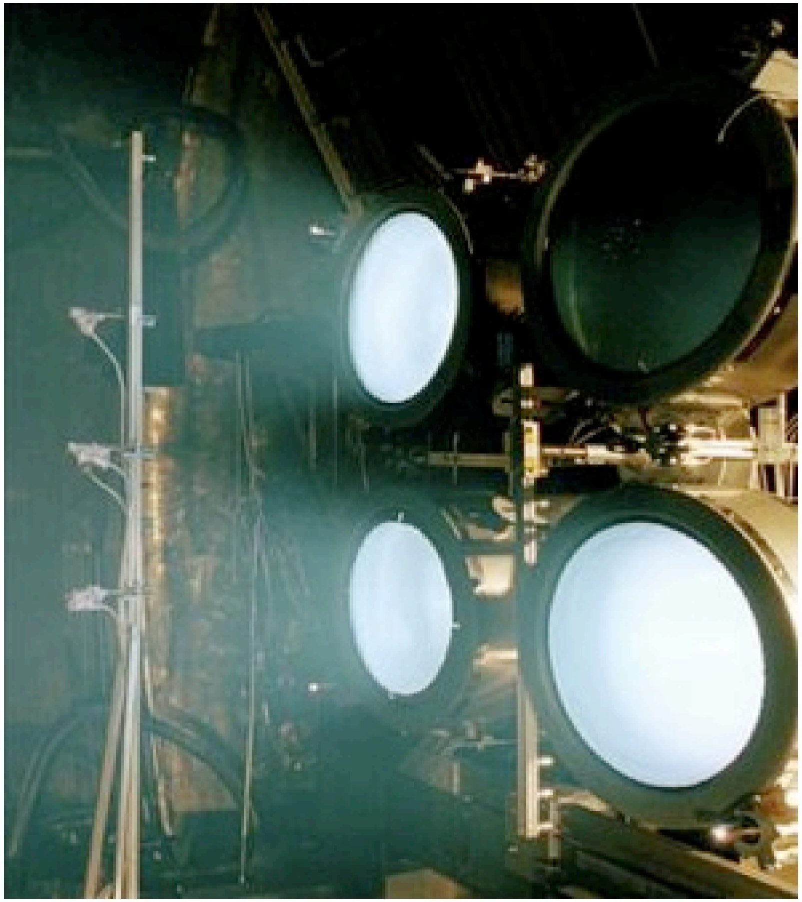
NASA's Evolutionary Xenon Thruster



The NEXT Ion Propulsion System for Solar System Exploration

Briefing prepared for New Frontiers AO participants

April 2009

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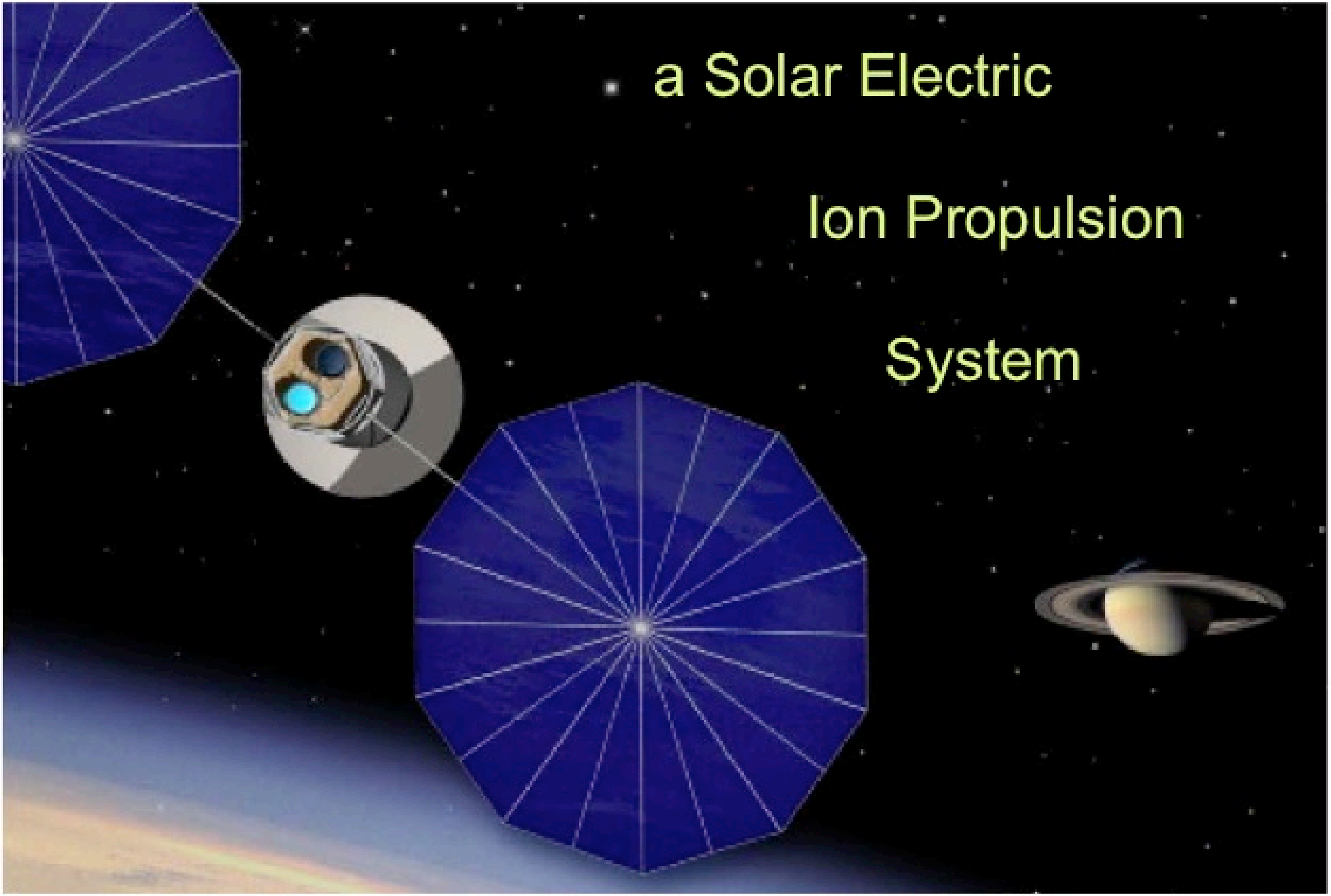
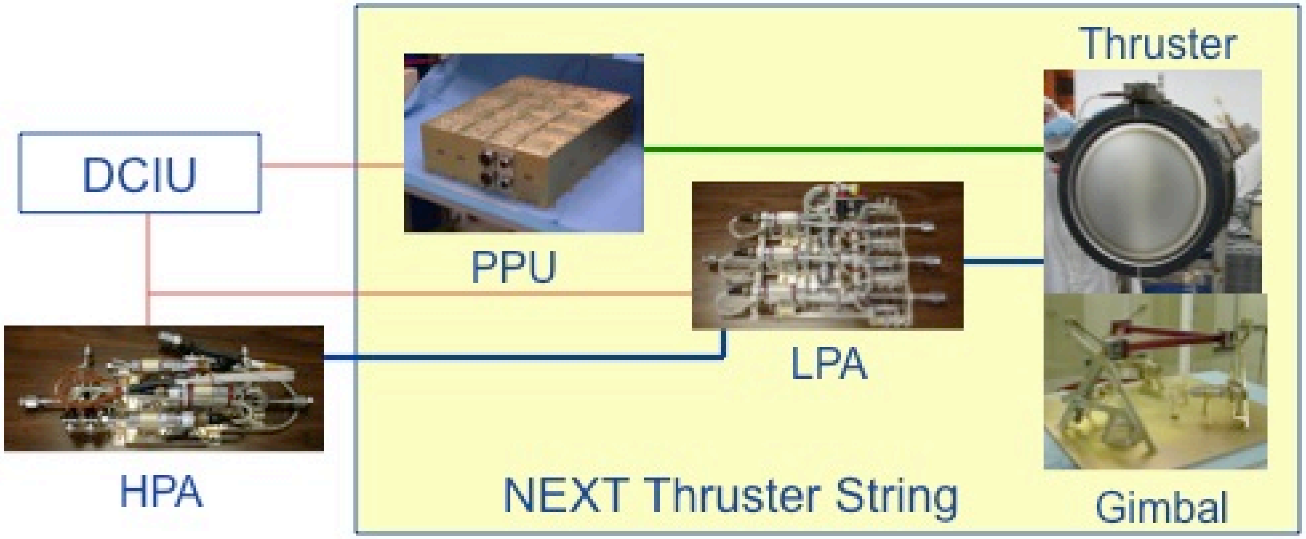


The NEXT System

- Thruster String composed of Thruster/Gimbal Assembly, Power Processing Unit (PPU), and Propellant Management System (PMS) Low Pressure Assembly (LPA)
- High Pressure Assembly (HPA) and DCIU complete system
- Thruster Strings are added for mission performance reasons and for failure tolerance (Nomenclature: N+1)
- Overall system is configurable to meet mission needs



The State of NEXT

- The NEXT project is advancing the capability of ion propulsion to meet NASA robotic science mission needs
- Mission analyses have demonstrated beneficial NEXT application over a range of missions from Discovery to Flagship
- Key ion propulsion system hardware has advanced to a high state of maturity
- The project is striving to ease transition to flight by addressing Dawn lessons learned and user needs
- First-user implementation and cost modeling will help users to assess NEXT, and to focus project resources on higher pay-off activities

NEXT is ready for the upcoming solar system exploration mission opportunities

NEXT Project Background

- Two-phase project to develop Next Generation Ion (NGI) technology to Technology Readiness Level (TRL) 5/6
  - Sponsored by NASA Science Mission Directorate, conducted under MSFC In-Space Propulsion Technology Program
  - Implemented through a NRA
  - First Phase: 1 year, completed August, 2003
  - Second Phase: Initiated October, 2003

The NEXT Team & Contacts

- **NASA Glenn Research Center** - Technology Project Lead
  - Michael Patterson, Principal Investigator, 216-977-7481
  - Scott Benson, Project Manager, 216-977-7085
  - George Soulas, GRC Thruster Lead, 216-977-7419
- **Jet Propulsion Laboratory** - System Integration Lead
  - Steve Snyder, System Integration Lead, 818-393-7357
- **Aerojet**, Redmond WA - Thruster, PMS, DCIU Simulator
  - Andy Hoskins, Aerojet Project and Thruster Lead, 425-936-6562
  - Randy Aadland, Propellant Management System Lead, 425-936-5251
  - Jeff Monheiser, DCIU Simulator Lead, 425-936-6663
- **L3 Comm ETI**, Torrance CA - PPU
  - Brian Wong, L3 Project Lead, 310-517-6099
  - Phil Todd, PPU Lead, 310-517-6859
- Participation by **APL, Univ. of Michigan, Colorado State Univ.**
  - Carl Engelbrecht, APL

NEXT Capabilities, Benefits and Applications

NEXT significantly improves performance over State-of-Art (SOA) EP

CHARACTERISTIC	NSTAR (SOA)	NEXT	BENEFIT
Max. Thruster Power (kW)	2.3	6.9	Enables high power missions with fewer thruster strings
Max. Thrust (mN)	91	236	
Throttling Range (Max./Min. Thrust)	4.9	13.8	Allows use over broader range of distances from Sun
Max. Specific Impulse (sec)	3120	4190	Reduces propellant mass, thus enabling more payload and/or lighter spacecraft
Total Impulse (10^6 N-sec)	4.6	>18	Enables low power, high ΔV Discovery-class missions with a single thruster
Propellant Throughput (kg)	150	450	

Mission Benefits

- Numerous mission analyses performed during NEXT project have demonstrated mission benefits

Mission	Performance Finding
Discovery - Small Body Missions • Near Earth Asteroid Rendezvous • Vesta-Ceres Rendezvous (Dawn-like) • Comet Rendezvous • Deimos Sample Return	Higher net payload mass with fewer thrusters than NSTAR system
New Frontiers - • Comet Surface Sample Return	Higher net payload mass than NSTAR, with, Simpler EP System: 2+1 NEXT vs 4+1 NSTAR thrusters
New Frontiers - • Titan Direct Lander	> 700 kg entry package with 1+1 NEXT system
Flagship - Saturn System Missions • Titan • Enceladus	> 2400 kg to Saturn Orbit Insertion with 1+1 NEXT system, Earth Gravity Assist and Atlas 5 EELV - Doubles delivered mass of chemical/JGA approach > 4000 kg to Saturn Orbit Insertion with 3+1 NEXT system, Earth Gravity Assist and Delta IV Heavy

NEXT provides mission benefits across *all* planetary science mission classes

NEXT - System & Integration Benefits

- NEXT retains critical heritage to NSTAR, while addressing complex system integration issues encountered on Dawn
- NEXT thruster is very similar to NSTAR thruster in physics, concept, and functions
  - High relevance in transferring NSTAR thruster life and throttling knowledge to NEXT thruster validation
- NEXT PPU encompasses functionality of NSTAR PPU
  - Additional functions simplify system and improve efficiency across throttle table
  - Main advances are in modularity and producability of unit
- Spacecraft integration is simplified by NEXT capabilities and features
  - Less thruster strings per mission total impulse
  - Modular, simplified xenon feed system
  - PPU is compatible with wider baseplate thermal range than NSTAR
  - Gimbal has smaller footprint than NSTAR

System Requirements

- Project Requirements are documented and controlled in:
  - Project Requirements Document (In-Space Req'ts)
  - Technical Requirements & Validation Document (Flowdown)
- Requirements developed :

Source	Requirement
NSTAR Heritage	Functional, design
Deep Space Design Reference Mission	Performance, environmental
Refocus Analyses	Throttling range, 300 kg throughput

- Requirements and design reviewed:
  - System Requirements and Integration Reviews
  - Subsystem and System-Level Design Reviews
  - Independent Review
- Formal Project Documentation
  - Plans: Project, Risk Management, Validation, Assurance
  - System ICD

NEXT Development Status

Thruster

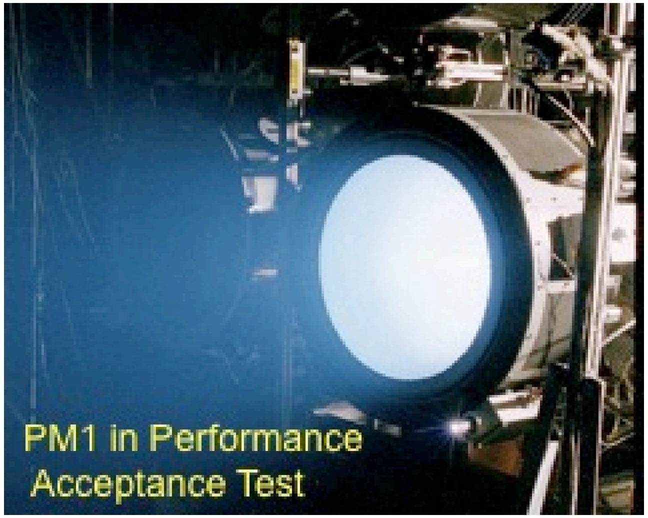
- The Engineering Model (EM) and Prototype Model (PM) NEXT ion thruster designs were derived from a laboratory model 40 cm beam diameter ion thruster developed in 2001 at the NASA Glenn Research Center (GRC)

- The EM thruster design was subsequently developed at GRC

- The PM thruster design was developed at Aerojet under contract to GRC, and matures the NEXT thruster design to ensure full-compliance with structural and thermal requirements, and improve thruster manufacturability

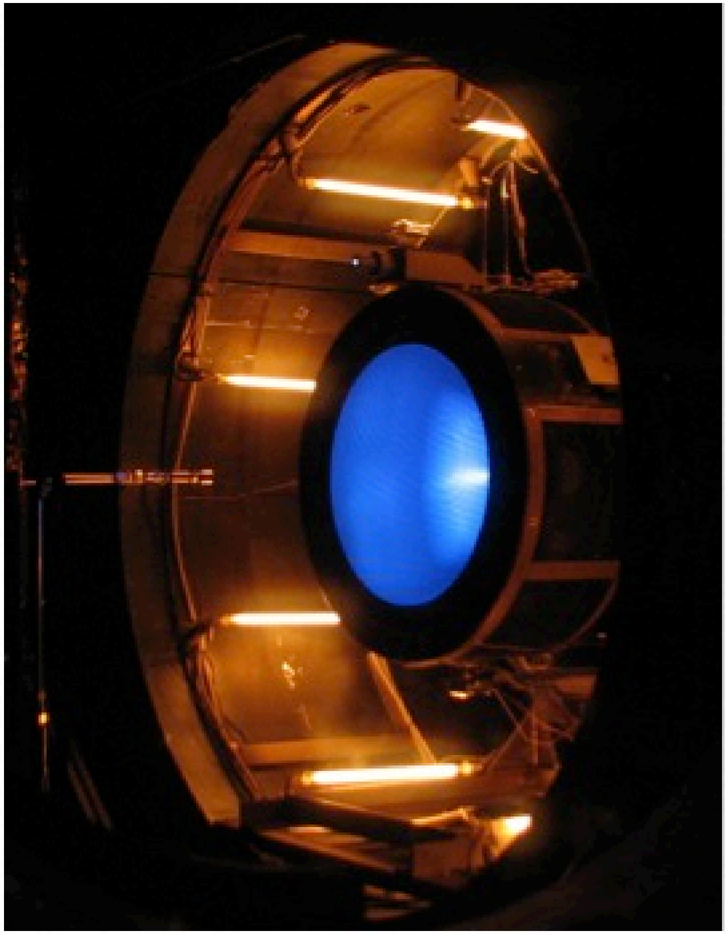
Thruster Characteristics

- 0.54 – 6.9 kW thruster input power
- Ring-cusp electron bombardment discharge chamber
- 36 cm beam diameter, 2-grid ion optics
- Beam current at 6.9 kW: 3.52 A
- Maximum specific impulse > 4170 sec
- Maximum thrust > 236 mN
- Peak efficiency > 70%
- Xenon throughput > 300 kg, 450 kg qualification level
  - Analysis-based capability >450 kg
- Mass is 12.7 kg (13.5 kg with cable harnesses)



NEXT Thruster

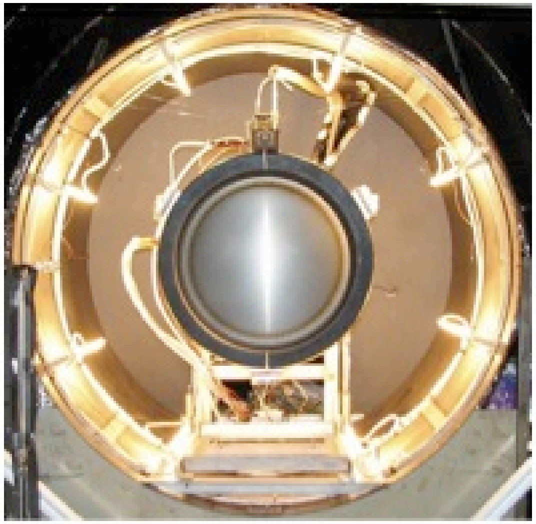
- Prototype Model Thruster (PM1) delivered by Aerojet to GRC
  - Flight-level design and fabrication processes
- Performance Acceptance Testing successfully completed at GRC
- Comprehensive PM1 environmental test sequence completed at JPL
- Two cycles of acceptance & environmental testing completed
  - Thruster reworked to resolve minor design issues
- PM1 now supporting System Integration Testing
- PM1 thruster to be incorporated into life validation program upon completion of testing

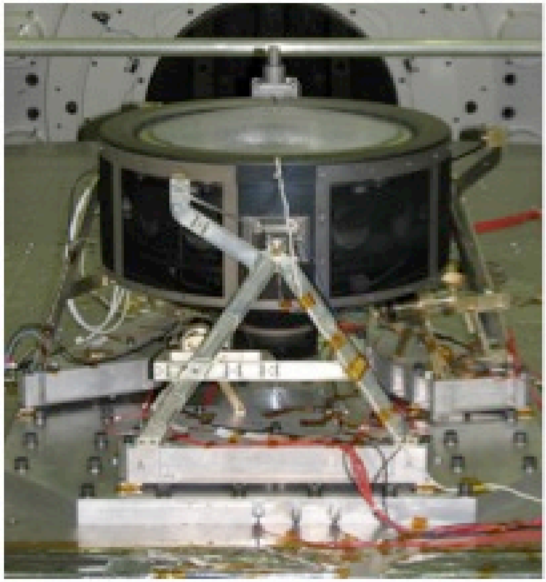


PM Thruster undergoing Thermal Vacuum Testing at JPL

Thruster Environmental Testing

- Thermal balance test performed to gather key thruster thermal data over wide range of operating and environmental conditions
  - Develop and validate thruster thermal model
  - Demonstrate thruster operation and temperature margins over large temperature range
- Integrated thruster/gimbal qualification-level vibe testing
  - 10.0 Grms, 3 axes, 2 min/axis
  - No changes in pre- and post-vibe gimbal functional results
- Thruster Thermal/Vacuum test to qualification levels
  - < -120° C cold
  - > 215° C hot (at reference location)
  - 3 cycles with hot and cold dwell
  - Hot and cold thruster starts





Development/Environmental Test Findings

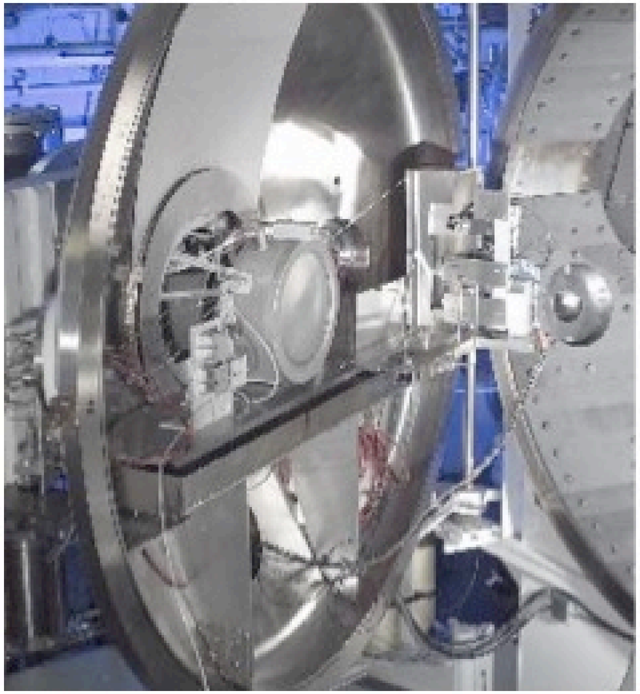
- PM thruster performs within predictions and is consistent with results from multiple EM thrusters
- PM thruster has significant thermal margin on critical components
  - Harness outer layer at thruster body exit needs to be resolved
- PM thruster compatible with dynamic and thermal environments
- Thruster performance was nominal over entire test sequence
- Implementation of EM to PM design and fabrication transition was very successful
- Gimbal is compatible with dynamic environments

PM Thruster Planning

- PM1R has been incorporated into life validation task with completion of system integration testing
  - Wear test of PM1R
- All thruster drawings and work instructions have been updated at Aerojet
  - Incorporated all redlines
  - Reflects PM1R as-built configuration
  - Released to development level
- PM2 parts and subassemblies to be put into controlled storage for later In-Space or user final assembly

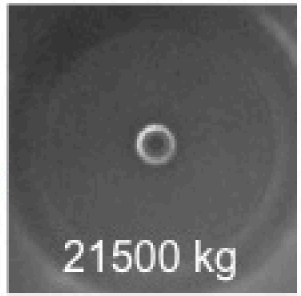
NEXT Thruster Life Validation

- Thruster life validation continuing through EM3 long duration testing and life analyses *(VF16, GRC Bldg 16)*
- Predicted first failure occurs after 750 kg xenon throughput
- Mission-derived design requirement has been 300 kg xenon throughput
  - Near-Earth Asteroids: < 200 kg
  - Comet Rendezvous: 260 kg
  - Saturn mission: 225 - 275 kg
  - Comet Sample Return: 300 - 355 kg
  - Titan-Saturn System Mission: 250 kg
- > 21,500 hrs, > 413 kg xenon throughput demonstrated to date (as of 4/10/09)
  - > 15.7×10^6 N-s total impulse
- Upcoming demonstration milestones
  - 450 kg throughput in CY09
  - 550 kg throughput under planned ISPT funding through FY10
- Continued testing and analysis will support FY09/FY10 competed mission proposals
- Short duration test of PM1 thruster initiated
  - Test results will be compared to EM results

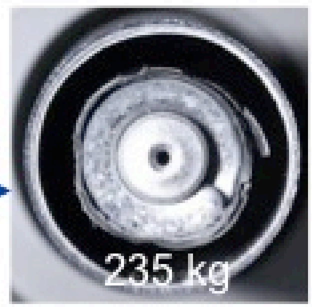


LDT and Life Validation: NEXT Thruster Discharge Keeper Erosion Rates within Expectations

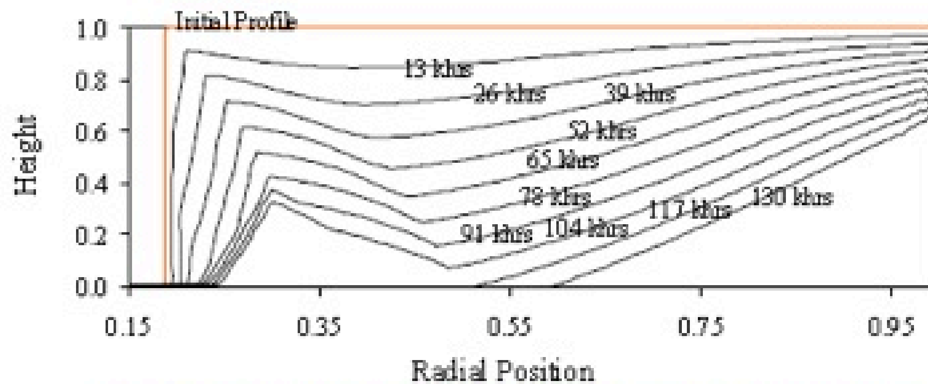
NEXT



NSTAR



Discharge Keeper erosion mitigated in NEXT

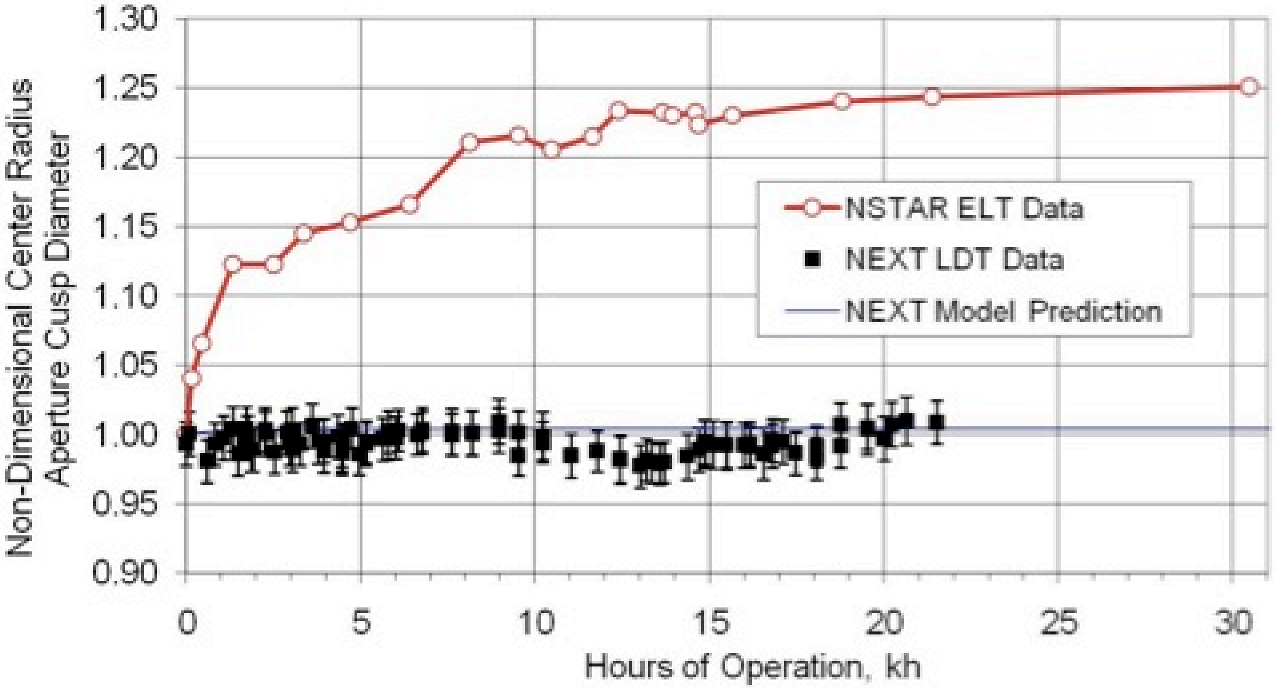


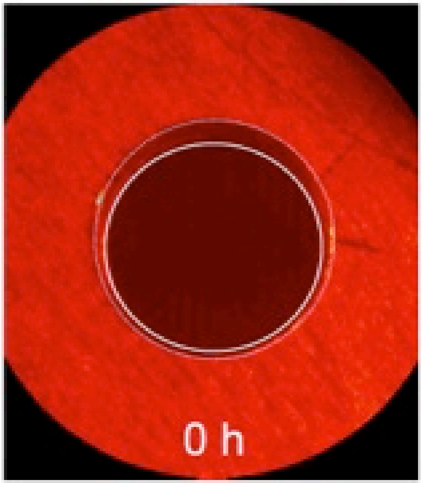
DCA Graphite Keeper Erosion Estimates from NEXT Service Life Assessment Model

Prediction assuming continued full power operation

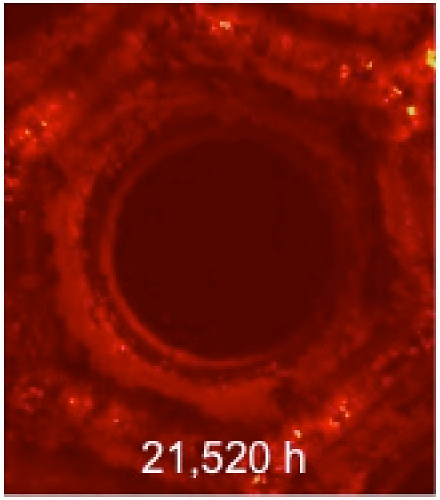
NEXT Design Mitigates Critical Erosion observed in other Ion Thrusters

LDT and Life Validation: NEXT Thruster Accel Aperture Erosion Rates within Expectations



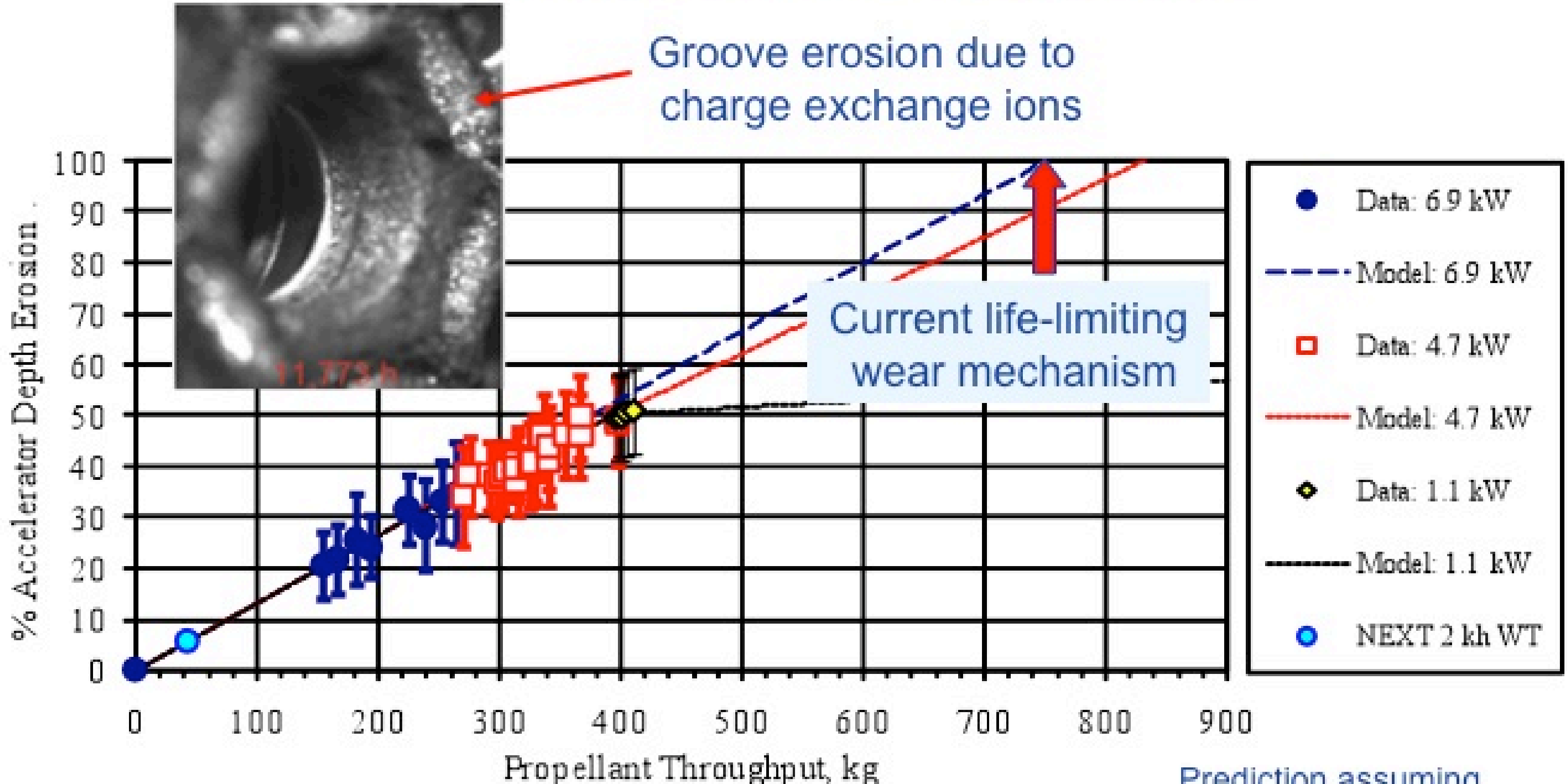


Prediction assuming continued full power operation



NEXT Design Mitigates Critical Erosion observed in other Ion Thrusters

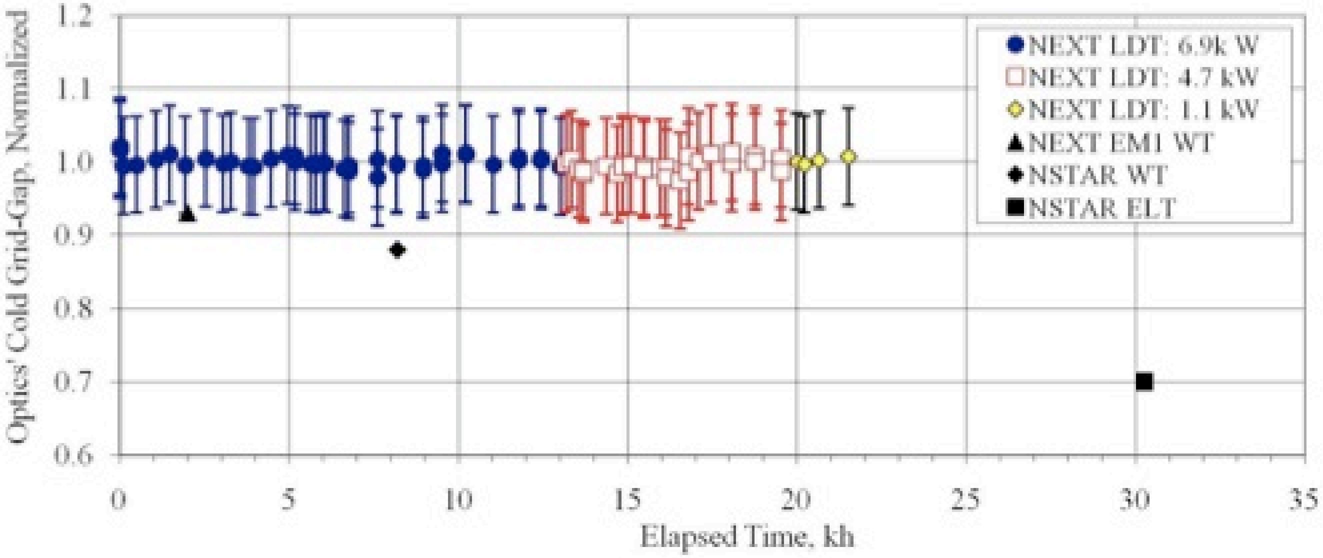
LDT and Life Validation: NEXT Accelerator Groove Erosion Rates within Expectations

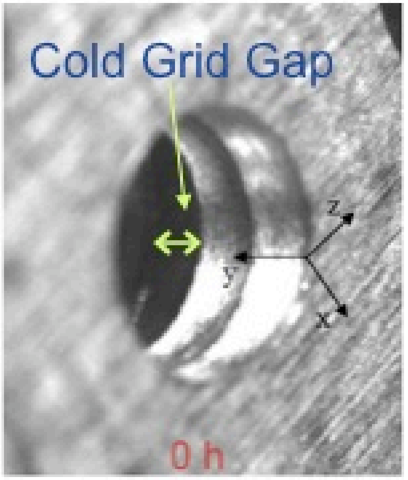


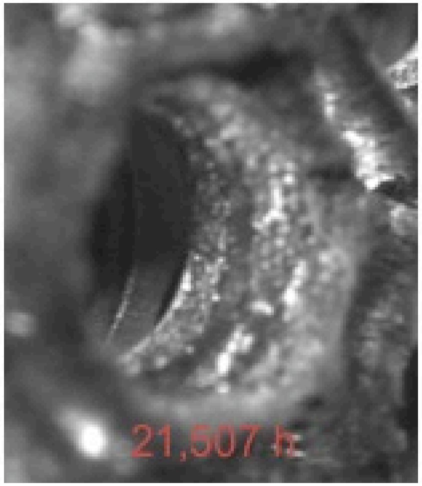
Prediction assuming continued full power operation

NEXT Design Mitigates Critical Erosion observed in other Ion Thrusters

LDT and Life Validation: NEXT Grid Gap within Expectations







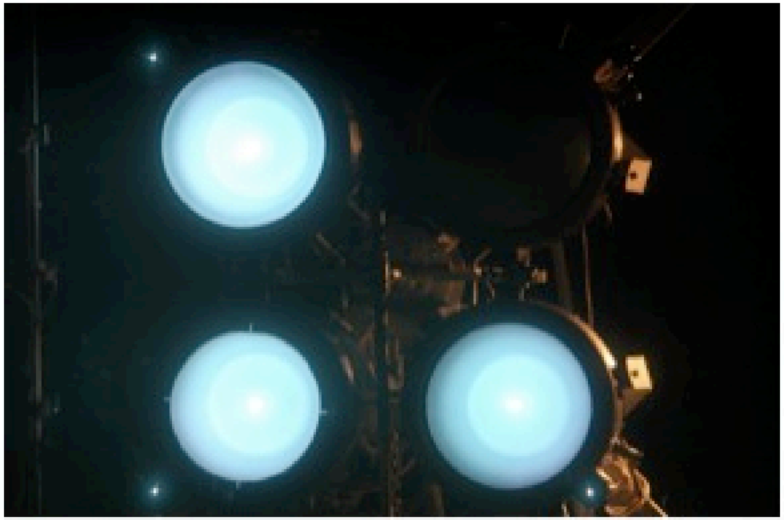
NEXT Ion Optics Design Compliant and Stable

LDT and Life Validation: Detailed Throttling Strategy Developed

Operating Condition Input Power, kW	Operating Condition	Duration, kh	Segment Throughput, kg	Post-Segment Throughput, kg	End of Segment Date
6.9	3.52A, 1800V	13.0	267.4	267.4	11/17/2007
4.7	3.52A, 1179V	6.5	130.0	397.5	12/22/2008
1.1	1.20A, 679V	3.0	21.9	419.4	5/10/2009
0.5	1.00A, 275V	3.0	19.9	439.3	9/26/2009
2.4	1.20A, 1800V	2.0	14.6	453.9	12/28/2009
	Totals	27.5	453.9		

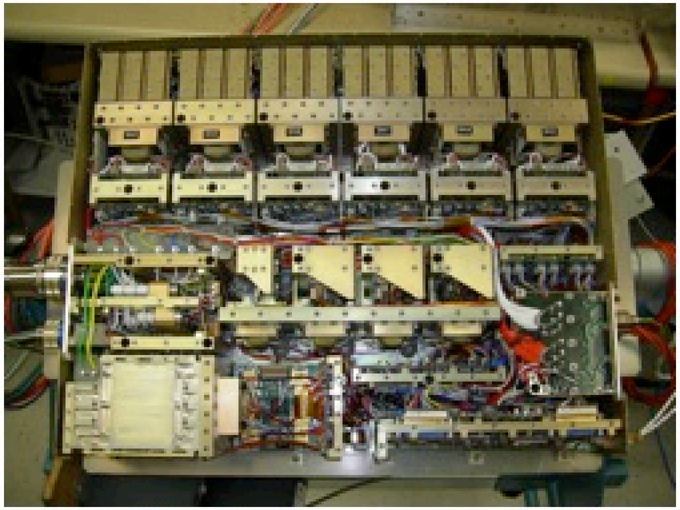
- Achieves the following:
  - Demonstration of >450 kg throughput per PRD and TRV by end of FY09
  - Total LDT duration > average mission thruster operating time
  - Demonstrate total impulse greater than mission requirement (1.75×10^7 N-sec)
  - Demonstrate intermediate power operation consistent with mission analyses
  - Demonstrate power throttling back to full-power consistent with mission analyses
  - Demonstrate low-power operation (< 0.5 kW) for 2X the average mission analyses duration
  - Operates at known worst-case wear conditions

NEXT Multi-Thruster Array Test

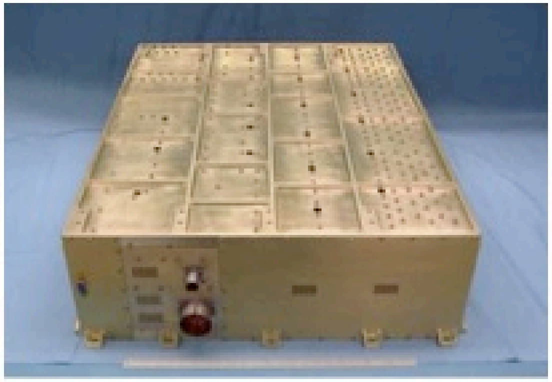


- Objectives
  - Assess thruster and plasma interactions, with sensitivities to thruster spacing, gimbaled thrusters, and neutralizer operating modes
- Configuration
  - Four GRC EM thrusters, three operating and one instrumented non-operating
  - Extensive diagnostics to collect data for multi-thruster system modeling and analyses
- Completed in December 2005 at GRC
- Single, Dual and Triple thruster operations conducted
- Initial data indicates expected performance was achieved, well -understood operations, without significant sensitivity to system configuration

Power Processing Unit

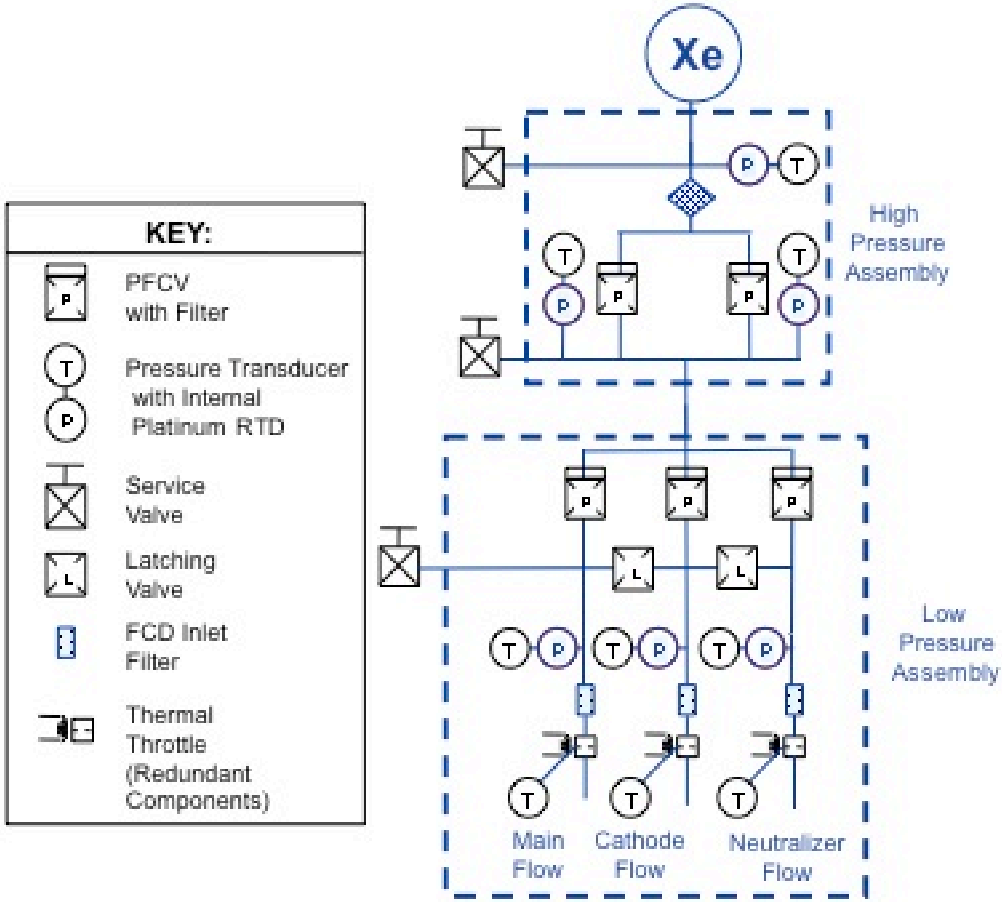


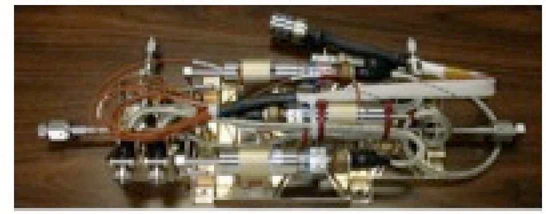
- EM PPU fabrication completed
- Integration testing initiated at GRC
  - Tests interrupted by part failures
  - After resolution PPU will be retested with thruster and feed system
- Thorough unit testing to follow
  - Qual-level vibration testing and post-vibe functional
  - Qual-level thermal/vacuum test
  - EMI/EMC tests
- Testing planned to be complete in CY2009



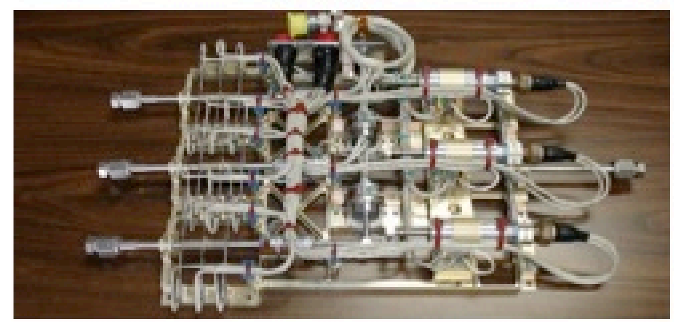
- DCIU can be integrated in next development phase
- Flexible, scalable architecture can be adapted to a wide range of thrusters and missions
- Wide throttle range capability: 250W to 7200W
- > 0.2 kW/kg Specific Power
- Simple thermal interface - 65 C baseplate

Propellant Management System (PMS)





NEXT PMS
High Pressure Assembly
(Aerojet)



NEXT PMS
Low Pressure Assembly
(Aerojet)

NEXT PMS provides significant volume and mass reduction over DS-1/Dawn approach

Propellant Management System

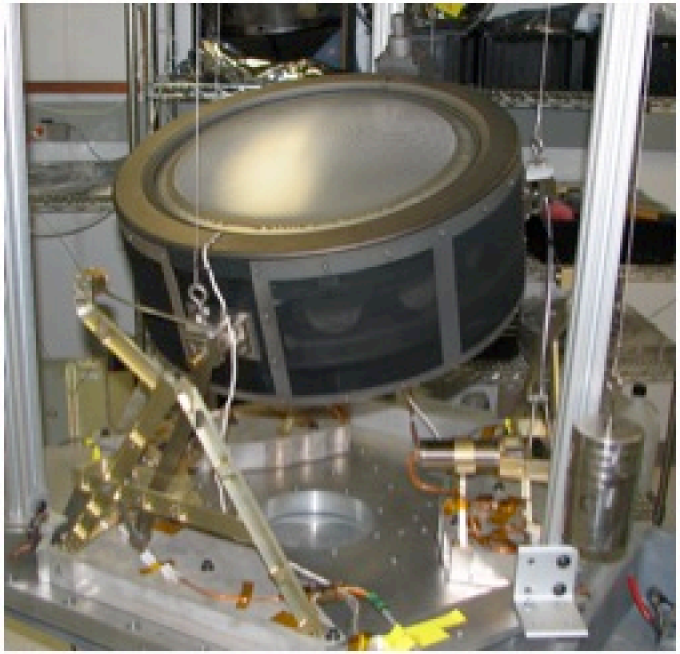
- All EM PMS assemblies are complete
  - 2 HPA's, one Flight-like
  - 3 LPA's, one Flight-like
  - Non-flight assemblies are identical except for use of lower cost equivalent parts
- All assemblies have completed functional tests
- Flight-like LPA and HPA successfully completed qual-level vibration testing and post-vibe functional testing
  - 14.1 Grms for 2 minutes in each axis
- Qual-level thermal/vacuum testing successfully completed
  - +12 to +70 °C temperature range, 3 cycles
- EM PMS has been delivered to NASA for use in system integration testing

Digital Control Interface Unit

- DCIU Simulators have been completed and are in use in tests
- Laptop-based test equipment, with brassboard-level PMS pressure loop control cards
- Capable of operating 3 thruster string system
- Validates control algorithms and PMS control card
- Supports
  - PPU input/output testing
  - PMS control during testing
  - Single-String and Multi-String Integration Tests
  - PMS kernel control in Long Duration Test

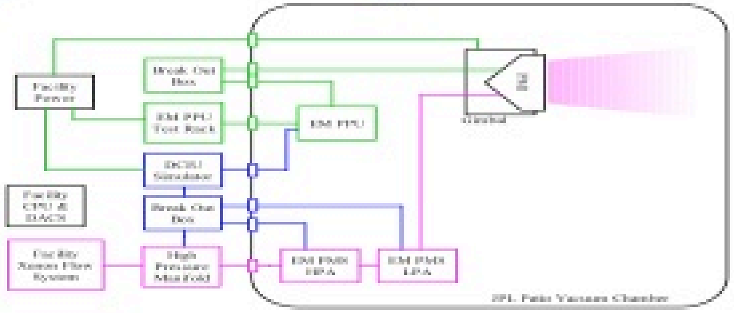
Gimbal

- Breadboard gimbal
  - Designed and fabricated by Swales Aerospace
  - Flight-like design using JPL-approved materials with certifications
    - Stepper motors have space-rated option
  - Mass < 6 kg
  - Two-axis range of motion: ±19°, ±17°
- Successful functional testing with PM1 engine
- Gimbal passed two qual-level vibration tests and low-level shock tests with minor issues
- Good baseline – few if any modifications needed to move into qual program
  - Need to perform torque margin tests with harness and propellant line routing



Single String and Multi-Thruster System Integration Testing

- Scope
  - Verify that the integrated system of NEXT components meets the project requirements
  - Verify the interfaces between the system components
- Primary Objectives
  - Demonstrate operation of thruster over throttle table with PPU and PMS
  - Demonstrate operation of system at off-nominal conditions
  - Demonstrate recycle and fault protection operation
- Status
  - Majority of single-string testing completed in Sept 2008.
  - 3-thruster/PMS system testing completed in Sept 2008.
  - Additional testing will be completed after PPU recovery.



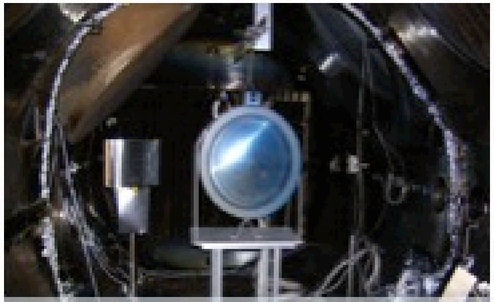
NASA GRC VF6, Bldg 301

- 90 separate requirements have been flagged for validation
  - Component functionals
  - Performance requirements
  - Environmental requirements
  - Interface requirements
  - Power allocations

Collaboration with The Aerospace Corporation

- Three-Year Non-Reimbursable Space Act Agreement with The Aerospace Corporation (TAC) /El Segundo, CA will improve NEXT's *Transition-to-Flight*:
  - Independent assessment of the **NEXT ion propulsion system (IPS)** (and other propulsion devices including **HiVHAC**) technology readiness and its suitability for missions of national interest
  - Broaden the potential application of NASA's NEXT IPS and other national propulsion capabilities and assets to support non-NASA missions.
- Aerospace's expertise in evaluation of electric propulsion is highly recognized
  - Unique capabilities in identifying and characterizing propulsion/spacecraft integration issues
- CY09-10: Conduct detailed quantitative characterization of the particle & field environment of the NEXT thruster and its potential impacts on the host spacecraft
  - IRAD investment by The Aerospace Corporation
  - NASA has nearly-continuous access to Aerospace facilities and personnel over 2 years at no direct cost
  - Depending on hardware availability, funding, and user interest, test matrix can be expanded to examine Prototype Model (PM) thruster.

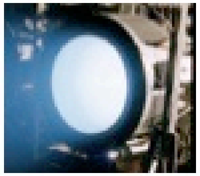
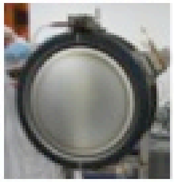
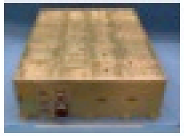
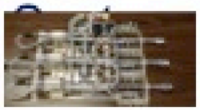
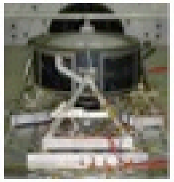
EVALUATIONS	EM THRUSTER
Beam Current Density	CY09 Q1
Charge-Exchange Plasma	CY09 Q1
High-Energy Widely-Divergent Ions	CY09 Q1
EMI Surveys & Transmissions through Plume	CY09 Q2
Optical Emissions	CY09 Q1, Q3
Erosion Products	CY09 Q2, Q3
Beam Charge State	CY09 Q3
Direct Thrust	CY09 Q4, CY10 Q1



Detailed Thruster/Spacecraft Interface Characterization Tests of the NEXT EM Thruster TAC EP2 Chamber

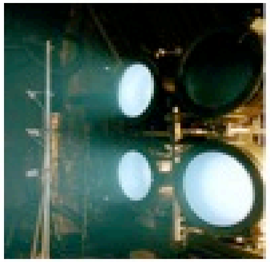
NEXT is Nearing TRL6 Validation

- Critical tests have been completed, or are imminent, on high fidelity hardware

	PM1 	PM1R 	PPU 	Feed 	Gimbal 
Functional & Performance Testing	Complete	Complete	Complete*	Complete	Complete
Qual-Level Vibration Test	Complete*	Complete	CY09	Complete	Complete
Qual-Level Thermal/ Vacuum Test	Complete	Complete	CY09	Complete	N/A

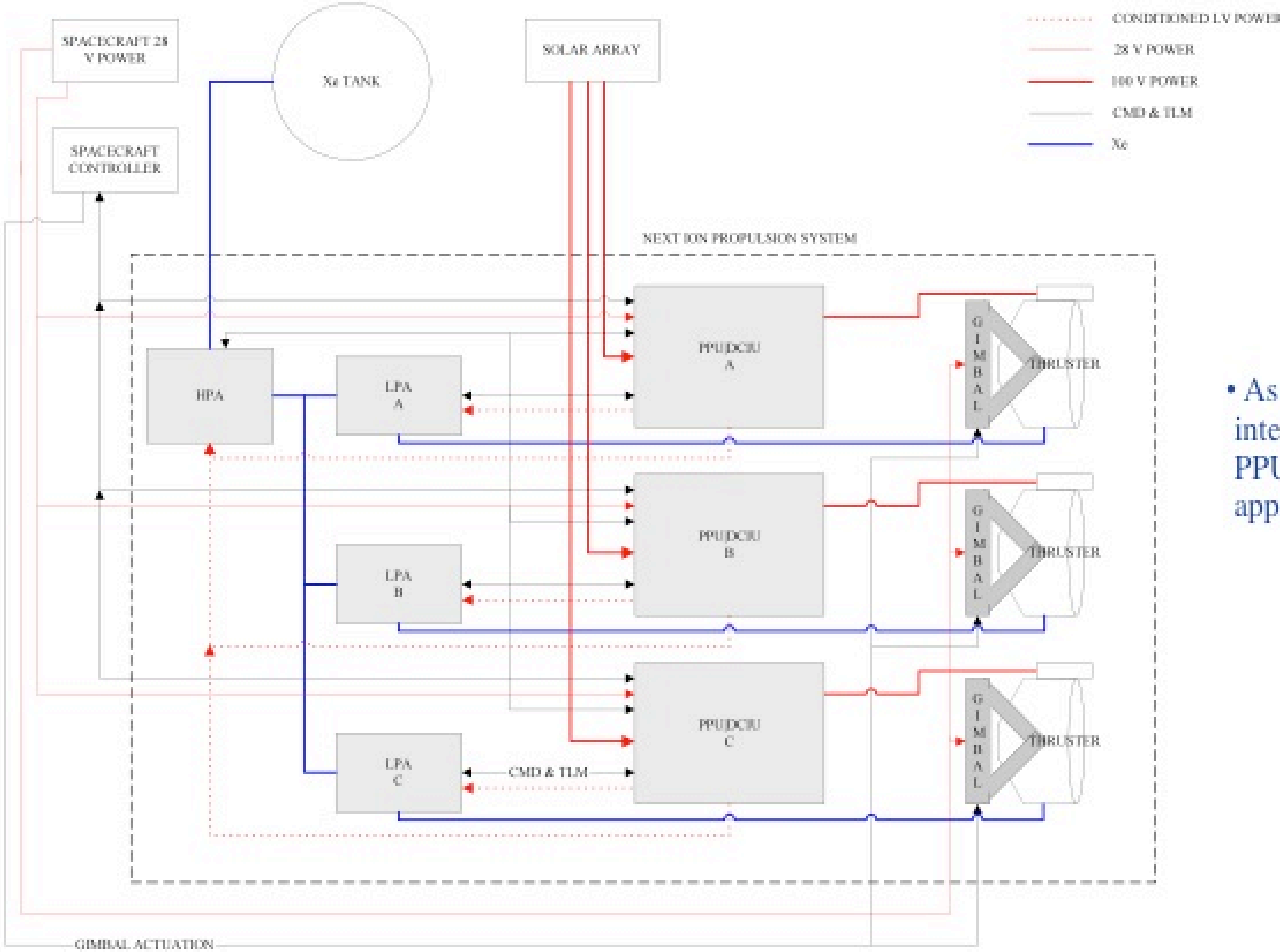
* - Test findings addressed in unit rework

- Single-String Integration Test (in progress) and Multi-String System Integration Testing (complete)
- Thruster Life Test: In progress & continuing through FY2010
- PM wear test: In progress (planned completion by FY09)



NEXT System

NEXT IPS 3-String Configuration



- Assumes integrated PPU/DCIU approach

Subsystem Characteristics

Resource	System		Current Best Estimate	Basis
Mass (kg)	Thruster		12.7	PM Actual, w/o harness
	PPU		33.9	EM Actual
	PMS	HPA	1.9	EM Actual, w/plate & Test Support Equip.
		LPA	3.1	EM Actual, w/plate & Test Support Equip.
	Gimbal		6	Breadboard Actual
Envelope (cm)	Thruster		55 dia. x 44 length	PM Actual
	PPU		42 x 53 x 14	EM Actual
	PMS	HPA	33 x 15 x 6.4	EM Actual
		LPA	38 x 30.5 x 6.4	EM Actual
	Gimbal		72 cm corner -corner, 61 cm flat-flat	Breadboard Actual
Power (W)	Thruster[1]		540-6860	PM Actual
	PPU		610-7220	Breadboard Actual
	PMS	HPA	4.3	EM Actual
		LPA	15.9	EM Actual
	Gimbal		N/A	-

[1] Input power to the thruster from the PPU.

Transition to Flight

Lessons Learned/Independent Review

- Project activities are being conducted to increase the likelihood of transitioning the NEXT IPS technology to flight in the near -term:
  - Reviewing Dawn IPS 'lessons-learned' and implementing strategies to mitigate the likelihood of experiencing similar difficulties;
  - Conducting independent reviews of NEXT technology status with representation from the user community and incorporating the feedback into the development plan;
  - Identifying additional technology development and validation activities which may be of value in transitioning the TRL6 IPS technology to flight and reduce barriers to 1st-user implementation (reduce non-recurring costs, etc.).

- The NEXT project has placed particular emphasis on key aspects of IPS development with the intention of avoiding the difficulties experienced by the Dawn mission in transitioning the NSTAR-based technology to an operational ion propulsion system

Lessons Learned

- Detailed review of Dawn (provided by IPS manager) and NSTAR lessons-learned conducted
- NEXT systematically attacking issues identified under these programs – example
  - Documentation
    - Dawn – inadequate Thruster and PPU documentation
    - NEXT – EM PPU manufactured by flight production group with all documentation (manufacturing drawings and assembly instructions) now under configuration control;
    - NEXT PM thruster design and assembly documentation has been updated with PM1R changes and placed under design control for future build cycles

Lessons Learned

- Additional examples
  - Propellant Management
    - Dawn – Complex, bulky, and required extensive modification to satisfy requirements
    - NEXT – DS-1 and Dawn feed system engineers heavily involved in NEXT design from project initiation; PMS design incorporates lightweight, compact design
  - Thruster
    - Dawn – Complex design elements, difficult to manufacture and assemble; long duration test results impacted flight configuration
    - NEXT – Thruster designed for manufacturability and assembly; extensive testing to evaluate erosion mechanisms conducted on EM hardware – resulting in modifications implemented on both EM and PM hardware and presently under extensive evaluations prior to committing to qualification build

Technology Readiness

- Programmed FY09/FY10 In-Space activities will bring NEXT to a high state of readiness for FY09/10 AO's
  - Complete functional and qual-level environmental testing of key system elements
  - Thruster Long Duration Test has exceeded throughput requirement of 300 kg
  - System Integration Test with most mature hardware products
- NEXT is approaching TRL 6 in CY 2009
  - Critical components will be demonstrated to TRL 5
  - Demonstrated in relevant system to TRL 6
  - Key proposal requirement in AO guidance

Transition to Flight Strategy

- Successfully complete all planned technology development activities for NEXT
- Reduce as much first user risk as future resources will allow. Work with users to jointly identify, address, and mitigate risks.
- Involve mission centers in upcoming Phase 2 Closeout Review and Technology Maturity Assessment
- Established in-place NEXT ion thruster hardware at Aerospace Corp. in CY08 for independent technology assessments
- Continue interactions with mission stakeholders to support mission studies using the NEXT IPS

Summary

- NEXT project activities through 2009 have brought next-generation ion propulsion technology to a mature state
- In-Space Propulsion Technology tasks will complete the majority of the NEXT technology validation in FY09
- NEXT will be ready for upcoming competed and directed robotic mission opportunities in the FY09/10 timeframe

Transition to first flight will be challenging. The ISPT Office welcomes your feedback and is looking forward to assisting you in developing compelling mission opportunities!