Sub-Micronewton Thrust Measurements of Indium Field Emission Thrusters*

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ABSTRACT

The performances of three indium field emission thrusters (In-FETs) developed by the Austrian Research Center Seibersdorf (ARCS) have been measured up to 200 μN, 2 mA, and 20 W using a submicronewton resolution thrust stand. Two of the In-FETs (InFEEP-25 and InFEEP-100) have a single needle emitter and plate extractor geometry, similar to the breadboard In-FET design currently being investigated for use on the ESA GOCE mission. The third In-FET (InFEEP-1000) is a multiple capillary tube emitter with a single plate extractor. In each case, thrust has been measured as a function of beam current and voltage and compared to the expected thrust based on a beam divergence thrust coefficient. For the needle geometry FETs, measured values of the thrust coefficient are seen to be near 80% and 60% for emitter-extractor distances of 0.6 mm and 0.1 mm, respectively, agreeing with plume measurements and direct thrust measurements from other institutions. For the InFEEP-1000, the thrust coefficient is close to 100% and 80% for emitter-extractor distances of 1.0 and 0.5 mm, respectively. In both cases above current levels of 1 mA the thrust coefficient increases beyond 100% indicating droplets or charged clusters may be significant in determining the thrust of this type and geometry of FET.

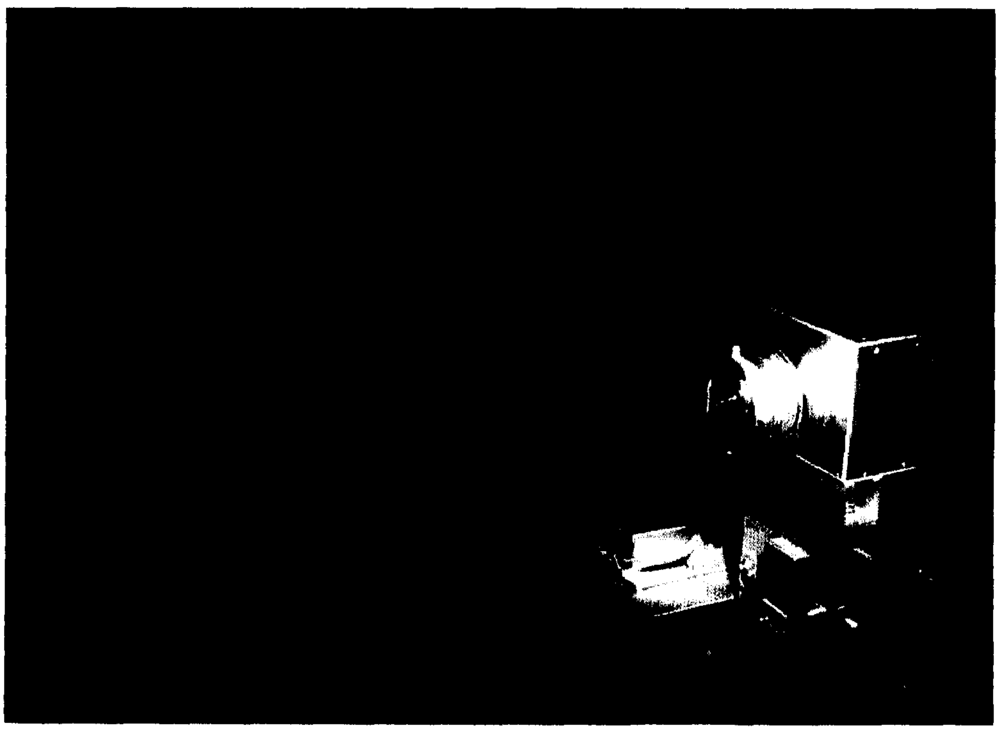

Figure 1: InFEEP-100 mounted on the JPL Microthrust Stand.

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1.0 Introduction

Field emission thrusters (FETs) such as Field Emission Electric Propulsion (FEEP) thrusters [1,2], liquid metal ion sources (LMIS) [3,4], and colloid thrusters [5,6] can provide perhaps the most precise and accurate, low-noise thrust of any propulsion system. Missions that call for drag-free operation or precision formation flying require these characteristics and are currently evaluating, and in some cases have already selected, FET technologies. The U.S. and European missions include Terrestrial Planet Finder (TPF), EX-5, LIRE, MAXIM, Laser Interferometer Space Antenna (LISA), Gravity Field and Steady-State Ocean Circulation Mission (GOCE), MICROSCOPE, two upcoming technology demonstration missions: ST7-DRS and SMART-2, as well as many others.

In general FETs operate by applying a high voltage between an extractor electrode and a conductive working fluid (such as a liquid metal or ionic liquid) at the end of a needle, capillary tube, or slit emitter. The high voltage deforms the liquid surface into a Taylor cone where the electrostatic pressure is balanced by liquid surface tension. Beyond a propellant-dependent threshold voltage, the cone tip produces a jet that subsequently breaks apart into charged ions, charged clusters, and both charged and neutral droplets on the order of 1-100 nm in diameter. The charged particles are also accelerated by the extraction voltage, which can be increased above the threshold level to provide precise increments of thrust. Neutral droplet production increases substantially at higher current values (> 10 μA) necessitating multiple emitters or emission sites to produce greater than 10 μN of thrust efficiently. Questions of performance, thrust precision and noise, lifetime, and contamination are being evaluated at many institutions [2,4,6] and continue to be the subject of current research.

To support the ST7-DRS and LISA missions, the Advanced Propulsion Technology Group at JPL has begun to evaluate the performance of candidate FET technologies. The goal of the program is to apply the same test standards to each technology and evaluate their future use for NASA missions. As a first step, a sub-micronewton resolution thrust stand has been developed at JPL for testing FETs and other microthrusters [7]. In coordination with the Austrian Research Center Seibersdorf (ARCS), an Indium FET has been procured and tested on the JPL Microthrust Stand (μTS). This paper documents the results from the performance measurements of three different Indium FETs, designated by ARCS as InFEEP-25, InFEEP-100, and InFEEP-1000. First, a brief description of the thrusters will be presented followed by a detailed review of the performance measurements for each thruster. Finally, the measurements to date will be summarized and the future direction of the FET testing program at JPL will be described.

2.0 Thruster Descriptions

As described in the introduction and shown schematically in Figure 2, the Indium FETs use a liquid metal ion source (LMIS) to produce thrust by emitting and accelerating indium ions at high voltage (4-12 kV) with a current proportional to the desired thrust. The indium propellant is supplied by a 12-15 g reservoir that is heated to 157 °C to melt the indium. The maximum thrust depends on the thruster model: 25 μN for InFEEP-25, 100 μN for InFEEP-100, etc. The thrust can be incremented in steps as small as can be provided by the high voltage power supply, usually 0.01-0.1 μN or better. In most applications the ion beam must be neutralized

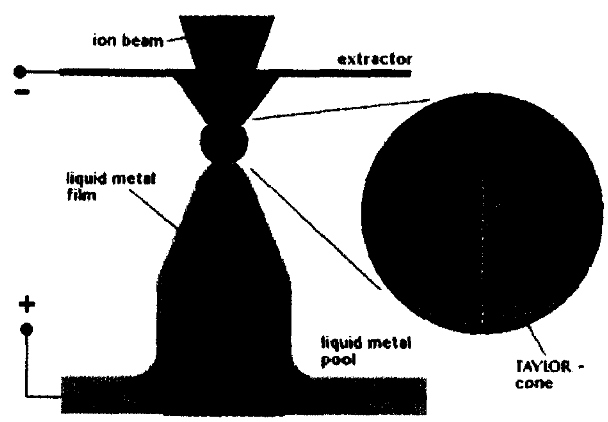

Figure 2: Schematic of indium liquid metal ion source (ILMIS) needle geometry.

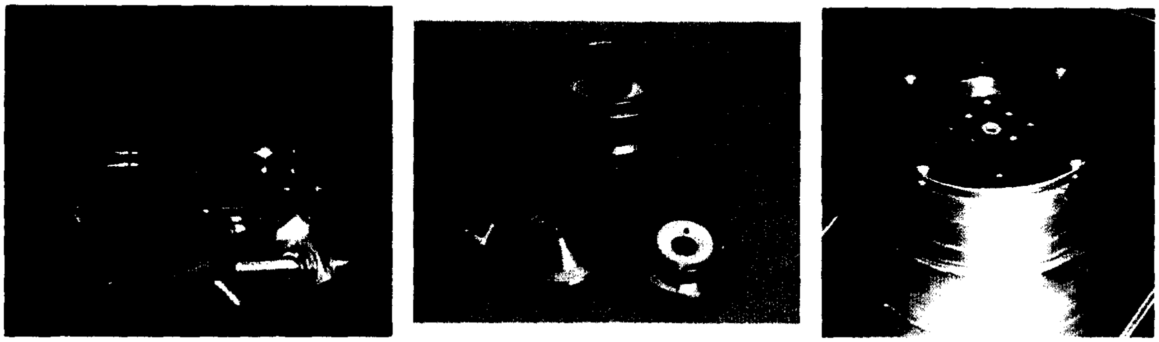

Figure 3: Pictures of InFEEP-25, InFEEP-100, and InFEEP-1000 (from left to right) taken at JPL during testing.

to prevent spacecraft charging; however, during conventional ground testing the beam is neutralized by background gases and the interaction of the ion beam with facility walls.

The three thrusters are shown in Figure 3. The InFEEP-25 has a single needle type emitter and is described in detail in refs. [4,8]. Although it has an normal operating range up to 25 μN, it can provide up to 100 μN for short periods of time as demonstrated during tests at JPL [7]. This thruster was also used for a neutralizer integration study at JPL [9]. The InFEEP-100 also has a single needle type emitter and is described in detail in ref. [10]. This model of thruster has two types of extractor electrodes: plate and wire ring that can both be adjusted to provide varying emitter-extractor distances. The InFEEP-100 has completed a 2000-hour lifetest that has now been extended [11]. This model is also being used as a GOCE breadboard thruster design and has been purchased by JPL for testing. The InFEEP-1000 has nine capillary tubes for emitters with a single extractor electrode. All capillary tubes are also at a common potential and share a common propellant reservoir. In theory each capillary should be able to produce more than 100 μN of thrust giving the entire thruster a large (1-1000 μN) dynamic range.

3.0 Performance Measurements

The performance of all three types of In-FETs has been measured using the JPL microthrust facility. During the tests, thrust was measured by the μTS and the relevant electrical parameters were stored on a computer data acquisition system. An on-board high-voltage DC-DC converter provided constant voltage operation up to 12 kV with 2 mA maximum current. To verify and examine the performance measurements, the expected thrust, T, can be inferred from beam current, J, and voltage, V, measurements by the following relation including a thrust coefficient, k_{bd},

$$T = k_{bd}\, J \sqrt{\frac{2 m_{In} V}{e}} = 1.54 \times 10^{-3}\, k_{bd}\, J \sqrt{V}. \qquad (1)$$

The thrust coefficient includes any losses due to beam divergence but assumes that only singly charged ions are emitted. For example, if instead of an ion, a cluster of atoms with a single charge were emitted (lower charge-to-mass ratio), we would expect the thrust to increase at the expense of the ion velocity. The expected centerline ion velocity, U_{ion}, can be calculated similarly,

$$U_{ion} = \sqrt{\frac{2 e V}{m_{In}}} = 1.30 \times 10^{3} \sqrt{V}. \qquad (2)$$

This can be related to the specific impulse by averaging over the beam ion velocity distribution and including a propellant utilization term. However, since we made no measurements of propellant mass before and after each test, specific impulse and propellant utilization cannot be calculated for these data. Other performance parameters such as thrust-to-power and efficiency relate to the ion acceleration process only. Losses in the DC-DC conversion process and the heater power are strongly dependent on the thruster and electronics design and are *not* included in these calculations.

3.1 Performance of InFEEP-25

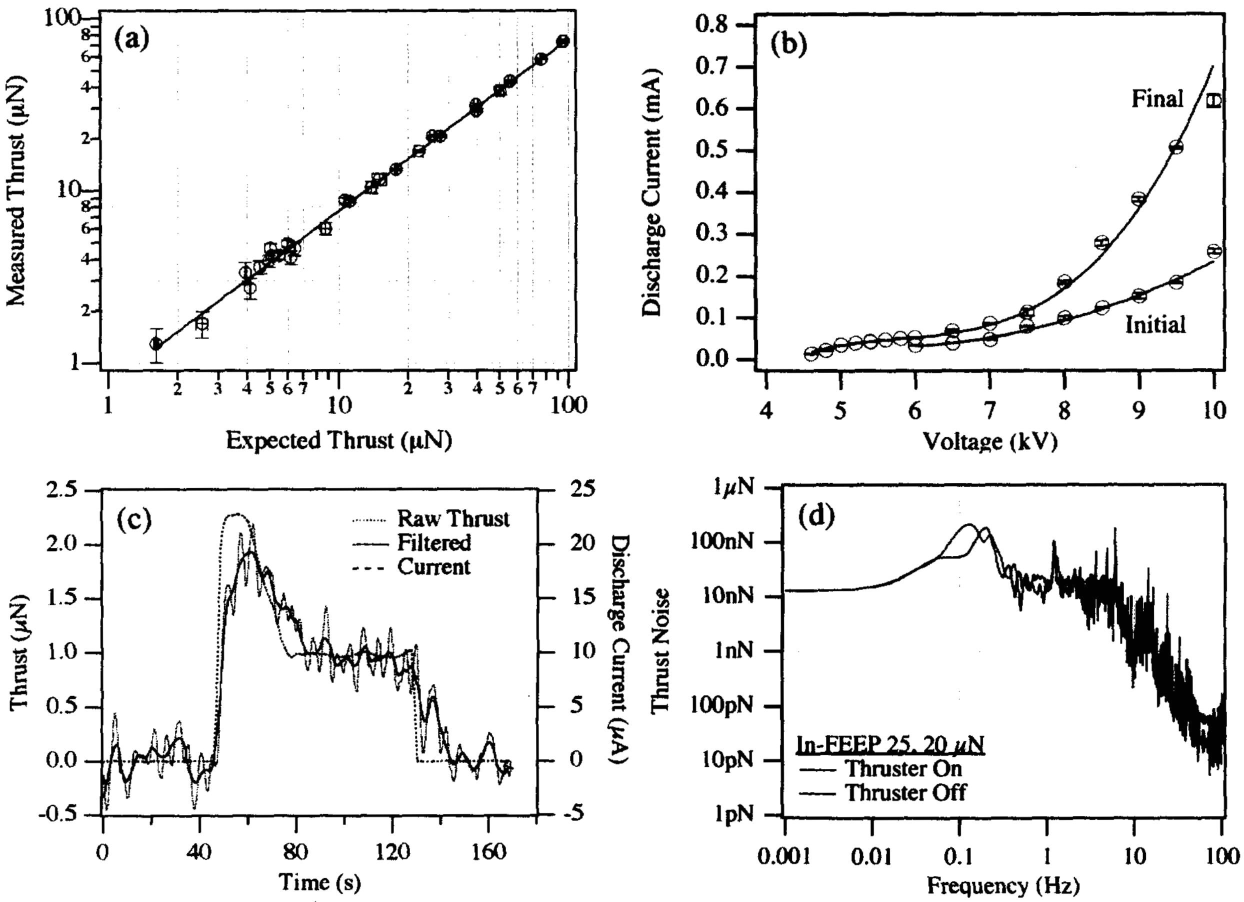

Figure 4: Performance of InFEEP-25 including full range of tests performed (a), current-voltage characteristics (b), minimal thrust measurement (c), and thrust noise (d).

The InFEEP-25 was tested over a period of a week including time to understand and correct for the difficulties of measuring the thrust produced by a FET. Due to the configuration and sensitivity of the µTS, the high voltage power supply necessary to operate the thruster was placed on the thrust stand itself, near the thruster. Since the DC-DC converter works in voltage control mode only, the thrust stability in this test and others was subject to brief and slight changes in beam current over time. Furthermore, due to a single event exposure of the thruster to atmospheric pressure at a slightly elevated temperature, the current-voltage characteristic changed significantly during the coarse of the measurements. Still, the thruster was able to operate effectively over its entire range.

As shown in Figure 4, the InFEEP-25 has a range of 1 µN to nearly 100 µN at the highest voltage and current values tested. A linear fit of the measured thrust to expected thrust based on Eq. (1) provided an average thrust coefficient of 77% over the entire range of operation with individual values at each condition between 75-80%. Thrust stand resolution varied between 0.2-0.5 µN depending on the individual test and thrust stand baseline drift. As mentioned above and shown in panel (b), the current-voltage characteristic changed over the course of testing. It is likely the propellant wetting conditions of the needle were changed by the exposure to atmosphere or continued testing at high currents and relatively high background pressure (10^{-6} Torr). In any case, measurements made before and after the change still conformed to the expected thrust curve shown in panel (a).

Panel (c) of Figure 4 shows the lowest direct thrust measurement made during the testing, reaching approximately 1 μN. To achieve this low value, the discharge was initiated at a higher voltage and current and gradually brought down to the conditions shown in panel (c). The thrust stand natural oscillation can be seen in the raw trace while a 0.1 Hz cutoff low-pass filter allows for better resolution (close to 0.1 μN) over longer periods of time. Using a Fourier Transform of the thrust data with and without the thruster operating over a long period of time provides an upper limit to the magnitude of the thrust noise. As shown in panel (d), there is no discernable difference between the two conditions. However, the thrust stand resolution itself, especially at the lower frequencies, does not meet with many of the projected requirements for thrust noise including the LISA requirement of 0.1 μN/√Hz. Furthermore, thrust noise would be amplified well beyond the requirements at the natural frequency of the thrust stand (approx. 0.1 Hz), which is intentionally kept below the driving frequency of the cryo-pumps (approx. 1.1 Hz) that provide the high vacuum environment. A new facility with a new thrust stand and pumping system designed to alleviate these problems is currently under development at JPL.

3.2 Performance of InFEEP-100

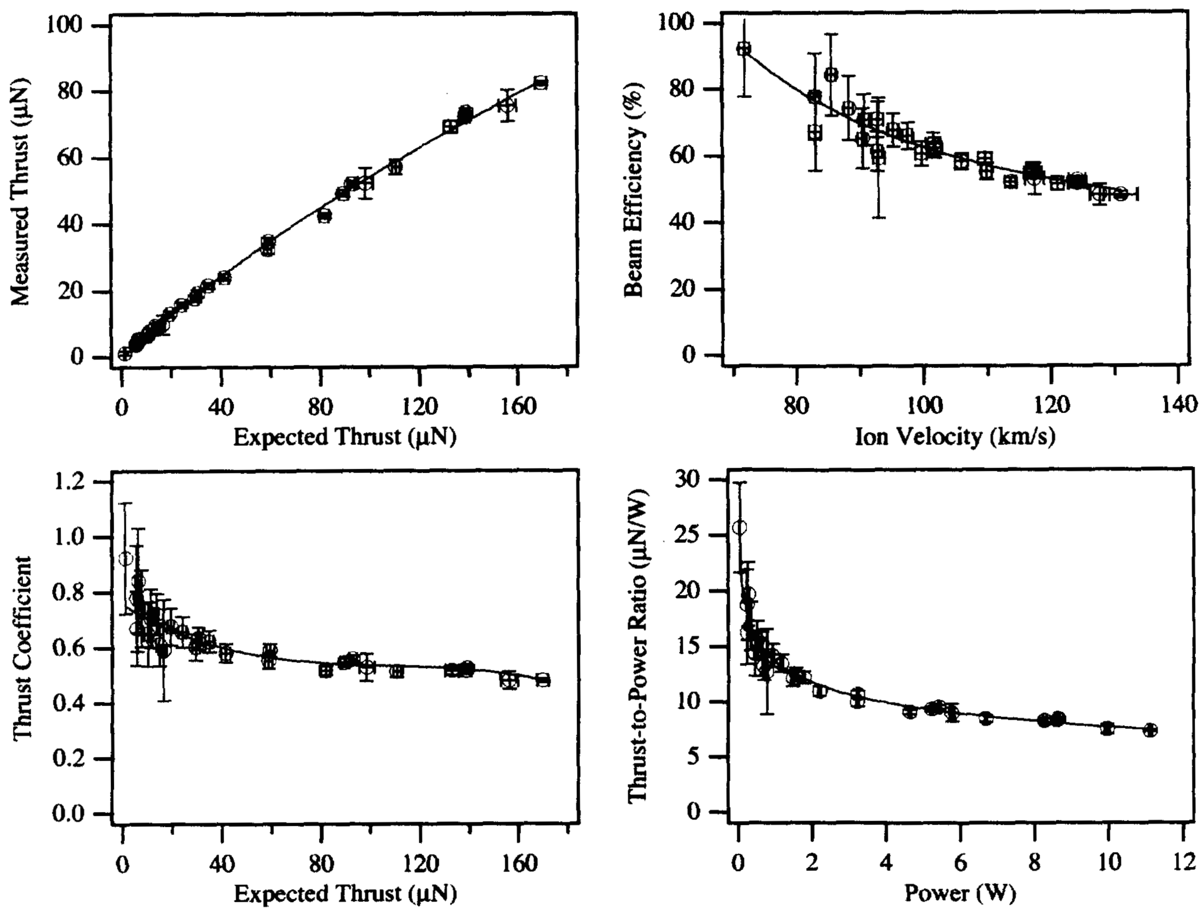

Figure 5: Performance of InFEEP-100 with an emitter-extractor distance of 0.12 mm (compared to a normal distance of 0.2-0.6 mm). The small distance leads to a large beam divergence with reduced performance.

The performance of an InFEEP-100 is shown in Figure 5. It must be noted that the emitter-extractor distance of 0.12 mm was below the normal range of 0.2-0.6 mm leading to a divergent beam and reduced performance. Although the distance was initially set at 0.5 mm, during handling and preliminary measurements it appears the position of the emitter shifted towards the extractor electrode. Future measurements will be made with a larger gap.

Figure 5 shows a thrust coefficient gradually decreasing to 60% as current, voltage, and thrust are increased. Although the typical value for the thrust coefficient based on electric probe measurements is closer to 80% for a normal emitter-extractor distance, a more divergent beam consistently explains the reduced performance. Still, the trend of a less divergent beam at lower current levels is apparent and also expected based on beam profile measurements [4]. The low value of the thrust coefficient also contributes to a lower than expected efficiency and thrust-to-power ratio, especially at the higher current levels.

Figure 6 shows a voltage stair-step function input and the InFEEP-100 thruster response. Again, due to the constraints on the high voltage power supply operating on the thrust stand, only the voltage can be kept fixed leading to small but noticeable fluctuations on the emitted current. However, examining the character of the thrust shows that it tracks with the emission current as expected from Eq. (1). Future tests will use a current controlled power supply that should provide for more stable operation. Also, due to the long duration of this test, the thrust stand experienced a significant amount of drift. We have assumed a linear drift that corrects the data as shown in Figure 6 and sets the error on the thrust measurement in this case to almost +/- 2 μN.

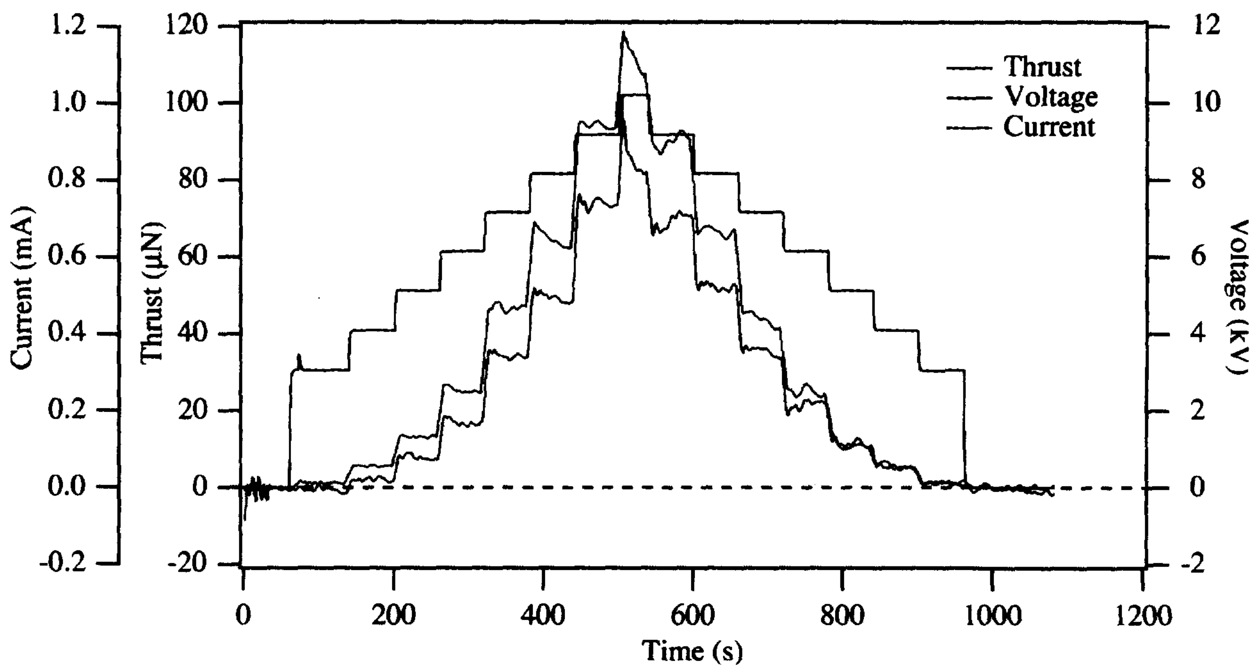

Figure 6: Characteristics of an InFEEP-100 responding to a stair-step voltage input function. Since the current cannot be held constant, thrust and current both fluctuate.

3.3 Performance of InFEEP-1000

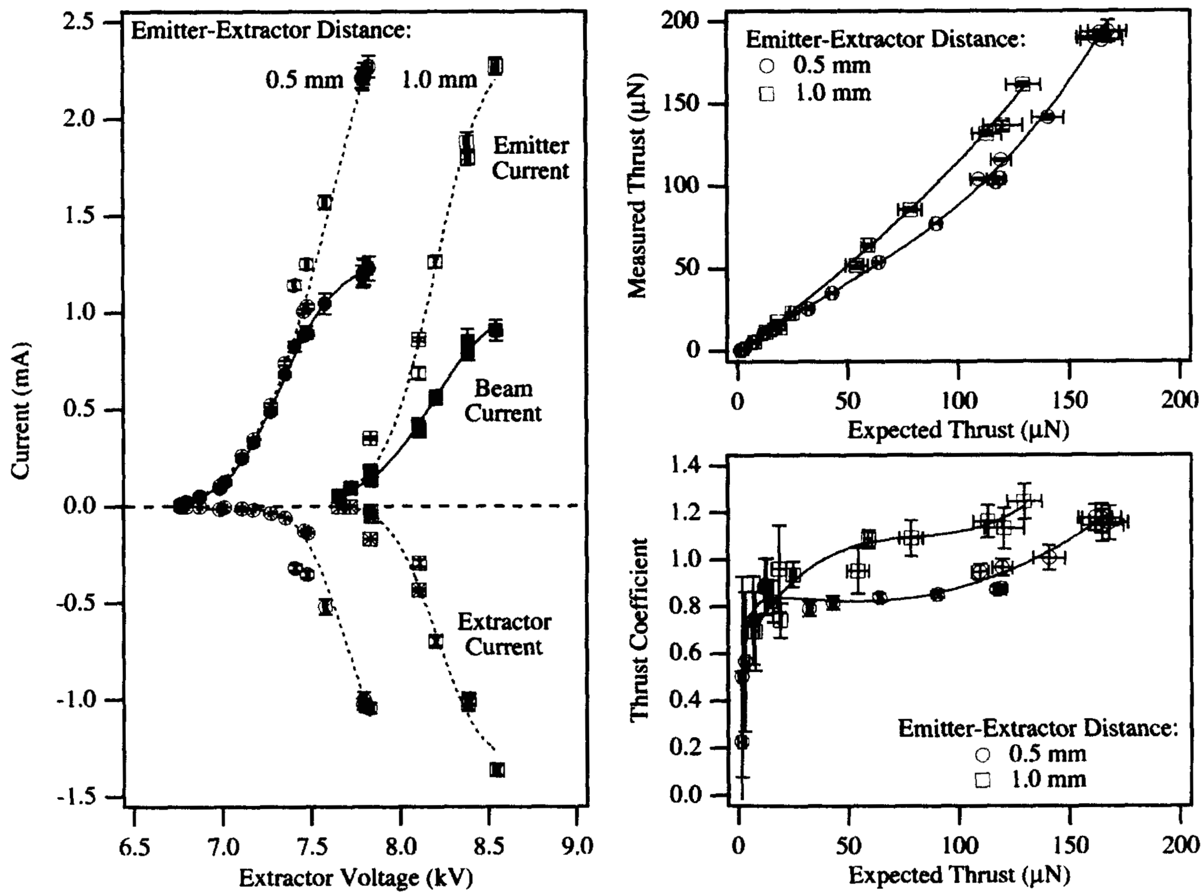

Figure 7: Performance of an InFEEP-1000 with two values of the emitter-extractor distance, power levels below 20 W and current levels below 2.5 mA due to power supply constraints.

The InFEEP-1000 is a multiple capillary tube emitter enabling much higher current, thrust, and power operation compared to the single needle emitter thrusters. However, since there is only one extractor electrode for all the tubes and since the tubes are at a common potential themselves, the individual emitter extractor distances and alignments are critical. If there are variations, some capillary tubes could experience a higher or lower voltage and a corresponding current level. This was apparent in our tests when, even at the highest current, only four of the nine needles were active by visual inspection. From the performance data, it seems likely that one or two of the capillaries were emitting most of the current. This condition could promote cluster and droplet formation. Unfortunately, again due to power supply constraints, we could not bring the voltage or current high enough to make all nine needles active. Although a new, higher power DC-DC supply was used initially, it failed to operate for more than a few minutes in vacuum. This required us to use the same power supply that we have used previously for the InFEEP-25 and InFEEP-100 tests that is limited to 2.5 mA and 12 kV.

As shown in Figure 7, within our limited current and power range, we were able to span between 0.5-200 μN with 0.2 μN precision using an emitter-extractor distance of 0.5 mm. It is interesting to note that the *higher* thrust values occurred with the *smaller* emitter-extractor distance, which we would expect to have a more divergent beam. In fact, from measurements of the thrust coefficients it is clear the beam is more divergent at 0.5 mm. This is the case because the extractor intercepts less of the beam when it is closer to the emitter. Examining the left-hand graph of Figure 7 shows that almost none of the beam is intercepted in the 0.5 mm case until approximately 7.5 kV and 1 mA of emitter current. While in the 1.0 mm case, the beam intercepts the extractor almost immediately and over half the emitted current is collected by the extractor at the highest power. From an inspection of the extractor after testing at 1.0 mm, there was a noticeable amount of indium deposited on the inside of the extractor, especially around the center needle.

Another point of interest is the measured value of the thrust coefficient being greater than 100% at some operating conditions. This occurs mainly for the larger emitter-extractor distance case and could indicate that more than single ions are being emitted. As mentioned at the beginning of Section 3, a larger than expected thrust can occur if either the actual emitted ion current is greater than the measured value or if the charge-to-mass ratio is less than expected. This would be the case if a significant fraction of the current is being emitted as clusters of atoms with single or just a few charges. Since the extractor intercepts only the edge of the beam, we can also propose that the clusters or droplets are more likely to have been created near the centerline. It seems that as the emitted current increases and more current is intercepted by the extractor, the fraction of charged clusters and the thrust coefficient increases.

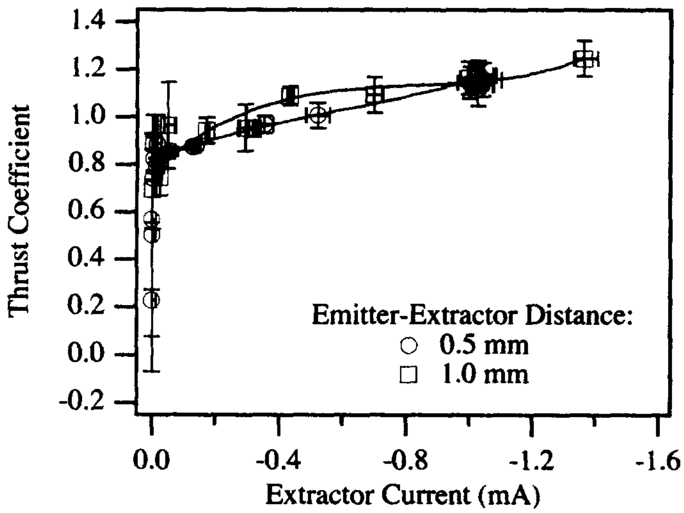

Figure 8: Thrust coefficient as a function of extractor current for an InFEEP-1000.

Figure 8 shows a plot of the thrust coefficient as a function of the extractor current. Since the curves are similar, it appears that the fraction of charged clusters (proportional to the square of the thrust coefficient) is not strongly influenced by the emitter-extractor distance as much as the amount of current being intercepted by the extractor. In fact, for the 0.5 mm case, the thrust coefficient does not reach above 80% until the extractor begins to intercept a significant amount of the total current. Again, we believe this points to the formation of the clusters near the centerline. The relative fraction of clusters in the beam current does not become apparent until the extractor electrode intercepts most of the beam exterior.

4.0 Conclusions and Future Work

The performance of three different models of indium FETs has been measured over a wide range of operating conditions, including different thrust and power levels as well as electrode geometries. Direct thrust measurements agree with models of performance based on measurements of current, voltage, and beam divergence in other laboratories. The InFEEP models tested at JPL have demonstrated an ability to produce precise thrust down to the level we are capable of measuring, currently near +/- 0.2 μN.

Overall the performance and beam divergence are seen to be strong functions of the emitter-extractor distance. In the case of the InFEEP-1000 multiple capillary emitter, it appears as though clusters of charged particles are influencing performance, especially when the extractor electrode intercepts a significant amount of the emitted current at the edge of the beam.

In the future we will continue to improve the resolution of our measurements and thrust noise measurement capability. With the addition of a new 2 m diameter ultra-high vacuum chamber arriving this summer, we will be able to investigate the performance, contamination issues, and the effects of neutralizer integration on system performance. We look forward to working with more FET designs including slit-geometry FEEP thrusters and colloid thrusters.

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