Electrospray Thruster Performance with Microfabricated Emitter Arrays and Indium Propellant

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The feasibility of a microfabricated indium-fueled electrospray thruster with excellent performance was demonstrated. High efficiency electrospray thrusters with microfabricated components are under development for very compact, distributable propulsion systems that can be employed on both very small and large spacecraft with 10X improvement over SOA in mass, volume and specific impulse The critical components of this technology are the microfabricated emitter arrays and the capillary force driven indium feed system. Grey scale electron-beam lithography patterning and reactive ion dry etching provided the required micron-scale etch precision and uniformity across an array of 400 emitters in 1 cm^2. Initial tests of single microfabricated silicon emitters demonstrated better performance than industry standard single emitters and the performance required to achieve 200 micronewtons when scaled up to a thruster with 400 emitters in 1 cm^2. Arrays of emitters tested in a preliminary prototype Microfluidic Electrospray Propulsion (MEP)

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thruster assembly demonstrated stable performance at estimated thrust levels of 5, 50, and 120 µN at extraction voltages less than 4 kV. Current stability was within 0.15 % at 120 µN with only 1.5% of the emitter current collected by the extractor electrode. Post-test inspections revealed that more than 99% of the 400 emitters were electrospraying during the test. Specific impulse was estimated to be >3100 s from measurements of total charge and consumed indium mass at an emitter voltage of 1470 V. The results of this investigation suggest that microfabricated indium electrospray thruster technology is both feasible and capable of excellent performance as a highly compact microthruster.

I. Introduction

Electrospray thruster technology enables compact, distributable propulsion systems that can be employed on small and large spacecraft for attitude control, precision pointing, and primary propulsion with extraordinary delta-V capability. In electrospray thrusters the ion formation and acceleration processes occur over micron dimensions, allowing the use of microfabricated emitter arrays. Liquid propellants such as indium allow the use of capillary-driven flow, which enables highly compact thruster head and feed system architectures. An electrospray propulsion system could deliver thousands of m/s of delta-V to cubesats for interplanetary exploration. They could also replace reaction wheels to precisely point small space telescopes or large exoplanet observatories. The state of the art in electrospray thrusters is the Colloid MicroNewton Thrusters (CMNTs) [1], which are now flying on the LISA Pathfinder (ST7) mission to demonstrate drag-free operations for future gravity wave detection missions such as the Laser Interferometer Space Antenna (LISA) mission. [2] State-of-the-art flight-qualified electrospray thruster system technology has a mass on the order of kilograms, a volume on the order of thousands of cm3, and thrust of 10s of micronewtons and specific impulse of hundreds of seconds. This technology will improve on the state of the art by an order of magnitude in mass, volume, thrust and specific impulse. Indium electrosprays have been developed for spacecraft propulsion systems and have flown on spacecraft for charge control as liquid metal ion sources (LMIS). [3] Similar LMISs using liquid gallium and tungsten needle emitters provide ion beams in commercially available Focused Ion Beam (FIB) systems. Ion sources with several emitters have been developed and arrays of microfabricated emitters have been attempted with limited success to enable a highly scalable electrospray propulsion at micronewton to millinewton thrust levels. [4,5]

Electrospray technology is highly miniaturizable because the ion formation and acceleration processes occur on micron scales and because of recent advances in microfabrication capabilities. An electrospray source includes an externally wetted needle emitter with axial capillary grooves or an internally wetted capillary needle, a propellant reservoir and an opposing electrode with a spray-through aperture aligned with the emitter needle, as shown in Figure 1. An indium electrospray thruster includes a heater to maintain the indium temperature above the melting point of 156.4°C. The emitter is positively biased and the extractor is negatively biased with thousands of volts between them to create a very high electric field at the apex of the emitter. This field distorts the liquid indium on the tip into a cone shape, from which charged particles are extracted by field evaporation or field ionization and then accelerated to high velocities to create thrust. The emitter needles have tip radii on the order of microns with a shank diameter on the order of 100 microns and are externally wetted with a thin indium film on the order of microns thick. The sharp emitter geometry enhances the electric field at the tip to approximately 10 V/nm. When the electrostatic stress on the indium balances the capillary pressure on the needle tip, a Taylor cone forms on the tip with an angle of 49.3°, a base radius on the order of microns, and a radius of curvature at the apex on the order of nanometers. The cone geometry results in additional geometric enhancement of the electric field. Increased electrostatic stress at the tip causes a nanometer scale jet-like protrusion to form, as shown in Figure 1. At jet tip radii on the order of nanometers the electric field reaches ~10V/nm and indium ions are emitted by field evaporation and formed by field ionization of thermally evaporated neutrals and subsequently accelerated to high velocities by the local electric field [6,7].

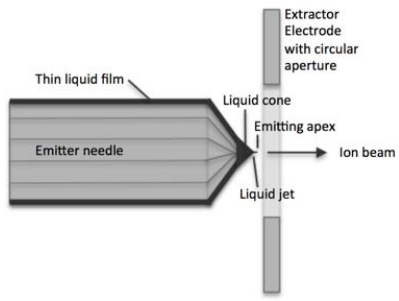


Figure 1. An illustration of an indium electrospray assembly.

Models have been developed to predict the voltage for current emission on-set and extinction and the relationship between the emitted current and voltage. The Mair model was derived from models of space-charge limited charged particle emission from an electrode, field evaporation of ions from the surface of a Taylor cone with a thin jet at the apex of it, the slender body approximation for the electric force on the apex of the jet and assuming that the indium is flowing to the tip with low flow impedance. The Mair model of the extinction voltage, V_x, and electrospray current, I, are:

$$V_x = (2kR\gamma cos\varphi/\varepsilon_0)^{\frac{1}{2}}, \text{ with } \ln\left(\frac{2h}{R}\right) < k < ln\left(\frac{4h}{R}\right)$$

$$I = a(\frac{V}{V_x} - 1) = 3\pi\gamma\left(\frac{2e}{m}\right)^{\frac{1}{2}}\frac{Rcos\varphi}{V_x^{\frac{1}{2}}}\left(\frac{V}{V_x} - 1\right)$$

with the gap between the emitter and the extractor, h, the Taylor cone base radius (approximated by the emitter tip radius), R, the surface tension, γ, the applied voltage, V, the extinction voltage, V_x, the angle of the fluid in the cone on the emitter and approximated by the Taylor cone angle, ϕ, the charge on an electron, e and the mass of an indium ion, m. [8] This model predicts an extinction voltage ≤ 993 V for h = 205 (with a 200µm radius extractor aperture and 50 µm gap) , R= 2 µm, gamma= 0.556 N/m and q/m =840,330 C/kg. It predicts a current of 10 µA at 1030 V. Reasonable agreement between theory and experiment has been shown for capillary emitters with low drag flow. This model is generally accepted to describe the I-V relationship for liquid metal ion sources. However, the Taylor cone base radius may not be fixed for needle emitters, depending on the geometry, and may change with voltage, therefore it is not predictive enough for emitter and uniformity design for microfabricated externally wetted emitter arrays for propulsion systems. The predicted voltages for externally wetted microfabricated emitter and extractor geometries have proven to be much lower than observed by more than 1000 V while the I-V slopes are more similar.

Other models have been developed to study trends and sensitivity of turn-on to needle emitter geometry that also include the emitter tip angle [9,10], however, they do not seem to be accurate enough to be predictive. Controlling the threshold voltage for emitter turn-on and current levels of all of the emitters in an array is considered to be one of the greatest challenge to enable thrusters to be developed using emitter arrays because the I-V curves are extremely steep and excessive single emitter current will cause extractor impingement and sputtering, emitter contamination, droplet emission and therefore premature device failure [11]. The required emitter geometry must be fabricated uniformly across the array to achieve the total required current and thrust while limiting the current level of each emitter to avoid extractor impingement. A model for the threshold voltage for emission was developed (but not all terms in the model were given for others to use) and validated by Bell and Swanson [9] Their modeling and experimental results showed that the emitter turn on voltage was not sensitive to the emitter tip radius if the emitter tip half cone angle was 49°. It did increase with tip radius for emitter tip half angles less than 30° and it did increase with tip cone angle. These results suggest that that only the uniformity of the gap between the emitters and extractor would have to be controlled to achieve uniform turn on voltages for all of the emitters in the array if the emitter design included a 49° tip angle. Uniformity of this gap will be achieved by controlling the height uniformity of the emitters in the array. Tip radius of ~ 1 micron is recommended to improve the stability of the Taylor cone [12].

Electrospray thrusters using externally wetted needle emitters have been under development using indium for several years. Needles have demonstrated electrospray indium ion current levels from a microampere to hundreds of microamperes. Beam half angles have been measured to be 10° at 2 microamperes and 20° at 10 microamperes. [13] 100% propellant mass utilization has been demonstrated up to 20 microamperes from a single indium electrospray needle [14]. Liquid indium metal ion sources have flown on several missions since 1991. [3] Thruster assemblies with single emitters have been demonstrated for thousands of hours. [15] Electrospray needles with gallium metal are highly controllable and are commercially available in FIB systems. Thrust levels of 2-70 micronewtons have

been measured for single emitter thrusters from the Austrian Research Center Siebersdorf. [16] Multi-tip macroscale emitters have been successfully demonstrated for propulsion systems for higher thrust levels with total current up to 5 milliamperes from 8 emitters on the end of a tube in a crown configuration and over 600 micronewtons from a porous tungsten crown emitter with 28 needles. [14] Emitter arrays have been microfabricated to electrospray indium for propulsion systems [17] with limited performance. Prior to this project, stable indium charged particle current levels were only demonstrated at 100 microamperes from an emitter array chip with 100 emitters in a first MEP thruster laboratory prototype at an estimated thrust level of 5 micronewtons without a repeatable emitter array fabrication and propellant loading process or a robust thruster design for development for 100 micronewtons.

The indium-fueled Microfluidic Electrospray Propulsion (MEP) thruster is under development to provide100-200 µN of thrust at >1500s Isp, <10 W of power, a mass less than 25 grams, and volume less than 100 cm^3 with scalable microfabricated emitter arrays. This propulsion technology could provide 1000s of m/s of velocity change at high efficiency with a highly compact architecture for small spacecraft. The efficiency of this thruster, $\eta_{thruster}$, is expected to exceed Hall thruster efficiency when scaled up to millinewtons of thrust. The key to this technology is the microfabricated silicon emitter array chip that is integrated with a capillary force driven feed system for indium propellant. The emitter array provides the required total thrust level while keeping individual emitter current levels targeted at 5-10 µN, which is below 20 µA to prevent droplet emission and achieve a 100% mass utilization efficiency, η_{util}. [18] Single emitter indium beam divergence half angles of 20° at 20 µA have been measured, providing a beam spread efficiency, η_{spread}, better than 90%. [19] The extractor efficiency, η_{ext}, is the fraction of beam current to escape through the extractor, and is expected to be greater than 98%. If the ionization efficiency, η_{ion}, is 95%, using the following thrust efficiency relationship, with the current, I, voltage, V, mass flow rate, $\dot{m}$, the thruster efficiency is expected to be greater than 84%. A system level efficiency of >50% is expected at 100 µN and >60% at 200 µN with a PPU efficiency of 88%. The specific impulse, Isp, is expected to be > 5000 s.

$$\eta_{thruster} = \frac{T^2}{2\dot{m}IV} = \eta_{util}\eta_{spread}\eta_{ion}\eta_{ext}$$

$$T = \eta_{ext} I \sqrt{\eta_{spread} 2 \frac{q}{m} \eta_{ion} V} = C_{thrust} I \sqrt{V}$$

$$I_{sp} = \frac{\eta_{util}\sqrt{\eta_{spread} 2\, {}^{q}/_{m}\, \eta_{ion} V}}{g_o}$$

The indium propellant enables a compact propulsion system. It is ideal for a capillary force driven feed system because of its high surface tension and low viscosity. A capillary force driven feed system eliminates the need for pressurized reservoirs and pressure sensors. Indium does not absorb water, therefore, there will not be bubble issues in the feed system to affect the thruster performance and lifetime. Indium also has a very high density, enabling a much more compact propulsion system architecture than ionic liquids, and a high enough melting temperature that it can be launched and maintained as a solid throughout the flight until use. Indium electrospray thruster technology offers an elegant solution for highly distributed, compact and efficient propulsion for both large and very small spacecraft and will enable revolutionary propulsion capabilities for small spacecraft.

II. MEP Thruster

The MEP thruster employs microfabricated components and a capillary force driven feed system with indium propellant to enable a highly compact and scalable architecture. A diagram of the prototype thruster design with labeled components and a prototype MEP thruster are shown in Figure 2. The components were microfabricated or macrofabricated to micron scale tolerances and integrated into an assembly with component alignment to within microns. Micron scale alignment is required between the emitters to prevent significant ion beam bombardment and sputtering of the extractor to enable controlled and stable operation and long thruster lifetime. The microfabricated emitter array chip and heater are the most critical components of the technology. They are also the most difficult to fabricate because they require unique fabrication facilities and expertise and hundreds of processing steps with micron precision. The microfabricated emitter array chip has 400 needle emitters with each emitter spraying at a current target of 5-10 µA to provide the total current required for 100-200 micronewtons of thrust. The microfabricated heater is bonded to the emitter array chip using several anodic bonds in the assembly process. It has demonstrated emitter array chip heating up to more than 230°C. The bonded emitter array chip and heater assembly are then pre-loaded with about 7 mg of indium propellant by a thermal evaporation process. All of the components are then stacked, aligned and bolted together as shown in Figure 2. It is expected that the entire assembly could eventually be bonded together, significantly reducing the mass and volume. The current thruster assembly volume is 9 cm^3 and the thruster assembly dry mass is 24 grams. Propellant reservoirs have been integrated with the emitter

array chips in the thruster assembly for thermal system characterization and propellant flow tests, but have not yet been tested together to support electrospray operation with a continuous feed of indium.

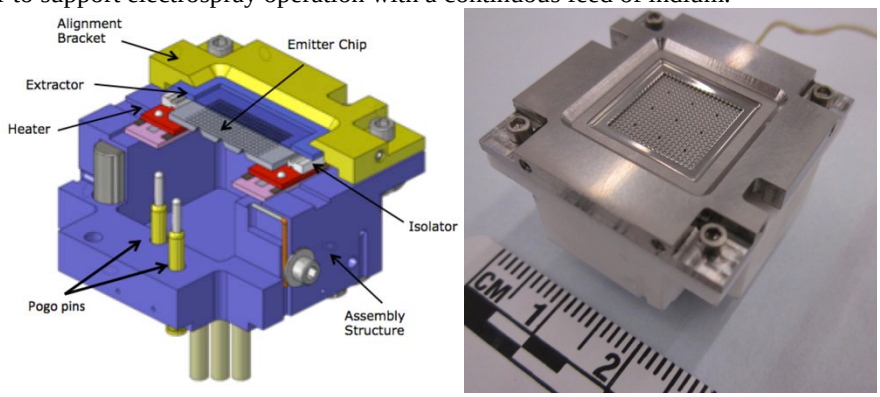


Figure 2. The MEP thruster design model (left) and a prototype MEP thruster (right).

A. Assembly Structure

The assembly structure integrates all of the thruster components and electrical connections and electrically isolates them. The surface in contact with the heater and emitter chip assembly is machined to micron tolerances for alignment to the extractor and to the propellant management device (PMD), which fits into the open volume in the assembly structure. The material is macor for high electrical resistance at temperatures over 250°C and for machinability. The thruster assembly structure shown in Figure 2 was machined at JPL in the instrument machine shop using a Sauer Ultrasonic DMG 20 Linear 5 Axis machining Center. Electrical connections to the various components were made with spring-loaded pogo pins from Everett Charles Technologies. These were epoxied into the assembly structure using an epoxy with a maximum operating temperature of 300°C. The assembly structure has a propellant reservoir volume of >1 cm^2, which is sufficiently large for the propellant management device (PMD) and indium for 500 hours of operation at 200 µN or 1000 hours at 100 µN.

B. Extractor

The extractor is biased to high voltage relative to the emitter array chip to establish a high electric field on the emitters to extract and accelerate the indium charged particles. It has 400 apertures with diameters of approximately 400 microns on the emitter side and tapered sidewalls that open the apertures to approximately 480 microns at the downstream side. The tungsten extractor grid was fabricated using a chemical etch process. With this geometry and a gap of 60 +/- 20 microns to the emitters, an indium beam with a half angle less than 55° can escape without impacting the extractor. The sputter yield of indium ions on tungsten is about 3.2 atoms/ion at 3 kV, so beam ions impinging on the the extractor will cause significant sputter erosion. This not only limits the life of the grid, but can contaminate the emitters with tungsten, possibly resulting in undesired droplet emission [20] and decreasing mass utilization efficiency. Droplet emission also causes increased beam divergence which further aggravates extractor impingement and decreases the beam spread efficiency.

C. Alignment Bracket

The alignment bracket, the top thruster component shown in Figure 2, holds the extractor and isolator with 8 set screws that enable alignment of the extractor apertures to the emitters in the x and y direction. It also serves to secure the components to the assembly structure. The material is titanium to minimize mass and provide an electrical path from the electrical pogo pin in the assembly structure to the extractor.

D. Isolator

The isolator electrically isolates the emitter array chip and the extractor electrode, sets the gap distance between the emitters and extractor. It has a frame shape with a wall width of about 2 mm and thickness of approximately 1 mm and incorporates a shadow shielding step in the wall to prevent electrical shorting due to indium deposition on the inside wall. The macor isolator material has a published dielectric strength of 40 kV/mm at 25°C and resistivity of $>10^{16}$ at a temperature of 25 °C. They are fabricated at the JPL Instrument Machine Shop using the Sauer Ultrasonic DMG 20 Linear 5 Axis machining Center with better than 5 micron precision. Macor isolators were tested at JPL MPL. The targeted resistivity was $3x10^9$ Ohm-cm and the macor isolators demonstrated an electrical resistivity of $1.61x10^{10}$ Ohm-cm at 260°C. The measured dielectric strength was >5.45 kV/mm and the targeted

dielectric strength was 6-8 kV/mm. The estimated electrical resistance of the macor isolator design in the thruster is 3.9 x10^9 Ohms. The macor isolator expansion was modeled using ANSYS software and the results predict 5 microns of out-of-plane and 20 microns of in-plane expansion at 250°C.

E. Heater

The heater is required to increase the temperature of the indium above its melting temperature of 156.4°C. It requires 1-3 W of power depending on the assembly and the operating mode. A pyrex heater bonded to the emitter chip is much more difficult to fabricate than integrating heaters into the assembly structure, however, the heater temperature is much lower and the performance is much more efficient, reducing the heater power by 50-70%. The heater is fabricated with two pyrex chips bonded together with a silicon frame interface and a heater filament deposited onto one of the pyrex chips. Pyrex is required as the heater material for high voltage isolation and to enable anodic bonding to the emitter chip for precision alignment, high temperature capability and optimal contact for heat transfer. It is fabricated at the JPL MicroDevices Laboratory(MDL). The heater bonded to an emitter chip is shown in Figure 3. It has been tested in the thruster assembly with and without a PMD that was loaded with indium and with and without the emitter array chip electrospraying. It heated the emitter array chip in the thruster assembly to 180°C at 2.9 W and to 230°C at 3.7 W. During thruster operation with an electrospray at > 1900 µA, the heater power was 0.74 W.

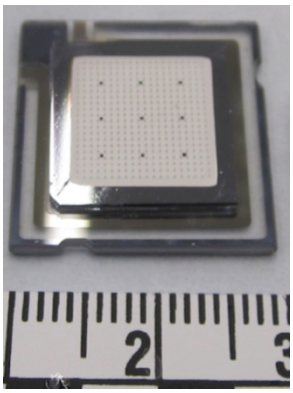


Figure 3. A pyrex heater bonded to an emitter array chip and loaded with indium propellant.

F. Emitter Array Chip

The emitter array chip is the most important component of this thruster technology and the key to the required performance and lifetime, providing capillary force driven indium flow, geometry induced electric field enhancement and an indium cone anchor for charged particle emission. The emitters are approximately 300 microns tall with sharp tapered tips and axial grooves. The derived requirement on the uniformity of the tip height across the array is <+/-10 microns for an average emitter-extractor gap of 40 microns, using the critical cone stabilizing voltage [21]. The critical cone stabilizing voltage is estimated by $1432\gamma^{1/2}R_o^{1/2}$. R_o (cm) is the distance between the emitter and extractor aperture and γ is the surface tension (556 dynes/cm for indium). With an extractor gap uniformity of 10 microns, the emitter turn-on voltage range across the array is predicted to be 50 V, using this relationship. The turn-on voltage range target is 100 V to ensure that the first emitters turn on and don't increase beyond 20 uA/emitter as the total current from the array is increased to achieve the required thrust level of 200 micronewtons at 3200 µA. Below 20 µA/emitter, less than 1% was intercepted by the extractor in testing as required and the mass utilization fraction should be 100%. [22] The emitter tip half cone angle design is 49°. At this angle, the turn-on voltage of the emitters is not sensitive to the tip radius of curvature. Recent preliminary modeling results have shown that the emitter should produce only one emission site anchored to the apex of the emitter, depending on the indium film thickness. [23] Having one emission site anchored to the tip of the emitter is critical to achieving high performance and long lifetime. The tip radius design is about 0.5-3 microns to support a stable emission cone at the required current levels [24]. The groove design is based on modeling and experimental results. Aptech macroscale tungsten emitters have 2-10 micron deep round axial grooves that provide capillary pumping along millimeters of the needle, as shown in Figure 4. Modeling results suggest that a single 2 micron deep groove would provide enough flow for the current levels targeted. [25] The emitter design and test results are discussed in more detail in another paper. [26]

The microfabrication process for the emitter array chips was developed for very high precision and tall structures with micronscale uniformity. They are microfabricated from silicon wafers using 3-D grey scale lithography etch mask patterning, pattern transfer to a thick oxide mask, and etching using a Deep Reactive Ion Etching (DRIE) machine that include more than 150 processing steps and procedures. There are 400 emitters in the arrays in an area of 1 cm^2 with a pitch of 500 microns. A height uniformity of +/-10 microns has been demonstrated over 85% of the emitters in an array using this fabrication process. Improved uniformity is possible with this same process using a more modern and uniform DRIE system and a distribution of emitter etch masks configurations to compensate for any DRIE etch rate variations across the emitter array chip. Microfabricated emitters and arrays are shown in Figure 4. Emitter array needle configurations are still varying some from chip-to-chip, however there are many process improvements that can be implemented. Despite the variations, the performance of the emitter array chips is very similar from chip-to-chip in current and voltage levels and stability. The emitters demonstrated operation at the required single emitter and array current and voltage levels for the required thruster performance as will be discussed in the Emitter Performance Section.

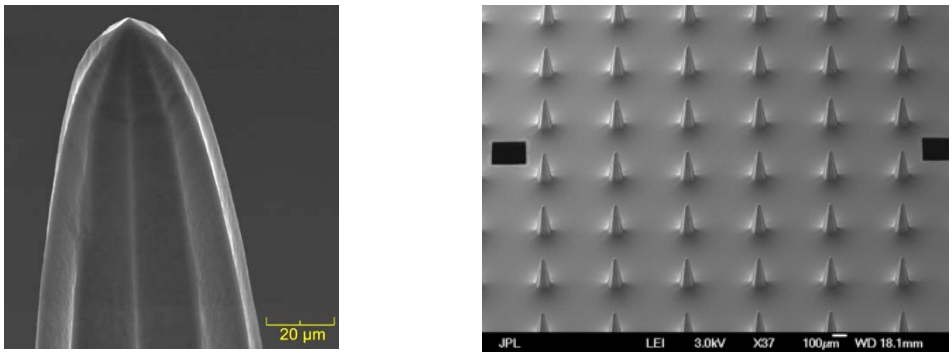
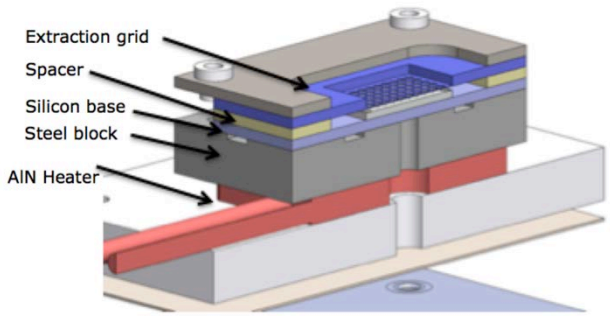


Figure 4. Microfabricated emitter (left) and microfabricated emitter array (right).

III. Experimental Apparatus

The thruster and components were tested in the Microthrust Propulsion Laboratory (MPL) cleanroom at JPL using multiple facilities and test fixtures. The cleanroom is operated as a class 1000 cleanroom. 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 turbo pumps. The test fixtures are shown in Figure 5. The silicon chip 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 tungsten extractor aperture diameter was approximately 400 microns and the axial distance to the emitter was approximately 54 microns. The electrical schematic for this test assembly is shown in Figure 6. 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.



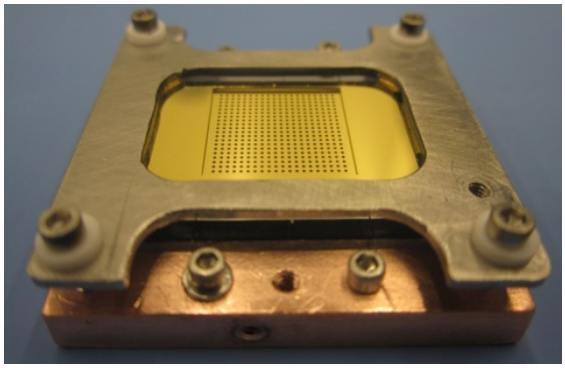


Figure 5. Microfabricated emitter chip test fixture model cut-away (left) and microscale silicon emitter array chip test fixture (right).

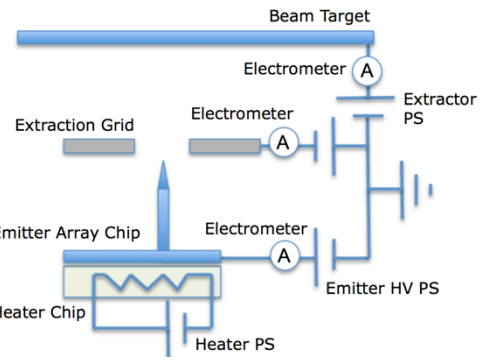


Figure 6. Emitter chip test electrical schematic.

IV. Emitter Performance

Single and arrays of electrospray needles were tested for current range, voltage range, and performance stability characterization with indium to support design of the MEP thruster emitter array test data informed extractor electrode, and power processing unit; and development of test and operating procedures. Single emitters were tested to understand their performance capability and to compare to industry standard macroscale emitters.

A. Single 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 tested is in Figure 4. Current and voltage data are shown in Figure 7. Data for an industry standard liquid metal ion source used in commercial FIB systems are also included in Figure 7 for comparison. This emitter was fabricated and loaded with indium by A-P-Tech. The data show that the microfabricated emitters operate at a lower voltages than the macroscale emitters and also have the characteristic linear I-V curve. Single microfabricated emitter and extractor current and voltage data are included in Figure 8. It was operated slightly beyond the range of current targeted for single emitters in the MEP thruster. 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. 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 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 9. It operated at 6.4 µA with a current stability 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.

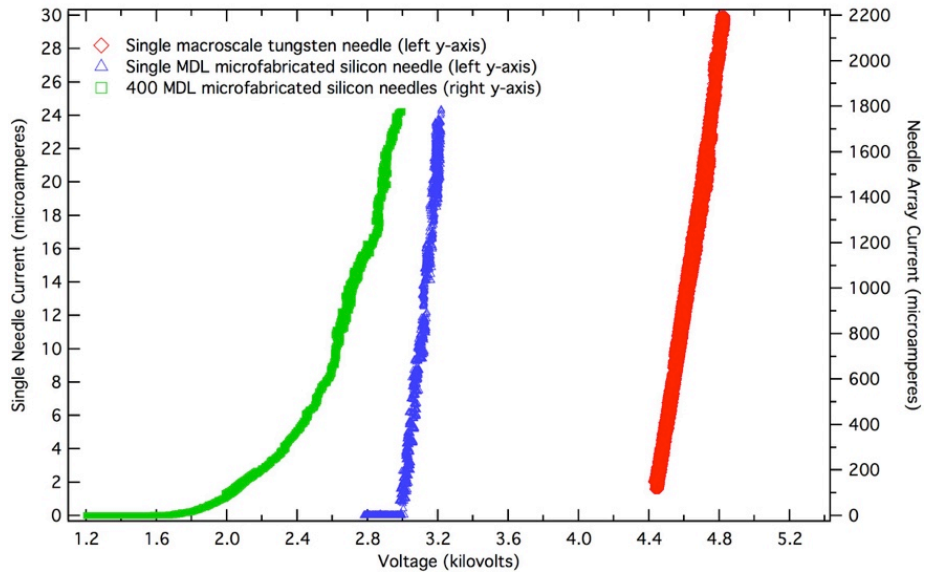


Figure 7. I-V data from the single A-P-Tech emitter represented by the red markers.

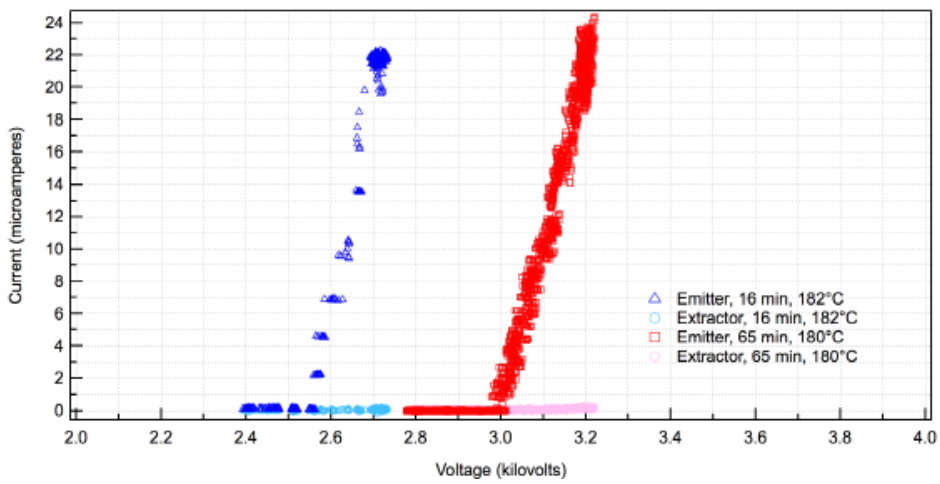


Figure 8. Single emitter and extractor current-voltage data.

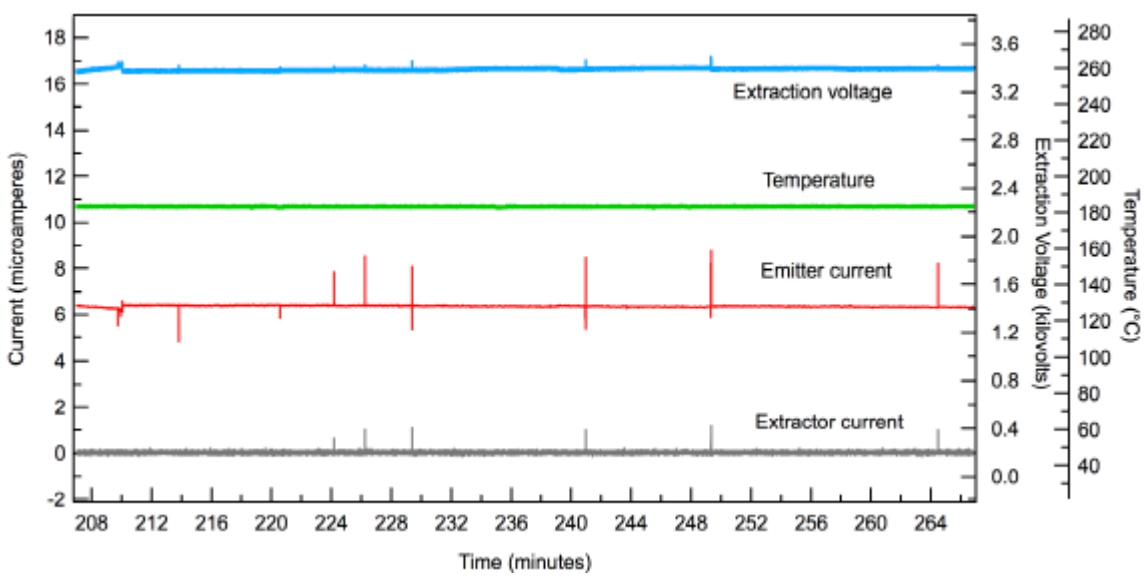


Figure 9. Microfabricated emitter array stability data over 60 minutes.

B. Microfabricated Silicon Emitter Arrays

The microfabricated silicon emitter arrays were tested to characterize current, voltage, and stability over 60 minutes of operation at a thrust level with less than 1% of the current to the extractor for the required performance. Current and voltage data are also shown in Figure 7. It was operated slightly beyond the 100 µN thrust level and 1600 µA current targeted for emitter array chips in the MEP thruster temporarily to demonstrate the capability to meet the requirements. Emitter array chip stability data is shown in Figure 10. It operated at 437 µA at less than 3000 V with a stability of +/- 1.4% with less than 1% of the emitter current to the extractor. The estimated thrust level is 25 µN at this current and voltage. 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 detection limit of the Energy-dispersive X-ray spectroscopy (EDS) detector in the electron beam microscope**.** A post-test emitter micrograph is in Figure 11. It shows excellent indium distribution on the emitter with an indium cone frozen on the apex of the emitter. Post-test inspection of the extractor revealed that some tungsten sputtering occurred and indium was deposited on most of the apertures, together suggesting that more than 99% of the emitters electrosprayed. Current and voltage characteristics were taken at multiple times throughout the test with repeatable results.

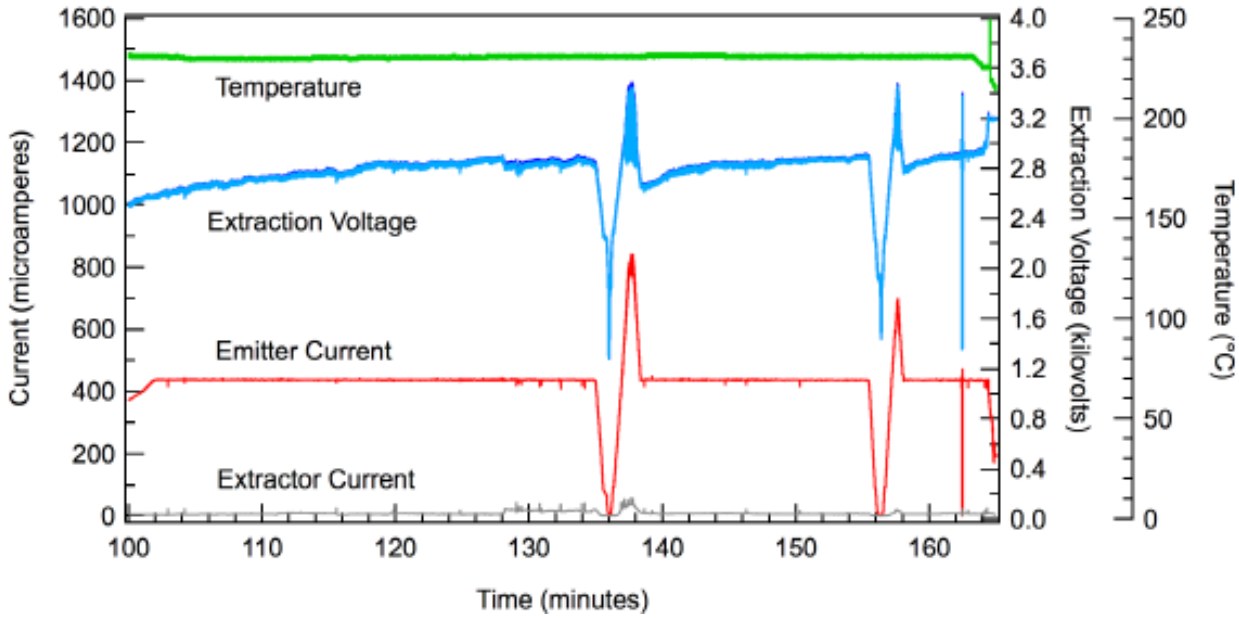


Figure 10. 400 emitter array stability data.

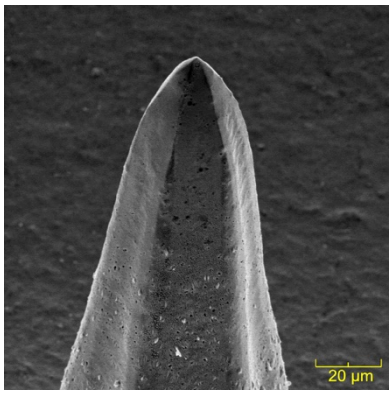


Figure 11. Post-test emitter image.

V. Thruster Performance

A short duration MEP thruster test was conducted to characterize the performance of the thruster assembly emitter chip, heater, isolator and extractor and alignment capability without a PMD. Emitter array chip EW9#3 and

a heater assembly were integrated into the thruster assembly. An image of one of the emitters on chip EW9#3 is shown in Figure 12. The gap between the emitters and the extractor and the emitter alignment in the apertures were measured for 9 emitters including emitter 1-1, 1-10, 1-20, 10-1, 1-10, 1-20, 20-1, 20-10, 20-20. The gap varied from 6.8 µm in the center to 78 µm on one of the corners where there are a few short emitters. The emitter misalignment from the center of the aperture varied from 1.5 to 22 microns behind 400 micron diameter extractor apertures. The thruster was heated over 90 minutes in vacuum to outgas the assembly. A picture of the thruster in the thermal socket in the vacuum chamber during testing is in Figure 12. It turned on at 3 kV and 2400 µA while being heated through the melting temperature of indium. The thruster start-up data is in Figure 13. The thruster started up at 2400 µA and within a few seconds was decreased down to 1906 +/- 3 µA (~120 µN) to achieve the objective 100 µN (1600 µA) with margin. These data are in Figure 14. The extractor current was 33 µA, which was 1.7% of the emitter current, at this beam current. The extractor current will be reduced with improved emitter height uniformity. The heater power was 0.74 W at the 1906 µA current level. The total thruster power was 3.5 W including the beam, heater and extractor. The thruster efficiency is estimated to be > 83% (with an estimated beam spread efficiency of 90%, a mass utilization efficiency of 100% and an ionization efficiency of 95%). The thermocouple was not reading correctly because it may have lost contact with the heater, therefore the temperature could not be precisely controlled as required to maintain flow rate stability at this high current level for more than 10 minutes. The current was dropped to 935 +/- 5.4 µA (~58 µN) for 10 minutes with an extractor current of 6.3 µA (0.7% of the emitter current). These data are in Figure 15. The current was increased to 1500 µA, but was not stable because the flow rate was not sustainable without the PMD. The current was then decreased to 100 +/- 4 µA (6 µN) and operated for 10 minutes to demonstrate thrust range capability. Data at this thrust level is in Figure 16. The extractor current was 8.5 µA (9% of the emitter current). The total test duration was 46 minutes. The mass of indium electrosprayed was 7.18 milligrams, which was 97% of the indium deposited onto the emitter chip. The ratio of the total charge and total mass of indium sprayed is 356,185 C/kg. At an emitter voltage of 1470 V and a 90% beam spread efficiency, the specific impulse can be estimated at 3100 s. In post-test inspections, some contamination was observed on the emitters and sputter damage was observed on the extractor, suggesting that the contamination was extractor material. The extractor inspection revealed that more than 99% of the emitters electrosprayed, which significantly exceeded the project objective of 80%. No emitter erosion was observed in the post-test inspections of the emitter array chip.

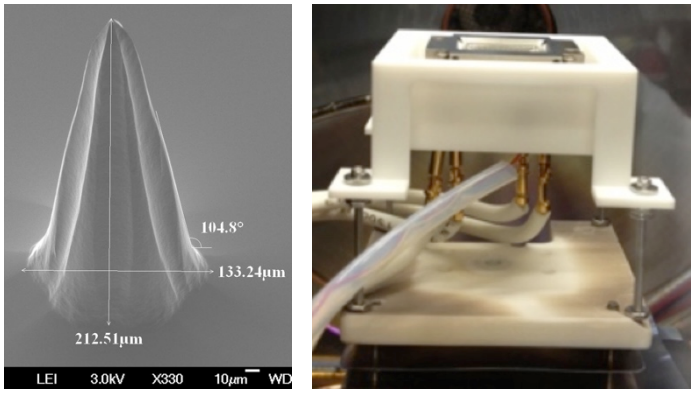


Figure 12. MEP thruster emitter array chip EW9#3 emitter (left) and the prototype thruster in the thermal socket during testing.

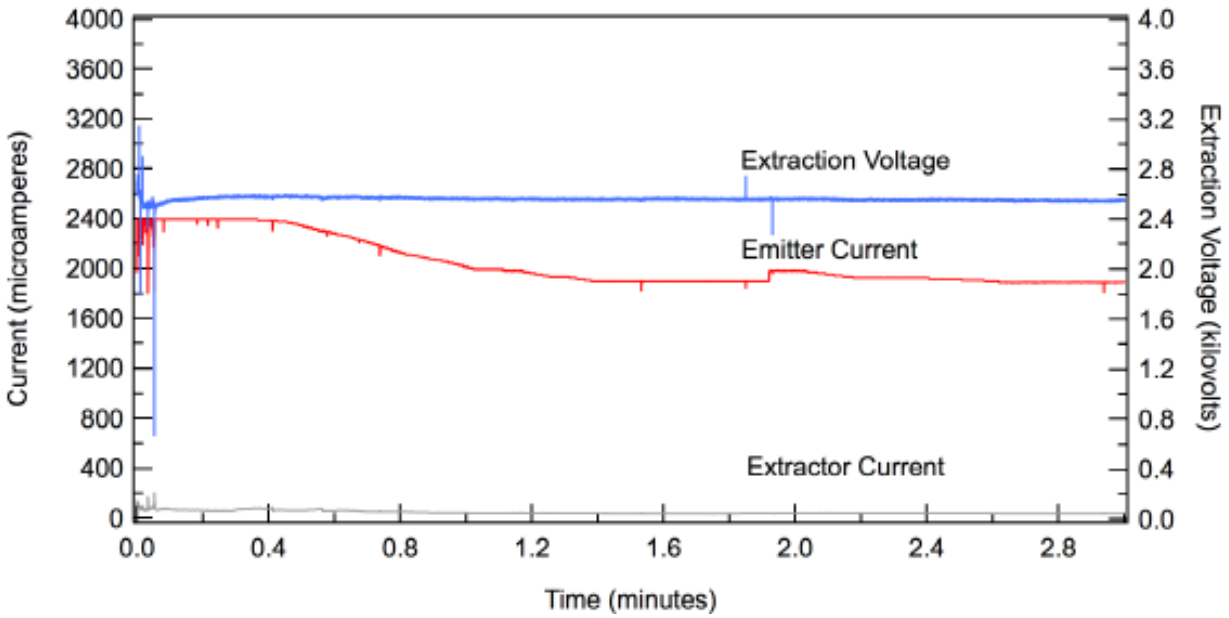


Figure 13. Thruster start-up data.

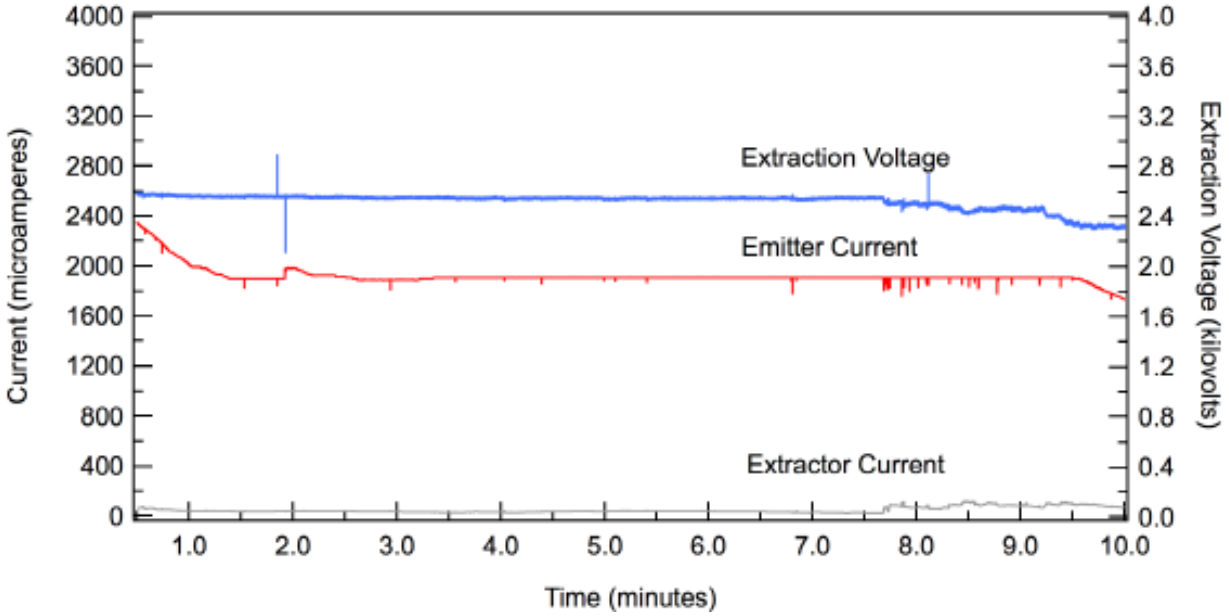


Figure 14. Thruster emitter array stability data at an estimated 120 µN and 2.6 kV (1906 +/- 3 µA).

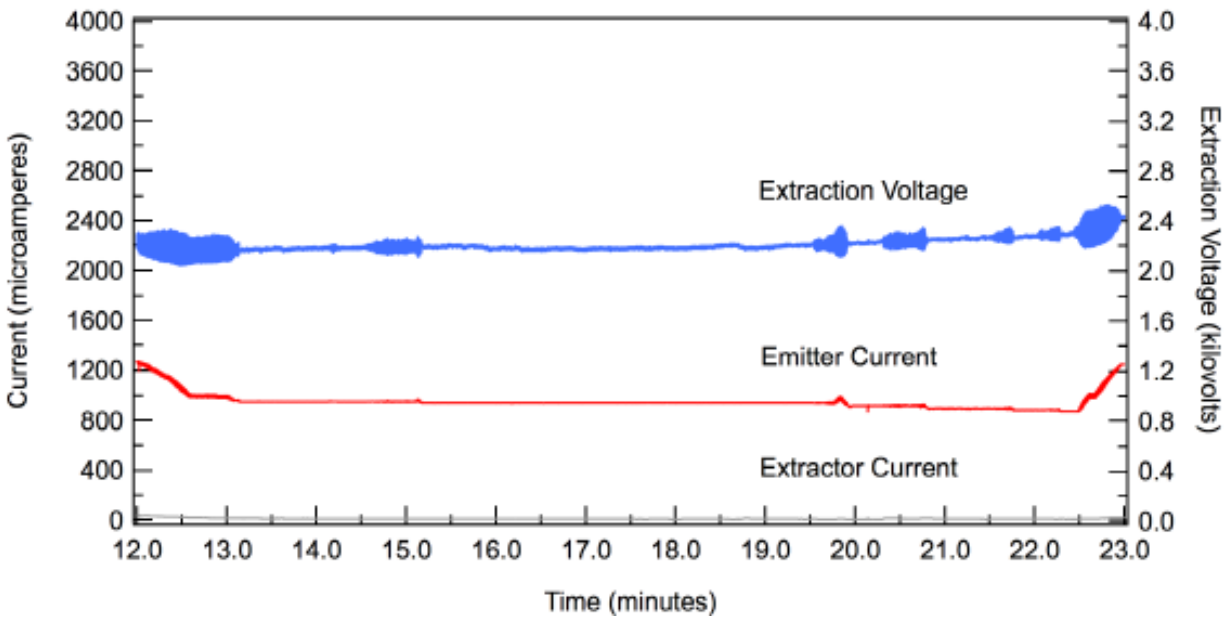


Figure 15. Thruster stability at an estimated 58 µN for 10 minutes (935 µA +/-5.4).

The thruster performance met all of the NASA MEP project requirements that were measured. The performance summary is in Table 1. The current and voltage levels measured produced an estimated 120 µN with an assumed beam spread efficiency of 90% and mass utilization efficiency of 100%. The required Isp was >1500s and is estimated to be >3100s from test results. The thruster dry mass was 26 grams. The thruster volume was less than 9 cm^3. The power for the 120 µN level was 5 W. The estimated thrust efficiency was >50%. This value needs to be confirmed on a thrust stand. The beam divergence and specific charge distribution of the charged particles in the beam should be characterized to determine the beam spread efficiency and propellant mass utilization. The reservoir must be integrated in the next phase of the project to achieve long lifetime of 100s-1000s of hours.

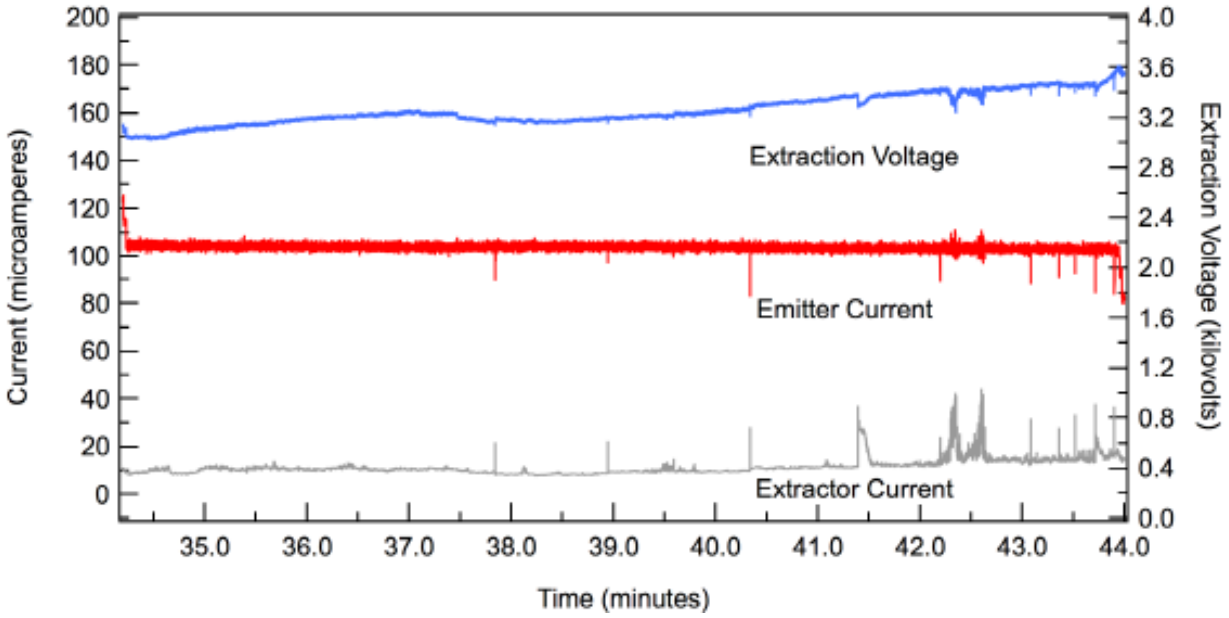


Figure 16. Thruster stability data at an estimated 6 µN (100 µA+/- 4µA).

Table 1. Thruster performance summary.

Parameter	Value
Emitter Voltage (volts)	**1470**
Extractor Voltage (volts)	**-600**
Emitter Array Current (microamperes)	**1906**
Extractor Current (microamperes)	**1.7%**
Beam Power (Watts)	**4.1**
Heater Power (Watts)	**0.74**
Estimated Thrust (micronewtons)	**120**
Estimate Specific Impulse (s)	**>3100**
Estimated Thruster efficiency (%)	**>50**
Thruster Dry Mass (grams)	**26**
Thruster Volume (cm^3)	**9**

VI. Conclusion

For the first time, an electrospray thruster was developed with a precision microfabricated emitter array chip and bonded heater assembly and demonstrated. Testing demonstrated an estimated 120 µN of thrust with indium propellant with 0.15% current fluctuations, >3100 s Isp, at <5 W with a dry mass of 26 grams and volume less than 10 cm^3. Many processes, facilities and tools were developed to enable micro and macroscale component fabrication and the integration with micron scale alignment. A novel process was developed in this project for the microfabrication of tapered, grooved silicon electrospray needle arrays for indium using a grey scale e-beam lithography patterning technique and deep reactive ion etching pattern transfer to the silicon to make complex emitter geometries in arrays of 400 emitters with micron scale precision and uniformity. A height uniformity of +/-10 microns over 85% of 400 emitters in 1 cm^2 was demonstrated using this process. The precision and uniformity can be significantly improved with the same process to achieve better uniformity with improved etching and patterning facilities and with distributed emitter mask etch patterns and improved tip angles in the next phase of this project. Emitter-to-extractor gap uniformity of +/-10 microns and tip angle of 49° is critical to achieving both the desired performance and lifetime from arrays of emitters by achieving initial emitter needle turn on to full thrust level within 100 V. The developed process using 3-D grey scale lithography is the only fabrication approach capable of achieving this precision and uniformity at this time. Processes were also developed for microfabricating the pyrex heater assembly and bonding it to the silicon emitter array chip with micron scale alignment using more anodic bond steps than ever achieved previously. A facility and process was developed for loading the high aspect ratio emitters in the arrays with a continuous film of indium propellant using thermal evaporation. Macrofabrication of macor isolators and assembly structures to micron scale precision was required and demonstrated for integration and micron scale alignment with microfabricated components. Microfabricated emitter arrays were aligned to macrofabricated extractors within several microns. Macrofabricated extractors were developed and demonstrated operation with several thousand volt isolation maintained throughout electrospray testing at temperatures up to 270°C across macor isolators with a thickness of approximately 1 mm. Procedures were developed for turning on the 99% of the emitters in a 400 element array and operating them at a very high stability for 10s of minutes with no detectable erosion or contamination.

With the significant progress made on the development of this technology, there remains additional technology development to achieve a complete propulsion system for flight. An integrated propellant management device (PMD) to continuously replenish the emitter chip with indium is required for longer duration operation of hundreds to thousands of hours. Thrust, beam divergence and specific charge distribution measurements have not yet been conducted on this thruster technology with microfabricated silicon emitter arrays and needs to be done as soon as possible to validate performance estimates. Slight improvements on emitter array tip angle and height uniformity is required for 1000s of hours of operation.

These novel results towards the development of this new thruster technology suggest that the technology approach is capable of 100-200 µN electrospray thrusters that should be scalable to millinewton thrust levels with high performance never before demonstrated from a propulsion system. The most significant remaining technology development challenge is improving the thruster lifetime with the integration of a propellant reservoir. The high performance, long lifetime and compact architecture are all required for the propulsion system to enable revolutionary interplanetary exploration capabilities with very small spacecraft.

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