon Feed System Development
  - Carbon-Carbon Grid Development
  - Flight System Testbed

- Hall Thruster Development Testing
  - Performance Mapping
  - Endurance Testing
  - Feed System Development
  - Technical Support in Engine Development

- High Power Electric Propulsion Systems
  - High Power Performance Evaluation
  - Cathode Lifetime Studies
  - 500 kWe Thruster Development

- Micropropulsion Component and System Development
  - Valve Technologies
  - Engine Miniaturization and Novel MEMS Engine Concepts
  - System-on-a-Chip Development
  - Highly Integrated Systems

- FEEP and Colloid Thruster Development
  - Performance Measurement Capability
  - Contamination Assessment
  - Field Emission Array Cathode Technology
  - Advanced Diagnostics

- Revolutionary Propulsion Concepts
  - Fundamental Feasibility Assessment
  - Mission and Systems Analysis

- Electrodynanic Tethers
  - Field Emission Array Cathodes

- Project Support
The Road to the Stars: Deep Space Advanced Propulsion

INTERSTELLAR PRECURSOR, INTERPLANETARY, ORBIT RAISING
- Laser Sails
- Laser Electric Propulsion
- Very high energy density and mission delta-V
- Wide range of applications

INTERSTELLAR MISSION CAPABILITY
- Highest energy density propellant known
- Spinoff technologies for medicine
- Interstellar capability

INTERSTELLAR PRECURSOR, FAST PILOTED MARS
- Propulsion system is primary power system
- First propulsion system with energy density approaching interstellar capability
- Human exploration of the Solar System

ROBOTIC INTERSTELLAR
- LEVITYC
- HELIOPAUSE
- Laser Electric Propulsion

BEAMED ENERGY
- Increasing energy density
- FUSION

ANTIMATTER
- INTEGRATION
- LASER ELECTRIC PROPULSION

SAILS
- Planetary Aerobots
- Sample Return Missions
  - Lunar regolith
  - Planetary atmospheres

PLASMA THRUSTERS
- Systems of distributed spacecraft
- New paradigm for space exploration

MICRO-PROPULSION
- LFA
- Higher power handling capability
- Fast Interplanetary transport

MICRO-SPACECRAFT
- ISRU
- ROBOTIC MARS EXPLORATION, PILOTED MARS
- Very high energy density and mission delta-V
- Wide range of applications
FY02 Program Content Spans the Range of Advanced Propulsion Concepts

- **Micropropulsion**
  - Vaporizing Liquid Microthruster
  - Micro-Valve Technologies
  - Revolutionary Cathode Technology
  - Vacuum Arc Plasma Sources (JPL, Caltech, AASC and LBL)

- **High Power Electric Propulsion**
  - Lithium-fed Lorentz Force Accelerators (JPL, Princeton and MSFC)
  - High Power Bismuth-fueled Anode Layer Thrusters
  - Megawatt-class Ion Engines

- **Fusion/Antimatter Propulsion**
  - ICAN Target and Systems Study (LLNL)
  - Beam Core Antimatter Rocket Systems Study

- **The Advanced Propulsion Concepts Website**
JPL Has Established Itself as a Leader for Micropropulsion in NASA

- JPL has established an unmatched capability in micropropulsion through a broad program involving small miniature thrusters, MEMS propulsion, components, and their integration.
- Micropropulsion will play a major role in many future, high-visibility space missions, such as
  - Interferometry/Constellation Missions (TPF, Planet Imager, Life Finder, Mag Con (Sun-Earth Connection))
  - Space Inflatables
  - Microspacecraft
  - Advanced Miniature Components for Conventional Spacecraft
- JPL has taken the NASA lead in assessing the available propulsion technologies, and developing future technologies to address these mission needs.
- JPL, in addition to thruster development, also focuses on important component developments and integration, allowing systems approaches
  - Mini and MEMS Thrusters
  - Microvalves
  - Light-weight tanks and components
- JPL has a unique suite of experimental facilities and skills to address the requirements of micropropulsion development
  - Microdevices Laboratory (MDL)
  - Micropropulsion Test Facility (Construction to begin in FY’02 for $1.2M)
  - Micro and Nano-Newton Thrust Stands
  - Packaging and System Integration (Center for Integrated Space Microsystems (CISM))
  - Large (2m x 2m) ultra-high vacuum system for plume studies
Why Micropropulsion?

Microspacecraft are becoming a reality!

Multiple NASA, DoD, and International Missions in Flight or Planning

Representative Microspacecraft Attitude Control Requirements:

<table>
<thead>
<tr>
<th>S/C Mass (kg)</th>
<th>S/C Typ. Dimension (m)</th>
<th>Moment of Inertia (kg m²)</th>
<th>17 mrad (1°)</th>
<th>0.3 mrad (1 arcmin)</th>
<th>0.02 mrad (5 arcsec)</th>
<th>Minimum Thrust for Slow (mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 s</td>
<td>100 s</td>
<td>20 s</td>
<td>100 s</td>
<td>20 s</td>
<td>100 s</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.017</td>
<td>1.4 x 10¹</td>
<td>2.9 x 10³</td>
<td>2.5 x 10⁶</td>
<td>5.1 x 10⁷</td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
<td>0.150</td>
<td>4.3 x 10⁴</td>
<td>8.5 x 10⁵</td>
<td>7.5 x 10⁶</td>
<td>3.0 x 10⁷</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
<td>0.533</td>
<td>1.1 x 10⁵</td>
<td>2.3 x 10⁴</td>
<td>2.0 x 10⁵</td>
<td>4.0 x 10⁶</td>
</tr>
</tbody>
</table>

* Assume cubical spacecraft shape
Many high-profile constellation missions are in planning and design within NASA and DoD for interferometry, gravity wave detection, and military communication and reconnaissance.

Constellation attitude maintenance and control may pose stringent propulsion requirements:

<table>
<thead>
<tr>
<th>Mission</th>
<th>Thrust:</th>
<th>Impulse Bit:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-3</td>
<td>5-10 mN</td>
<td>50 μNs</td>
</tr>
<tr>
<td>LISA</td>
<td>2 - 20 μN</td>
<td>0.1 μN</td>
</tr>
<tr>
<td>TechSat 21</td>
<td>Min. Thrust: 2 mN</td>
<td>Impulse Bit: 2 mNs (2003), 2 μNs (est.)</td>
</tr>
<tr>
<td>TPF</td>
<td>0.1 N (re-formation)</td>
<td>~ μN (pointing)</td>
</tr>
</tbody>
</table>
Inflatable Structures on Spacecraft may experience significant solar disturbance torques due to non-symmetric mass distribution.

Thrusters and propellant will be required to off-set these disturbance torques.

ARISE studies have shown that significant propellant mass savings may be obtained when integrating attitude control thrusters with the inflatable structure, utilizing the large moment arm:

- Conventional Hydrazine (integrated with S/C Bus) 350 kg/year
- Conventional Ion (integrated with S/C Bus) 50-80 kg/year
- Micro-Ion Engine (integrated with inflatable structure) 8 kg/year (!)
Advantages:
- Small size and weight components
- Highly integrated systems (thrusters, valves, PPU electronics, sensors) achievable through System-on-a-Chip/Chip-to-chip bonding.
- Performance: Low impulse bits and thrust due to small machinable nozzle throats.
- Low cost due to batch fabrication and wafer-level assembly.
- Possibly enabling technology for very small microspacecraft (<< 10 kg).

Challenges:
- Mostly silicon-based fabrication.
- Silicon/propellant materials compatibility issues => Need thin-film coatings: do-able
- Silicon is a very good heat conductor: 150W/mK
  Need to contain heat in propellant in propulsion systems.
- Silicon is hard but brittle. Pressure cycling issues in propulsion systems.
- Need Si/metal joins to interface Si components with feed lines/propellant tanks.
Vaporizing Liquid Microthruster (VLM)

Programmatic:
- Task Lead: J.Mueller
  (juergen.mueller@jpl.nasa.gov)
- Funding Source: CETDP (Code R)
- Potential Customers:
  New Millenium, Sun-Earth (Mag Con and follow-on),
  Micro-missions, Interferometry/Constellation Missions
  (TPF, PI, LF, ...)

Description of Concept:
- Liquid propellant, pressure-fed
- Vaporize propellant in thin-film heater assembly.
- Exhaust gaseous propellant to produce thrust.
- Performance goals:
  - Isp: 50-100 sec
  - Thrust: \( \mu \text{N} \) to <1 mN
  - Power: <2 W
  - Efficiency \( \geq 50 \% \)
  - Mass/Size: few grams/ 1 cm\(^2\)
- Key Accomplishments: Demonstrated feasibility of concept (vaporization at 0.7 W, 0.2 g/hr water flow rate, est. 50 \( \mu \text{N} \) thrust).
- TRL \~ 2-3

Applications and Benefits:
- Microspacecraft/Constellation Attitude Control
- Liquid propellant storage (compact, low leakage).
- Extremely small and light.
- Amenable to on-chip integration schemes, high levels of integration.
- Scalable to very small thrust and impulse bits.

J.Mueller 5/29/01
Micro Isolation Valve (MIV)

Description of Concept:
- One-time actuation valve.
- Melt doped silicon plug to open valve. Upstream pressure removes plug.
- Trap debris inside chip through appropriate channel/filter design.

Performance Goals:
- Pressure handling capability 2000 - 3000 psi
- Flow Rates: mg/s-range
- Mass/Size: few grams, 1 x 10 x 10 mm

Key Accomplishments:
- Demonstrated Feasibility of Concept: Actuated Valve with 0.01 J Input Energy within 0.1 ms.
- Obtained burst pressures as high as 3,000 psig!

TRL ~ 3

Programmatic:
- Task Lead: J.Mueller (juergen.mueller@jpl.nasa.gov)
- Funding Source: CETDP (Code R)
- Potential Customers:
  Advanced Feed Systems (NSTAR Follow-on, etc.),
  New Millenium, Sun-Earth Connection (Mag Con and follow-on), Micro-missions, interferometry/constellation missions (TPF, PF, LI, etc.), inflatables (ARISE, etc).

Applications and Benefits:
- Miniature component for microspacecraft and advanced EP Feed systems.
- Provide isolation/zero-leak rate for micropropulsion systems.
- Extremely small, light-weight alternative to pyrotechnically actuated isolation valves
- Amenable to on-chip integration schemes.

J.Mueller 5/29/01
Micro-Fabricated Field Emission Cathodes: A Technology with Tremendous Potential

- **Arrays of micro-machined tips and gate electrodes produce high electron current densities by field emission**
  - Enabling technology for micro-gas discharges for micropropulsion applications
  - Propellantless current emission for tether applications
  - Cold cathode technologies enable use of reactive propellants such as oxygen

- **Propulsion applications demand emitter array operation in gas discharges or ambient plasma environments**
  - Increased risk of arcing
  - Sputter erosion of tiny structures
  - Space charge limitations in tenuous gas environments

- **Technical approaches:**
  - Smaller scale structures
  - Current-limiting architectures
  - New materials
  - Electrode designs to filter out ions

Array of field emitter tips
Geometry of a single emitter tip
Dulling of emitter tip due to ion sputtering
Arcing damage to tips and gate electrode
Cathode Spots in Vacuum Arcs Create Extreme Plasma Environments

Vacuum Arc Electron Emission Processes

**Site Initiation**
Field emission from micropoint or dielectric inclusion.

**Explosive Evaporation**
Excessive joule heating in micro-emission site generates plasma by explosive vaporization.

**Crater Formation**
Power deposited by joule heating and ion bombardment heats surface to extreme temperatures. Electrons emitted by thermal-field emission.

**New Site Formation**
Decreasing power density leads to site extinction and field emission at a nearby micropoint causes spot to shift.

Laser absorption image shows ultra-high density plasma plumes created by cathode emission sites in a vacuum arc

- Vacuum arcs generate environments with unique properties
  - Current densities of $10^8$ A/cm$^2$
  - Surface heat fluxes of $10^8$--$10^9$ W/cm$^2$
  - Plasma densities of $10^{20}$--$10^{21}$ cm$^{-3}$ (nearly the density of the solid metal!)
  - Nearly 100% ionization of metal vapor
  - Plasma expansion velocities of $10^4$ m/s

- Pressure ionization, not electron bombardment processes, creates plasma efficiently in a tiny volume

J.Mueller 5/29/01
Exploiting Extreme Conditions in Vacuum Arc Plasmas for Propulsion

CONCEPT
Metal vapor plasmas can be used to produce thrust in several ways
- Direct thrust from plasma plume expansion
- Electrostatic or electromagnetic acceleration of the dense plasma

ADVANTAGES
- Vacuum arc plasma sources provide unique scaling advantages
  - No magnetic field required to confine or generate plasma
  - Plasma is created in small volume
  - No gas feed system is required
  - Discharge current can be tailored to produce wide range of plasma densities
- Plasma plume expansion allows higher current density extraction through ion optics

APPLICATIONS
- Miniaturized thrusters for microspacecraft applications
- Very high density plasmas may enable very high power thrusters

J. Mueller 5/29/01
Performance Models Suggest Vacuum Arc Thrusters Have High Performance Potential

- Simple vacuum arc thrusters have efficiencies and Isp's that are competitive with pulsed plasma thrusters and may have advantages in scaling.
- Vacuum arc ion thrusters may yield excellent performance in a very small device.

J. Mueller 5/29/01
Lithium Lorentz Force Accelerators are Ideal for Very High Power Applications

Electromagnetic acceleration allows >200 times the power of the NSTAR ion engine to be processed in the same volume.

Lithium-fed Lorentz Force Accelerators (LFA’s) are under investigation because:
- Physics of operation yield high power processing capability
- Lithium propellant has potential for very high efficiency—low first ionization potential, high second ionization potential, and high first excited state of the ion yield low frozen flow losses

Very high power propulsion systems enable many far-term missions:
- Orbit-raising heavy payloads in Earth orbit
- Piloted Mars and Mars cargo missions
- Fast robotic and piloted outer planet missions
- Interstellar precursor missions
Large Russian Experience Base Demonstrates Technology Potential for HEDS

<table>
<thead>
<tr>
<th>Organization</th>
<th>Power (kWe)</th>
<th>Current (kA)</th>
<th>Specific Impulse (s)</th>
<th>Efficiency</th>
<th>Typical Operating Period</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIITP</td>
<td>300-1000</td>
<td>6-15</td>
<td>3500-5000</td>
<td>40-60</td>
<td>5 min</td>
<td>NIITP design</td>
</tr>
<tr>
<td>Fakel</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>500</td>
<td>9</td>
<td>4500</td>
<td>55</td>
<td>500 hours</td>
<td>Endurance test of Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>250-500</td>
<td>5-8</td>
<td>3000-4500</td>
<td>35-55</td>
<td>30-60 min</td>
<td>Coaxial thruster with long cathode. Stopped because of cathode failure</td>
</tr>
<tr>
<td>MAI</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
</tbody>
</table>

- Development of high power Li-fed thrusters continued in Russia.
- Capabilities required for HEDS largely attained.
  - High performance verified at 3 different institutions.
  - 500 hour lifetest at 500 kWe successfully completed.
    Several thousand hour life projected.
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 midterm 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
Recent Experimental and Theoretical Results Show Path to MWe Plasma Thrusters

**POWER**
- Anode Texturing
- Heat Pipes

**PERFORMANCE**
- Lithium Propellant
- Active Turbulence Suppression

**LIFETIME**
- Multi-Channel Hollow Cathodes
- Barium Addition

**PLUME CONTAMINATION**
- Plume Shields
- Booms

- \( \eta = 60\% \)
- Isp \( \leq 8000 \) s

200 kWe Lithium-fed Thruster At 3000 A

**STATE OF THE ART**

200 kWe Steady State

1 - 5 MWe Steady State

10000 Hrs At 20000 A

10^-10 g/cm^2 s at 30 m

10^-8 g/cm^2 s at 0.3 m

100's of Hrs At 3000 A

DIRECT ACCESS TO THE SOLAR SYSTEM
Experiments at MAI Demonstrate Performance Potential at High Power Levels

- Research to-date involved the development of a 100-250 kWe applied-field, lithium-fed LFA
- The objectives were to demonstrate operation at 200 kWe, 50% efficiency at 4500-5000 s
- Facility problems prevented operation at 200 kWe, but preliminary measurements of performance yielded 49% efficiency at 4100s and 185 kWe
- Engine characteristics agree reasonably well with analytical models of operation

200 kWe-class lithium thruster built and tested at the Moscow Aviation Institute.
First Generation 500 kWe Engine is Under Development:
Subscale Component Tests Support Design Effort

Design of a 500 kWe, radiation-cooled, steady-state engine

100 kW-e-class applied-field thruster at JPL

Sub-scale tests of a radiation-cooled tungsten anode

Multichannel hollow cathode operating on argon at 2500 A
Lithium LFA’s Show Great Promise for Ambitious Future Missions

- Exciting results continue to support the conclusion that Li LFA’s have the potential to meet the performance and lifetime requirements of high power missions
  - Performance of 49% at 4100 s and 185 kWe with MAI applied-field device
  - Applied-field and self-field engine models support high performance claims
  - Approaches to achieving required cathode lifetime have been identified
  - Spacecraft contamination issues appear tractable

- LFA’s fill unique niches in high power propulsion
  - Lithium-fed thrusters are the only propulsion option for near- to mid-term applications that require high power/thruster in the Isp range of 4000--6000 s
  - Hydrogen- or deuterium-fueled thrusters may meet the requirements of far-term systems with 10’s of MWe’s per engine at Isp’s above 10000 s

- Research in the next few years should yield additional confidence in the feasibility of high power thrusters
  - Demonstration of performance at 500 kWe and further development of performance models
  - Better understanding of multi-channel hollow cathode thermal behavior
  - Further experimental characterization and modeling of lithium plumes
Bismuth-fueled Anode Layer Thrusters are a Viable Alternative to Ion Engines for NEP Missions

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. $\langle v_i \rangle \approx 2.7 \cdot 10^6 \sqrt{U_{ac}} \text{ cm/s}$
2. Theor. $\langle v_i \rangle = 3.05 \cdot 10^6 \sqrt{U_{ac}} \text{ cm/s}$
3. Efficiency
Title: 1-MW Anode Layer Thruster Feasibility Assessment

Principal Investigator: Jay Polk, JPL, (818) 354-9275, james.e.polk@jpl.nasa.gov

Partners: TsNIIMASH, Russia

Specific Technical Objectives:
- Study scaling of anode layer thruster technology to assess the feasibility of MWe-class thrusters
- Specific Impulse >10,000 s
- Required engine lifetime >10,000 hours

Approach:
- Use bismuth propellant and high voltage, 2 stage operation
- Design and fabricate a subscale engine to test component technologies and bismuth discharge operation
- Design, fabricate and test a 200-A hollow cathode with bismuth propellant

Milestones/Dates for FY02:
- Initiate contract with TsNIIMASH to design a subscale 200 kW-class bismuth anode layer thruster (Q2, 3/02)
- Complete design study (Q4, 8/02)
1-MW Ion Engine Feasibility Assessment

- **Title:** 1-MW Ion Engine Feasibility Assessment
- **Principal Investigator:** John Brophy, JPL, (818) 354-0446, john.r.brophy@jpl.nasa.gov
- **Partners:** California Institute of Technology
- **Specific Technical Objectives:**
  - Develop key component technologies to enable the development of a 1-MW ion engine
  - Specific Impulse ~ 12,000 s (on krypton)
  - Required engine lifetime >10,000 hours
- **Approach:**
  - Use segmented engine design based on 6-ea, 160-kW, 1-m diameter ion sources
  - Design and fabricate slotted, 1-meter diameter, carbon-carbon grids
    - Develop techniques for the fabrication of carbon-carbon rods
    - Develop techniques for the assembly of carbon-carbon rods into a complete large-diameter ion accelerator system
  - Design, fabricate and test a 150-A hollow cathode with krypton propellant
  - Design a 1-meter diameter ion source
- **Milestones/Dates:**
  - FY'02:
    - Q3: Complete carbon-carbon grid design
    - Q3: Complete 150-A cathode design and fabrication
  - FY'03:
    - Q1: Initiate 150-A cathode tests
    - Q2: Perform ion source discharge chamber tests without beam extraction
    - Q4: Perform ion beam extraction tests from 1-m ion source
Evaluating the Feasibility of Antimatter-Catalyzed Fission/Fusion Propulsion Concepts

CONCEPT
- Use of small amounts of antimatter to catalyze fission reactions which ignite ICF targets

ADVANTAGES
- Use of antimatter catalyzed fission may reduce the requirements for the ICF driver

APPLICATIONS
- Fast piloted planetary missions, interstellar precursors

FEASIBILITY ISSUES
- Neutron yield of fissile material bombarded with antiprotons
- Fusion yield of target

FY00 ACCOMPLISHMENTS
- Initiated feasibility assessment of antimatter-catalyzed fission/fusion (in progress at LLNL)
  - Study target design using approximate models and detailed design codes
  - Assess feasibility based on target design (yield vs antiproton dose and compression)
  - Estimate system benefits from use of antimatter (reduction in driver mass)
- Completion of Mark I antimatter trap (PSU)
  - Storage of $3\times10^6$ H$^-$ ions demonstrated for over 5 days
  - Delivered to MSFC for continued testing with Mark II trap

JPL TECHNICAL POC: Bob Frisbee
(robert.h.frisbee@jpl.nasa.gov)
Candidate Propulsion Systems for Interstellar Missions

- Need to achieve at least 0.1 c
- Requires energies and power levels hundreds of times current Human output
  - Saturn V at liftoff represented 0.5% of total Human power output in 1969
- Requirement for velocities >> 0.1 c eliminates all but Antimatter (Isp~0.33c), Beamed Sails, and Interstellar Ramjet (last two "cheat" the Rocket Equation)

**FISSION**
Fission
Fragment
"Rocket"

**FUSION**
Inertial / Magnetic Confinement Fusion (ICF / MCF)
Daedalus ICF

**MATTER-ANTIMATTER**
Beam-Core Antimatter Rocket

**BEAMED MOMENTUM SAILS**
Laser Lightsail
Relativistic Particle Beam / MagSail

**COMBINATIONS**
Antiproton-Catalyzed Fission / Fusion

**ADVANCED ELECTRIC PROPULSION**
Bussard Interstellar Ramjet (Fusion)

**ELECTROMAGNETIC CATAPULTS**
EM Catapult
Micro-Spacecraft
Interstellar Mission Profile Using Matter-Antimatter Propulsion

4-Stage Matter-Antimatter Rocket

Payload

TBD Orbit

Antimatter Rocket Assembly

Burn and Discard First 2 Stages

Accel = 0.01 gee

- 40 LY Rendezvous
  4-Stage, w/ Coast
- 4.3 LY Rendezvous
  2-Stage, w/o Coast
- 4.3 LY Flyby
  1-Stage, w/ Coast

Maximum Velocity (%c)

Mission Timeline (Years)

60%
50%
40%
30%
20%
10%
0%

Burn Remaining 2 Stages

Decelerate

Planetary Orbit Insertion

Use A/M Rocket (or NEP ?) to Explore New Solar System
Beam-Core Antimatter Propulsion Concept

- React proton (p+) and anti-proton (p-) to produce charged pions (π±) and neutral pions (π°): p+ + p- → 1.5 π± + 2.0 π°
- Charged pions deflected by magnetic fields ("magnetic nozzle") and used as rocket exhaust to produce thrust (Isp ~ 0.33 c)
- Neutral pions decay into ~200 MeV gamma rays (γ): π° → 2.0 γ
Systems modeling effort determined scaling relationships for major subsystems

- Dust Shield (Thickness ~ velocity, distance traveled, H/cc)
- Electric Power System (specific mass ~ $A\cdot(Pe)^B$; propellant feed system dominates $Pe$)
- Payload (generic robotic - assumed 100 MT)
- Spacecraft Miscl. Systems (avionics, telecom, attitude control, etc. - assumed 100 MT)
- Sorption Compressor Refrigerators (100 K for superconductor magnets, 1 K for solid anti-H2, none needed for LH2 because it passively radiates to 4 K space)
- Propellant Storage and Feed System (tankage, MLI insulation, and heat soak determined analytically; feed system and propellant losses estimated as % of propellant mass, $Mp$; effective anti-SH2 density 10 times that of solid H2)
- Main Shield Radiator (Liquid Drop Radiator, LDR, at 1500 K - 0.5 kg/m²)
- Gamma-Ray Radiation Shields (Tungsten shielding superconductor, electronics, radiator)
- Superconductor Magnets for Magnetic Nozzle (100 K, $I_c = 10^{10}$ A/cm²)
- Overall Prop System Dry Mass Contingency (30 %)
Multi-stage Vehicles Become VERY BIG

- Enormous vehicle mass, antimatter mass, and engine (jet) power required for most ambitious missions:
  \[ \frac{M_0}{M_b} = 5.45 \text{ for } \Delta V = 0.25 \text{ c and } M_p = M_b \times (\frac{M_0}{M_b} - 1) \]

### Stage 4
- Propellant
- Upper Stage (as Payload)
- Propellant Tanks & Refrigs
- 30% Contingency
- Radiator for Hot Shields
- Pwr, Misc Syst, Dust Shield
- Magnet, Insulation, Refrig
- Radiation Shields
- Payload

### Stage 3
- Mass of Asteroid 350 m in Dia.
- Mass of Asteroid 175 m in Dia.
- Mass of Asteroid 80 m in Dia.
- Mass of Asteroid 35 m in Dia.

### Stage 2
- Total Mass (MT) of Anti-H2

### Stage 1
- Total MC^2 Power (p+/p-)
- Jet Power (P_j)
- Electric Power (P_e)
- Total Sunlight Hitting Earth
- Total Human Civilization Power
Conclusions of Antimatter Study

- An interstellar mission is enormously difficult, but not impossible
  - Represents a national (international?) “stretch” goal that could focus NASA, DoE, DoD, Academia, and Industrial expertise over the next century

- Three propulsion concepts previously identified that are capable of fast (0.5 c) interstellar rendezvous mission: Beamed Sail, Antimatter, Interstellar Ramjet
  - ”Fast” (0.5 c) Rendezvous significantly more difficult (total mission $\Delta V = 1 \text{c} !)$ than “slow” (0.1 c) Flybys
  - All three concepts have major unresolved feasibility issues
  - NO CLEAR WINNER ! (Given our current knowledge)

- Antimatter propulsion systems for interstellar missions are enormous, but this is true for any interstellar mission propulsion system
  - Example: 3,000 TW Laser required for 40 LY Laser Sail rendezvous mission would weigh $3 \times 10^9 \text{MT}$ at a specific mass of 1 kg/kW (beam power)

- Results of this work can be used to evaluate technology benefits and requirements for antimatter propulsion systems, and identify those with high leverage - For example:
  - Required: Long-Life Active Refrigeration, etc.
  - High-Leverage: Lightweight Propellant Storage and Feed, Advanced Radiators (e.g., high-temperature LDR), etc.
Application of High Performance Computing and Simulation Tools to Advanced Propulsion

CONCEPT

- Use of first principles-based computer simulations to investigate the physics underlying advanced propulsion concepts

ADVANTAGES

- Provides a means for more rapidly evaluating the feasibility of advanced concepts
- Often less costly to perform virtual experiments with high fidelity simulations than comparable laboratory experiments
- Provides more insight into the physics of plasma processes in advanced propulsion schemes
- A suite of 3-dimensional models, employing almost all existing plasma particle simulation algorithms, have been developed at JPL for advanced propulsion and plasma physics research
  - Electrostatic (ES) and electromagnetic (EM) particle-in-cell (PIC)
  - Hybrid fluid-particle PIC
  - PIC with Monte-Carlo Calculation (MCC) for collision calculation
  - Non-orthogonal grids and sub-grid scale grids for complex geometry
- Many codes are designed to run on a variety of massively parallel supercomputers at JPL and Caltech (SGI Origin2000, HP spp2000, Cray T-3D, Intel Paragon). Capable of running simulations using hundreds of millions of particles at a speed of <100 ns/particle/step.

APPLICATIONS

- Many advanced propulsion concepts employing plasmas or plasma-surface interactions
Plasma Simulations Have Been Used to Study a Number of Problems in Advanced Propulsion in FY00

TYPICAL APPLICATIONS
- Field Emission Array Cathode:
  - Space-charge limited emission: 3-D full particle ES PIC simulations (Marrese et al., 2000)
- Micro-Ion Engine:
  - Micro-discharge chamber/scaling laws: 3-D full particle ES PIC-MCC simulations (Wang et al., 2000)
- Field Emission Electric Propulsion (FEEP):
  - FEEP neutralization and contamination: 3-D full particle ES PIC simulations (Tajmar and Wang, 2000)
- Vacuum Arc Plasma Propulsion:
  - Ion acceleration/plasma sheath: 3-D ES PIC with sub-grid scale grids
- Ion Optics:
  - Ion acceleration/charge-exchange ion interactions with the grids: 3-D ES PIC-MCC with sub-grid scale grids
- Magnetospheric Plasma and M2P2:
  - Micro-plasma instabilities and magnetic reconnection: 3-D EM hybrid fluid-particle PIC

JPL TECHNICAL POC: Joe Wang
(joseph.j.wang@jpl.nasa.gov)
The Advanced Propulsion Concepts Website: A Valuable Resource

Soon to be accessible to the general public:

http://sec353.jpl.nasa.gov/apc/
Advanced Propulsion is the Key to Enabling New Capabilities in Exploration

The Challenge:
- New Propulsion Concepts
- Innovative Ways to Exploit New Capabilities