Silicon Emitter Needle and Array Design for Indium Electrospray Arrays for Spacecraft Propulsion

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A design for silicon microfabricated emitter arrays was developed for electrospray thrusters for indium propellant in compact architectures with scalable thrust, low mass and volume, high specific impulse and high efficiency operation. The design elements include tip height, height uniformity across the array, tip radii, axial groove depth, tip angle, emitter shank sidewall angle and number of emitters. They were derived from commercial liquid metal ion source designs and modeling, fabrication and test results. The most critical results of the emitter array design analysis suggest that microfabricated silicon emitter array emitters should have a height greater than 280 microns with a height uniformity of +/-10 microns, a tip half angle of 49° for uniform turn-on voltages and current across the array, low beam divergence and high mass utilization efficiency. Elements of the design were fabricated and demonstrated in single emitter and in 400 element emitter arrays to validate the design, fabrication and performance capability. The design height and uniformity of arrays was demonstrated for 85% of the emitters in a prototype array. Required tip and sidewall angles and groove depths have been microfabricated. Single microfabricated silicon emitters demonstrated better performance in current and voltage characteristics than commercially available liquid metal ion sources. Microfabricated emitters and arrays demonstrated the required current and stability performance to enable the MEP thruster development for indium propellant.

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I. Introduction

Microfabricated silicon emitter array chip design has been developed to enable the development of electrospray thrusters with indium propellant with arrays of emitters for micronewton to millinewtons of thrust with high performance and compact architectures. These thrusters are underdevelopment for primary propulsion on small spacecraft, precision pointing large spacecraft and drag-free operations for small and large spacecraft. They operate at high efficiency, can be highly compact, scalable and distributable with arrays of emitters if they be fabricated with the required design and feature uniformity to deliver uniform and focused current distribution from an array. They can be highly compact with indium propellant because of its high density. The design was derived from published research results, demonstrated macroscale emitter designs, advanced microfabrication capabilities, thruster and emitter performance requirements for mission applications and microfabricated single and emitter array test results. The design details include emitter height and height uniformity, diameter, tip radius, tip angle and groove depth and shaft sidewall angle. The microfabricated silicon emitter array chip is the heart of the MEP thruster and the most challenging component to design, fabricate and test. A solid model illustration of the thruster configuration with the emitter array chip is in Figure 1. The thruster is discussed in detail in another paper [1]. Indium is preloaded onto the emitter array chip and then into the Propellant Management Device (PMD) and the PMD will replenish the indium through vias to the emitter tips by capillary forces. The PMD is not included in Figure 1. It will be integrated with the emitter chip and into the open volume in the assembly structure in the next phase of the technology development. The heater is bonded to the emitter chip to optimize thermal contact and efficiently melt the indium. High voltage is applied between the emitter array chip and the extractor to deform indium into liquid cones and extract and accelerate ions to create thrust. The emitter performance requirements are given in Table 1 for a 100-200 µN indium fueled MEP thruster. The design requirements are summarized in Table 1 and described in the following sections. Microfabricated single emitter and array test results are also included to verify the single emitter performance requirements and demonstrate the current performance capability of the fabricated emitter arrays.

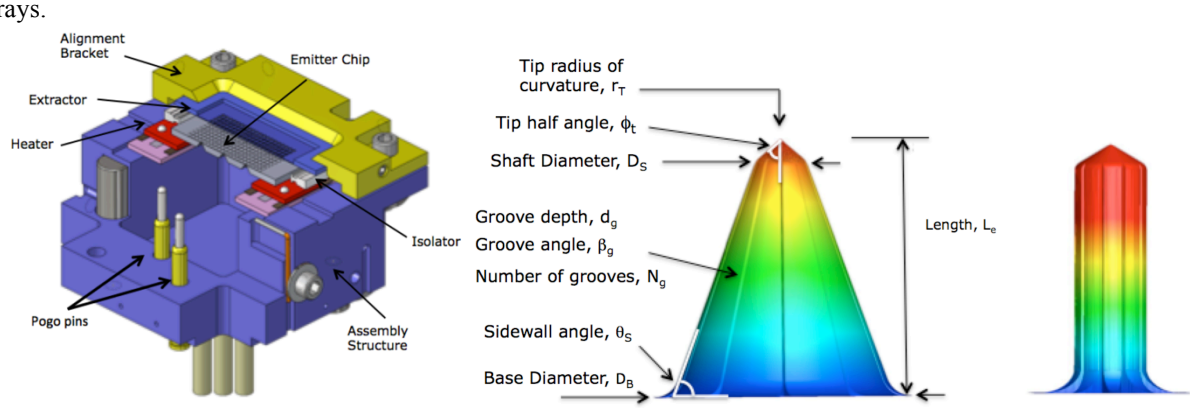

Figure 1. JPL MEP thruster configuration (left) and the emitter configurations and design elements (right).

Table 1. Emitter performance requirements.

Parameter	Emitter Array	Single Emitter	Rationale
Thrust (µN)	10-210	0.03-0.67	Total/320 emitters
Current (µA)	1600-3240	5-10	For 100% mass utilization
In flow rate (mg/s)	4.8×10^{-3}	15×10^{-6}	For current in ion mode
Number of emitters	400	1	To provide 200 µN
% on at nominal current	80	n/a	320 emitters required for total current
Operating voltage (kV)	< 4	< 4	For PPU and switch voltages

The current per emitter in the array and the number of emitters in the array for the required thrust level were derived from experimental and modeling results and to achieve 100% mass utilization efficiency. The emitters are required to operate in an ion emission mode for the required specific impulse of >1500s. Mair developed a model to predict the critical emission current at which the charged particle emission transitions from pure ions to ions and droplets. He predicted that droplet mode starts for a sharp needle emitter at 12.7-15.8 µA. [2] Published experimental data on indium electrospray thruster needle propellant mass efficiency [3] shows that the propellant mass efficiency of an indium needle emitter decreases quickly at current levels greater than 20 µA from 100% down

to 50% at 100 μA. Therefore, 5-10 μA current level was targeted for the emitters for emission in an ion mode with 100% mass utilization efficiency for maximum thruster efficiency.

II. Emitter Design

The emitter design has many critical features required for the MEP thruster development to a 200 μN propulsion system that have been derived from analysis, fabrication capabilities, test results, previous research and published work. A model of the emitter design is in Figure 1 with critical design elements identified. The design elements are summarized in Table 2 and described in detail in the following sections.

Table 2. Emitter design element summary.

Design Element		Value	Rationale
1	**Length of emitter, L_e, (μm)**	>280	To ensure that electric field drops by 10x between tip and emitter base
2	**Emitter base chip Height uniformity, ΔL_e, (μm)**	+/- 10	To limit turn on voltage range across the array to within 50V for current uniformity across an array
3	**Base diameter, D_B, (μm)**	100-250	For robust emitters and to provide spacing between emitters on a 500 micron pitch and indium flow through vias between the emitters
4	**Shaft diameter, D_S, (μm)**	30-50, 100-180	30-50 if tapered sidewall and 100-150 if straight for robust emitter with turn on voltages <4 kV
5	**Shaft Sidewall Angle, θ_S (°)**	65-90	1. To enable 500 micron emitter pitch and required tip base geometry. 2. Smaller angle receives higher deposition rate of indium and requires depositing less indium on the emitter chip
6	**Tip half angle, ϕ_T (°)**	49	1. Limits cone formation to the apex of the emitter to improve beam divergence 2. Eliminates turn-on voltage sensitivity to tip radius, therefore, tip radius uniformity does not need to be controlled precisely across an array [4] 3. Pins indium on the tip without applied voltage prevents draining when molten 4. Enables melting indium on the tips to smooth out indium surface morphology before start-up to improve uniformity across the array
7	**Tip radius, r_T (μm)**	2	1) Sharp tips have less steep I-V traces to mitigate current non-uniformity sensitivity to geometry variations 2) Sharp tips have more stable cones that are less likely to emit droplets at higher currents [5]
8	**Tip radius uniformity, Δr_T, (μm)**	+/- 1	Sharp tips have more stable cones that are less likely to emit droplets at higher currents [5]
9	**Depth of grooves, D_g, (μm)**	2-30	APTech emitters for FIBs and model of flow in v grooves shows that one 2 micron deep groove with 60° open angle and 400 μm length provides required flow rate for 10 μA from one emitter. Round grooves shallower than 10 microns did not work if large open angles, but worked if submicron width. One groove is required and 5-9 are redundant in case one or more become contaminated.
10	**Length of grooves, L_g, (μm)**	~275-500	
11	**Groove angle, β_g (°)**	45-120	
12	**Number of grooves, N_g**	6-10	

A. Macrofabricated Emitter Design Elements

Many of the microfabricated emitter design parameters are derived from the macroscale APTech electrospray emitters. They have been fabricated for the commercially available Focused Ion Beam (FIB) systems that electrospray gallium that have been loaded at APTech with indium and then electrosprayed at JPL. Images of the APTech emitter are shown in Figure 2. The tungsten emitter length is approximately 4 mm. The tip radius of curvature is ~10 microns. The tip half angle is ~50°. The diameter of the emitter is 180 microns. The tip roughness is 2-3 microns. The axial grooves have a depth of 2-10 microns to pull the indium from the indium reservoir to the end of the emitter by capillary forces. Indium distribution in the axial grooves and on the tip roughness after electrospraying is shown in Figure 3. The indium reservoir is a continuous tungsten wire coil from the emitter tip, as shown in Figure 3. It effectively transported indium by capillary forces and electrosprayed it stably, therefore critical elements of the macroscale needle design were captured in the microfabricated emitter design including the tip angle and groove geometry.

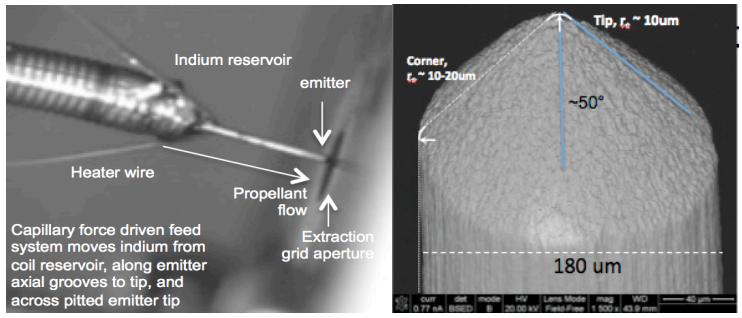

Figure 2. Macroscale tungsten emitter during testing at JPL (left) and before loading with indium (right).

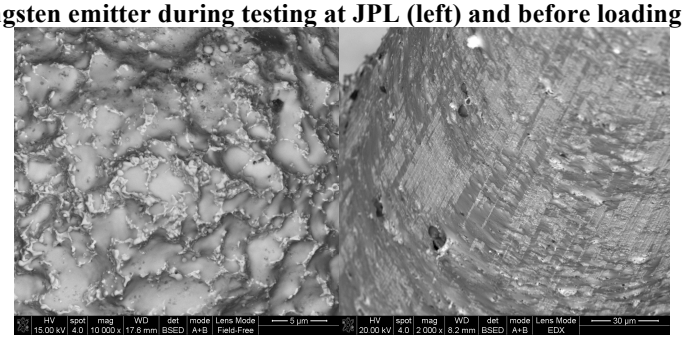

Figure 3. Macroscale tungsten emitter tip surface roughness and axial grooves along the shaft after testing at JPL. The scale of the roughness is ~2-4 microns. The scale of the grooves is 2-10 microns.

B. Microfabricated Emitter Design Elements

The microfabricated emitter design and feature tolerances are derived from the macroscale emitter design, microfabrication capabilities (demonstrated and expected), test results and modeling results.

1. *Emitter height*

The emitter height is important for the electric field distribution on the emitter. The sensitivity of electric field to emitter height was modeled in COMSOL to determine the emitter height required to achieve an electric field at the base of the emitter that is an order of magnitude lower than the electric field strength at the tip of the emitter to preclude emission cone formation at the base. The results in Figure 4 show that these conditions are met with an emitter tip height ≥280 microns. Therefore, the emitter design height is >280 microns, and preferred to be greater than 300 microns to include margin in the design and to improve high voltage isolation.

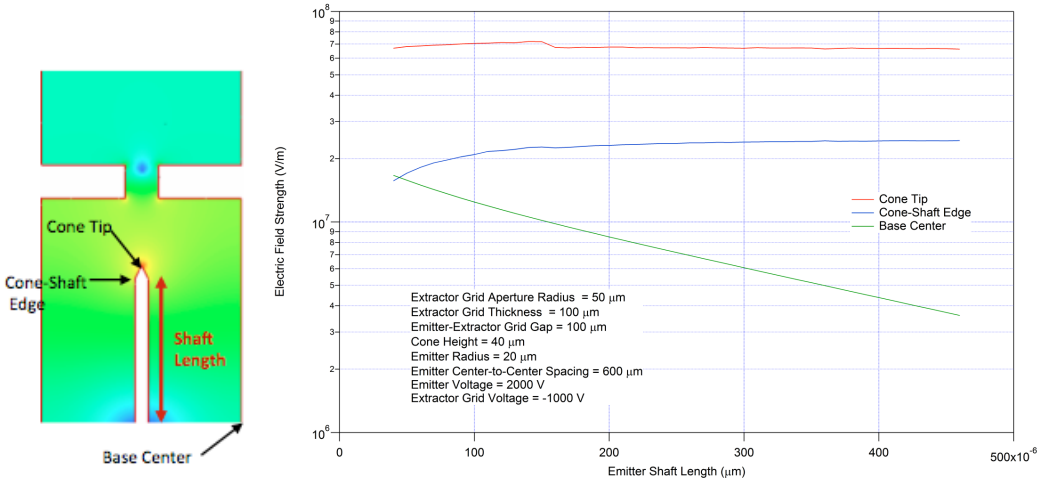

Figure 4. Electric field at the tip, cone shaft edge and base for a range of emitter shaft lengths showing that the electric field is an order of magnitude lower at the base for a length of ~280 μm.

2. *Height uniformity*

The emitter height uniformity is important across the emitter chip because it affects the current distribution across an array and total current capability, performance and lifetime. The emitter turn-on voltage varies with gap between the emitter tip and extractor. Single microfabricated emitter data show that emitter current can increase from 0 µA to >20 µA within <120 V near start-up and within <200 V after 65 minutes of electrospraying when some of the propellant has been drained. The single emitter current objective for the thruster is 10 µA. Test data showed that less than 1% of the current from a single emitter was intercepted by the extractor at ≤20 µA. The extractor aperture diameter in this test was 400 microns and the gap was 54 microns. The emitters will be operating within the range of that current depending on their turn-on voltage. If the turn-on voltage range of all of the emitters in the array varies by more than 100 V, then some emitters will be emitting more then 20 uA while others are just turning on. If emitters are emitting more than 20 µA, they could emit droplets, hit and sputter the extractor and contaminate the emitters and reduce operating efficiency and lifetime. The turn-on objective for all of the emitters is within less than 50 V of the first emitter turning on in the array at a voltage estimated by the critical cone stabilization voltage. The critical cone stabilizing voltage can be roughly predicted by $1432\gamma^{1/2}R_o^{1/2}$. [6] R_o (cm) is the distance between the emitter and extractor aperture and γ is the surface tension (556 dynes/cm for indium). Figure 5 shows the average extractor gaps and emitter height uniformity required to achieve turn on for all emitters in the array in less than 50 V. In this case, all of the emitters should be operating at less than 20 µA of current and not impacting the extractor to cause premature failure. The curves in Figure 5 show that an emitter height uniformity of +/-10 µm will require an average extractor gap of 40 microns for a turn-on voltage range less than 50 V. These requirements have been achieved and demonstrated by the microfabricated emitters and in testing at JPL. Emitter height fabrication uniformity is shown in Figure 6 for one emitter array chip. Height uniformity of +/- 10 microns has been microfabricated in an array of 400 emitters for 85% of the emitters. Smaller gaps and better uniformity will further improve the turn-on voltage range for the array and current uniformity. They are achievable with our emitter array chip and heater microfabrication, other thruster component macroscale fabrication and thruster assembly process. The e-beam technology approach of writing the mask patterns will enable 100% of the emitters to achieve the desired height and uniformity by writing a distributed mask pattern and using a reactive ion etching system with a more uniform etch rate across the array of emitters.

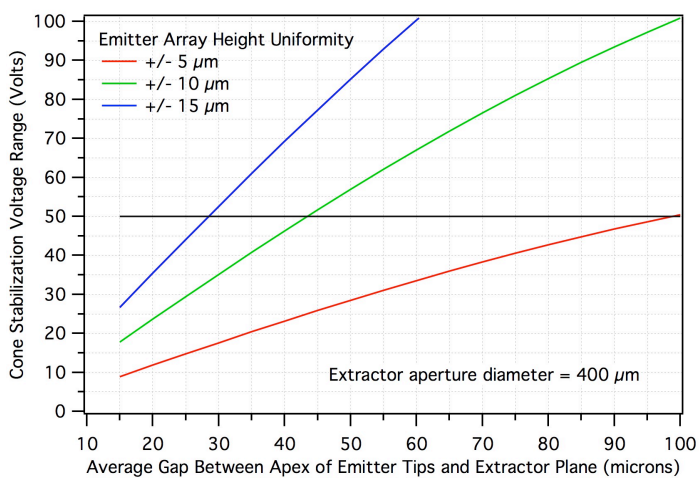

Figure 5. Cone stabilization range for emitter height variations in an array of +/-5, 10 and 15 µm for a range of average grid gaps for an array. The graph shows the stabilization voltage sensitivity to gap and emitter height uniformity required to achieve a 50 V range for all of the emitters in an array to enable uniform current distribution.

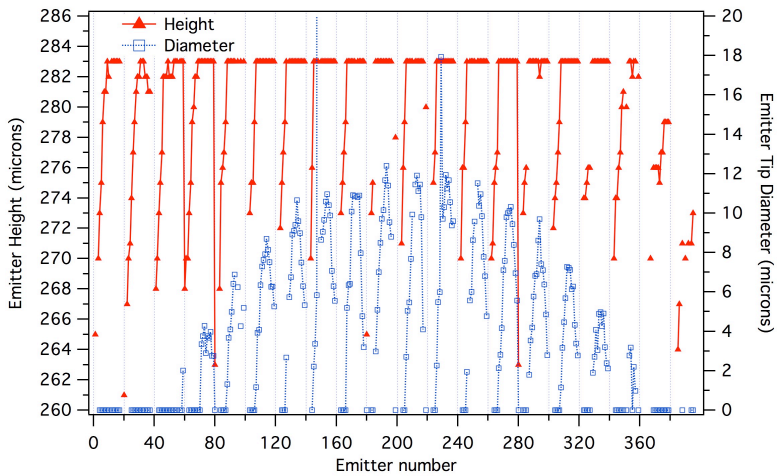

Figure 6. Emitter height and tip radius distribution of a microfabricated array of 400 emitters. The height of 184 emitters is ~283 microns. The height of 232 (58%) emitters is within +/- 3 microns of 283 microns. 264 (66%) of the emitter heights are within +/- 5 microns of 283 microns. 340 (85%) emitters are within +/- 10 microns of the 283 micron height.

3. Shaft Diameter

The emitter array shaft diameter is important for robust emitters, to support multiple axial grooves and to achieve the required operating voltages. Emitter array testing results revealed that microfabricated emitters with a 180 micron diameter shaft and length of 400 microns with an extractor gap of 100 microns required over 4 kV to emit only ~100 µA of current despite being very well loaded with indium propellant. Emitters with much smaller shaft diameters and the same extractor gap electrosprayed comparable currents at voltages below 4 kV. Thruster emitter array operation at 3240 µA for 200 µN is required at < 4 kV. Experimental data published by Bell and Swanson [7] on the threshold voltage at several shaft diameters and emitter radii in the range of 0.5 to 11.4 microns at a half cone angle of 49° shows that the threshold voltage significantly increases with shaft diameter. The shaft diameter design in the microfabricated emitter arrays is 30-50 microns for a tapered emitter and 100-150 microns for a straight–walled emitter to ensure that it is both robust and has an operating voltage less than 4 kV with a ~50° tip angle.

4. *Shaft sidewall angle*

The shaft sidewall angle is important for propellant loading and tip pitch on the emitter array chip. Emitter designs were fabricated with different sidewall angles. The needle emitter has a straight sidewall at 90° from horizontal at the tip. The tapered emitter has a sloped shaft sidewall. Analysis using COMSOL software has shown that increasing the width of the base does not affect the electric field at the tip. It does provide two advantages in the design including reducing the electric field at the tip corner to mitigate the risk of emission cone formation there. The sloped sidewall emitter also requires less indium loading for complete emitter sidewall and groove coverage than the straight sidewall on the needle emitter. The results showed that even a 10° taper results in a 33% higher sidewall indium loading rate than a straight sidewall in the indium thermal evaporation facility. Figure 7 shows the configuration of the loading facility at JPL with the emitter chip, QCM and thermal evaporation source of indium. The loading rate of the emitter shown in Figure 7 was modeled. The height of the emitter is 265 microns with a tip half cone angle of 33° and a shank sidewall angle of 82°. The grooves are about 3 microns deep with a ~120° open angle. Modeling results, shown in Figure 7, suggest a deposition rate on the emitter sidewalls that is 0.28x the chip base rate (between the emitters), and is 0.21x the base rate at the groove base. At these rates, the needle emitter will require deposition of 14 microns of indium to get 3 microns in the grooves at the base of the emitter where the deposition rate is the lowest. The outer sidewall of this emitter will require deposition of only 10.7 microns, as indicated by the QCM, to deposit 3 microns on the outer sidewalls. Reducing the shank sidewall angle further towards 65° will increase the deposition rate on it and reduce the amount of indium to deposit to achieve a continuous 3 micron thick indium film on the emitters across the emitter array chip. Extensive deposition tests have shown that deposition of 3 microns of indium is required for a continuous film of indium under the loading conditions in the facility employed, because of the rough surface morphology of the films deposited. The angle cannot be decreased beyond ~65° if the 500 micron emitter pitch is to be maintained and because the reactive ion etching process at smaller angles results in silicon grass on the emitter sidewalls that disrupts the axial grooves.

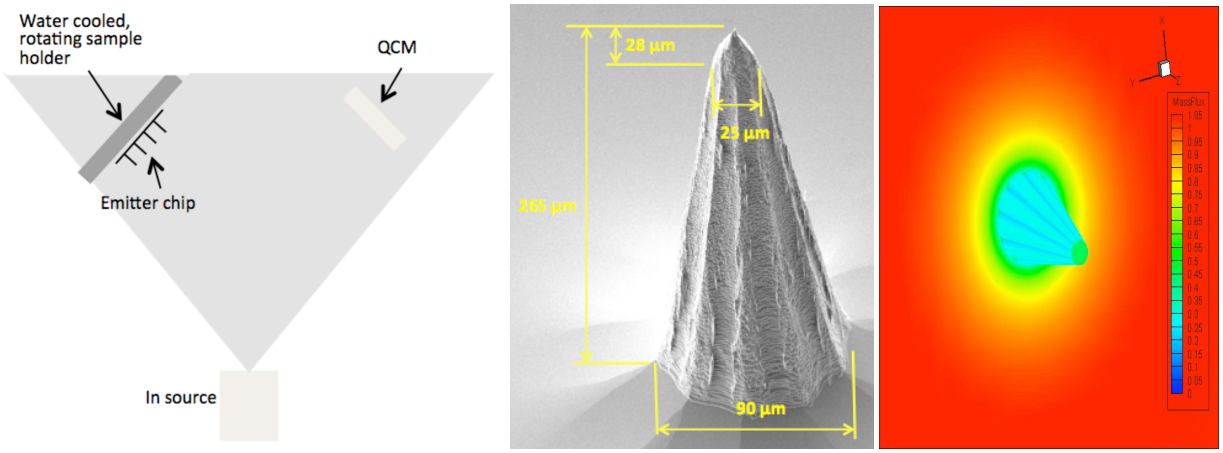

Figure 7. Configuration of facility used for loading the emitter array chips with indium (left), an emitter (center) and modeling results (right)

5. Tip half angle

The emitter tip angle is critically important for multiple reasons. It can affect the location of the emission cone on the emitter tip. It affects the capability of the tip to hold indium with or without voltage applied. It affects the turn-on voltages, increasing turn-on voltage with cone half angle. It has been shown that if the emitter tip angle is 49°, then the emitter turn-on voltage is not sensitive to the tip radius [8]. Tip radii of 1-10 microns and half angles of 30-50° were considered. This result is incredibly important for the development of an indium electrospray thruster with arrays of emitters. It is important because it suggests that the emitter tip radii uniformity does not have to be controlled in the fabrication process also across the microfabricated array of emitters to achieve uniform turn-on voltages within 50V. Precisely controlling this feature across the microfabricated array of emitter would have been much more difficult than precisely controlling the emitter tip height.

The tip angle is important to control indium distribution and enable reliable and repeatable operation and start-up. A tip with a cone half angle greater than 49° will trap the indium on the tip when it is molten to improve start up surface morphology and therefore cone start-up uniformity. If indium is pinned by capillary forces at the tip of the emitters, all of the emitters will have indium on them at start-up and it will not drain off of the tips without applied voltage. Heating the emitters up to 250°C in this state will enable smoothing out of the indium uniformly across the array as the rough oxide crust has been observed to smooth out or dissolve into the molten indium at this temperature and the surface becomes very smooth. The emitter in Figure 8 shows how the tip can maintain a film of indium on the tip even when heated above the melting temperature without applied voltage. If the emitter tip angle is much smaller than 49°, then it has been observed that the indium drains off of it when heated above the melting temperature without applied voltage. This condition will result in unpredictable and non-uniform emitter start-up across the array of emitters, if at all.

Recent preliminary modeling results show that an emitter tip with a half-cone angle of ~49° is also more likely to support the formation of only one emission cone on the apex of the emitter through a broad range of expected indium film thicknesses. [9] This modeling was conducted at Caltech by Prof. Sandra Troian and Teddy Albertson using COMSOL Multiphysics software. It is a 2D axisymmetric model that includes the emitter and extractor geometry, the indium fluid and the applied electric field. It models the flow distribution of the indium on the emitter in the applied electric field. This result is significant because having only one emission cone on the apex of the emitter will minimize the beam divergence and the current intercepted by the extractor to maximize performance and lifetime. The modeling results suggest that if the tip half angle is 30°, then off axis emission sites can form with indium film thicknesses within our expected range. Multiple cones have been observed frozen in place on the emitters in post-test inspections. The modeling results suggest that if the tip half angle is 49°, then only one cone forms on the apex of the emitter at expected film thicknesses. Operating the emitters with a single emission site anchored on the apex of the emitters is imperative to the successful operation of arrays of emitters in a thruster for the required performance and lifetime. The emitter tip half angle design is 49°.

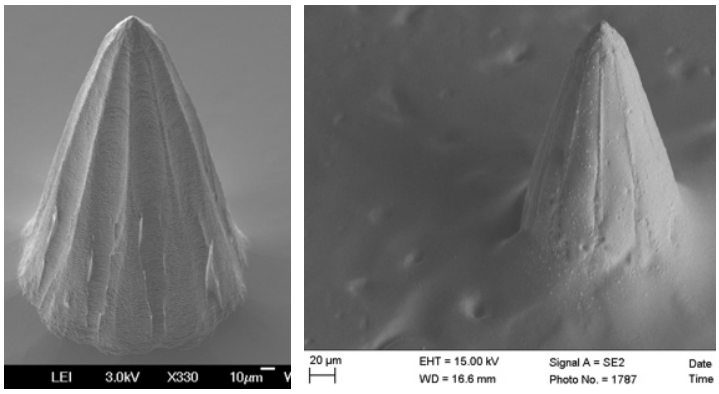

Figure 8. An bare silicon emitter (left) and the same emitter after loading with indium and melting the indium to flow on the emitter (right) without an applied electric field.

6. *Tip radius*

The tip radius is important because it can affect the turn on voltages, current and voltage characteristics, emission stability and emission cone base radius. The tip radius requirement is derived from the macro emitter design and published electrospray emitter data. Research results on the sensitivity of emitter I-V slope and turn-on voltage to emitter tip radius showed that sharper emitters and smoother tips resulted in less steep I-V traces. [11] Needle and capillary emitters with indium and gallium and smooth and rough emitters were considered. Tip radii were 3-10 microns for needle emitters and 50-400 for capillary emitters in the investigation. Steep I-V characteristics for an emitter will result in high current sensitivity to electric field and therefore emitter geometry and gap variations. Electric field variations across an array will be caused by emitter height and grid gap variations and will cause emission non-uniformity which could limit the performance and lifetime of an array of emitters prohibitively for spacecraft applications. Smaller tip radii are suggested to improve both turn-on voltage and I-V slope, however, uniformity of radii is also important if the tip angle is not ~49°. A ~1 micron tip radius is recommended for a stable emission cone [10] from a study of cone instabilities and droplet emission. A 2-10 micron tip radius has been recommended to encourage the formation of a single cone-jet at its apex [11]. The APTech emitter radius is ~10 microns. The tip radius design target for the MEP emitter array chips is ~2 microns.

7. *Grooves*

The axial grooves are important to deliver indium to the emitter tip and maintain a continuous film of indium on the emitters with or without an applied voltage using only capillary forces. The flow of indium in axial grooves has been modeled using COMSOL multiphysics software to determine the design of the grooves capable of supporting the required flow rates with the expected electric field applied. The modeling results show that 2 micron deep v-shaped grooves with a length of 400 microns are capable of providing much more than the required 15×10^{-6} mg/s for 10 μA of current. [12] The model considered groove depths of 1 to 10 microns. The flow rate capability increased from 1 to 10 micron groove depth. The results show that 2 micron deep grooves with a 400 micron length and 70° open angle can support more than 10^{-14} m^3/s, which is 73×10^{-6} mg/s. The results suggest that 70° grooves provide the maximum flow rate. 6-10 grooves are included in the emitter design, however, only one groove is necessary to deliver the required flow rate of indium to a single emitter tip.

III. Emitter Tests

Indium-fed single and arrays of electrospray needles were tested for performance and for the design development of all of the components of the MEP thruster. The emitters were tested for current range, voltage range and stability performance characterization to demonstrate their performance capability, develop operating procedures and characterize the performance of the extractor and isolator with them. Both macro and microscale single emitters were tested to understand their performance capability. The performance of the silicon microfabricated emitters was compared with a tungsten needle electrospray emitter that is an industry standard needle used in Focused Ion Beam (FIB) systems.

A. Test Apparatus

The thruster and components were tested in the Microthrust Propulsion Laboratory (MPL) cleanroom at JPL using multiple facilities and test fixtures. The test facilities included a 10 inch ultra-high vacuum cube and 12 inch diameter cylindrical vacuum chamber with indium or indium and tungsten beam targets. The facilities achieve base pressures of approximately $5x10^{-7}$ Torr using turbomolecular pumps. The test fixtures are shown in Figure 9. The APTech emitter and Vogel mount assembly was integrated with a 2.75" conflat flange and then mounted onto a UHV chamber port. The extractor material was porous stainless with a 0.75 micron thick film of titanium. The extractor aperture diameter was 1.27 mm with no axial emitter gap, such that the apex of the emitter was flush with the entrance of the extractor plate. Figure 9 shows the test fixture for the silicon emitter chips. This test fixture enables micronscale component alignment uniformity with the emitter chip, isolator and extractor stacked on a precision silicon plate with alignment marks on a copper block with a Watlow AlN Ultramic ceramic heater behind it. The isolator material was macor. The extractor material was silicon with titanium and gold metallization for the single emitter tests and tungsten for the emitter array test. The extractor aperture diameters were approximately 400 microns and the axial distance to the emitter was approximately 54 microns. This assembly was mounted inside of a UHV cube for testing. The electrical schematic is shown in Figure 10. Ultravolt high-voltage regulated DC-DC converters were used to control the emitter and extractor current and voltage to microampere current levels. High voltage electrometers were used to measure emitter, extractor and beam target currents at high voltages. A National Instruments LabVIEW Data Acquisition System was used to control the power converters and record currents, voltages, temperatures and pressure. National Instruments BNC 2110 modules were used with a PCI 6229 card to record data and control the power system at >10 Hz.

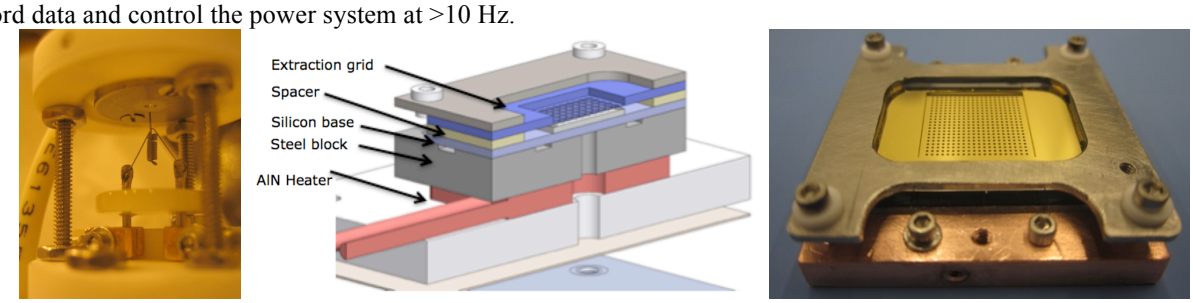

Figure 9. Macroscale tungsten emitter test fixture (left) and microscale silicon emitter array chip test fixture design (middle) and test assembly (right) with a silicon and gold extractor.

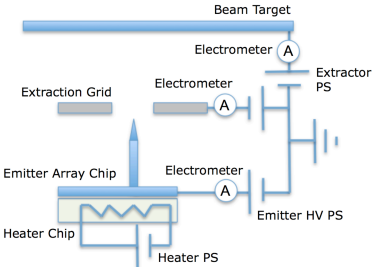

Figure 10. Emitter and emitter chip test electrical schematic.

B. Macrofabricated Emitter

A tungsten needle emitter from APTech was tested to characterize current and voltage range, and stability. Current and voltage data are shown in Figures 11 and 12 in the range targeted for single emitters in the MEP thruster of 5 to 10 μA. A micrograph of a single emitter is shown in Figure 2. This single emitter operated for hundereds of hours at JPL and stably at more than 12 microamperes of current and at over 25 microamperes temporarily at 4.8 kV.

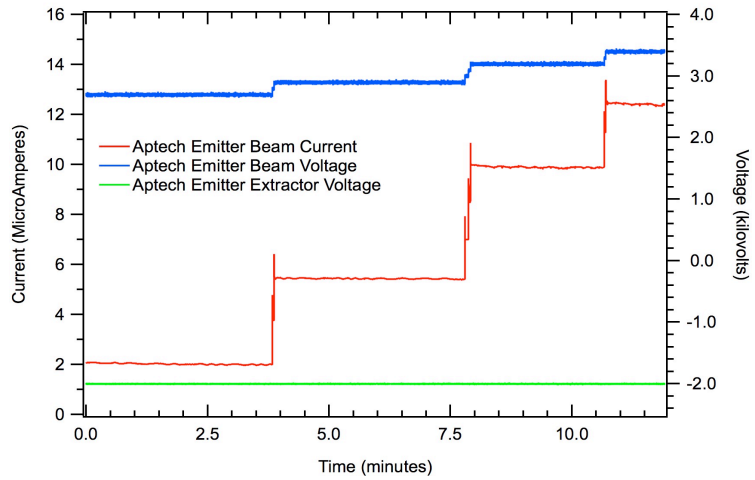

Figure 11. APTech macroscale tungsten emitter tip performance data.

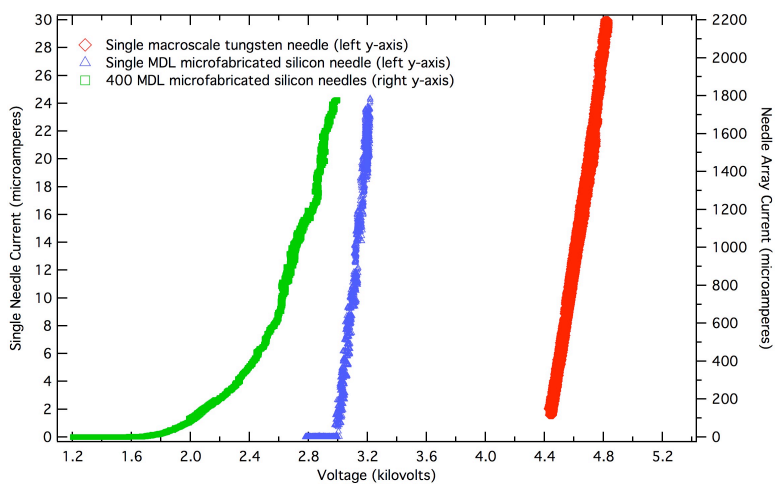

Figure 12. APTech macro emitter electrospray data (left) and a comparison to microfabricated emitter data from a DARPA/JPL project (right).

C. Microfabricated Emitters

The microfabricated silicon emitters were tested to characterize current, voltage, and stability in the targeted current range for a single emitter in the MEP thruster emitter array and significantly beyond it. A micrograph of the single emitter array emitter tested is in Figure 13. The height of the emitter is 336 microns. The tip radius of curvature was ~0.25 microns. The emitter had 10 grooves that were about 3-5 microns deep. Current and voltage data are shown in Figures 12 and 13. It was operated beyond the range of current targeted for single emitters in the MEP thruster. The extractor material was silicon with titanium and gold metallization. The extractor gap was 54 microns with an extractor aperture diameter of 400 microns. Both the emitter and extractor currents are included in the graph. Within the 50 minutes of operation, the I-V trace only shifted higher in voltage by approximately 100 V as typically observed with propellant consumption since the chip is not being replenished with indium without an integrated reservoir. These data show that the single emitter and extractor assembly can operate from <1 μA to >20 μA with less than 1% of the beam intercepted by the extractor. The emitter turned on at 3-10 μA, but could turn off at 1 μA. The data show that the emitter current turns on and then increases up to 10 μA within 100 V and 20 μA within 200 V. The MEP thruster project objective for the emitters in the arrays includes 5 μA/emitter for 100 μN and 10 μA/emitter for a total thrust of 200 μN. The higher current range capability allows for 100% margin on the emitter current requirement. Emitter stability data over 60 minutes is shown in Figure 14. It operated at 6.4 μA with a current fluctuations of +/-0.5%. Post-test inspection of the emitter revealed that a continuous film of indium was maintained in the axial grooves and on the tip as required throughout operation for stability and repeatable turn on voltages and currents and performance. The current-voltage data for this single microfabricated silicon emitter is

compared to the industry standard single macrofabricated APTech tungsten emitter performance in Figure 12. The data comparison shows that the microfabricated emitter and extractor configuration not only operated at equivalent current levels, but even at higher currents and lower voltages than the macroscale emitter and extractor. This demonstration validated the performance of the microfabricated silicon emitters for the thruster development for 100-200 micronewtons from 400 emitters.

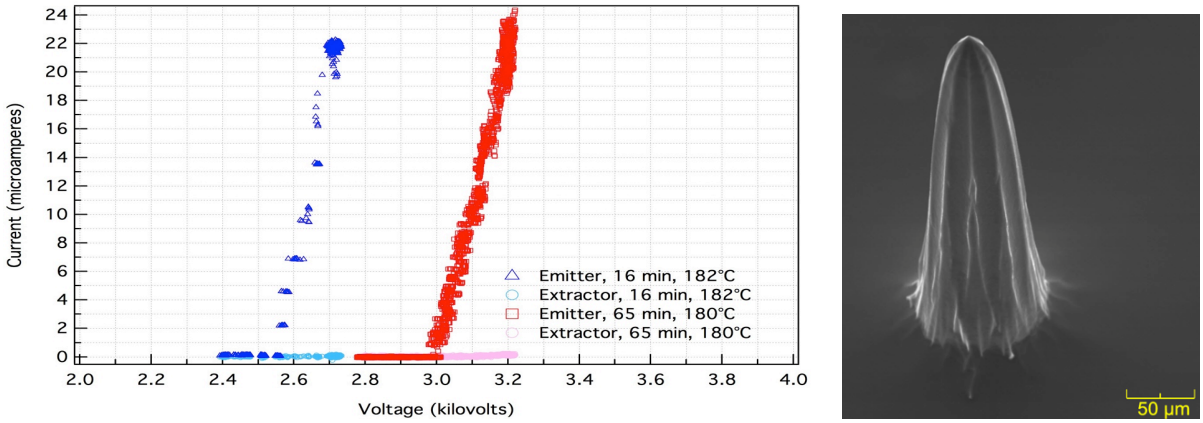

Figure 13. I-V characteristics of a single emitter (left) and the emitter tested (right) showing that the current increases from 0 µA to >20 µA within 120V near turn-on and within 200 V after electrospraying for 65 minutes.

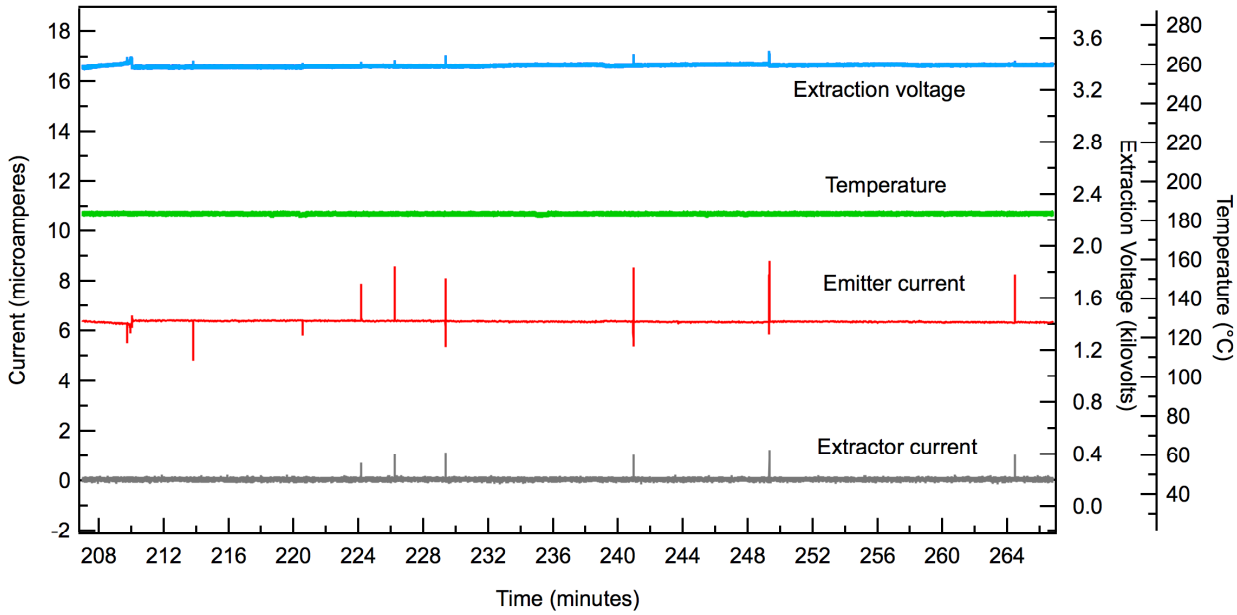

Figure 14. Microfabricated emitter array stability data over 60 minutes.

D. Microfabricated Emitter Arrays

Prototype thruster emitter array chips were also tested to verify the required perforamnce before integration and testing with the thuster. They were tested for total current, voltage, stability and extractor efficiency with only 7.43 mg of indium. There were 400 emitters in the arrays. The emitter array emitter heights were ~244-298 microns. The tip radii were ~1-2 microns. The emitters had 6 axial grooves. The indium was loaded onto them by a thermal evaporation process at JPL. Data from tests with emitter chip EW9#4 are shown in Figure 15. The extractor gap was 42-81 microns. The extractor material was tungsten with tapered apertures that had a diameter of ~400 microns at near the emitter and ~450 microns at the downstream surface. The test was conducted to demonstate the 1600 µA current range and to determine the current level with only 1% of the beam current to the extractor. The current was reduced after turn-on to 400 µA to achieve that extractor current level. The data show that the 25 µN thrust level at 400 µA can be achieved at <4kV with <1% of the emitter current intercepted by the extractor with a 400 emitter array for 60 minutes with 7.43 mg of propellant. This chip was tested up to 3200 µA temporarily to demonstrate the

200 µN thrust level capability of the emitter. A post-test emitter micrograph is in Figure 16. It shows excellent indium distribution on the emitter with an indium cone frozen on the apex of the emitter and no evidence of off-axis emission cones. Post-test inspection of the emitters revealed that the emitters were not eroded in any way and any tungsten contamination from the extractor was below the limit of the Energy-dispersive X-ray spectroscopy (EDS) detector in the electron beam microscope**.** Post-test inspection of the extractor revealed that some tungsten sputtering occurred and indium was deposited on most of the apertures, suggesting that more than 99% of the emitters electrosprayed. Current and voltage characteristics were taken at multiple times throughout the 60 minute long test with repeatable results. These tests were conducted on a second emitter chip, EW9#6, to demonstrate repeatability of the results and perforamnce of the emitter array chips. The extractor gap was 26-81 microns in that test. The test results are in Figures 17 and 18. They are very similar to the test results from emitter array chip EW9#6 in current, voltage and stability. This chip was tested up to >1600 µA temporarily to demonstrate the 100 µN thrust level capability of the emitter. The voltage shifted to higher values with propellant consumption for the same current range. This issue will be resolved with ingration of a propellant reservoir to replenish the indium on the emitter chip. The results of the post-test inspection conducted in the SEM were consistent with emitter chip 9#4. The emitters did not appear to be contaminated or eroded. The pattern of the indium deposited onto the extractor suggested that 98% of the emitters electrosprayed indium.

These test results both validate the feasibility of the technology, the emitter array fabrication process and some of the critical emitter features. Limited resources were available for the emitter array fabrication and testing. The results also demonstrated the need for improved emitter array tip angle and grooves and uniformity in height beyond the emitter arrays that were fabricated to achieve the required design as described in Table 2 to reduce beam divergence and extractor current to increase efficiency and lifetime at higher current leveles for the thruster devleopment. The proposed design feastures were demonstrated in different fabrication cycles to prove the capabilty, however, the project ended before the emitter array chips with all of the recommeded design features were accomplished.

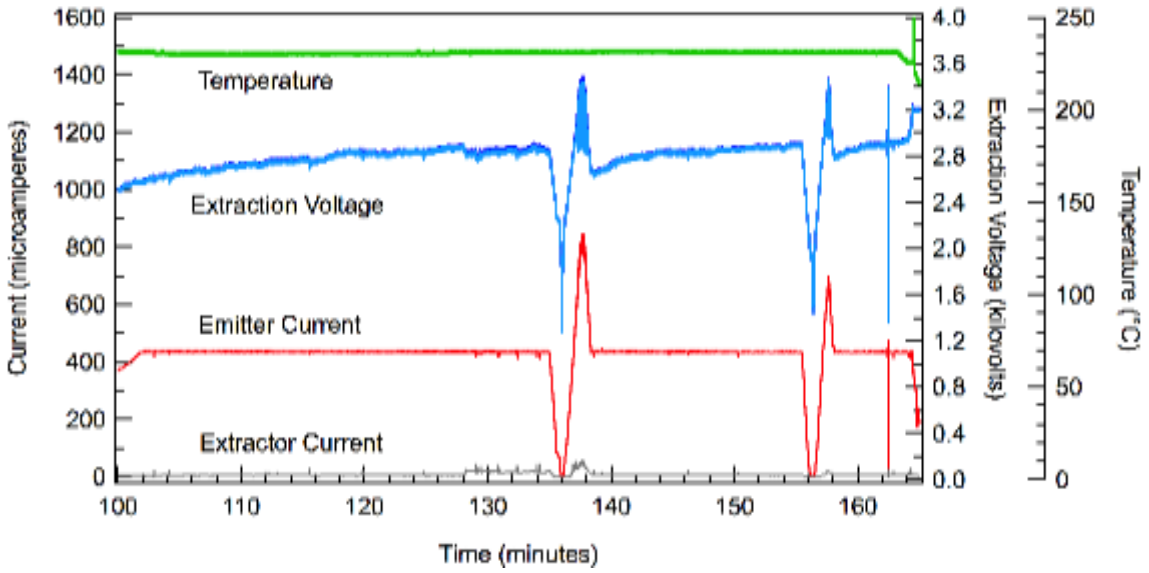

Figure 15. Emitter array chip EW9#4 current, voltage, temperature and stability data in a 60 minute test. The extractor gap was 42-81 microns and extractor aperture diameter was 400 microns.

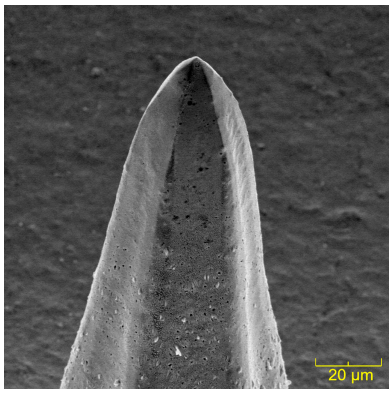

Figure 16. Post-test emitter image.

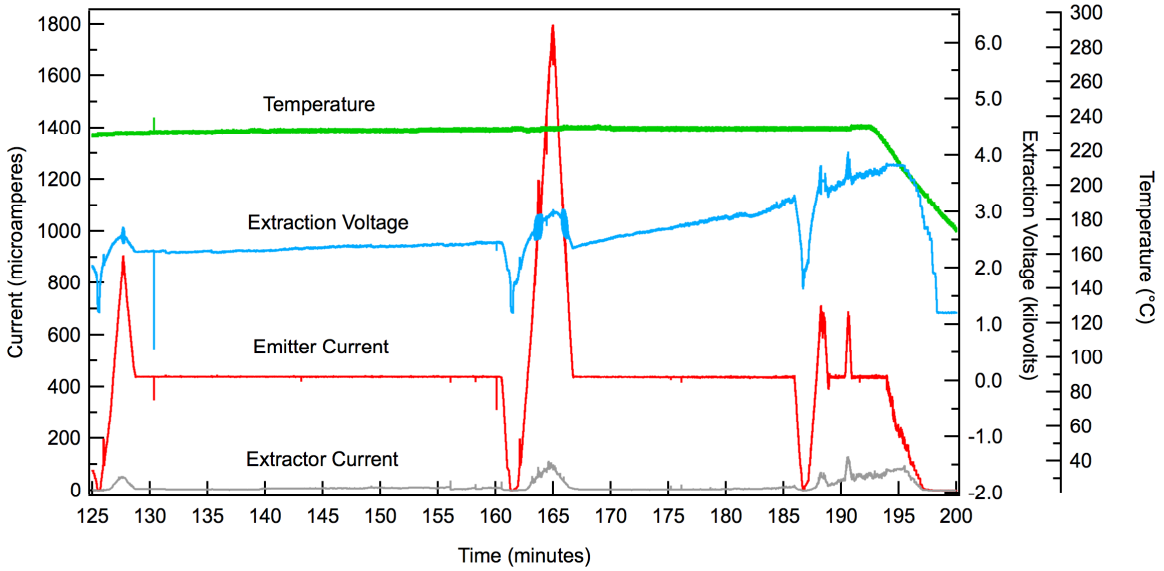

Figure 17. Emitter array chip EW9#6 current, voltage, temperature and stability data in a 60 minute test. The extractor gap was 26-81 microns and extractor aperture diameter was 400 microns.

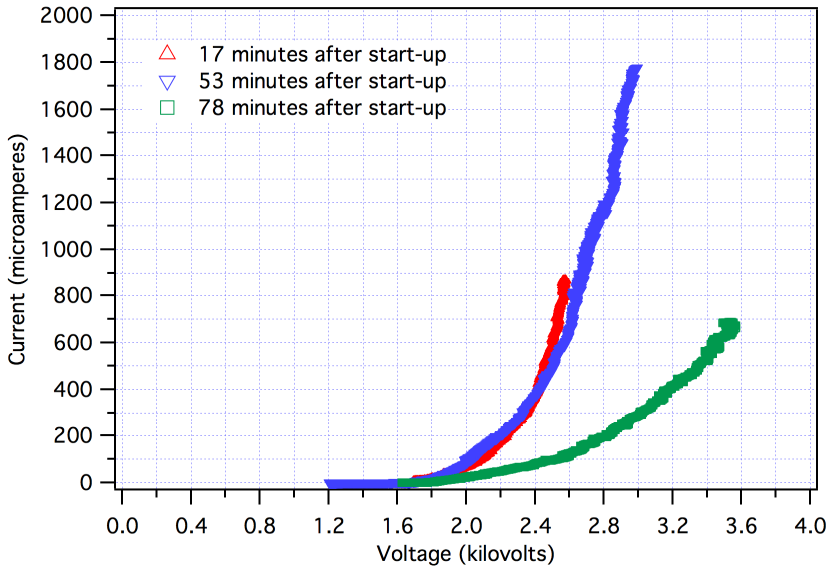

Figure 18. Emitter array chip EW9#6 current-voltage data.

IV. Conclusion

A prelimiary indium-fueled MEP thruster emitter array design was developed and the feasibility of the microfabrication and performance capabilty of many design elements was demonstrated. Required emitter tip heights, tip radii, groove shape, number of grooves, groove length, sidewall angle and number of emitters electrospraying have been demonstrated for different emitter array chips to validate the capabilty of the microfabricated emitter array chips and fabrication process to make them. The most critical elements of the design of the emitters to enable the development of emitter arrays for electrospray thrusters for indium propellant is the tip angle of ~49°, emitter heights > 280 microns and height uniformity of +/- 10 microns across the array. Single emitter array emitters fabricated in this project demonstrated perforamance better than industry standard macrofabricated emitters, validating the expected capability of the fabrication approach and thruster technology. The emitter height and uniformity across an array of 400 emitters in 1 cm^2 was demonstrated for 85% of the emitters without process optimization. The emitters had continuous axial capillary grooves, sloped sidewalls and tip radii of ~1 micron. Test results demonstrated excellent performance in current and voltage and current stability to meet the MEP thruster development requirements for 400 emitters to provide 100-200 μN of thrust. Test results suggested that 98% of the emitters sprayed in 2 different emitter array chip tests with 400 emitters. Further improvements beyond these demonstrations are required in the fabrication process to achieve the proposed emitter array design for both thruster performance and lifetime. However, this technology and approach to fabrication of the required emitter array design was demosntrated to be feasible and will enable the MEP thruster development for indium propellant for 100-200 μN thrusters or possibly larger.

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