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

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Abstract: NASA's Double Asteroid Redirection Test (DART) will be the first-ever planetary defense mission to demonstrate asteroid deflection using kinetic impactor technology. The DART spacecraft will utilize the NASA Evolutionary Xenon Thruster (NEXT), which is a successor to the NSTAR ion propulsion system that successfully propelled NASA's Deep Space 1 and Dawn spacecraft. In 2015, NASA partnered with Aerojet Rocketdyne and ZIN Technologies on the NEXT-Commercial (NEXT-C) effort to manufacture a Flight-Qualified (TRL 8) power processing unit (PPU). 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 design goals of the NEXT-C PPU were to achieve the technical performance goals of the PPU in size, mass, and efficiency over a wide range of input voltage and output power. This paper discusses the lessons learned from the design, build, and test of the NEXT-C PPU, and how challenges were overcome to deliver a Flight PPU.

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I. Introduction

The NASA Evolutionary Xenon Thruster (NEXT) gridded-ion thruster propulsion system was developed at NASA Glenn Research Center (GRC) as part of a comprehensive technology development program. This effort developed a prototype (TRL 6) thruster, which was successfully life tested for eight years, setting records for ion thruster life test duration. However, the concurrent effort to develop a prototype Power Processing Unit (PPU) did not achieve the TRL6 goal due to a combination of technical and management issues that stalled the PPU development at TRL 4.

In 2015, NASA GRC partnered with Aerojet Rocketdyne (AR) and ZIN Technologies (ZIN) on the NEXT-Commercial (NEXT-C) effort to manufacture a Flight-Qualified (TRL 8) thruster and PPU string for use on future NASA missions. The thruster design, build, and test was led by AR, and the PPU design, build, and test was led by ZIN. The first NEXT-C propulsion string was delivered to Johns Hopkins Applied Physics Laboratory (APL) for use on the Double Asteroid Redirection Test (DART) in early 2020.

The NEXT-C PPU was based on heritage gridded ion thruster PPU designs from NSTAR and NEXT, but with significant improvements in performance and manufacturability. The NEXT-C PPU program built a Prototype Unit, which was system-tested with the development NEXT thruster to 7 kW output at 94.8% efficiency in March 2019. The objective of the NEXT-C Prototype PPU was to achieve the technical performance goals of the PPU in size (50.80 x 40.89 x 13.97 cm; 29,019 cm^3), mass (34.5 kg), and efficiency over a wide range of input voltages (80 to 160 V) and output powers (0.5 to 7 kW). The NEXT-C program then built a Flight PPU for DART, which was tested with the Flight Thruster to 3.7kW output at 93.9% efficiency in January 2020. The goal of the DART Flight PPU was to build and test a PPU to the specific range of output powers that the DART mission will use.

The NEXT-C PPU successfully incorporated improvements to the heritage PPU functionality from GRC's prior experience with the NSTAR and NEXT programs. Additionally, ZIN introduced efforts to simplify the design to reduce cost and improve reliability and mission integration. For example, the number of custom magnetics in the PPU was reduced, the PPU was modularizied for manufacturability, and telemetry and fault handling was expanded.

II. Power Processing Unit Overview

The block diagram of the PPU in Figure 1 shows six interconnected DC-DC converters that are used to power the thruster. These six supplies are described below.

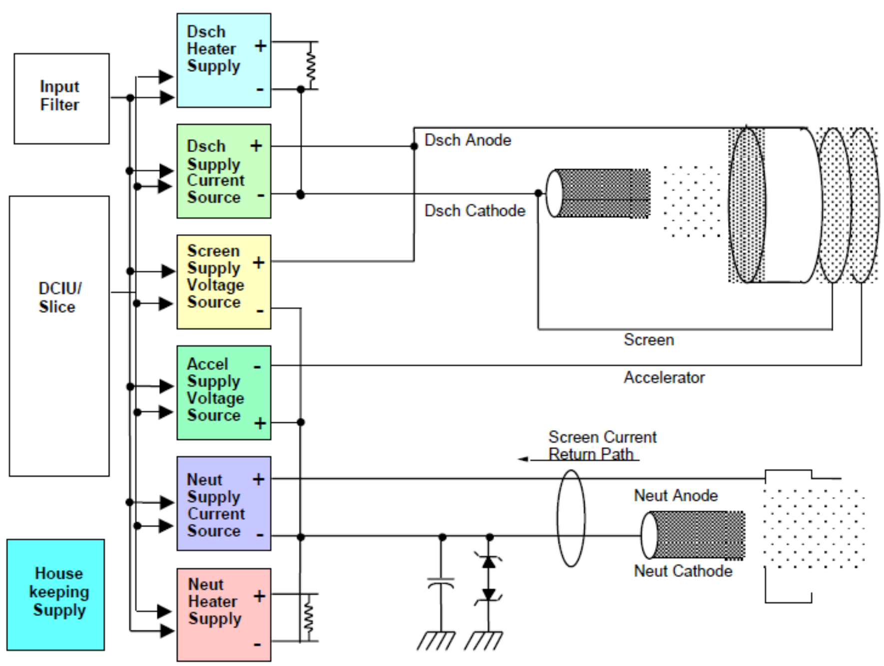


Figure 1. Block Diagram of the NEXT-C PPU [1].

The voltage-controlled Beam Supply (also known as the Screen Supply) is the highest-power supply in the NEXT-C PPU, providing up to 3.52 A at 1800 VDC (6.34 kW). The Beam Supply dominates the overall efficiency of the PPU, as it yields up to 90% of the PPU's total power output. The NEXT-C PPU is designed for a wide range of deep-space missions, and therefore the PPU must be capable of efficient operation over a wide range of throttle levels. This ensures that the PPU can optimally utilize the available solar input power to create the desired output thrust change. There are 40 defined NEXT-C thruster Throttle Levels (TL), denoted from TL01 (lowest power) to TL40 (highest power), and 30 Extended Throttle Levels (ETL) in between. As such, the Beam Supply must be capable of outputting anywhere from 1800 to 275 V (a 6.5:1 ratio), and 6.34 to 0.275 kW (a 23:1 ratio). The Beam Supply has the most stringent telemetry accuracy requirements on its output current (1% of full scale / 40 mA max error) and output voltage (1% of full scale / 20 V max error), as these parameters are directly used to calculate the thrust of the system.

The NEXT-C Beam Supply is constructed from six individual current-programmed Beam Modules connected in parallel, which each output up to 600 mA at 1800 V. The benefit of this modular approach is that the PPU can be controlled to turn modules on or off as the Beam Supply output power demand changes. In addition, each Beam Module has two modes of operation: Pulse Width Modulated (PWM) and Phase Shifted. The Beam Module effectively doubles its transformer turns ratio in Phase Shift mode, which means that the full-bridge can operate at optimal duty cycles over a wide range of input and output voltages.

The voltage-controlled Accelerator Supply (Accel Supply) is the lowest-power supply in the NEXT-C PPU, providing up to 40mA steady-state at 525 VDC (21 W). However, the design driver for the Accel Supply is the thruster startup surge when high voltage is applied to the thruster grids. Together, the Beam Supply and Accel Supply are termed the "High Voltage" supplies.

The current-controlled Discharge Supply is the highest-current supply in the NEXT-C PPU, providing up to 24 A at 35 VDC (840 W). The Discharge Supply is a standard full-bridge DC-DC converter, but its positive output is referenced to the Beam Supply. Therefore, the Discharge Supply output must float at up to 1800 V, which makes its output telemetry measurements challenging. Additionally, the Discharge Supply must output high-voltage, short-duration ignition pulses to start the thruster's discharge cathode.

The current-controlled Neutralizer Supply provides 3A at 32 VDC (96 W). Similar to the Discharge Supply, the Neutralizer Supply must also be capable of outputting high-voltage, short-duration ignition pulses to start the thruster's neutralizer cathode.

The four supplies (Beam, Accel, Discharge, and Neutralizer) outlined above are used in steady-state operation of the thruster. However, the PPU also has two cathode heaters that are only used during the thruster startup sequence. The current-controlled Discharge (Cathode) Heater Supply provides up to 8.5 A at 24 VDC (204 W). The Discharge Heater return is referenced to the Discharge Supply Cathode, which must float at up to 1800 V. This makes output telemetry measurements challenging. The sixth and final supply is the current-controlled Neutralizer (Cathode) Heater Supply, which provides up to 8.5 A at 12 VDC (102 W).

The Beam, Accel, Neutralizer, and Neutralizer Heater Supply returns are all referenced to Neutralizer Common, which serves as the output return of the PPU. The Discharge and Discharge Heater Supply returns are referenced to Discharge Cathode, which may float at up to 1800 V from Neutralizer Common. Table 1 below summarizes the six PPU supplies. A 22-34 VDC low power bus is used by the PPU for housekeeping functions, and an unregulated 80-160 VDC high power bus powers the six supplies.

Table 1. NEXT-C PPU Output Power

	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%	
Output Ripple (% of Setpoint Value)	5%		5%		5%		5%		5%		5%	
Max Power Out (W)	96		102		840		204		6336		21	
Minimum Efficiency (%) at Max Power Out @ TL40 (W)	> 93.5% @ 7360 W											

The NEXT-C system compares favorably to the other Flight Qualified PPU options for a Discovery-class NASA mission, as shown in Table 2. Note that the NEXT-C PPU is the only PPU option that is designed for an unregulated input voltage bus. The NEXT-C system is therefore a compelling option for missions that require high specific impulse, operation from an unregulated bus, and/or deep throttling.

Table 2. Survey of Electric Proposition Options for Discovery-Class NASA Missions [3] [4] [5]

	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.

The NEXT-C program started in 2015, with the goal to design, build, and qualify a thruster and PPU system to TRL 8 to be provided to a future NASA mission (DART) as Government Furnished Equipment (GFE). Aerojet Rocketdyne was responsible for the thruster, and ZIN Technologies was responsible for the PPU, with AR oversight. GRC was the lead NASA center. The PPU design was divided into two tasks: first, from 2015 to 2019, a Prototype PPU was designed, built, and tested over the full operating range, with the goal to reach TRL 6. Then, from 2019 to 2020, a Flight PPU was built and tested over the DART operating range, with the goal to reach TRL 8. The Flight PPU was delivered to APL in March 2020 for the DART mission, which is scheduled to launch in July 2021.

III. NEXT-C PPU Design and Test

The Prototype NEXT-C PPU was designed from 2015-2016, and was based on the heritage PPU design from NSTAR and NEXT, but with significant improvements in performance and manufacturability. Notable improvements achieved in the NEXT-C PPU are described below.

A. Add PWA Connectors to Internal Power/Signal Wires for Improved Modularity

ZIN's approach to the PPU mechanical design was to preserve the heritage NEXT PPU exterior size envelope (50.80 x 40.89 x 13.97 cm; 29,019 cm^3), mounting bolt pattern, and mass (34.5 kg). Preserving the heritage NEXT PPU envelope dimensions and mounting bolt pattern was beneficial because the NEXT-C PPU could use the heritage Test Support Equipment (TSE) such as the coldplate, vacuum chamber, and transportation equipment. The heritage NEXT PPU was a TRL 4 design that was very difficult to manufacture because it was constructed with hand-soldered wire-to-turret connections, rather than connectorized subassemblies. ZIN's mechanical team successfully redesigned the interior of the NEXT-C PPU to add connectors to the signal and power interfaces inside the PPU, while maintaining the heritage outside envelope and mounting bolt pattern. Figure 2 shows the NEXT-C PPU with its lid and sidewalls removed.

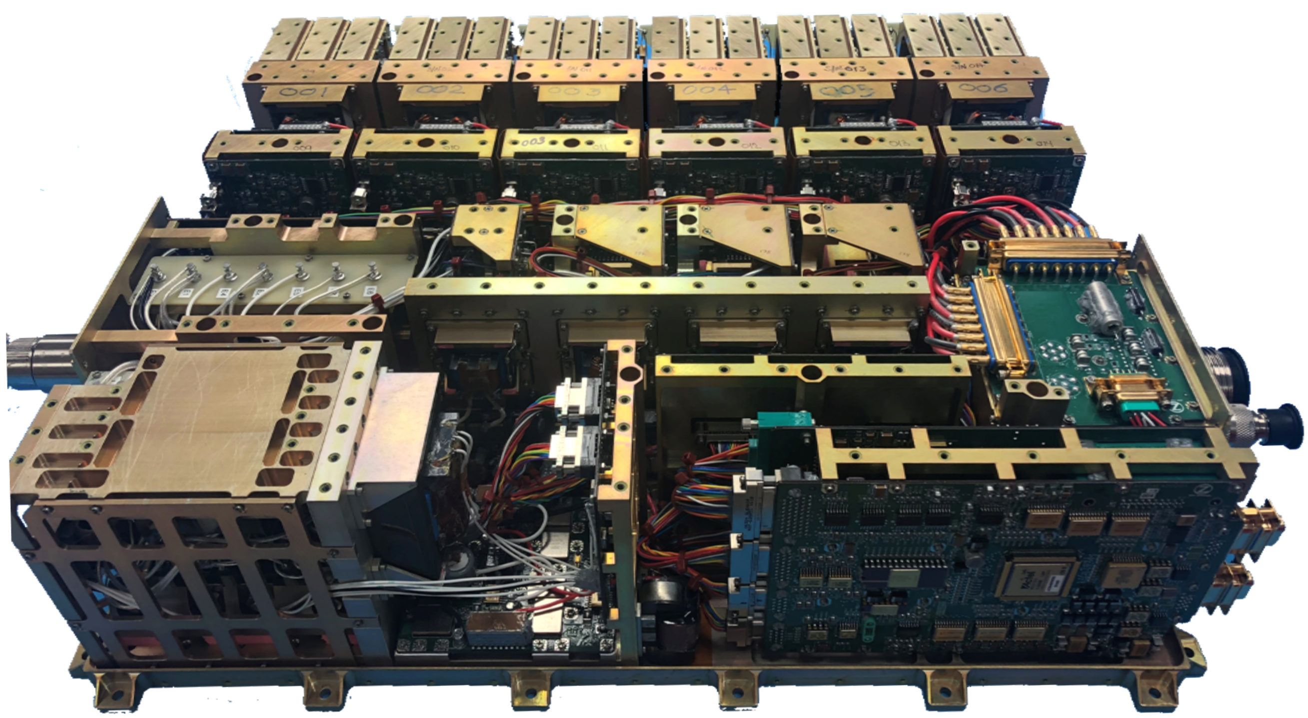


Figure 2. NEXT-C PPU, Lid and Sidewalls Removed.

The input high power bus (80-160 VDC) and low power bus (22-34 VDC) connectors feed into the Input Filter module (Figure 2, center right). The Input Filter module distributes the high power bus to each of the DC-DC converter modules in the PPU. The DC-DC converter outputs are tied together at the Output Module (Figure 2, center left), which provides the output voltage and current telemetry for the PPU. The Output Module has two output connectors to the thruster, one for the high-voltage Discharge harness, and the other for the low-voltage Neutralizer harness. The low power bus connects to the Housekeeping PWA, which creates the supply voltages for the PPU's electronics. Finally, the RS-485 serial data connectors are connected to the Slice PWA (Figure 2, bottom right). The Slice PWA implements the serial data interface between the PPU and the mission's Flight Computer.

B. Improve the Beam Supply (Mode Transition, Module Addressing, and Voltage/Current Telemetry)

The voltage-controlled Beam Supply is the highest-power supply in the NEXT-C PPU. The Beam Supply dominates the overall efficiency of the PPU, as it yields up to 90% of the PPU's total power output. There are 40 defined NEXT-C thruster Throttle Levels (Figure 3, highlighted in green), denoted from TL01 (lowest power) to TL40 (highest power), and 30 Extended Throttle Levels (Figure 3, highlighted in yellow). As such, the Beam Supply must be capable of outputting anywhere from 1800 to 275 V (a 6.5:1 ratio).

	V_{bps}, 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].

The combination of unregulated input voltage and wide throttling range creates a design challenge for the Beam Supply. Typically, the maximum duty cycle is set by a combination of the minimum input voltage (80 V) and the maximum output voltage (1800 V). If this duty cycle is nominally set to 100%, then the duty cycle for maximum input voltage (160 V) and minimum output voltage (275 V) would be less than 8%. It becomes very difficult to maintain efficient operation over this large range of duty cycles because lower duty cycles create larger RMS currents, which cause increased losses in the full bridge converter FET switches and transformer. For example, with input voltage and output power held constant, a full bridge converter running at 50% duty cycle has an input RMS current 1.41 times larger than a converter operating at 100% duty cycle, with I^2R power losses that are two times larger.

Therefore, the Beam Supply for the NEXT-C PPU demands a design solution which allows for operation over large input voltage and output voltage ranges with optimum efficiency. To achieve this, each NEXT-C Beam Module has two modes of operation: Pulse Width Modulated (PWM) and Phase Shifted. The Beam Module effectively doubles its transformer turns ratio in Phase Shift mode, which allows the converters to operate at optimal duty cycles over a wide range of input and output voltages.

In PWM mode, the circuit behaves like a standard full bridge converter, with the output voltage given by Eq. 1.

$$V_{out} = V_{in} * 6 \cdot \frac{N_s}{N_p} \cdot d \qquad \text{(Eq. 1)}$$

Where: V_{in} is the Beam Module input voltage

V_{out} is the Beam Module output voltage

$\frac{N_s}{N_p}$ is the transformer turns ratio, equal to 37/16 for the Beam Module

d is the Beam Module duty cycle, variable from 0 to 1

For the Beam Module, the output voltage in PWM mode varies from 0 to 1110 V at 80 V input.

In Phase Shift Mode, there is a phase shift introduced between the full bridge drives on the transformer primaries. This modifies the output voltage, given by Eq. 2.

$$V_{out} = V_{in} * 6 \cdot \frac{N_s}{N_p} \cdot d_{eff} \qquad \text{(Eq. 2)}$$

$$d_{eff} = d \cdot \left[1 + \left(\frac{\emptyset}{180°}\right)\right] \qquad \text{(Eq. 3)}$$

Where: $\emptyset$ is the Phase Shift between the Transformer primaries, variable from 0 to 180 degrees.

For the Beam Module, the output voltage in PWM mode varies from 1110 to 2220 V at 80 V input.

The NEXT-C Beam Module uses Phase Shift Mode to effectively double its maximum output voltage, while each of the two full bridge circuits run at maximum duty cycle, and therefore optimal RMS input current. Figure 4 plots the effective duty cycle of a NEXT-C Beam Module over its range of input voltage and output voltage. Note that the DART operating region utilizes both PWM and Phase Shift Modes.

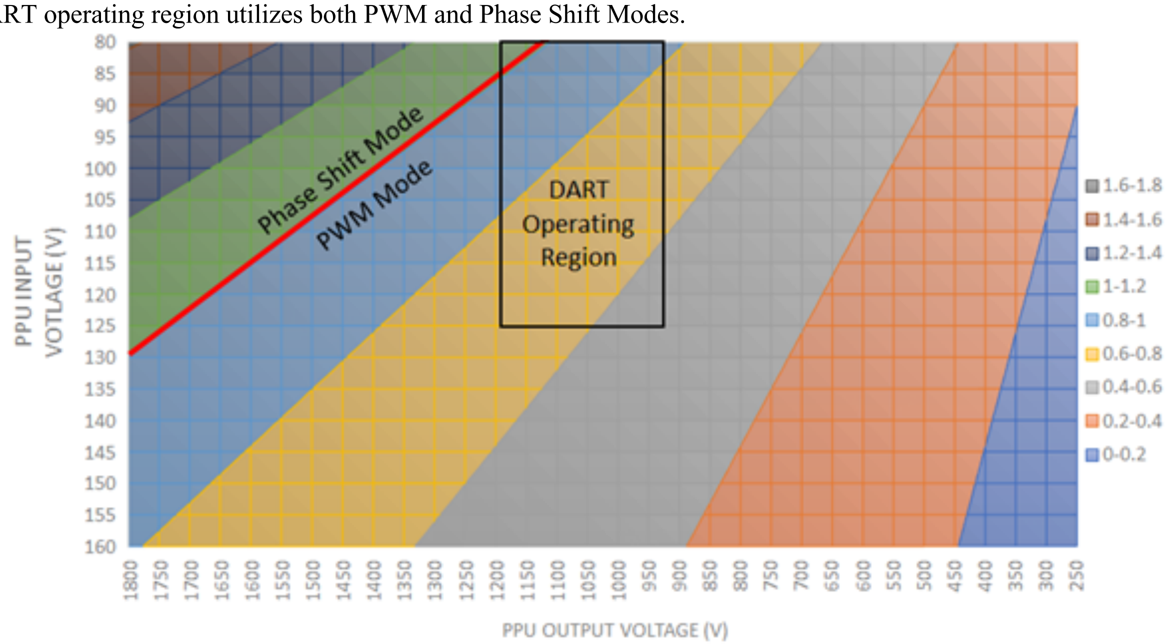


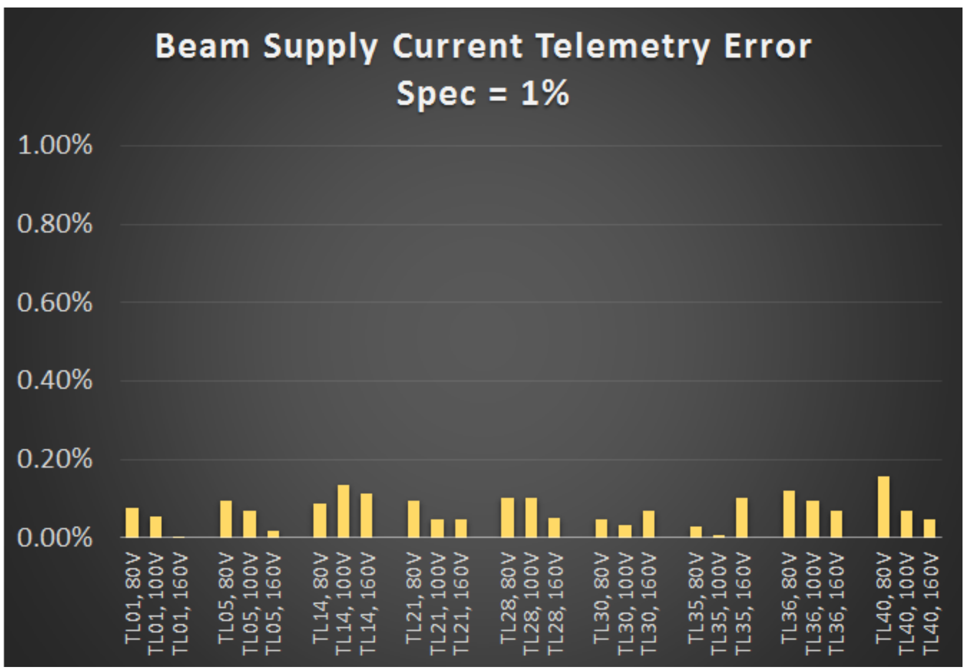
Figure 4. NEXT-C Beam Module Effective Duty Cycle vs. Input, Output Voltage.

The NEXT-C Beam Supply is constructed from six individual Beam Modules connected in parallel, which each output up to 600 mA at 1800 V. The benefit of this modular approach is that the PPU can turn modules on or off as the Beam Supply output power demand changes. Turning a Beam Module off eliminates the gate drive losses of its FETs, and runs the remaining modules at optimum loading. For example, the DART mission Throttle Levels (ETL2.7A, TL28, TL29) require the Beam Supply to output 2.7 A at 936, 1021, or 1179 V, respectively. The baseline throttle table turns on all six Beam Modules, with each outputting 450 mA to create 2.7 A total. However, the PPU design can individually address each Beam Module. Therefore, if a Beam Module is damaged or non-functional, it can be commanded off, and the remaining 5x Beam Modules would output 540 mA each to create 2.7 A total.

The minimum number of Beam Modules required at a given Throttle Level is determined by the total Beam current divided by 0.6 A. This feature is extremely useful, as 53 of the 70 NEXT-C Throttle Levels (defined in Figure 3) use less than six Beam modules. Therefore, the Beam Supply has built-in redundancy for these Throttle Levels.

The Beam Supply has the most stringent telemetry accuracy requirements on its output current (1% of full scale / 40 mA max error) and output voltage (1% of full scale / 20 V max error), as these parameters are directly used to calculate the output thrust of the system. Therefore, ZIN redesigned these telemetry circuits to achieve the lowest error possible.

The Beam voltage is measured using high voltage, precision film resistors. The Beam current is measured using current sense resistors. ZIN performs a telemetry calibration procedure, where the voltage and current outputs, measured by calibrated test equipment, are plotted against the raw count outputs of the telemetry ADCs. A calculated best-fit line removes the initial fixed bias and scale factor errors. Drift error due to temperature, aging, and radiation cannot be removed with this simple calibration approach, but are bounded by the Worst-Case Analysis performed on all NEXT-C telemetry circuits. The Beam voltage and current telemetry errors as measured on the NEXT-C Prototype are shown in Figure 5.



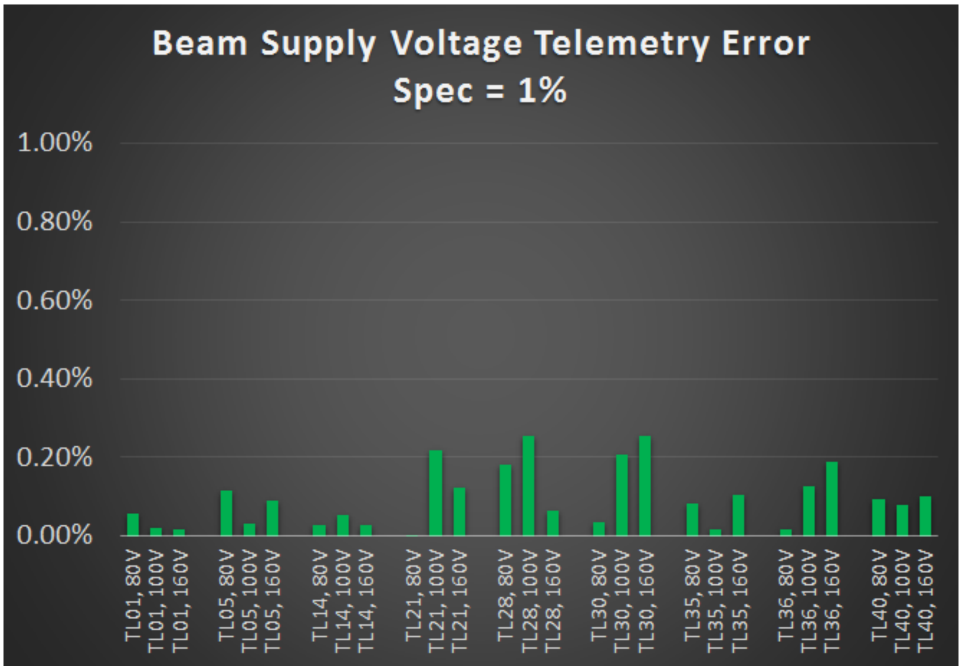


Figure 5. NEXT-C Beam Supply Current (Top) and Voltage (Bottom) Telemetry Error, TL01 to TL40, 25°C.

Figure 5 shows that the maximum Beam current telemetry error was 0.16%. The maximum Beam voltage telemetry error was 0.26%. Therefore, the 1% maximum error specification is satisfied with margin. ZIN similarly re-designed telemetry circuits for all other supplies in the PPU utilizing low temperature coefficient sensing, carefully designed gain amplifiers, and precision ADC with low temperature coefficient voltage references. The Discharge and Discharge Heater supplies were particularly challenging, given that they float at up to 1800V.

C. Reduce the Custom Magnetics in the PPU Design

All PPU designs must use custom magnetics for power transformers, filter inductors, and other critical DC-DC functions. Flight PPUs are required to qualify each magnetic part per MIL-STD-981, which includes Group A screening testing on every magnetics assembly, and Group B qualification testing on destructive test samples. Therefore, every magnetic device in the PPU requires a source control drawing which specifies its construction and testing. Group B testing can be particularly expensive (>$10K per line item) and time-consuming (4 to 6 months). This means that each magnetic device is a "project within a project".

The heritage NEXT PPU design used 33 unique magnetics parts and 133 total magnetic parts. One of ZIN's goals with the NEXT-C design was to reduce the number of custom magnetics wherever possible to simplify and commercialize the PPU design. The NEXT-C PPU design reduced the use of custom magnetics to 24 unique magnetics parts and 88 total magnetic parts.

D. Prototype PPU Test Results

The NEXT-C Prototype PPU testing included Calibration, Performance/Functional, EMI/EMC, Random Vibration, Sine Vibration, Shock, Thermal Vacuum Cycling, and System Integration Testing with a development thruster. This testing proved that the Prototype design had achieved TRL 6, and allowed the project to move on to the Flight phase. Figure 6 shows the performance of the Prototype PPU, showing the input power, output power, and efficiency measured during the March 2019 Prototype PPU system integration test with a development thruster at full power (TL40).

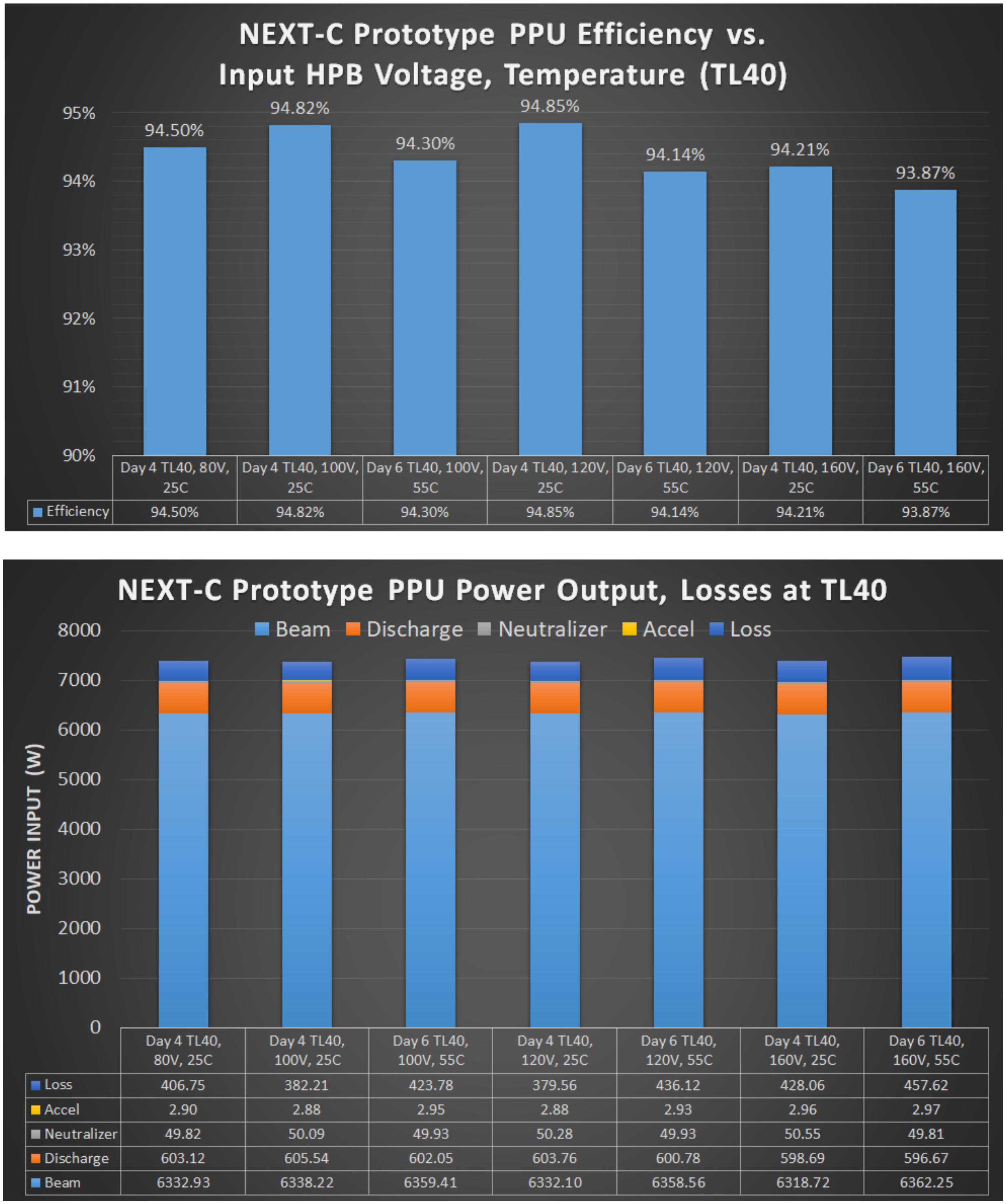


Figure 6. Prototype PPU Input Power, Output Power, and Efficiency Data operating the Development Thruster at TL40 as a Function of Input Voltage and Temperature.

Figure 6 shows that the Prototype PPU successfully operated at TL40 over the 80 to 160 V input range at nominal (25°C) and maximum (55°C) baseplate temperatures. The PPU output approximately 7 kW to the thruster at 94.8% maximum efficiency (120 Vin, 25°C). The PPU efficiency drops to 93.8% at high temperature (55°C) and maximum input voltage (160 Vin). The Beam Supply dominates the output power of the PPU, accounting for approximately 90% of the output power in all cases. The PPU rejected less than 460 W to the coldplate throughout the test.

E. Flight PPU Test Results

The NEXT-C Prototype phase resulted in a TRL 6 unit, and the goal of the Flight phase was to deliver a TRL 8 Flight PPU. The NEXT-C Flight PPU and Thruster system was selected by APL to provide electric propulsion for the DART mission, NASA's first-ever planetary defense mission that will demonstrate asteroid deflection using kinetic impactor technology.

The NEXT-C Flight PPU was built from the Prototype PPU design. However, the DART spacecraft uses a more specific range of the NEXT-C PPU capability per Table 3. For further comparison, Figure 3 shows the DART operating region on the NEXT-C throttle table, and Figure 4 shows the DART operating region on the Beam Supply. The Flight PPU test campaign followed the DART operating range to maximize the philosophy of "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

The DART Flight PPU is shown in Figure 7. The Flight PPU has identical size (50.80 x 40.89 x 13.97 cm; 29,019 cm^3) and mass (34.5 kg) compared to the Prototype PPU. However, the Flight PPU was built using EEE-INST-002 Level 2 parts, whereas the Prototype PPU was built with parts that generally did not undergo full screening and qualification testing. The Flight PPU build took place from January to August 2020. The build process included unit tests at the printed wiring board level, unit-level magnetics testing, and development of Test Support Equipment (TSE) hardware and software.

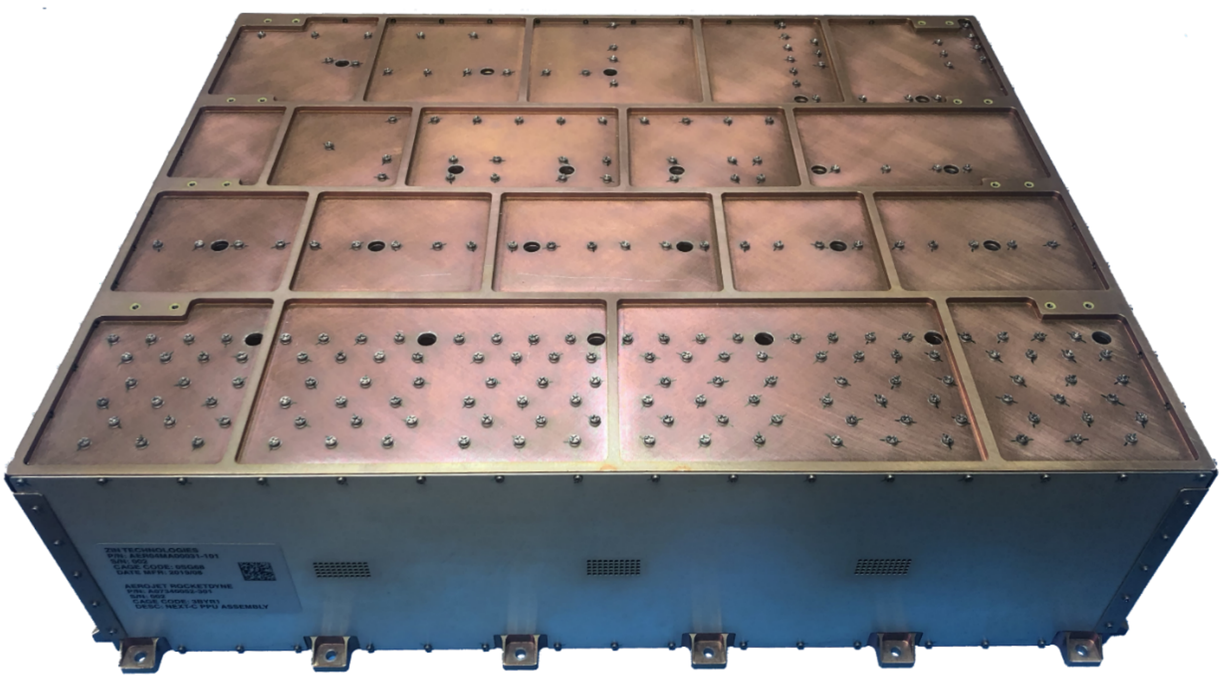


Figure 7. NEXT-C Flight PPU.

The Flight testing of the NEXT-C PPU for DART was performed at the PPU-level from September to December 2020, and included Calibration, Performance/Functional, EMI/EMC, Random and Sine Vibration, Thermal Vacuum Cycling, and 300-Hour Burn-In at elevated temperature. The System Integration testing of the Flight PPU and Thruster string was performed from January to February 2020, and included PPU Thermal Vacuum Cycling while powering the Flight Thruster at the DART Throttle Levels. The Flight PPU accumulated over 590 hours of operation during the test campaign. Figure 8 shows the Flight Thruster during system testing.

Figure 9 shows the PPU input power, output power, and efficiency during the Flight PPU System Integration test with the Flight Thruster at DART Throttle Level TL29. The Flight PPU operated at TL29 over the 80 to 125 V input range, at baseplate temperatures ranging from -29 to +55°C. The PPU output 3.7 kW at 93.9% efficiency at nominal conditions (100 Vin, 25°C). The PPU efficiency drops to 91.8% at high temperature (55°C) and maximum input voltage (125 Vin). The Beam Supply dominates the output power of the PPU, accounting for approximately 87% of the output power in all cases. The PPU rejected less than 332 W to the coldplate throughout the test.

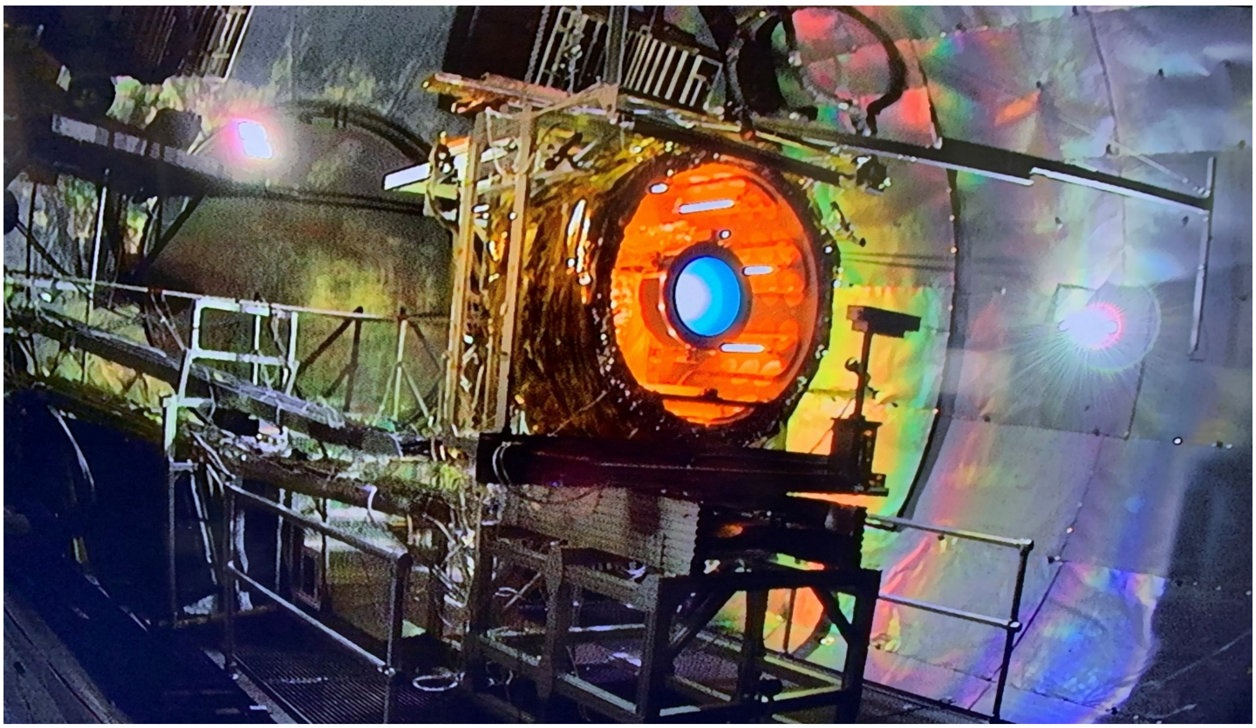
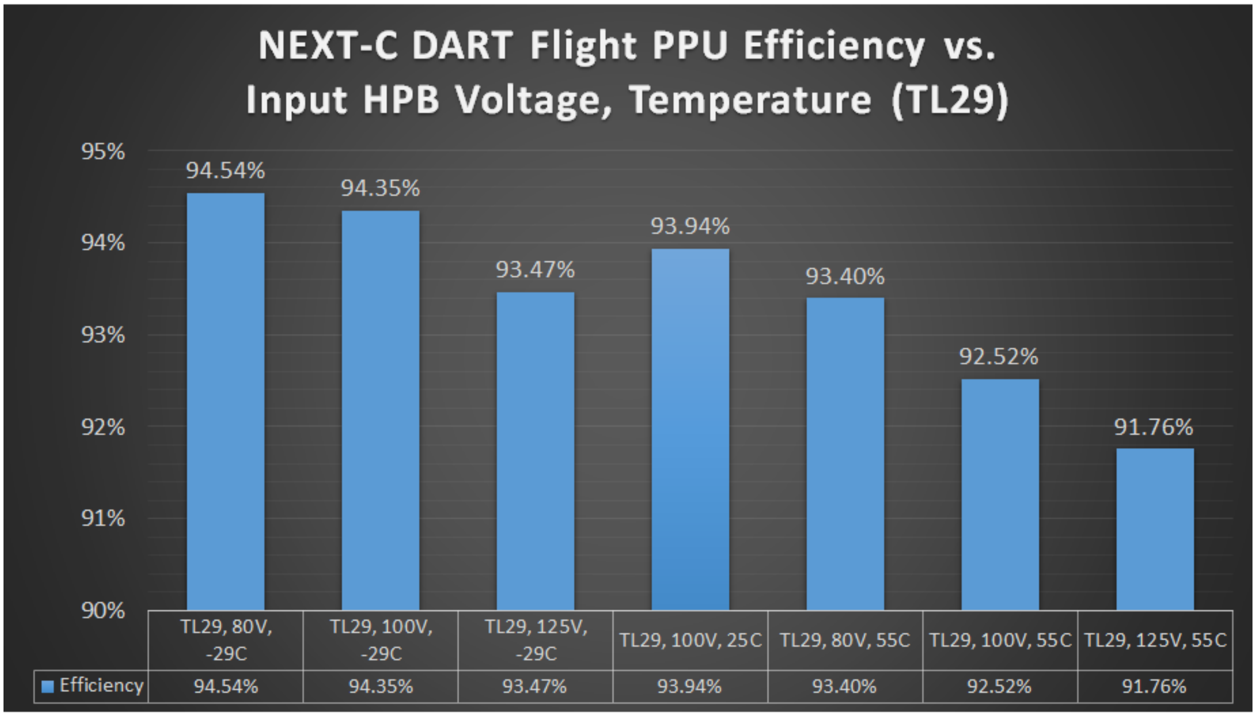


Figure 8. Flight Thruster During System Integration Testing



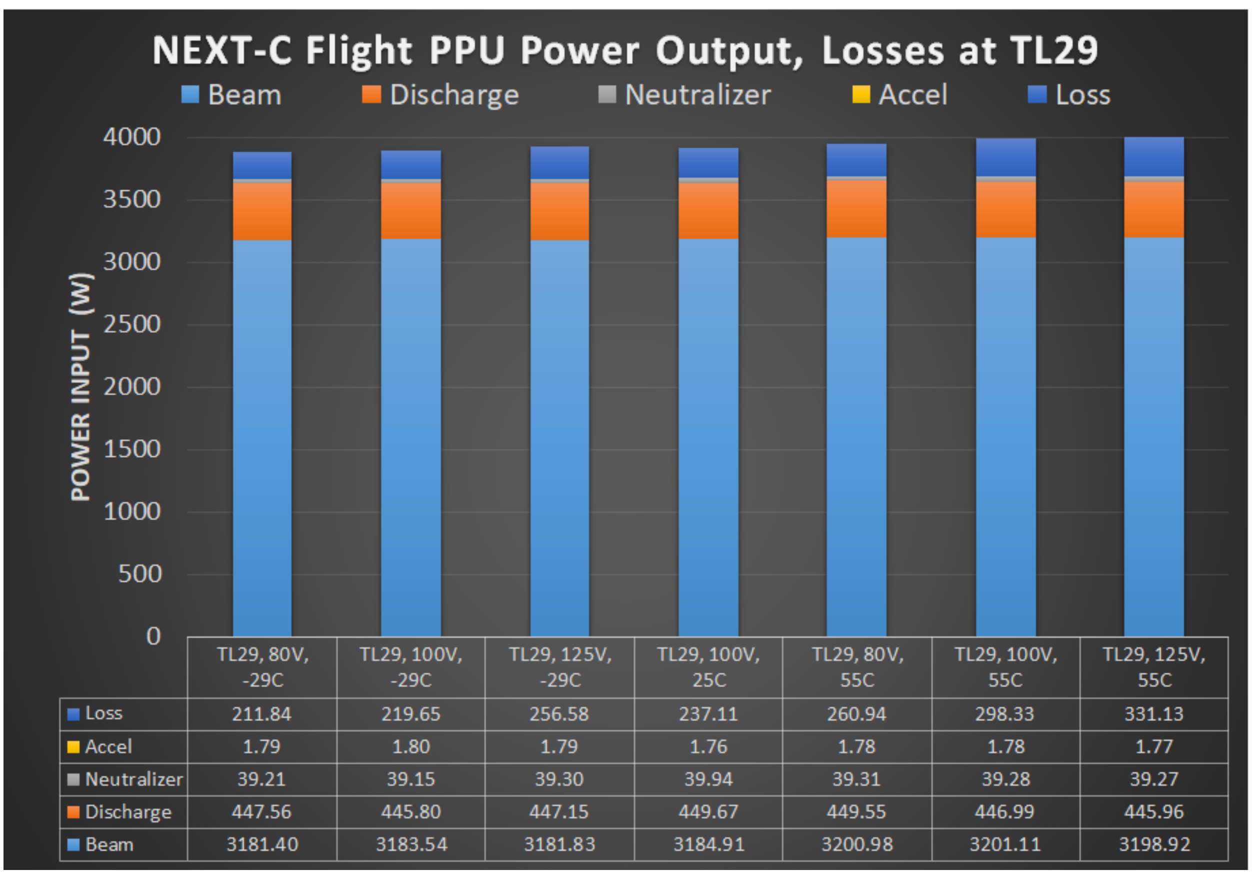


Figure 9. Flight PPU Input Power, Output Power, and Efficiency Data Operating the Flight Thruster at TL29 as a Function of Input Voltage and Temperature.

IV. 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. Future work planned for the NEXT-C PPU team is to build a second Flight PPU qualified to TRL 8 over the full operating range (80 to 160 Vin, up to TL40). This effort is proposed to be funded by NASA GRC in Fiscal Year 2021.

The NEXT-C PPU was developed over five years. From the project start in early 2015, the Prototype PPU was designed and built by the end of 2016. The Prototype was tested for two years (early 2017 to early 2019). Then, the Flight PPU was built, tested, and delivered from early 2019 to early 2020. The NEXT-C team iterated the PPU design at the Prototype level before building the Flight unit, which allowed the Flight PPU to be successfully tested with minimal issues and delivered in less than six months. The time spent working on the Prototype hardware, where trial-and-error is tolerated, accelerated the Flight hardware, which cannot be designed by trial-and-error. PPU development is a long-term, complex effort because PPUs are inherently complex. The NEXT-C PPU has six DC-DC converters, 44 circuit cards, and 88 custom magnetic parts. Few organizations have created a Flight-qualified PPU design, and the NEXT-C effort provides a compelling electric propulsion option for future NASA missions.

Acknowledgments

The authors would like to thank NASA for funding the NEXT-C effort over the contract period. The authors would like to thank those at ZIN Technologies, Aerojet Rocketdyne, and NASA Glenn Research Center who contributed to the effort and made this project a reality. Special thanks to the DART team at Johns Hopkins University Applied Physics Laboratory, who were instrumental in selecting the NEXT-C system for the DART mission, and helping the team with mission integration. Finally, the authors would like to thank the NASA NEXT-C Internal Review Board (IRB), consisting of specialists from NASA Glenn Research Center, NASA Goddard Space Flight Center, and NASA Jet Propulsion Laboratory. The guidance and expertise that was provided was invaluable.

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