NEXT-C Flight Ion System Status

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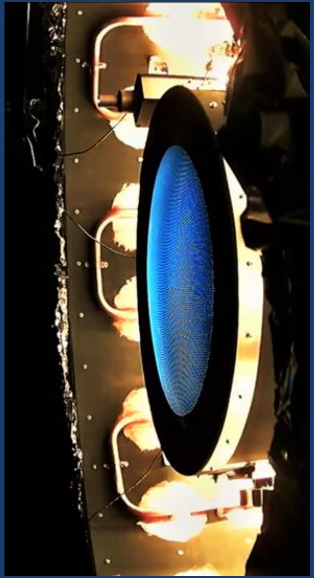

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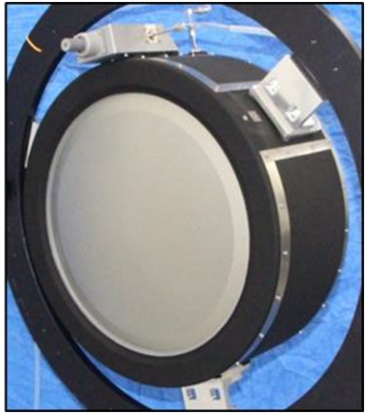
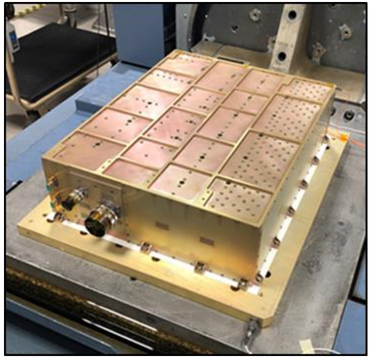
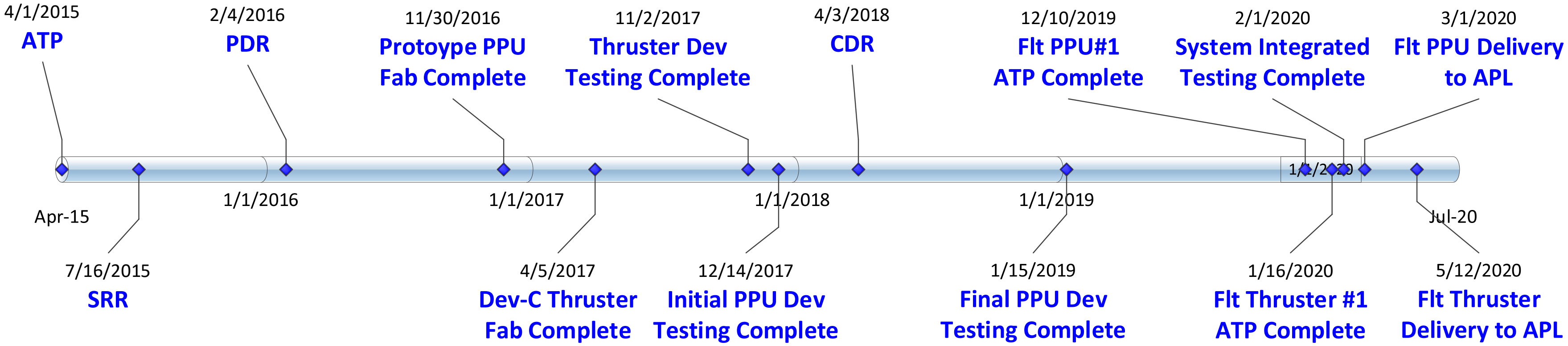
NEXT-C Flight Ion System Status: Background and Objectives

- 7.4 kW NEXT-C (NASA Evolutionary Xenon Thruster-Commercial) Program
  - Follow-on to the NEXT Program (2003-2013), which demonstrated > 50 khrs and 900 kg Xenon during Long Duration Testing
  - Primary Objectives:
    - Mature PPU and Thruster TRL levels from 4/6 to 8
    - Provide flight hardware in support of NASA and Commercial Missions
- Awarded by NASA GRC to Aerojet Rocketdyne in 2015
  - AR responsible for System Integration, Thruster development and manufacturing, and development/manufacturing oversight of PPU
  - ZIN Technologies subcontracted for PPU development and manufacturing





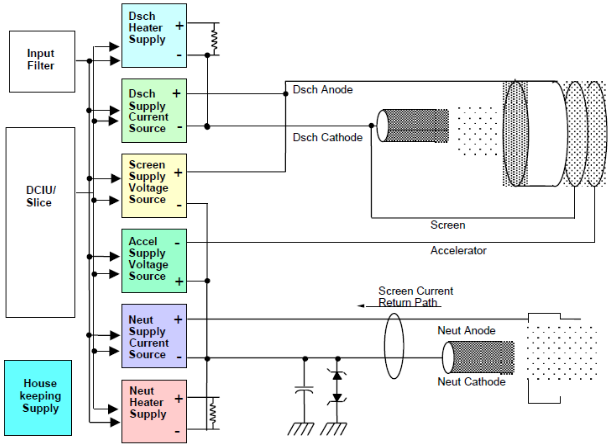
NEXT-C Flight Ion System Status: Major Program Milestones/Timeline



- Program included significant design activities/reviews, manufacturing process development, extensive development, protoflight and qualification level component and system testing, resulting in delivery of the first set of flight hardware in support of the Double Asteroid Redirection Test (DART) mission
- Paper summarizes the status of the program, including both development and flight hardware test results, including system integrated testing

NEXT-C Flight Ion System Status: PPU Design Overview

- 7 kW Gridded Ion Thruster PPU
  - Power Input:
    - 22 to 34 VDC Low Voltage Input
    - 80 to 160 VDC High Voltage Input
  - Power Output : 0.5 to 7 kW (>40x Throttle Points)
  - 42X Circuit Boards, 88X magnetics, Mass: 34.4 kgs
  - Envelope: 20” x 16.1” x 5.5”
- Six Interconnected DC-DC full bridge converters
  - Discharge Supply: Ionizes Xenon atoms
  - Screen Supply: Positive grid voltage (up to 1800V)
  - Accelerator: Negative grid voltage (to -525V)
  - Neutralizer: Keeps Neutralizer lit
  - Neutralizer/Discharge Cathode Heaters (Startup Only)
- Communicates via RS-485 serial link
- **See Ref. [16] for additional PPU details**



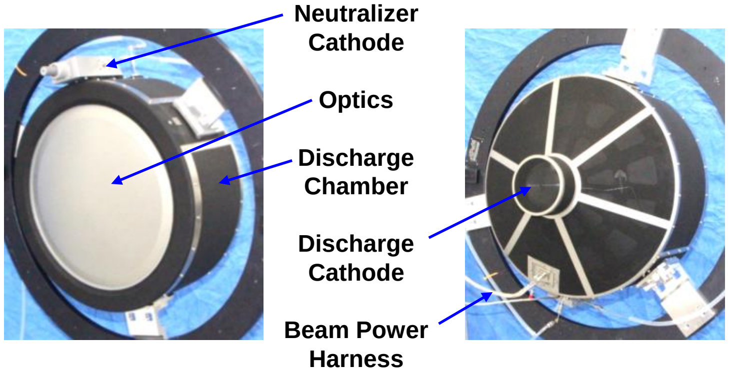
	Neutralizer		Neutralizer Heater		Discharge		Discharge Heater		Screen		Accel	
Input Voltage	80 to 160 Volt DC High Power Bus, 22 to 34 Volt DC Low Power Bus											
Output Voltage (VDC)	8	32	3	12	15	35	3	24	275	1800	115	525
Output Current (ADC)	1	3	3.5	8.5	4	24	3.5	8.5	1	3.52	0	0.04
Regulation	Current-Controlled		Current-Controlled		Current-Controlled		Current-Controlled		Voltage-Controlled		Voltage-Controlled	
Max Power Out (W)	96		102		840		204		6336		21	
Min Efficiency (%)	> 93.5%@ 7360 W											

NEXT-C Flight Ion System Status: Thruster Design Overview

- 7.4 kW Gridded Ion Thruster
  - Propellant: Xenon
  - Mass: < 14 kg
  - Envelope: 28” (diam) x 19” (depth)
  - Throttle Range: ~ 10 to 1

Beam Voltage V	Beam Current A	PPU Input Power kW	Thruster Efficiency	Thrust mN	Specific Impulse s	Thrust / Power mN/kW
1800	3.52	7.33	0.70	235	4155	32
1800	2.70	5.65	0.68	178	4082	32
1800	1.20	2.61	0.61	78	3882	30
1396	3.52	5.84	0.69	208	3683	36
1396	2.70	4.51	0.67	159	3626	35
1396	1.20	2.15	0.59	69	3432	32
1021*	2.70	3.48	0.66	137	3137	39
1021	1.20	1.70	0.57	59	2953	35
679	2.70	2.55	0.60	111	2565	43
275	1.00	0.64	0.32	25	1395	39

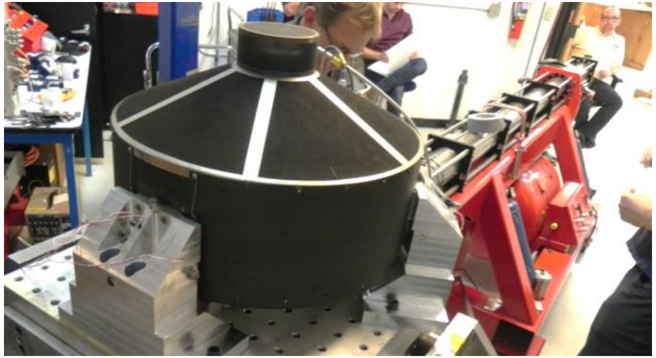
* DART operating throttle point

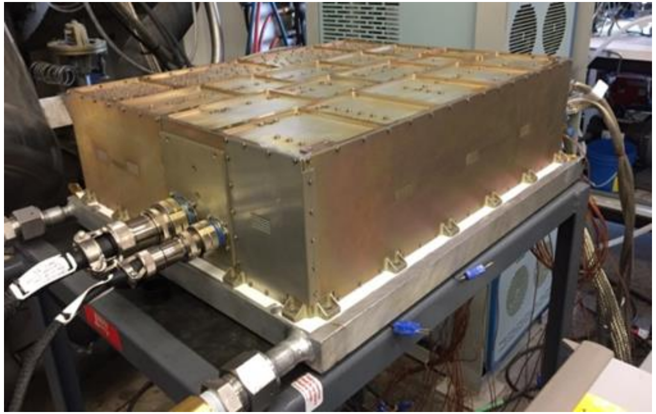


NEXT-C Flight Ion System Status: Development Testing Summary

- Prototype Thruster Development Testing
  - Characterized performance, demonstrated qualification level vibration, shock, and TVAC testing over full NEXT-C Throttle levels

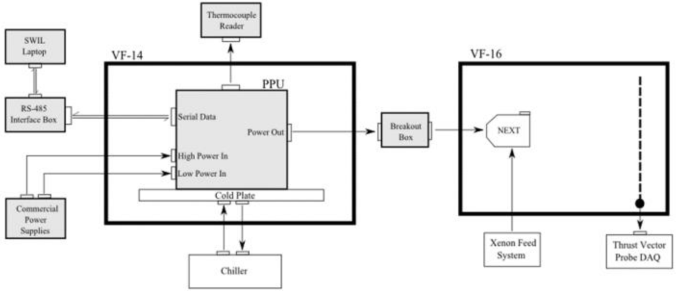
- Prototype PPU Development Testing
  - Characterized performance, demonstrated qualification level vibration, shock, EMI/EMC and proto-flight level TVAC testing
  - After initial round of PPU development testing, various design enhancements were incorporated and successfully demonstrated during a complete second round of development tests
- **See Ref. [16] for additional test details**

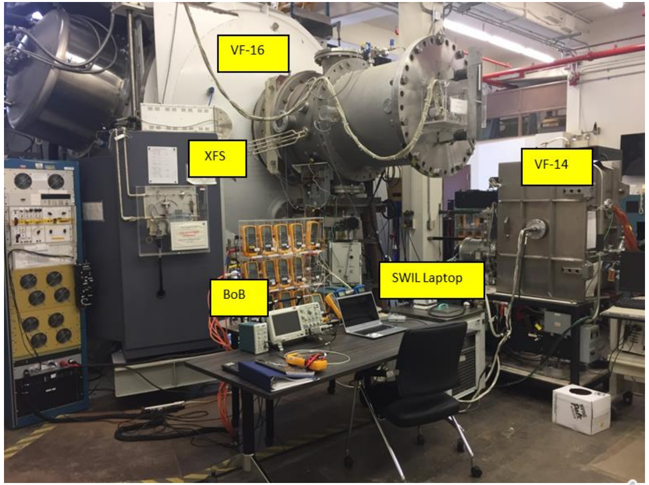




NEXT-C Flight Ion System Status: Development Testing Summary

- Three Prototype System Integrated Tests (SITs) performed at NASA GRC's VF-14 & 16
  - Preliminary SIT held in Sep '18 to initially demonstrate test system and command interfaces
  - DART SIT accomplished in Oct'18 that demonstrated DART flight conditions over full range of Xe flow rates and input voltage ranges
  - NEXT-C level SIT successfully demonstrated full throttle range (TL05 – TL40), input voltage (80V-160V) and PPU cold plate -29°C to 55°C
  - **See Ref. [15] for additional test details**



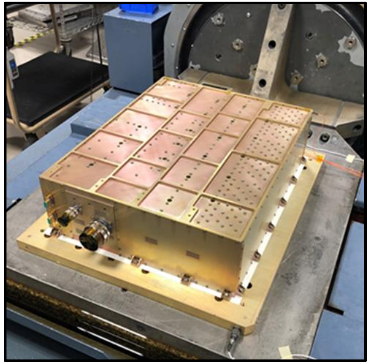


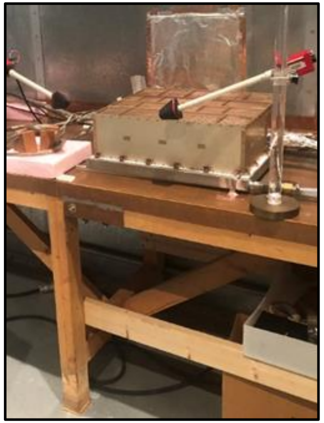
NEXT-C Flight Ion System Status: DART Mission Influences

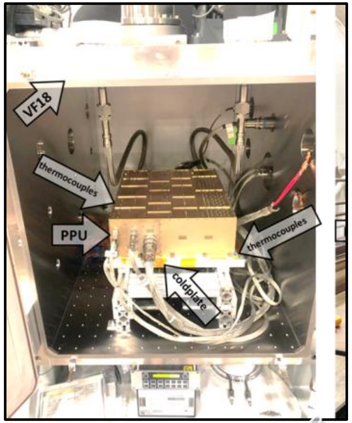
- In 2018, the first set of NEXT-C flight hardware was designated to support NASA's Double Asteroid Redirection Test (DART) mission
  - Launching in mid-2021, will impact the smaller of a co-orbiting binary asteroid, now designated as "Dimorphos", in the Fall of 2022
  - Goal is to demonstrate and characterize the deflection of a hazardous asteroid with the momentum transfer from a very high speed spacecraft by monitoring the change in it's orbit
- Based on available DART Spacecraft power, the NEXT-C system will be operated at Throttle Level 28 (~3.5 kW input power to PPU)
- Flight PPU and Thruster protoflight level testing was tailored to be consistent with the DART mission
  - Flight hardware built with full NEXT-C Functionality
  - TLs, input voltage range, environments tailored
  - Note: Flight Thruster hot fired at full power (TL37/40)

NEXT-C Flight Ion System Status:
Flight PPU Testing

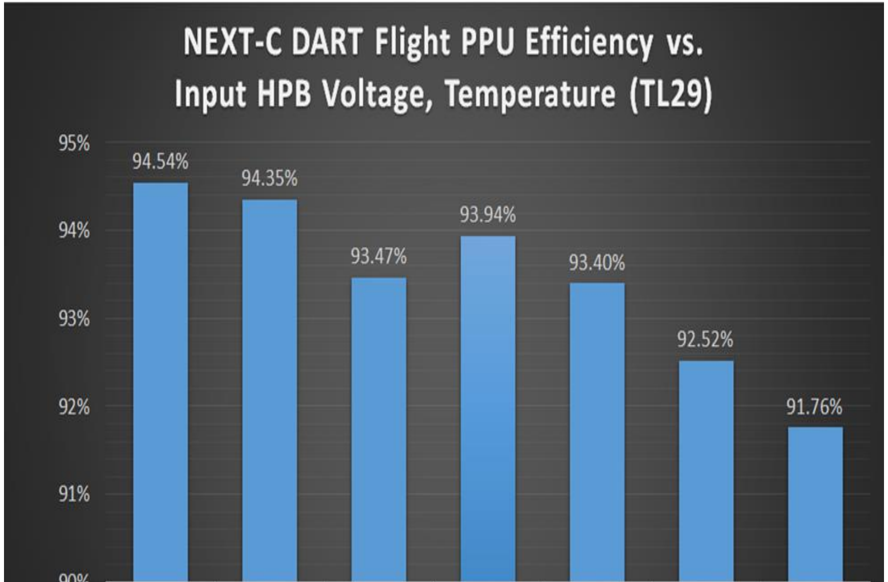
- Flight PPU Protoflight Level Acceptance Testing
  - Performed between Sep'19 and Dec '19
  - "Open Box" testing extensively characterized PPU functionality and performance
  - Protoflight level vibration (both random and sine) with successful post vibration functional testing
  - EMI/EMC testing at NASA GRC's EMI facility
  - Ten (10) Thermal Vacuum Cycles (-29C to 55C)
  - 300 hrs of elevated temperature burn-in testing
- **See Ref. [16] for additional test details**



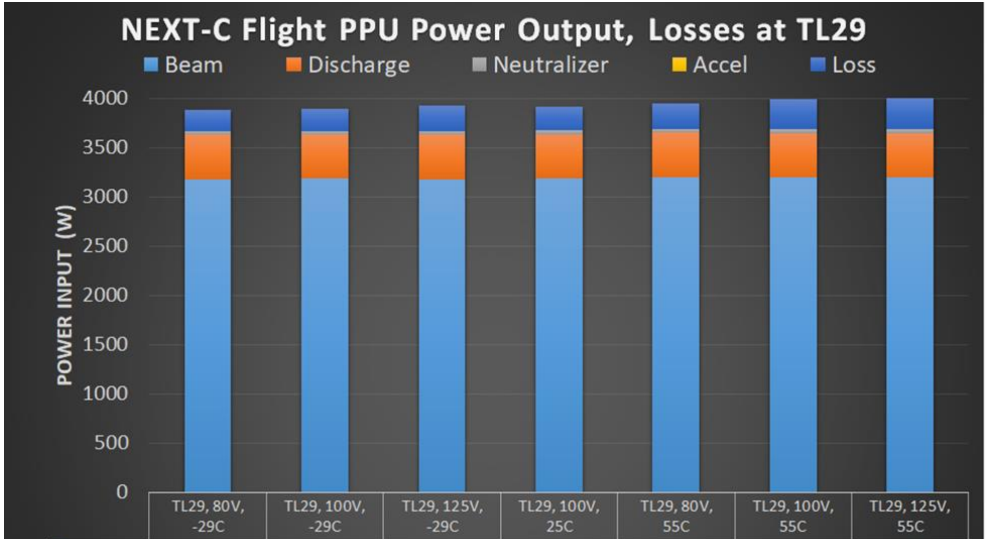




NEXT-C Flight Ion System Status: Flight PPU TVAC Efficiency Data



	TL29, 80V, -29C	TL29, 100V, -29C	TL29, 125V, -29C	TL29, 100V, 25C	TL29, 80V, 55C	TL29, 100V, 55C	TL29, 125V, 55C
Efficiency	94.54%	94.35%	93.47%	93.94%	93.40%	92.52%	91.76%

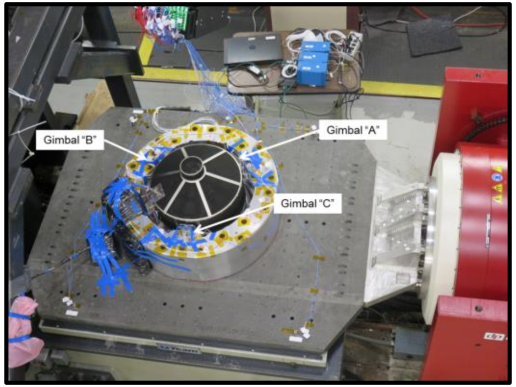


	TL29, 80V, -29C	TL29, 100V, -29C	TL29, 125V, -29C	TL29, 100V, 25C	TL29, 80V, 55C	TL29, 100V, 55C	TL29, 125V, 55C
Loss	211.84	219.65	256.58	237.11	260.94	298.33	331.13
Accel	1.79	1.80	1.79	1.76	1.78	1.78	1.77
Neutralizer	39.21	39.15	39.30	39.94	39.31	39.28	39.27
Discharge	447.56	445.80	447.15	449.67	449.55	446.99	445.96
Beam	3181.40	3183.54	3181.83	3184.91	3200.98	3201.11	3198.92

Flight PPU successfully demonstrated over full DART input voltage, temperature and throttle level ranges in TVAC

NEXT-C Flight Ion System Status: Flight Thruster Testing

- Flight Thruster Protoflight Level Acceptance Testing
  - Performed between Oct'19 and Jan '20
  - Hot fire testing performed at NASA GRC's VF-6 facility and included a suite of Plasma Diagnostics to characterize the ion beam downstream of the thruster
  - Initial Performance Acceptance Testing (PaT) extensively characterized flight thruster operating characteristics and performance, included operation at full power (TL40)
  - Protoflight level vibration (both random and sine) performed at NASA GRC's Structural Dynamics Laboratory
  - Post-vibe Functional Performance Testing (FuT)
  - Three (3) cycles of Thermal Vacuum (-110°C to 190°C)
  - Post-TVAC Functional Performance Testing (FuT)
  - A dedicated paper detailing flight thruster performance will be presented at a future TBD conference



NEXT-C Flight Ion System Status: Flight Thruster Performance Data

Throttle Level	TL40	TL37	TL29	TL28	ETL2.7A	TL09	TL05
Thruster Performance (Performance Acceptance Test)							
P_{tot}, kW	6.83	4.69	3.62	3.21	2.99	1.70	1.12
T, mN	233.7	192.1	146.7	137.5	131.7	63.8	48.9
I_{sp}, s	4148	3410	3365	3153	3055	3190	2443
ε	69.5%	68.4%	66.9%	66.2%	66.0%	58.7%	52.3%

Flight Thruster Hot Fire Performance during Performance Acceptance Testing

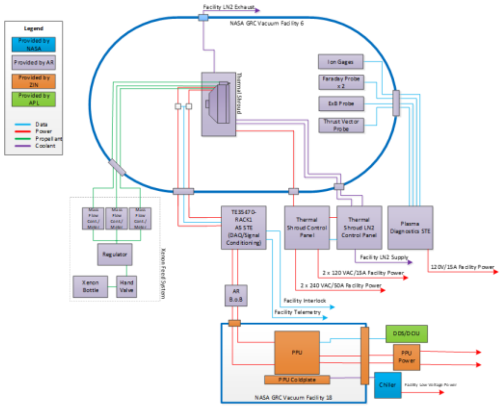
TL:	TL29				TL28				ETL2.7A				TL05			
J_b, V_b:	2.70 A, 1179 V				2.70 A, 1021 V				2.70 A, 936 V				1.20 A, 679 V			
Perf.	PaT	FuT	FuT	Req	PaT	FuT	FuT	Req	PaT	FuT	FuT	Req	PaT	FuT	FuT	Ref
P_{input}, kW	3.62	3.63	3.63	≤ 3.640	3.21	3.21	3.22	≤ 3.225	2.99	2.99	2.99	N/A	1.12	1.13	1.13	1.152
T, mN	146.7	145.6	147.8	≥ 140	137.5	136.0	135.8	≥ 130	131.7	130.3	130.1	N/A	48.9	48.8	48.9	49
I_{sp}, s	3365	3339	3338	≥ 3206	3153	3118	3114	≥ 2982	3055	3022	3017	N/A	2443	2443	2443	2455
ε	0.669	0.657	0.656	≥ 0.66	0.662	0.647	0.645	≥ 0.65	0.660	0.646	0.643	N/A	0.523	0.519	0.516	0.51

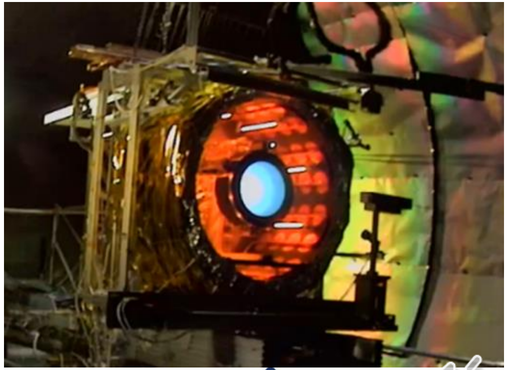
Comparison of initial thruster performance to that measured after vibration and TVAC testing

The Flight Thruster exhibited in-family and stable performance during Protoflight level acceptance testing

NEXT-C Flight Ion System Status:
Flight System Integrated Testing

- Flight System Integrated Testing (SIT) performed in Jan’20 at NASA GRC’s VF-6 and VF-18 and consisted of three phases
  - Phase 1: PPU operated into load using DART DCIU Simulator to verify flight software
  - Phase 2: “Test Like You Fly” testing performed with Flight PPU, Flight Thruster, simulated XFS, and DART DCIU/Software
    - Demonstrated system performance at expected DART operating conditions (flow rates, TLs, temps, startup sequences)
  - Phase 3: Four TVAC cycles performed to characterize the system operation over a large range of operating conditions
    - Flow rates and temperatures of both the thruster and the PPU were varied to simulate various operating conditions, including multiple cold starts, enveloping DART parameters





NEXT-C Flight Ion System Status: Flight System Integrated Testing

Throttle Level	P_{tot} (W)			T (mN)			I_{sp} (s)		
	PAT	FuT 2	SIT	PAT	FuT 2	SIT	PAT	FuT 2	SIT*
TL28	3203	3207	80V: 3203 100V: 3201 125V: 3205	137.9	136.2	136.06 (125V)	3162	3123	2986 (125V)
TL29	3608	3622	80V: 3612 100V: 3614 125V: 3615	147.2	146.0	145.61 (125V)	3375	3347	3201 (125V)

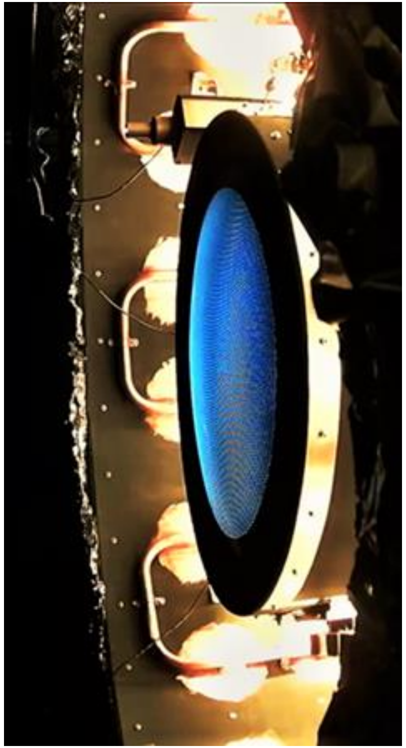
Thruster performance from SIT compared to ATP data

*Note: SIT testing was performed with higher (DART flight level) Xe flow rates than PAT & FuT, predictably reducing I_{sp}

Flight Hardware SIT Testing Successfully Demonstrated In-family System Performance over a Large Range of Operating Conditions

NEXT-C Flight Ion System Status: Conclusion

- The NEXT-C Ion Propulsion system has been shown to be ideally suited for a wide range of NASA, Defense and Commercial missions
- The NEXT-C Program has completed all planned development testing, demonstrating full NEXT-C operating parameters
- Flight hardware fabrication and protoflight level testing has successfully been completed and included both Component and System level testing
- The first set of flight hardware has been delivered to JHU/APL in support of the DART mission, with a scheduled launch date of mid-2021



NEXT-C Flight Ion System Status: Paper Authors

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  ZIN Technologies

- Terry O'Malley, George Soulas, Rohit Shastry, and Marcelo C. Gonzalez
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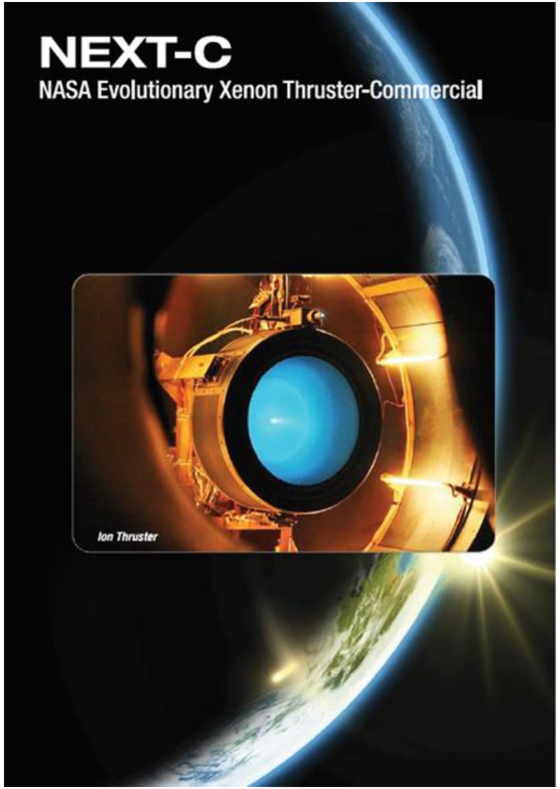

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