The NEXT-C Power Processing Unit: Lessons Learned from the Design, Build, and Test of the NEXT-C PPU for APL's DART Mission

James Bontempo
ZIN Technologies

AIAA Propulsion and Energy Forum, August 24th – 26th 2020

NEXT-C PPU: Background

- NASA GRC is a leader in Electric Propulsion (EP) since 1960s
  - NASA's mission-creating centers (JPL, GSFC, APL) rely on GRC for EP expertise
- GRC was a key player in every EP System that has ever flown for NASA
  - Deep Space 1 (JPL, 1998): Used NSTAR system (Hughes Thruster, Hughes PPU)
  - Dawn (JPL, 2007): Used NSTAR system (Hughes Thruster, Hughes PPU)
- The NEXT Program (2003-2013) is the follow on to NSTAR
  - Larger thruster: 3x more power (2.3 kW NSTAR to 7kW NEXT)
  - Aerojet Rocketdyne (AR) successfully developed the Thruster, life-tested for ~8 years
  - The Hughes NSTAR PPU team was bought by Boeing (2000), then L3 (2005)
  - L3 did not deliver; developed troubled Testbed PPU, could not get to TRL6
- The NEXT-C Program (2015-2020) uses AR Thruster w/ ZIN PPU
  - **DART (APL, 2021): Double Asteroid Redirection Test**

Launch

- July 22, 2021

DART
Double Asteroid Redirection Test

IMPACT: September 27, 2022

DART Spacecraft
650 kg arrival mass
18.8 m × 2.4 m × 2.0 m
6.65 km/s closing speed

Didymos-B
163 meters
11.92-hour orbital period

65803 Didymos (1996 GT)
1,180-meter separation between centers of A and B

Didymos-A
780 meters, S-type
2.26-hour rotation period

Earth-Based Observations
0.07 AU range at impact
Predicted ~10-minute change in binary orbit period

- Target the binary asteroid Didymos system
- Impact Didymos-B and change its orbital period
- Measure the period change from Earth

Credit: JHU APL

NEXT-C PPU: Background

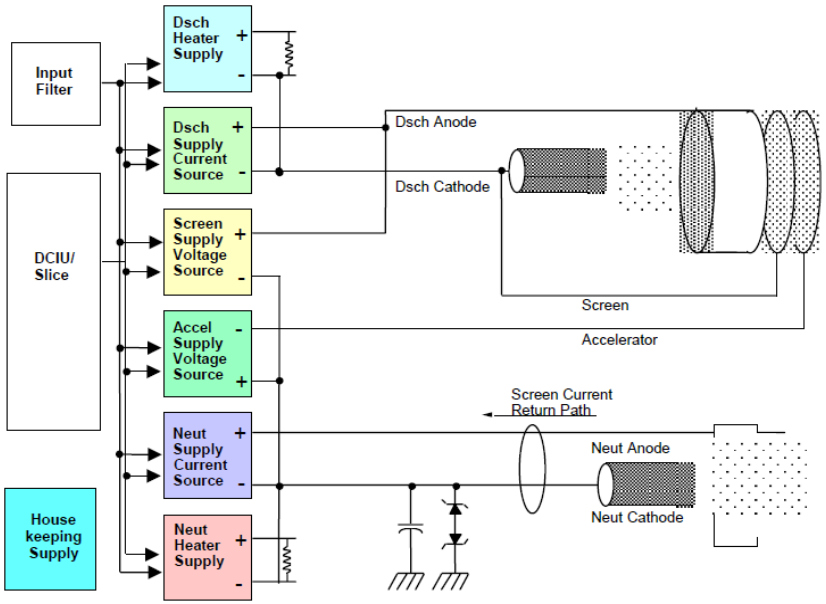
- In 2015, NASA selected the Aerojet Rocketdyne / ZIN Technologies Team
  - AR led the thruster design, build, and test
  - ZIN led the PPU design, build, and test
  - In March 2020, the first NEXT-C string was delivered to Johns Hopkins Applied Physics Laboratory (APL) for use on the Double Asteroid Redirection Test (DART)

- NEXT-C Goal: Design, Build, and Test a Flight-Qualified (TRL 8) Power Processing Unit (PPU) for the NEXT Gridded Ion Thruster
  - The NEXT-C PPU was based on the heritage gridded ion thruster PPU from NSTAR and NEXT, but with significant improvements in performance and manufacturability

- The paper discusses the design, build, and test of the NEXT-C PPU, and how challenges were overcome to deliver a Flight PPU

NEXT-C PPU: Technical Specs

- **7kW Gridded Ion Thruster PPU**
- Power Input:
  - 22 to 34 VDC Low Voltage Input
  - 80 to 160 VDC High Voltage Input
- Power Output : 0.5kW to 7kW (>40x Throttle Pts)



	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	
Setpoint Accuracy (% of Setpoint Value)	2.5%		2.5%		2.5%		2.5%		2.5%		2.5%	
Max Power Out (W)	96		102		840		204		6336		21	
Min Efficiency (%)	> 93.5% @ 7360 W											

- **Six Interconnected DC-DC full bridge converters**
  - **Discharge Supply: Ionizes Xenon atoms**
  - **Beam Supply: Positive grid voltage (up to 1800V)**
  - Accelerator: Negative grid voltage (up to -525V)
  - Neutralizer: Returns electron to ion
  - Neutralizer/Discharge Heaters (Startup Only)

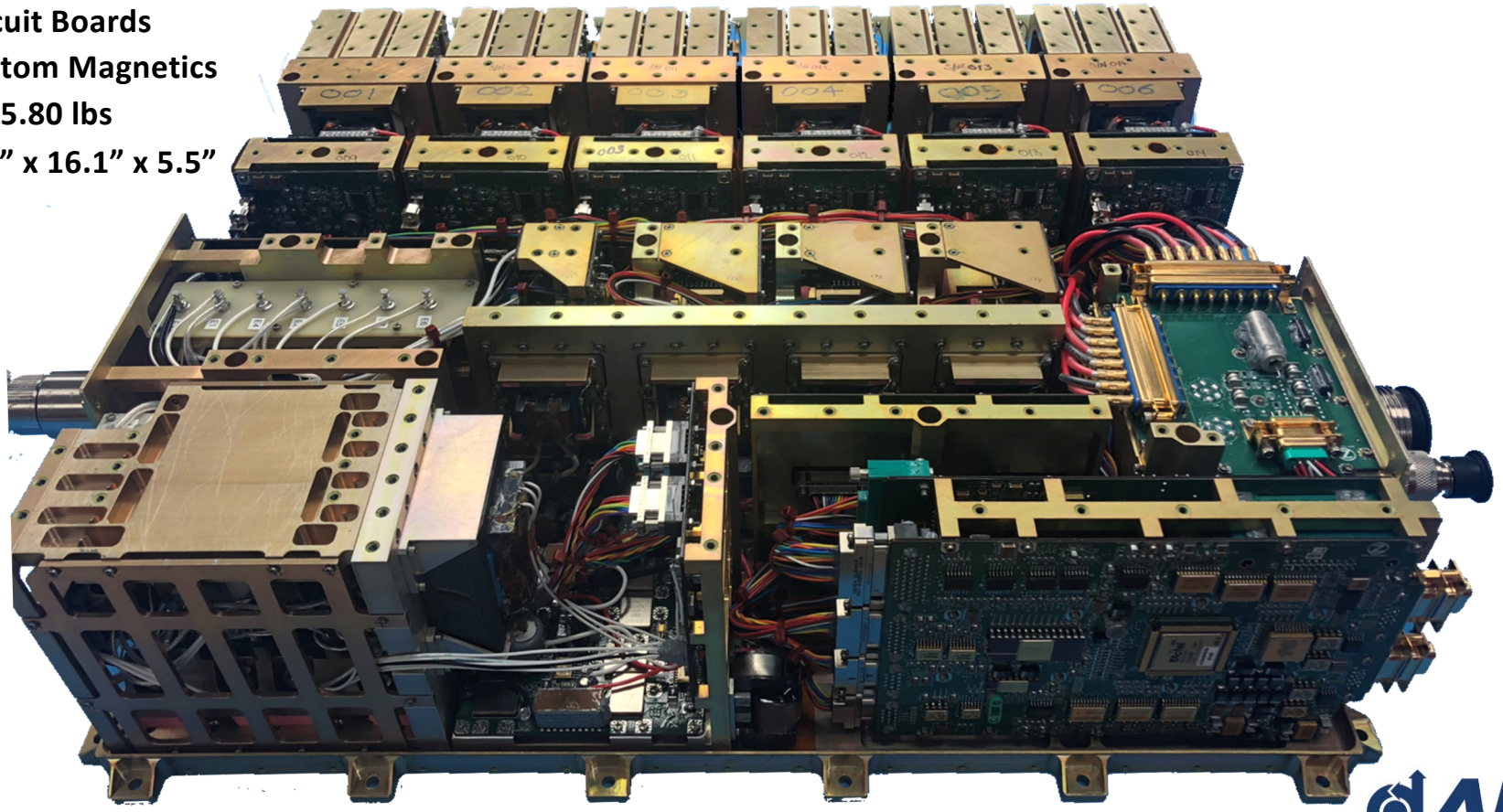
NEXT-C PPU Project
Lessons Learned

- PPU Development : 5 Year Project
  - NEXT-C PPU Design: Contract Start (March 2015) to PDR (Feb 2016)
  - NEXT-C Prototype Build: Feb 2016 to Dec 2016
  - NEXT-C Prototype Test Round 1: Jan 2017 to CDR (April 2018)
  - NEXT-C Prototype Test Round 2: April 2018 to Gate Review (June 2019)
  - NEXT-C Flight Build: Jan 2019 to Aug 2019
  - NEXT-C Flight Test: Sep 2019 to Dec 2019

	ZIN
Hardware	PPU
TRL Level Start	4
Reverse-Engineered Heritage Design?	Yes
Made Design Improvements?	Yes
Built Prototype Hardware?	Yes
Built Flight Hardware?	Yes
Finished Flight Testing	December 2019
TRL Level End	8

NEXT-C PPU Project
Flight NEXT-C PPU

- **42x Circuit Boards**
- **88x Custom Magnetics**
- **Mass: 75.80 lbs**
- **Size: 20” x 16.1” x 5.5”**



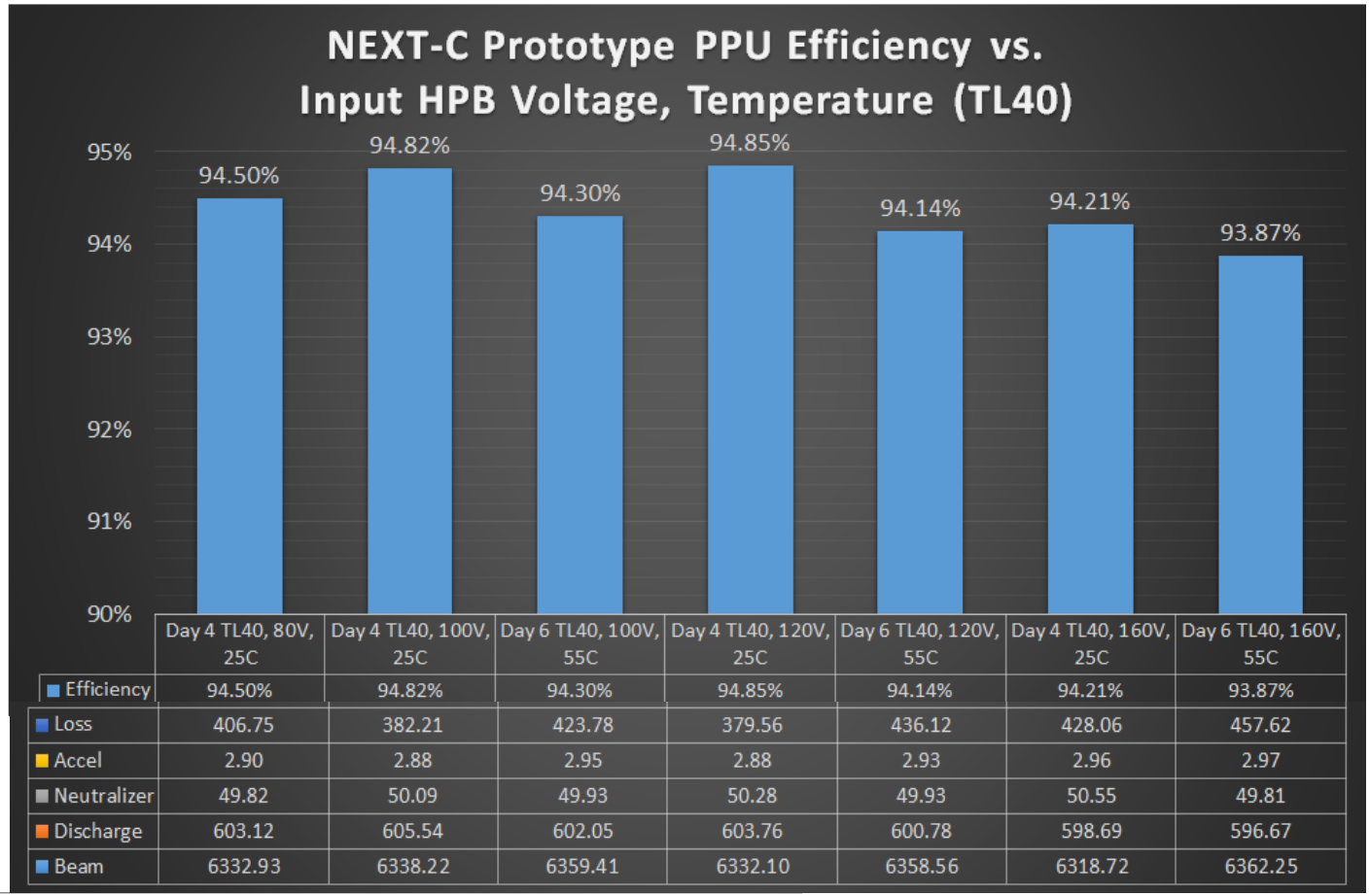
Electric Propulsion Options for Discovery-Class NASA Missions

	NSTAR* [3]	NEXT-C**	25 cm XIPS [4]	T6 [5]	SPT-100 [3]	SPT-140 [3]	XR-5 [3]
Thruster Type	Ion	**Ion**	Ion	Ion	Hall	Hall	Hall
Thruster Manufacturer	L3	**Aerojet Rocketdyne**	L3	QinietiQ	Fakel	Fakel	Aerojet Rocketdyne
PPU Manufacturer	L3	**ZIN**	L3	Airbus Crisa	Maxar	Maxar	Aerojet Rocketdyne
PPU Max Output Power (kW)	2.3	**7.4**	4.5	5.0	1.5	4.5	4.5
PPU Mass (kg)	14.5	**34.5**	21.3	47	7.5	15	12.5
Unregulated Voltage Input	Yes	**Yes**	No	No	No	No	No
PPU Input Voltage Range (V)	80 to 145	**80 to 160**	97 to 103	95 to 100	95 to 105	95 to 105	68 to 74
Flight Qualified	Yes	**Yes**	Yes	Yes	Yes	Yes	Yes
Flight Mission(s)	DeepSpace1 Dawn	**DART**	Boeing 702SP (many)	BepiColombo	Maxar (many)	Maxar (many)	AR (many)

* The NSTAR system is no longer manufactured.

** The NEXT-C system was Flight qualified for the DART mission (80-125 Vin, 3.7 kW max out).
Full qualification (80-160 Vin, 7 kW out) is pending additional qualification testing, scheduled for FY 2021.

NEXT-C Prototype Efficiency @ Full Power (TL40)



	Day 4 TL40, 80V, 25C	Day 4 TL40, 100V, 25C	Day 6 TL40, 100V, 55C	Day 4 TL40, 120V, 25C	Day 6 TL40, 120V, 55C	Day 4 TL40, 160V, 25C	Day 6 TL40, 160V, 55C
Efficiency	94.50%	94.82%	94.30%	94.85%	94.14%	94.21%	93.87%
Loss	406.75	382.21	423.78	379.56	436.12	428.06	457.62
Accel	2.90	2.88	2.95	2.88	2.93	2.96	2.97
Neutralizer	49.82	50.09	49.93	50.28	49.93	50.55	49.81
Discharge	603.12	605.54	602.05	603.76	600.78	598.69	596.67
Beam	6332.93	6338.22	6359.41	6332.10	6358.56	6318.72	6362.25

NEXT-C Throttle Levels

- The NEXT-C Flight PPU was built from the Prototype PPU design
- However, DART uses a more specific range of the NEXT-C PPU capability per Table 3
- Figure 3 shows the DART operating region on the NEXT-C throttle table
- The Flight PPU test campaign followed the DART operating range to “test as you fly”, although the Flight PPU is capable of full-range operation

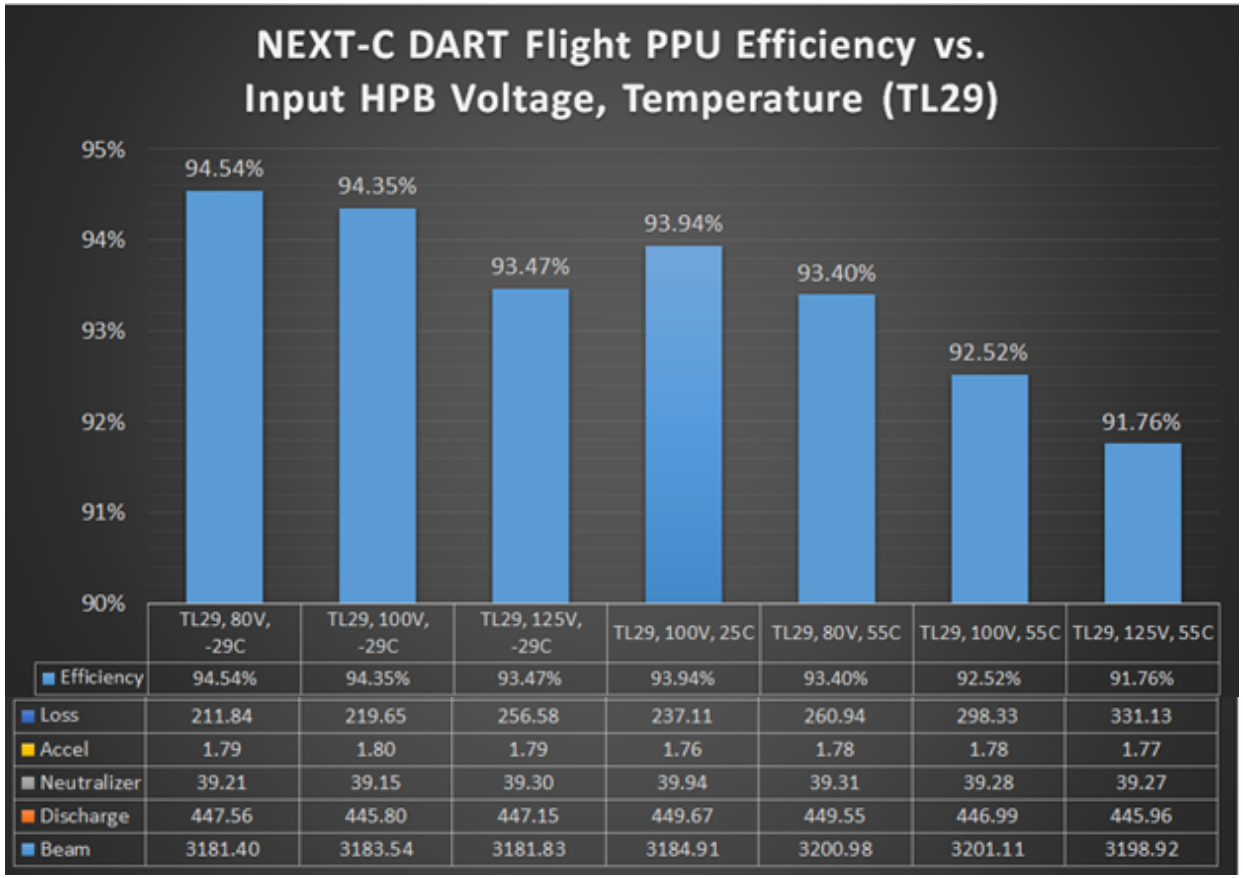
Table 3. Comparison between NEXT-C PPU Capability and DART PPU Operating Range

	NEXT-C PPU Design Capability	DART Flight PPU Operating Range
Input Voltage (V)	80 to 160	80 to 125
Max Throttle Level	TL40	TL29
Max Output Power (kW)	7.0	3.7
Max Beam Voltage (V)	1800	1179
Max Beam Current (A)	3.52	2.7

	V_{bpv}, V												
I_b, A	1800	1567	1396	1179	1021	936	850	700	679	650	400	300	275
3.52	TL40	TL39	TL38	TL37	ETL3.52A	ETL3.52B	ETL3.52C	ETL3.52D					
3.10	TL36	TL35	TL34	TL33	ETL3.1A	ETL3.1B	ETL3.1C	ETL3.1D	ETL3.1E				
2.70	TL32	TL31	TL30	TL29	TL28	ETL2.7A	ETL2.7B	ETL2.7C	ETL2.7D	ETL2.7E			
2.35	TL27	TL26	TL25	TL24	TL23	ETL2.35A	ETL2.35B	ETL2.35C	ETL2.35D	ETL2.35E			
2.00	TL22	TL21	TL20	TL19	TL18	ETL2.0A	ETL2.0B	ETL2.0C	ETL2.0D	ETL2.0E			
1.60	TL17	TL16	TL15	TL14	TL13	ETL1.6A	ETL1.6B	ETL1.6C	ETL1.6D	ETL1.6E	ETL1.6F		
1.20	TL12	TL11	TL10	TL09	TL08	TL07	TL06		TL05	TL04	TL03	TL02	
1.00													TL01

Figure 3. NEXT-C Throttle Table, with the highlighted region showing DART operating conditions [2].

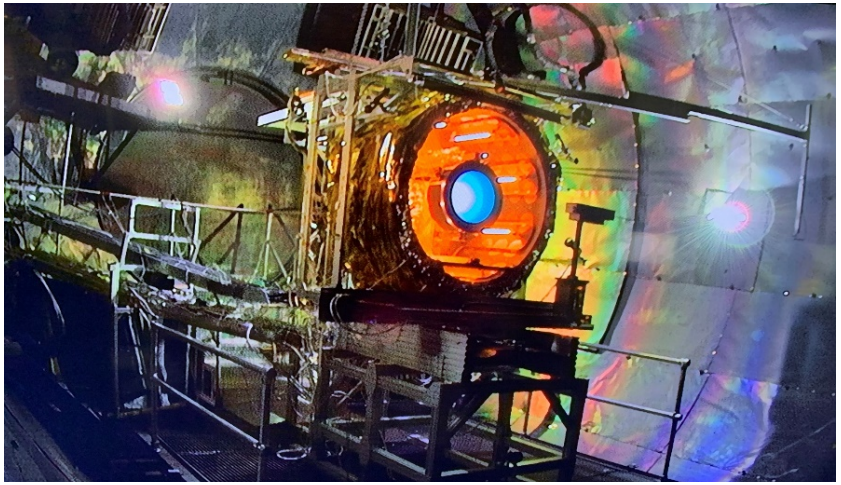
NEXT-C Flight Efficiency @ DART Throttle Level (TL29)



	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%
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

NEXT-C PPU: Conclusion

- The ZIN, Aerojet Rocketdyne, and NASA GRC team designed, built, tested, and delivered a TRL 8 Flight Power Processing Unit for APL's DART mission
- The NEXT-C PPU is designed for deep-space missions that run on an unregulated solar bus with advantages in size, mass, power output range capability, and efficiency
- The NEXT-C system provides DART and future NASA Discovery-class and New Frontiers-class missions with a high-performance PPU and thruster string
- Few organizations have created a Flight-qualified PPU design, and the NEXT-C effort provides a compelling electric propulsion option for future NASA missions



NEXT-C Flight PPU Powering the Flight Thruster in System Integration Testing

NEXT-C PPU: Paper Authors

- James J. Bontempo and Alyssa N. Brigeman
  ZIN Technologies

- Henry B. Fain , Marcelo C. Gonzalez ,
  Luis R. Pinero , and Michael V. Aulisio
  NASA Glenn Research Center

- Arthur G. Birchenough
  HX5, LLC

- Jack R. Fisher and Brian Ferraiuolo
  Aerojet Rocketdyne

AIAA
SHAPING THE FUTURE OF AEROSPACE

AMERICAN INSTITUTE OF
AERONAUTICS AND ASTRONAUTICS