Qualification of the BET-MAX Electrospray Propulsion System

IEPC-2022-196

Presented at the 37th International Electric Propulsion Conference
Massachusetts Institute of Technology, Cambridge, MA USA
June 19-23, 2022

Nathaniel Demmons[1] and Jacob Knott.[2], Timothy Fedkiw[3], & Nereo Alvarez[4]
Busek Company, Natick, MA, 03048, USA

Abstract: The BET-300-P electrospray thruster has been the focus of development by Busek within the field of passively-fed electrosprays, with significant work performed towards characterization, environmental testing, and life demonstration. Early work focused on development of a robust thruster design that was well characterized through direct thrust and mass flow measurements, as well as near and far-field plume diagnostics. Through understanding of the underlying life-limiting mechanisms and subsequent improved designs, total impulse is now only limited by the propellant capacity within the present design. The thruster was then subjected to extensive environmental testing including vibration testing, temperature and humidity exposure, followed by thermal-vacuum and life demonstration testing. However, thruster-only testing does not achieve the Technology Readiness Level 6 (TRL6) distinction until demonstrated at the complete system level. Herein, Busek describes the subsequent successful qualification of the complete Busek BET-MAX system, which consists of four BET-300-P thrusters, one propellant-less carbon nanotube field emission cathode, driven by a compact common set of electronics, to the NASA General Environmental Verification Standard (GSFC-STD-700A) protoflight. The system in question was intended for flight and a protoflight approach was pursued, with testing completion and customer delivery occurring in March of 2022. Complete [functional testing of all relevant thruster, cathode, and control software functionality were validated throughout the environmental test program. Necessary documentation has been developed to support integration for missions and mission concepts that may benefit from unprecedented precision thrust capability of the BET-MAX system. Given that that precision pointing is the most compelling near-term application for such a system, the BET-MAX has been configured as a disaggregated system, allowing for each of the four thrusters to be independently placed by systems integrators. Unit production scaling is underway to support increased demand for such products as mission planners incorporate the benefits of precision pointing into their mission concepts.

Nomenclature

α = thruster parameter
I_B = beam current
I_{sp} = specific impulse
T = thrust
V_B = beam voltage
V_C = cathode voltage

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[1] Director, Micro-propulsion Group, 11 Tech Circle, Natick MA 01760, AIAA Senior Member
[2] Research Engineer, Micro-propulsion Group, 11 Tech Circle, Natick MA 01760, AIAA Member
[3] Senior Research Engineer, Micro-propulsion Group, 11 Tech Circle, Natick MA 01760, AIAA Member
[4] Research Engineer, Micro-propulsion Group, 11 Tech Circle, Natick MA 01760, AIAA Member

I.Introduction

The Busek Electrospray Thruster – Multi-Axis (BET-MAX) system has been successfully matured through a protoflight qualification program in support of present and future space micro-propulsion applications. While well suited for general thrust applications due to high impulse density at compact scales, of specific near-term interest is its use as a modularized reaction control system (RCS), providing orders of magnitude improvements over state-of-the-art alternative attitude control systems (ACS). Vibrational disturbances and resolution limitations of state-of-the-art (SOA) ACS presently limit precision body-pointing and position control accuracy. Towards that end, advancing the BET-MAX system through environmental testing has demonstrated the system-level maturity necessary for inclusion in new and innovative mission concepts requiring precision pointing well beyond what is presently available.

Passively fed electrospray thrusters, such as those in the BET-MAX system, are highly compact, including fully integrated propellant supplies, and are capable of ~100nN thrust precision with 10's of nN noise. Thrust can be accurately throttled over >30x, up to a scalable maximum of 10's to 100's of µN. These traits, combined with >800s specific impulse and thereby low propellant mass, enable these systems to complement or replace traditional reaction wheel ACS, providing both unprecedented levels of control authority along with competitive slew rates. Specifically enabling milliarcsec control authority versus the present arcsec level SOA. Realization of these goals necessitates critical developments of the thruster head, emphasizing precision and robustness, and a multi-axis power processing unit (PPU) with integrated thrust control laws. The BET-300-P engineering model thruster maturation, utilized in the BET-MAX system, dates back several years, where extensive performance measurements have been obtained and multiple life test performed to propellant exhaustion. More recently, integrated electronics and neutralizer elements of the system have been advanced through engineering to flight model, with flight control software demonstrated that is commensurate with the precision thrust target application.

II. BET-MAX System Overview

The BET-MAX consists of four BET-300-P thrusters (**Figure *1***), one CNTFEC with deflector assembly (Fig. *2*) and one electronics assembly (Fig. 3). The thrusters are provided disaggregated from each other and the electronics to allow for positioning within the spacecraft in accordance with required thrust vectors for attitude control. Each thruster is approximately the size of a 5cm cube and contains sufficient propellant for 92Ns of total impulse per thruster in configuration option A, as described by the general performance specifications outlined in Table 1. While configuration B is available and has been through environmental testing, it has not yet been subjected to a complete 250Ns life test (65Ns to date) and is not the focus of the protoflight qualification discussed herein.

Each thruster has an integrated heater and temperature measurement sensor, allowing for independent thermal control. Electrospray emission is dependent on the physical properties of the ionic liquid propellant, which are temperature dependent. Performance can be tuned based on operating temperatures selected within the specified operational temperature range, providing a significant amount of operational flexibility.

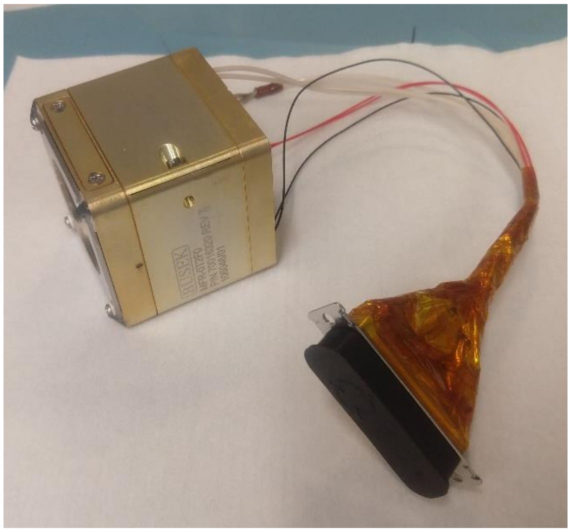
Figure 1: Protoflight BET-300-P thruster

Through prior efforts, a BET-300-P thruster was subjected to a complete environmental test campaign consisting of 1.) initial functional testing, 2.) vibration testing to NASA GEVS qualification levels, 3.) extended exposure to elevated temperatures and high humidity to simulate pre-launch environments, 4.) thermal-vacuum testing, and 5.) complete demonstration of total impulse [1]. Direct thrust and mass flow measurements have been obtained to determine operational performance over a range of operating conditions, at multiple temperatures, and throughout the total impulse capability of the thruster [2]. Far field electrospray beam characteristics have been investigated via angularly resolved time-of-flight and Faraday probe measurements. Near-field plume (few mm's from point of emission) electrospray plume measurements have been captured using an in-house developed computed tomography measurement device, which was used to identify emission distribution over the entire ~90Ns life of the thruster [3,4]. High speed pulsed operation has been demonstrated for precision impulsive thrust applications and found to be controllable, with high-speed thruster telemetry being in agreement with steady state results [5]. Through the entirety of this work, the performance of the BET-300-P was well characterized through numerous lab-model and multiple engineering model units prior to initiation of protoflight qualification. To retain full traceability to these prior results, no changes were made between the engineering model and flight design that underwent this qualification.

Table 1 Performance specification for BET-300-P in A and B configuration

Config Option	T (μN)	T/P (μN/W)	I_{sp} (s)	η (%)	Impulse (Ns)
A	<1 - 150	65	850	32	92*
B	<1 - 75	40	2,300**	47**	TBD**

* Demonstrated, propellant loading limited, per thruster
** Reduced mass flow rates measured increases uncertainty, w/ 65Ns demonstrated to date

Busek utilizes single polarity, positive emission electrospray thruster system architectures, which necessitates a cathode for spacecraft charge balancing. Busek's in-house developed propellant-less Carbon Nanotube Field Emission Cathode (CNTFEC) is utilized. The ½" CNTFEC, shown in Fig. 2, was flight qualified as part of the NASA ST7-DRS mission and demonstrated in space aboard the ESA LISA Pathfinder spacecraft. This cathode was selected for the BET-MAX system to leverage that design heritage, while having sufficient electron emission capability to use a single cathode to charge balance against four thrusters. A single stage electron multiplier has been added, predominantly to transition the high energy primary electrons (200eV to 800eV typ.) of the CNTFEC to low energy secondaries more suitable for charge balancing applications [6]. However, through material selection, secondary electron yields (δ) greater than one are achieved, thus increasing useful electron output current available for charge balancing.[6] (if necessary)

Fig. 2 1/2" CNTFEC in integrated deflector assembly.

The flight BET-MAX electronic external dimensions are approximately 10cm x 10cm x 6.5cm and contain all the necessary power conditioning and control to independently drive the cathode and four BET-300-P thrusters. Internal functions are distributed across three main boards that perform 1.) internal supply voltage generation from a singular supply voltage, 2.) communication and control, and 3.) power outputs to drive the thrusters and cathode. A hybrid approach was taken with respect to radiation hardness, with critical components being selected for upgrade. While this approach is commensurate with near-term applications, all components within the bill of materials have direct upgrade paths to support future full radiation-hardened designs. Functional testing in vacuum of engineering model designs has been previously reported [2], with both hardware and software lessons learned being incorporated into the flight electronics shown in Fig. 3.

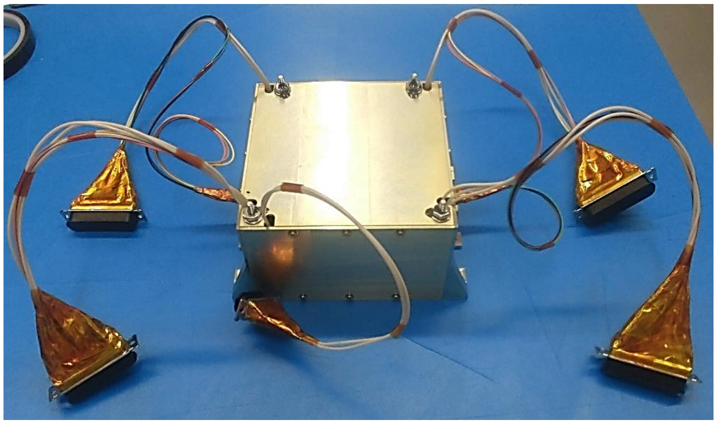

Fig. 3 BET-MAX protoflight electronics.

III. Pre-Integration Thruster Testing

Prior to integration into the BET-MAX system, each thruster was characterized via direct thrust measurements, which are performed to obtain individualized thrust characteristics that vary slightly from unit to unit. The thrusters are operated for approximately 20 hours, accumulating approximately 3.5N*s (Fig. 4) of total impulse to ensure emission characteristics stability. For each segment, an initial thrust sweep is performed, followed by a 1hr steady state emission at nominal thrust (55μN). Segments are repeated 16 times to monitor changes to thrust and voltage characteristics as the thruster settles into a repeatable operating regime. Voltage and current telemetry were collected in conjunction with thrust and mass measurements, and individualized thruster parameters, α, calculated in accordance with known scaling laws. These parameters were subsequently loaded into software at the system level and used to perform commanded thrust operations.

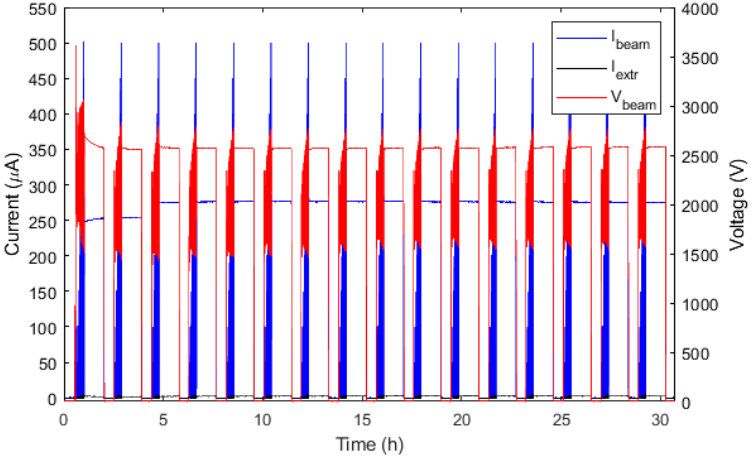

Fig. 4 Data for thruster characterization consisting of repeated current sweep & thrust hold segments.

Processed thruster telemetry from a single beam current-controlled sweep is shown in Fig. 6, where time periods of data selection for processing at each setpoint is shown in grey. A modified mass balance is used for both mass and thrust measurement, shown in Fig. 5. Off times between operational points are used for detrending of thrust estimation due to mass loss of the thruster, using methods detailed in previous characterization work of the BET-300P [5]. Grid interception is shown on a current basis and was on the order of 1% and generally in line with historical values from engineering model thrusters tested previously.

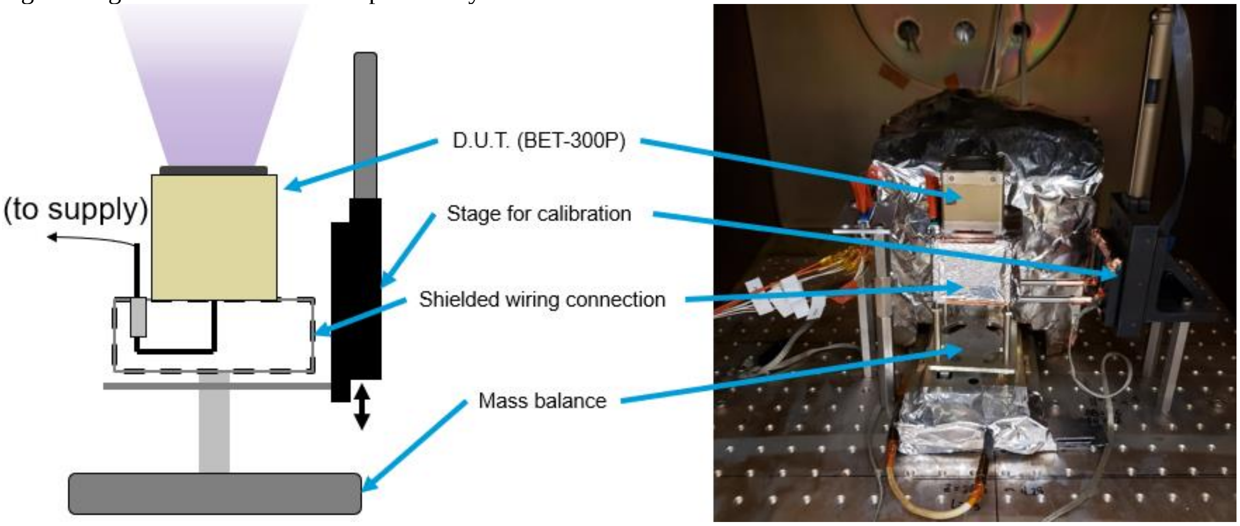

Fig. 5 Diagram of thruster characterization test stand (left) and photograph of engineering model BET-300P inside T-67 vacuum test facility (right).

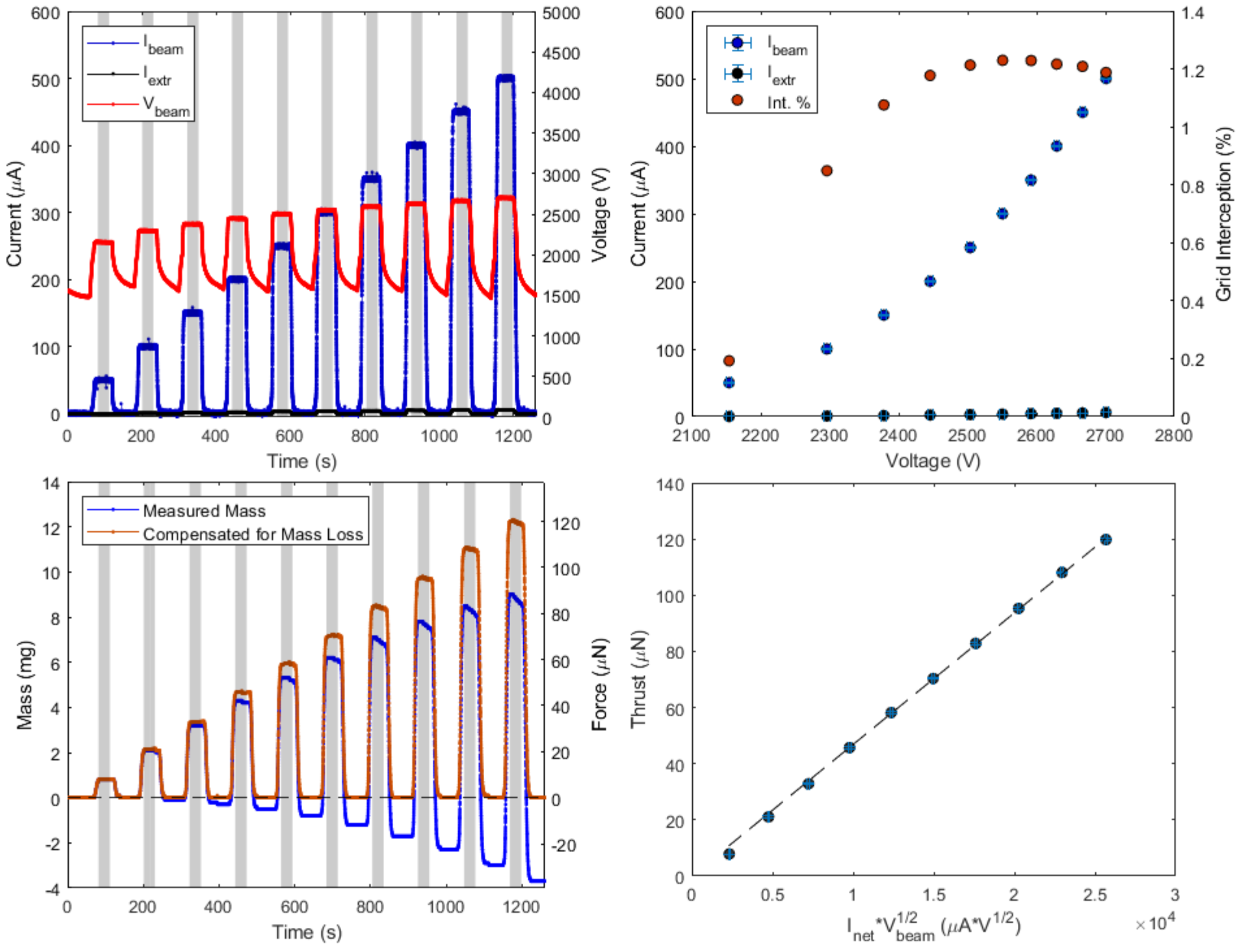

Fig. 6 Sample current sweep data used for thruster characterization taken from FM03 after 3.7h of operation. Highlighted sections of plots (left) used to calculate mean values for characteristic plots (right).

Voltage and current relations during the first ~20h of operation for the four protoflight thrusters are shown in Fig. 7 through Fig. 10. Of note is the progression of the operational behavior over this time. This is common and is the reason why the final thruster parameter for flight operations is not measured until sufficient impulse & operating time have been demonstrated. After this initial operation, the VI curve is generally settled into its long-term trends, and, as can be seen in Fig. 11, the resulting thruster parameter used to correlate to thrust generated is also settled.

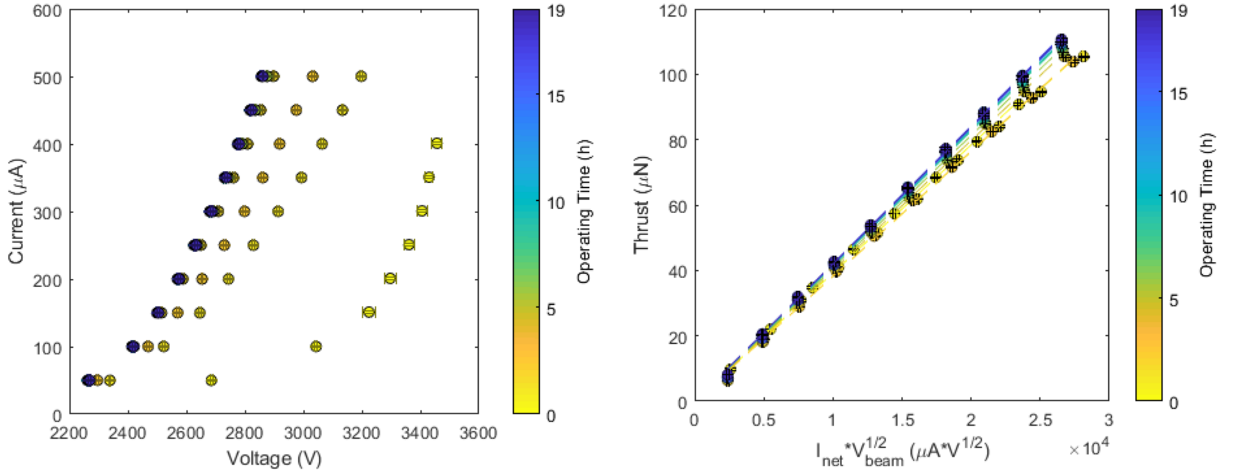

Fig. 7 FM01 VI curves (left) and thrust curves (right) from characterization testing.

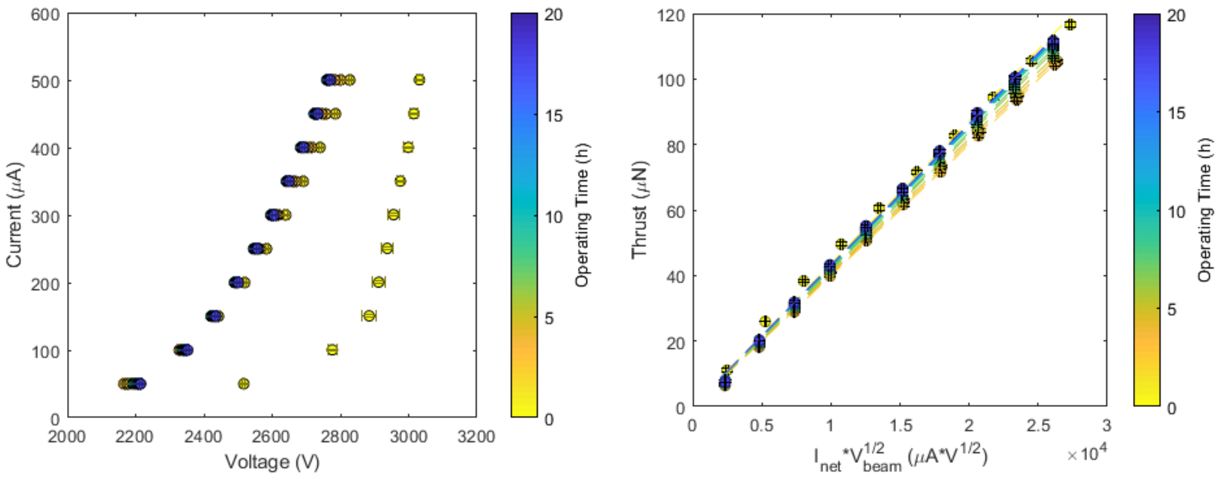

Fig. 8 FM02 VI curves (left) and thrust curves (right) from characterization testing.

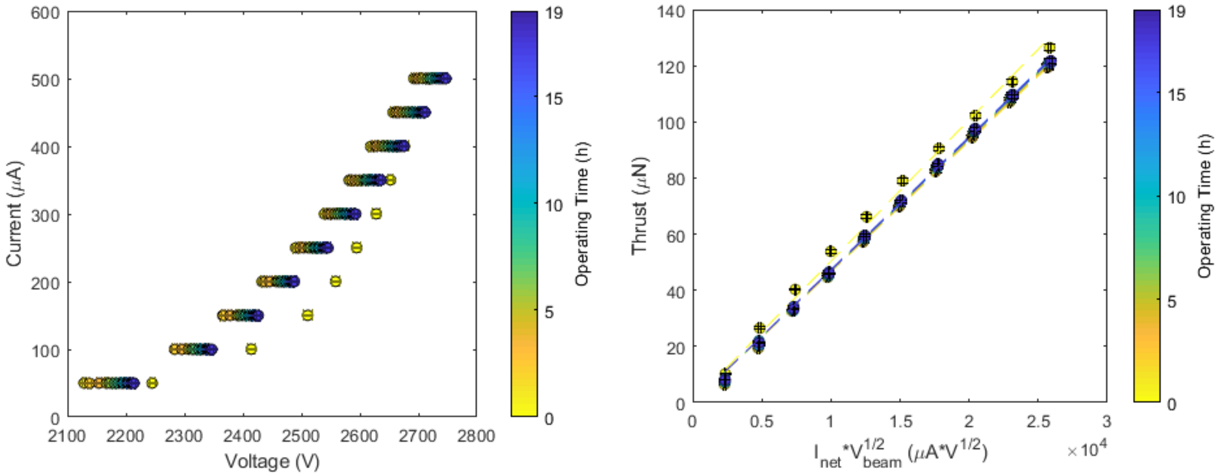

Fig. 9 FM03 VI curves (left) and thrust curves (right) from characterization testing.

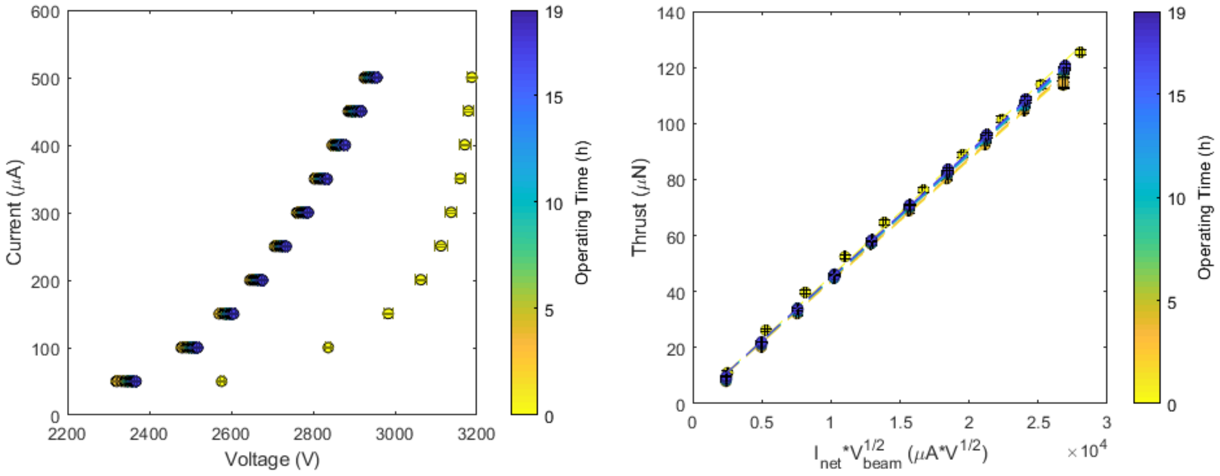

Fig. 10 FM04 VI curves (left) and thrust curves (right) from characterization testing.

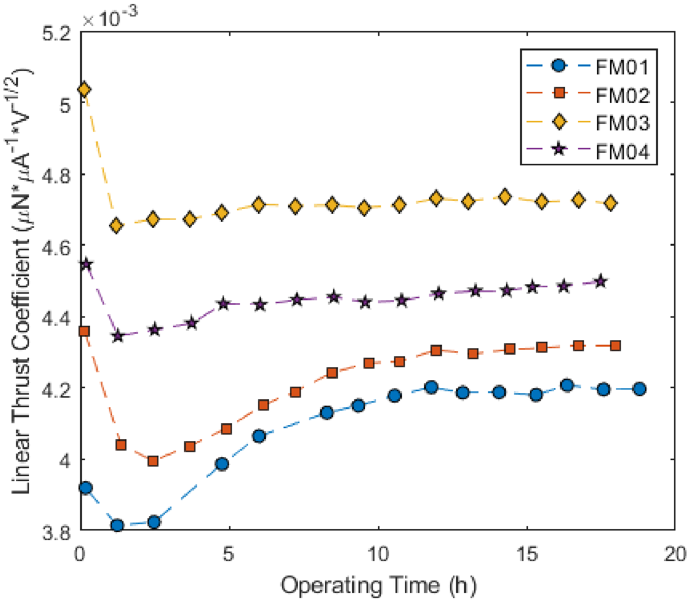

Fig. 11 Linear thrust coefficients measured during characterization testing

For this particular protoflight system, thruster parameter values varied by approximately ±6% around a mean value of 4.442 x 10^{-3} μN/μA$V^{1/2}$, which is well within prior observed variability from both lab and engineering model testing with the BET-300-P in configuration A. This variability does not significantly impact thruster operational range, as there is margin on operational voltage. As can be seen in the figures above, at beginning of life, thrusts approaching 150μN are obtained at voltages of approximately 3.0kV to 3.2kV, while the electronics are capable of operation at up to 5kV. This additional voltage authority allows for retention of maximum thrust with the noted variation in thruster parameter values, as well as across the life of the thruster as propellant is depleted.

IV.Environmental Testing Plan

A. Vibration Levels and Thermal-Vacuum Testing Ranges

The BET-MAX system was tested in accordance with NASA General Environmental Verification Standards (GEVS) protoflight guidelines (Table 2). The system was placed into Busek's T-17 vacuum test facility for initial operation, following which the system was removed for vibration testing. Specifically for vibration testing, GEVS protoflight guidelines indicate qualification vibration levels ($14.1g_{rms}$) for acceptance durations (1min), as outlined for spacecraft components with a mass of less than 50kg. However, it is noted that electronics reworks were necessary after the initial vibration test, and those reworks were subsequently verified at the system level via and additional workmanship-level vibration ($6.8g_{rms}$) to avoid over testing protoflight hardware.

Table 2 Component workmanship & protoflight qualification vibration levels per NASA GEVS.

Frequency (Hz)	Component Minimum Workmanship (g^2/Hz)	Protoflight Component-Level Qualification (g^2/Hz)
20	0.01	0.026
20-50	+3 dB/oct	+6 dB/oct
50-800	0.04	0.16
800-2000	-3 dB/oct	-6 dB/oct
2000	0.01	0.026
	Total: 6.8G_{rms}	**Total: 14.1G_{rms}**

Following vibration testing, the system was returned to T-17 for a repeat functional test to verify functionality post-vibration testing, followed by thermal-vacuum testing, seen in Fig. 12. As shown in Fig. 13, 10°C margins were placed on all imposed survival and operational limits, resulting thermal-vacuum testing target ranges of -30°C to 60°C for survival and 0°C to 40°C for operational or functional testing. A total of six hot/cold operational cycles were performed, short of the 10-12 recommended by GEVS, with the remaining cycles to be performed during spacecraft-level testing. To demonstrate the widest possible operational capabilities of the BET-300-P within the BET-MAX system, thruster temperatures during operational thermal cycles were set to 0°C and allowed to follow system temperature when above this threshold.

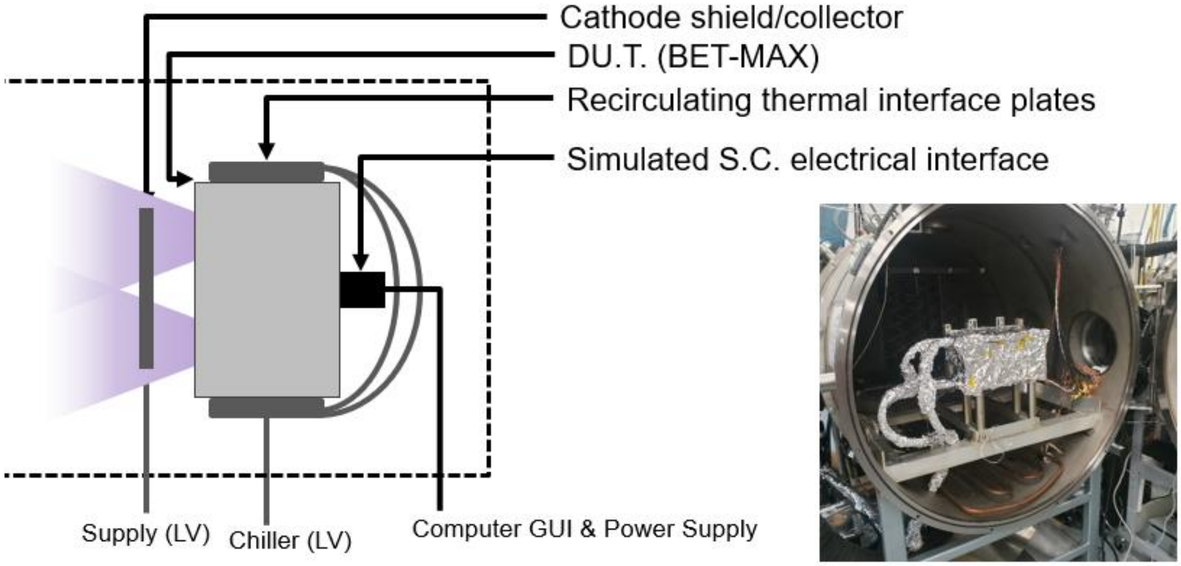

Fig. 12 BET-MAX system as configured for functional and TVAC testing as part of protoflight qualification.

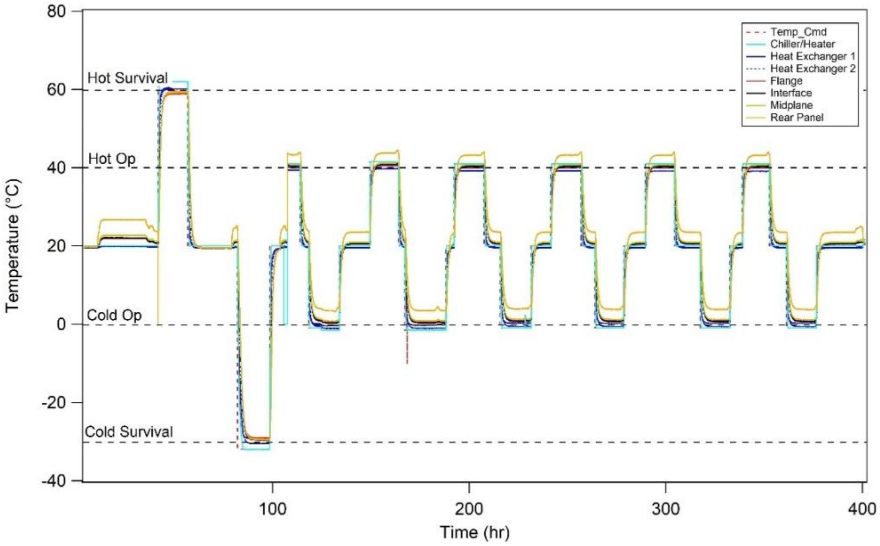

Fig. 13 Thermal profiles during TVAC testing, with 10°C margin added to survival/operational limit requirements

B. Functional Testing Overview

Established functional testing procedures from prior electrospray flight qualification programs were adapted to the requirements of the BET-MAX system. The purpose of the functional test was to verify complete system functionality before and after each step in the protoflight qualification campaign. Once acceptable high vacuum pressures (< 1x10^{-5} Torr) had been reached for at least 24 hours, functional testing entailed the following steps: 1.) CNTFEC low level current conditioning, 2.) CNTFEC current control characterization sweep, 3.) thruster impedance checks below emission onset voltages, 4.) thruster current control characterization sweep, and 5.) thrust command mode sweep, with an active cathode. The post-vibrational test results for the cathode and thruster on channel #1 are shown in Fig. 14 through Fig. 16 as example data of these five functional steps, from post-vibration testing in this instance. Some of these modes are specific only to ground testing, as operation of the thruster in a space environment, without an active cathode is not advisable due to spacecraft charging implications. It is anticipated that the bulk of on-orbit operations after commissioning will be performed in thrust command mode where cathode operation during thruster operations is enforced.

C. Cathode Functional Test

The purpose of the cathode conditioning step (Fig. 14, left) for the CNTFEC is to drive off any water that has been adsorbed into the carbon nanotubes due to prior atmospheric exposure by operating at relatively low electron emission currents. This is performed prior to operating at elevated emission currents (>500µA) to avoid accelerated degradation of the emission substrate. Successful conditioning is evident through recovery of onset voltage, which is assessed through observation of cathode voltage at low commanded current (e.g., 5µA). In this instance, a 50V reduction in onset voltage towards the prior observed ~220V is seen. Subsequent cathode operation (Fig. 14, right) was demonstrated up to 1.5mA. Note that, as discussed earlier, the cathode is equipped with a single stage electron multiplier, with a common electrical connection with the cathode extraction gate. As such, the gate current shown here is the sum of these two currents and useful current available for charge balancing is equal to the difference between the cathode and gate shown, which was corroborated by external anode collection plates.

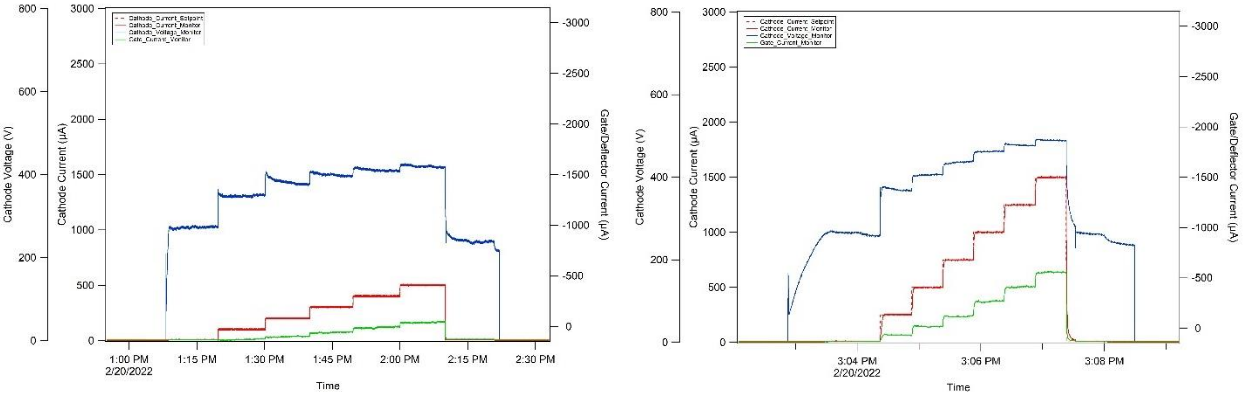

Fig. 14 Cathode conditioning (left) and current controlled sweep (right) from post-vibration testing.

D. Thruster Functional Test

Thruster emission onset voltages are typically between 1.25kV and 2.0kV. Impedance checks (Fig. 15, left) were performed up to 1.5kV to assess each thruster for potential leakage currents within each thruster assembly. As can be seen, no current was observed on the beam and, while not shown, separate extractor and housing current monitors confirmed no discernable leakage currents within the thruster assembly. Subsequent emission current controlled operation above onset voltage (Fig. 15, right) indicated typical beginning-of-life emission characteristics, with extraction grid interception on the order of 1%, which is typical based on prior engineering model environmental testing results. Note that the thruster was only operated up to 500µA, approximately 110µN for this thruster. Under most environmental testing, exercising of the complete thruster operational range was limited by the facility vacuum pressure meeting the operational criteria of $<1x10^{-5}$ Torr. Decomposition of the electrospray beam upon impact with the target, as well as water liberated from facility surfaces due to the impact of the beam, increases proportionally with emission current. However, as discussed above, each thruster was fully characterized up to near its maximum beam current during pre-integration testing.

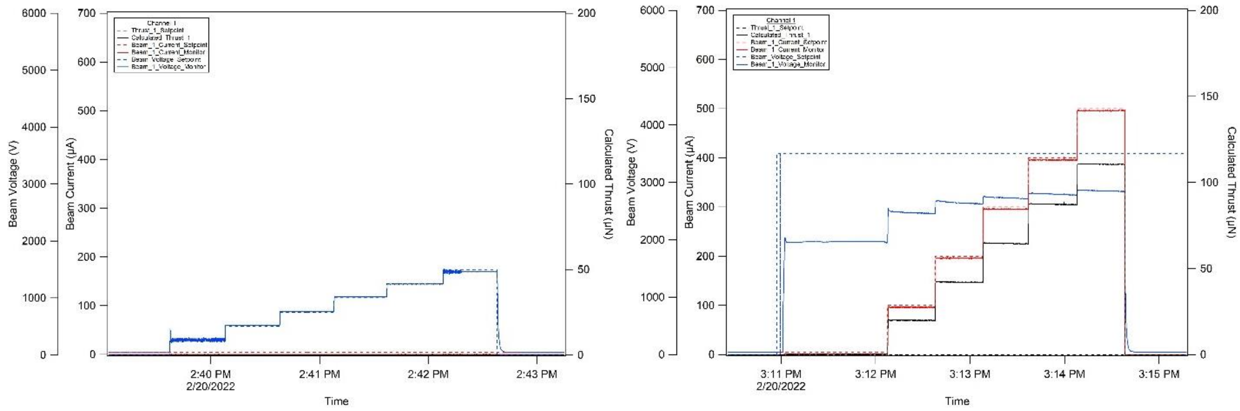

Fig. 15 FM01 impedance check (left) and current controlled sweep (right) from post-vibration testing

Thrust command mode engages the complete hardware and software control of the BET-MAX system. Within this mode, each thruster can be brought to an "Armed" state from which a thrust and duration fire can be rapidly initiated. As part of progression from armed to thrust active, the cathode is first operated at currents greater than that required to balance against the positive thruster beam current for the given requested thrust. This software logic is inclusive of all four thrusters within the BET-MAX system, where, in the event of simultaneous operation, the sum of total thruster beam currents is limited to less than the circulating electron current in the cathode available for charge balancing.

Note that the calculated (black solid trace) thrust reported by the electronics is based on the thruster parameter entered into the flight software determined from prior direct thrust measurements, as well as the voltage and current monitors. The commanded thrust level (black dashed line) is shown, which does not return zero when exiting a prior thrust and duration command execution. This telemetry setpoint reporting issue has been subsequently remedied.

Cathode operation is shown in the right graph of Fig. 16 and was automated as part of the entry into thrust command mode. It was verified that cathode circulating current reaches required levels prior to onset of positive thruster beam emission. This necessary in order to enter into thrust operations without the risk of spacecraft charging to unsafe potentials with respect to the local plasma environment.

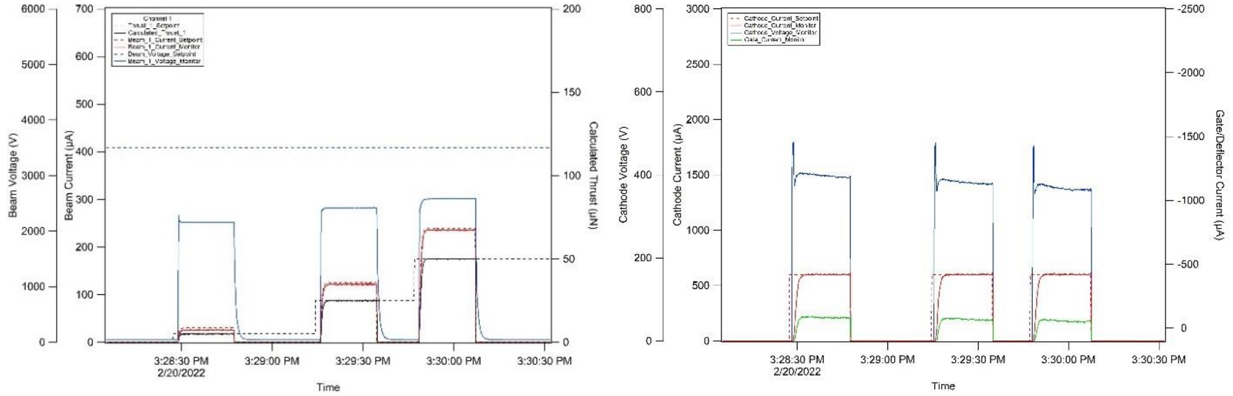

Fig. 16 FM01 thrust sweep (left) and cathode operation during same thrust sweep (right).

The functional testing described above was performed pre- and post-vibe, post-hot survival, post-cold survival, 6X at hot-operational, 6X at cold-operational, and one final time at nominal temperature before concluding environmental testing. Independent thermal control of each thruster was also demonstrated during nominal temperature thruster firing operations to demonstrate additional system functionality. There were no significant deviations in results beyond those anticipated due to changes in operational temperature.

V.Environmental Testing Compiled Results

A. Cathode Results

Compiled voltage and current characteristics for cathode throughout environmental testing are shown in Fig. 17. Cathode operation for all temperature setpoints is included in a single graphic, as field emission cathode operation is not significantly temperature dependent. CNTFEC cathode voltage and current behavior collected from initial pre-vibe functional testing to final post-TVAC functional is shown in Fig. 17. The first and last hot/cold operational cycles are included; however, cycles two through five are omitted, but results were in line with the data shown below. Linear regression in accordance with the Fowler-Nordheim equation for field emission (Fig. 17, right) indicates that the currents observed behave as anticipated throughout environmental testing. Of note is that the difference between the pre-vibe characteristics and post-vibe results. While the observed shift is well within the operational range, the initial shift is not uncommon and is attributed to early-stage operation burn-in. With the Busek CNTFEC, it is known that over the thousands of hours of life of the CNTFEC device [7], there is a gradual trend towards higher operating voltages for a given current. This is the result of thermalization of the most favorable emission sites and a transition to sites requiring additional voltage to reach emission onset. However, this gradual trend in the cathode is not established until it has been operated for at least several hours. The protoflight cathode did not receive this “burn-in” period prior to integration into the BET-MAX system and the shift due to accumulation of operating time from pre- and post-vibration cathode conditioning runs that constituted approximately 2 hours of operation time before capturing the post-vibe cathode current sweep to 1.5mA. However, additional testing continues to confirm this and eliminate other potential sources such as mechanical shifting within the assembly during vibration testing. After this point there were no significant trends in cathode VI characteristics through the remainder of testing.

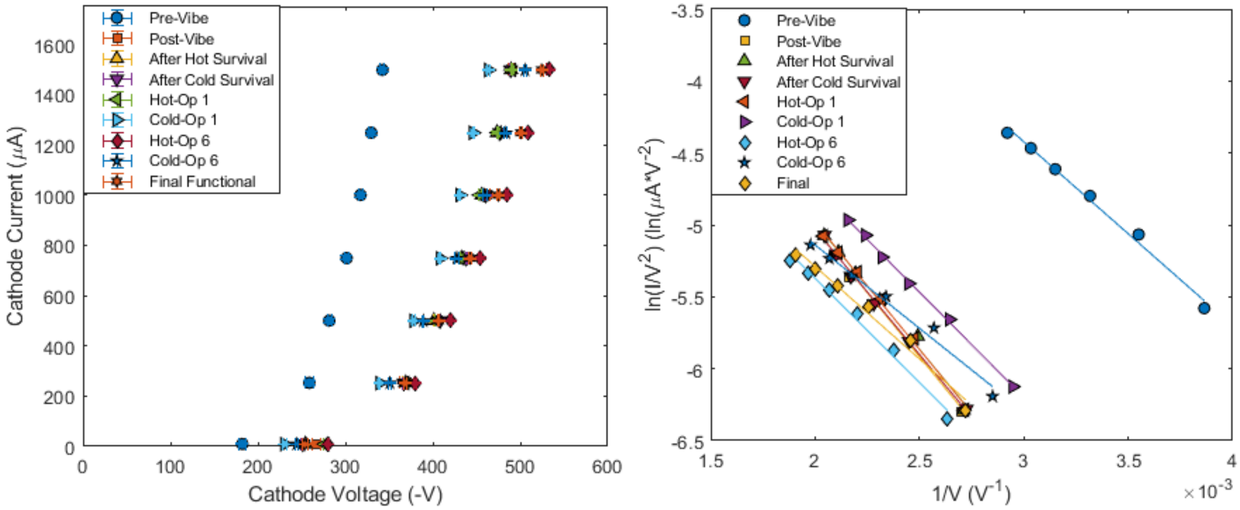

Fig. 17 CNTFEC voltage-current characteristics throughout environmental testing.

B. Thruster Results

FM01 through FM04 nominal voltage and current characteristics, as well as at operational thermal limits, are shown in Fig. 18 through Fig. 23. Due to the changes in physical properties of the propellant (e.g., electrical conductivity & viscosity) thruster behavior is temperature dependent, and results have been separated with respect to cold (0°C), nominal (25°C), and hot (40°C) operational conditions.

Nominal temperature thruster VI characteristics from throughout environmental testing is shown in Fig. 18 and Fig. 19. Results are generally in agreement, indicating no significant shift in behavior due to vibrational or thermal environment exposure. As can be seen, established BET-300-P assembly and operational procedures result in minimal emission variability with regards to emission onset and behavior. Similarly, thrust produced for a given $IV^{1/2}$ operating point all fall within a narrow range that has been consistent through testing, as indicated in their calculated thruster parameters determined during pre-integration testing.

Hot operational (40°C) thruster VI characteristics from the first and last cycle are shown in Fig. 20 and Fig. 21. As with the cathode data above, data from hot operational cycles two through five have been omitted but are not discernably different from the results shown here. Early during TVAC testing, thruster operation at up to 400µA was possible at 40°C, without exceeding acceptable vacuum facility pressures; however, that point degraded over duration of the test. By the last hot operational cycle, the thrusters were limited to 300µA to avoid operation in elevated pressures. With respect to this facility-limiting issue, hot operation is more problematic than cold, as changes in viscosity dominate over electrical conductivity and surface tension, resulting in lower specific impulse operation and increased mass flux for a given beam current. The increased propellant flux results in larger increases in facility pressures.

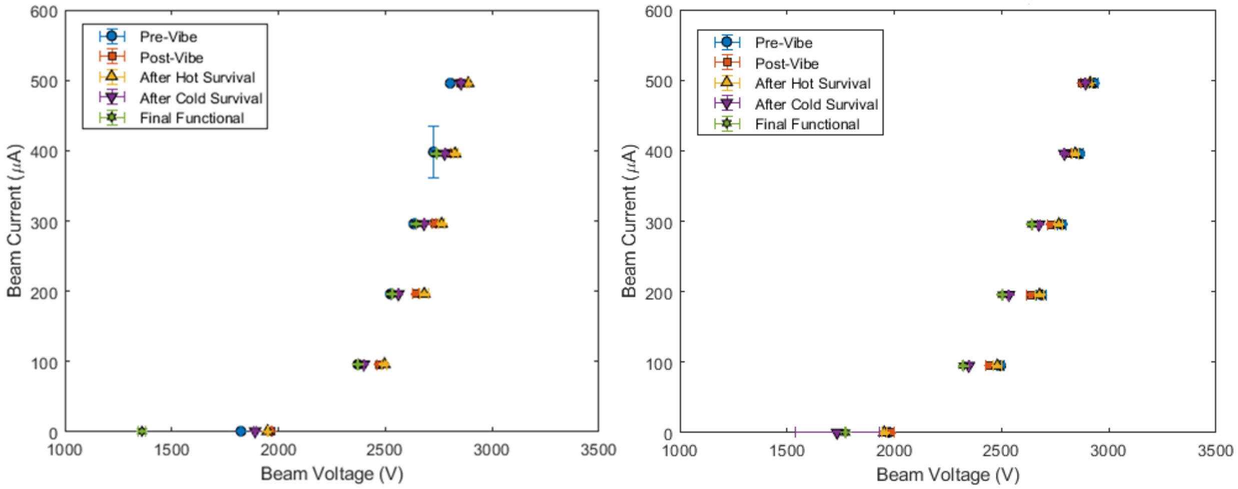

Fig. 18 25°C VI characteristics for thruster FM01 (left) and FM02 (right).

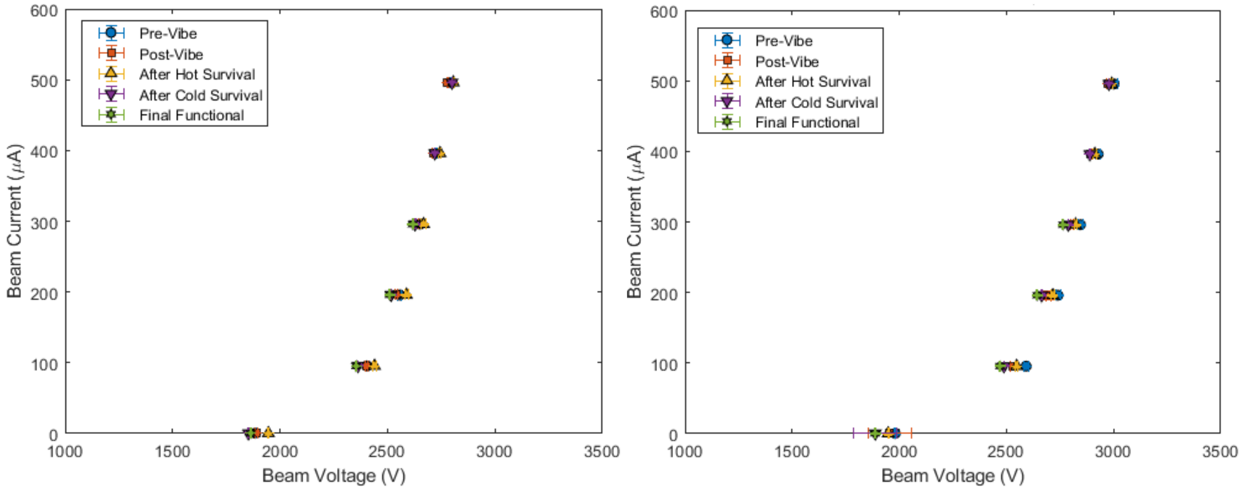

Fig. 19 25°C VI characteristics for thruster FM03 (left) and FM04 (right).

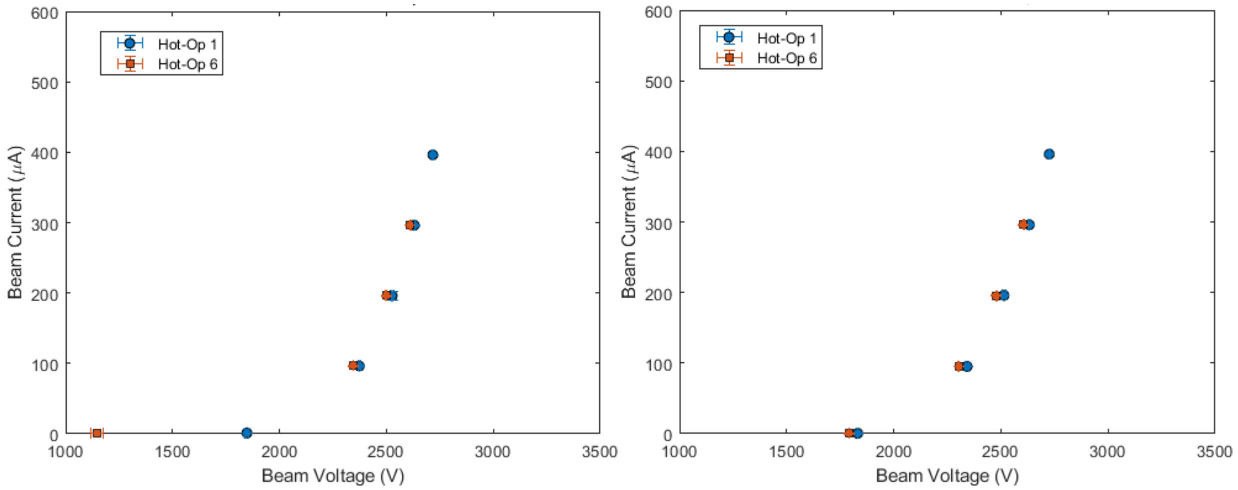

Fig. 20 40°C VI characteristics for thruster FM01 (left) and FM02 (right).

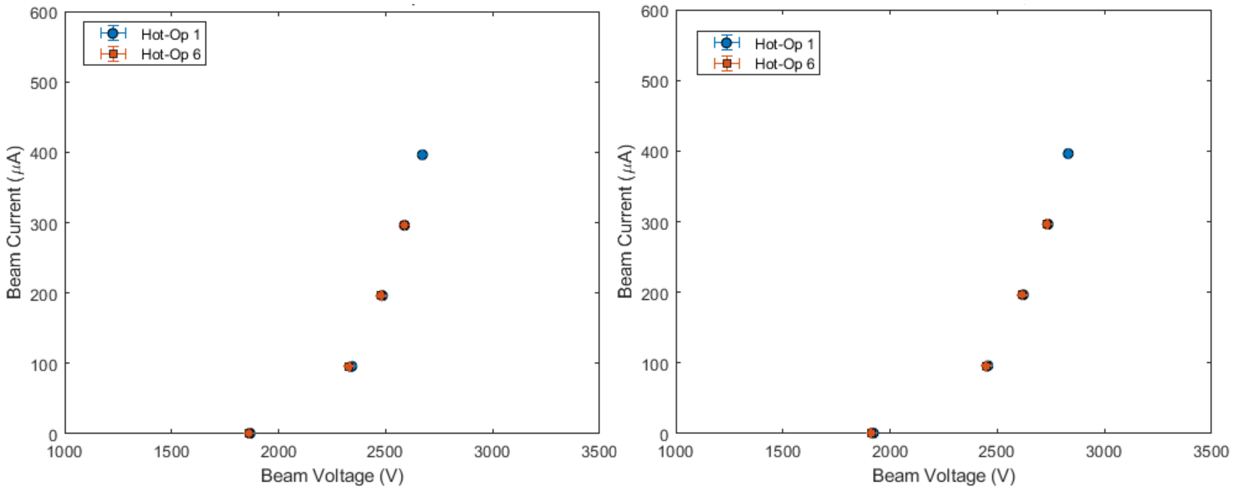

Fig. 21 40°C VI characteristics for thruster FM03 (left) and FM04 (right).

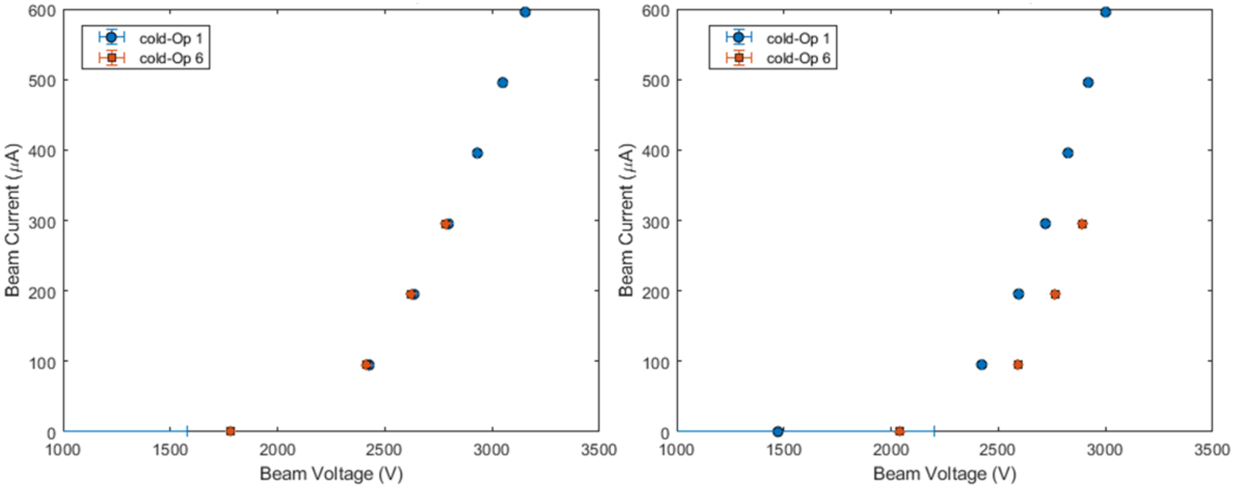

Fig. 22 0°C VI characteristics for thruster FM01 (left) and FM02 (right).

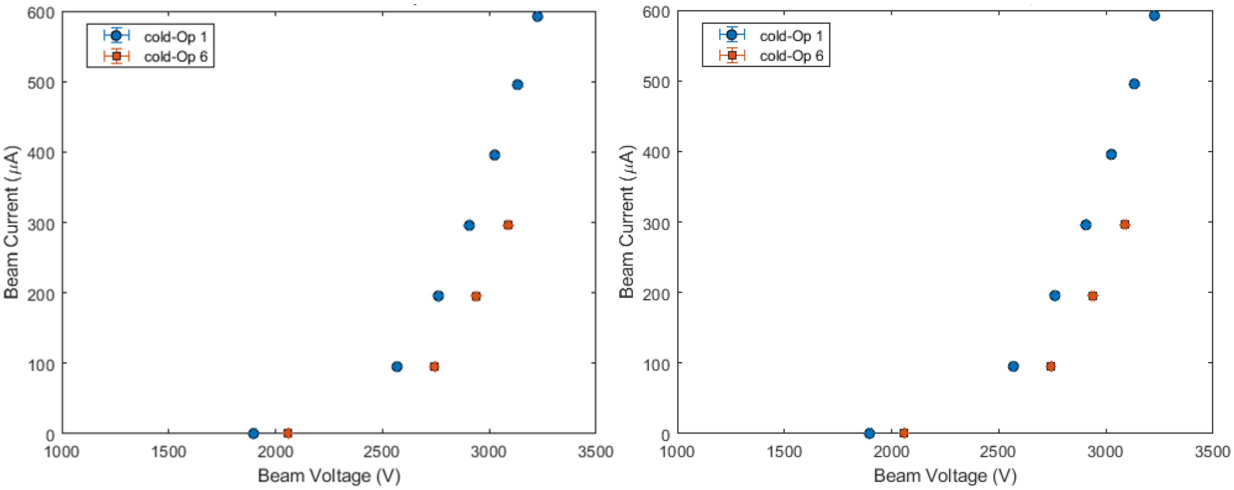

Fig. 23 0°C VI characteristics for thruster FM03 (left) and FM04 (right)

As previously reported [2], variations in thruster performance due to temperature, through the entire total impulse range of the BET-300-P has been characterized and the flight software automatically applies correction factors to thrust command mode based on the measured thruster temperature. This functionality was again verified as part of thermal-vacuum testing, as shown in Fig. 24, where the thrust command for both the left and right graph was 5μN, 25μN, and 50μN. However, the data on the left was taken at hot operational limits (40°C) and the right at cold operational limits (0°C). Operating at 0°C increases thruster specific impulse to greater than 1,000s and higher beam currents (~300μA @ 50μN) are required to obtain the same thrust. Temperature-corrected thruster parameters were back-calculated from this telemetry and verified against existing temperature relations and were in agreement.

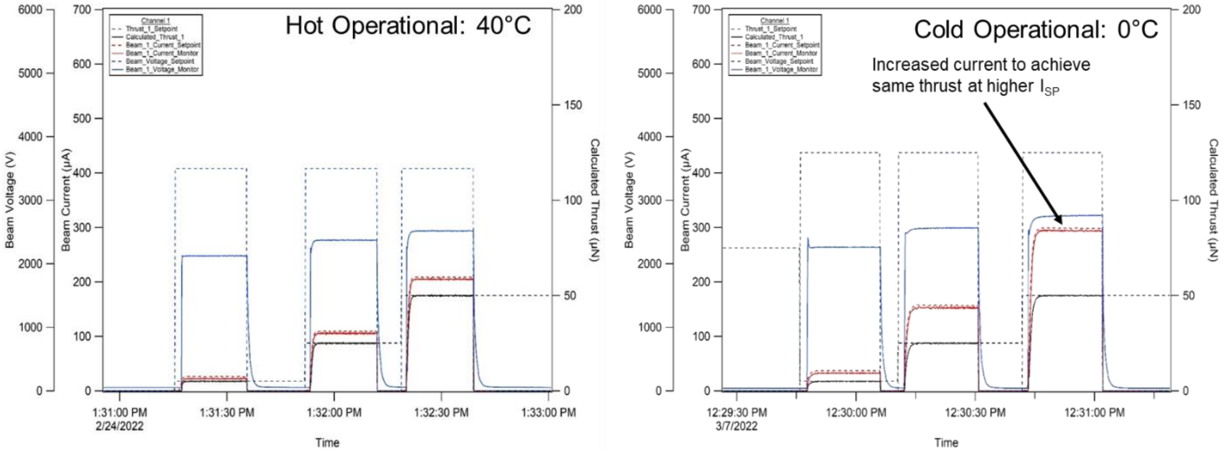

Fig. 24 FM01 operation in thrust command mode with automatic thrust temperature correction

VI.Future Plans

Future plans for the BET-MAX focus on providing electrical/mechanical and firmware interface documents to planners for mission trades, particularly missions focused on precision pointing, where the performance of the BET-MAX is unmatched. Busek also intends to restart life testing of the configuration B thruster that has accumulated 65Ns to date. Given the high specific impulse of this configuration, it offers considerably higher impulse density that will be advantageous for CubeSat missions, if it can reach the estimated 250Ns per thruster estimated by its present propellant loading.

VII.Conclusion

The BET-MAX system has successfully completed a protoflight qualification program and has been delivered for subsequent flight demonstration. Its disaggregated configuration is viewed to be optimal for ease of integration into spacecraft, especially for precision-thrust attitude control applications where mission planners distribute thrust vectors around spacecraft center of mass and pressure. The BET-300-P thruster has been well characterized and demonstrated to be a very robust mechanical design, with protoflight thrusters demonstrated here falling well within the range of previously observed thruster operating characteristics. Busek is leveraging its flight carbon nanotube field emission cathode with a single stage deflector to support charge balancing with the BET-300-P thruster. The electrospray and cathode control electronic architectures have demonstrated all the necessary functionality in a relatively compact electrical package that has functioned without issue in vacuum for periods commensurate with thruster lifetimes. All components of the BET-MAX protoflight system retained nominal functionality throughout protoflight qualification-level testing and have been delivered for an upcoming flight demonstration.

With the completion of a complete environmental program at the system level, the BET-MAX is now a Technology Readiness Level 6 (TRL6) system. Busek is now making this product available in the marketplace for mission planners to take advantage of the demonstrated high total impulse and precision pointing capabilities afforded by the BET-300P.

Acknowledgments

Prior BET-300-P engineering model development and environmental testing was funded as part of a NASA Phase II SBIR effort (80NSSC18C0052). BET-MAX system late-stage design, fabrication, and engineering model testing was funded by Air Force Phase III contract #FA9300-20-C-3002. Subsequent flight system fabrication and protoflight qualification was funded by Air Force contract # FA9300-21-C-6012.

References

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[1] Fedkiw, T., Wood, Z. and Demmons, N., “Environmental and Lifetime Testing of the BET-300-P Electrospray Thruster”, AIAA Propulsion and Energy 2020 Forum, Virtual Event, August 24-28, 2020.

[2] Demmons, N., Knott, J., Margousian, A., Fedkiw, T., and Alvarez, N., “Electrospray Attitude Control System Flight Preparation”, AIAA Science and Technology Forum, San Diego, CA, January 3-7, 2022.

[3] Courtney, D., Wood, Z., & Fedkiw, T., “Reconstructing electrospray plume current spatial distributions using computed tomography”, International Electric Propulsion Conference, Vienna, AT, September 15-20, 2019.

[4] Fedkiw, T., Wood, Z., & Demmons, N., “Improved Computed Tomography Current Mapping of Electrospray Thrusters”, 2021 AIAA Propulsion & Energy Forum, Virtual Event, August 9-11, 2021.

[5] Courtney, D., Alvarez, N., & Demmons, N., “Electrospray Thrusters for Small Spacecraft Control: Pulsed and Steady State Operation, AIAA/ASME/ SAE/ASEE Joint Propulsion Conference, Cincinnati, OH, July 9-11, 2018.

[6] Demmons, N., Margousian, A., Knott, J., Robin, M., and Chiu, Y., “Characterization of CNT Field Emission Cathode with Deflector Technology”, AIAA Science and Technology Forum, San Diego, CA, January 3-7, 2022.

[7] Hruby, V., Gasdaska, C., Falkos, P., Robin, M., Demmons, N., McCormick, R., Spence, D., Young, J., Connolly, B., “Carbon Nanotube Field Emission Cathodes as Neutralizers for Electric Propulsion”, International Vacuum Nanoelectronics Conference, Cambridge, MA, July 11-16, 2004.