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A Fully Integrated Microfabricated Externally Wetted Electrospray Thruster

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This paper reports the performance of a fully-integrated planar electrospray thruster array. Electrospray thrusters work by electrostatically extracting and accelerating ions or charged droplets from a liquid surface to produce thrust. Emission occurs from sharp emitter tips, which enhance the electric field and constrain the emission location. Electrospray propulsion is desirable for its simplicity, high thrust efficiency and tunable specific impulse. However, the electrospray process limits the thrust from a single tip, so that achieving millinewton thrust levels would require an array with tens of thousands of emitters.

We have used silicon batch microfabrication technology to make an array of 502 emitters in a 113 mm^2 area. The thruster, weighing 5 g, was tested with the ionic liquid EMI-BF$_4$. Time of flight measurements show that the thruster operates in the ion-emission regime, which is most efficient for propulsion, with a specific impulse around 3000 s at a 1 kV extractor voltage. Emission starts as low as 500 V. Currents of 370 nA per emitter have been recorded at 1500 V, for an estimated thrust of 26 nN per emitter or 13 μN total, and a 275 mW power consumption. The thrust efficiency is estimated around 85%. In good operating conditions, the current intercepted on the extractor electrode is well below 1 %, increasing to a few percent at the highest current levels.

I. Introduction

This paper presents performance measurements made on a fully microfabricated planar electrospray thruster operating in the pure ion emission regime using the ionic liquid EMI-BF$_4$. In an electrospray thruster, charged particles are electrostatically extracted from a liquid surface and accelerated. In the pure ion regime, the extracted particles are ions. Emission takes place from the tip of a Taylor cone,[1] a structure which forms when a liquid surface is placed in a sufficiently strong electric field. For field enhancement purposes, the Taylor cone is usually at the tip of a sharp emitter structure. An extractor electrode is placed in front of the emitter with an aperture for the emitted beam. The thrust which can be emitted from a single emitter is limited by the electrospray physics to about 100 nN in the pure ion regime most efficient for propulsion. Arrays of emitters must be used to achieve higher thrusts, and broaden the possible range of missions. Microfabrication techniques are well suited to producing these arrays cheaply and with good uniformity.

Electrospray propulsion has numerous promising features. It reduces tankage mass by using unpressurized liquid propellant. It is highly efficient in the pure ion emission regime, requiring only 7 to 8 eV to produce an ion,[2] and having a small velocity spread in the emitted beam. With an accelerator electrode downstream

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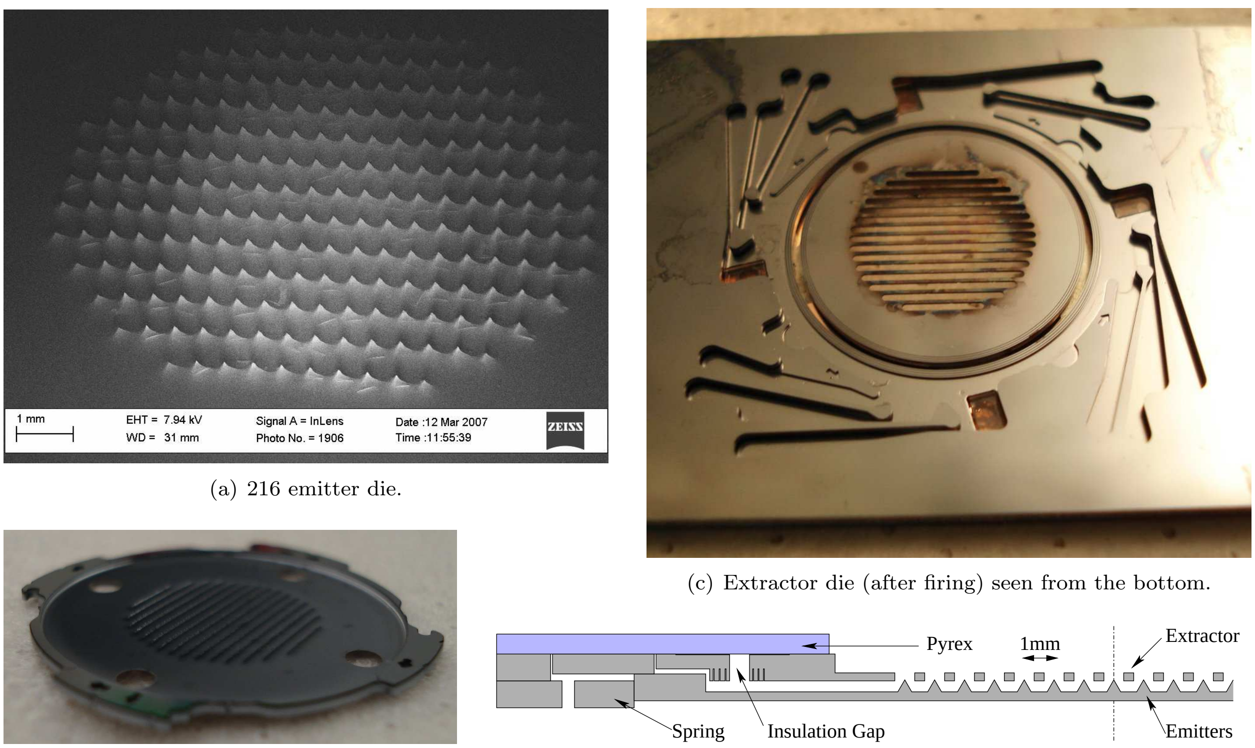
of the extractor electrode, the specific impulse of the thruster can be tuned from 500 s to many thousands of seconds, limited only by the available power and breakdown resistance of the insulators. Finally, the overall design is very simple.

A number of microfabricated electrospray thrusters have been previously reported.[3–8] The thruster reported in this paper is unique because it is a planar array operating in the pure ion emission regime with an integrated extractor electrode. In Ref. 9 we presented a thruster that made similar claims using a different extractor assembly technique. However, with that thruster, we were unable to get stable enough operation to run time-of-flight measurements and properly characterize the emitted beam.

II. The Microfabricated Thruster

The thruster is made using Deep Reactive Ion Etching (DRIE) and wafer bonding techniques, in a six mask process, and comprises two components. The emitter die in Figures 1(a) and 1(b) with 216 or 502 emitters in a 113 mm^2 area, is formed using DRIE and SF6 etching, and is plasma treated to transport liquid to the tips in a porous black-silicon surface layer.[5] In these experiments, the whole propellant supply is contained in this porous layer. The extractor die in Figure 1(c) incorporates the extractor electrode, a Pyrex layer for insulation, and springs which are used to reversibly assemble the emitter die.[10,11] This versatile assembly method, with 10 μm RMS alignment accuracy and 1.3 μm RMSD repeatability, allows the extractor die to be reused with multiple emitter dies, and potentially with different emitter concepts than the one presented. A cross-section of the thruster is shown in Figure 1(d). Full fabrication details can be found in Ref. 12.



(a) 216 emitter die.

(b) Emitter die.

(c) Extractor die (after firing) seen from the bottom.

(d) Cross-section

Figure 1. The microfabricated electrospray thruster array.

III. Experimental Results

In this section, we present the experiments that were carried out on the thruster. We describe the experimental setup and present I-V characteristics, interception data and time of flight measurements, which allow the performance of the thruster to be estimated.

III.A. Thruster Preparation

The thruster was fired with the ionic liquid EMI-BF_4.[13] An estimated 0.1 to 1 mm^3 of propellant was supplied to the emitter die using a syringe and allowed to spread across the black-silicon surface. Once wetted, the emitter die was assembled to the extractor component, and the assembly was mounted on a high density polyethylene holder. Electrical contact to the thruster was made via copper tape and a flexible clamp which also held the thruster in place on the holder. Measurements suggest contact resistances on the order of 100 kΩ in operation. Experiments were carried out at base pressures below $1 \cdot 10^{-5}$ torr.

III.B. Current-Voltage Characteristic

We measured the Current-Voltage (I-V) characteristic of the array with the experimental setup shown in Figure 2. In this experiment, the array was fired against a grounded collector plate. Currents to the collector and extractor were measured using Keithley 6514 and 6517A electrometers. A secondary electron suppression grid was placed in front of the collector plate, and biased to -50 V.

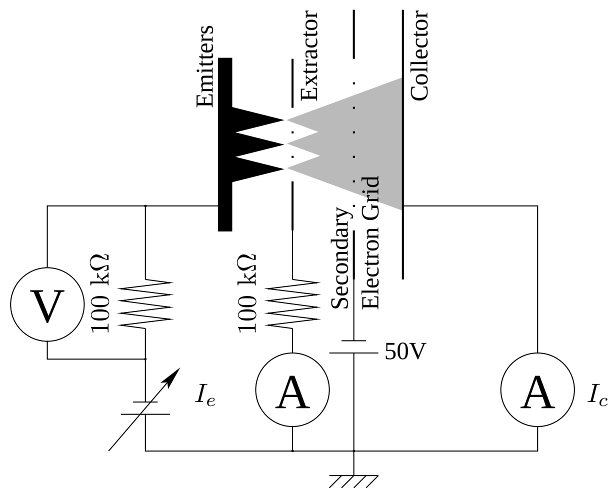


Figure 2. Experimental setup to take I-V characteristics.

The I-V measurements were entirely computer controlled. Collector current, extractor current, emitter voltage and time were logged. The voltage was ramped across the desired range three times to check consistency. Since there is no emission at low voltage, the ramp rate was usually increased at low voltages. About 3 samples per second were taken, with increments between 5 and 250 volts between samples, depending on the experiment. For experiments that reached high currents, larger increments were used to avoid depleting the propellant supply. Measurements taken with different ramp rates are consistent with each other at low currents, but some depletion is visible for long runs at high currents.

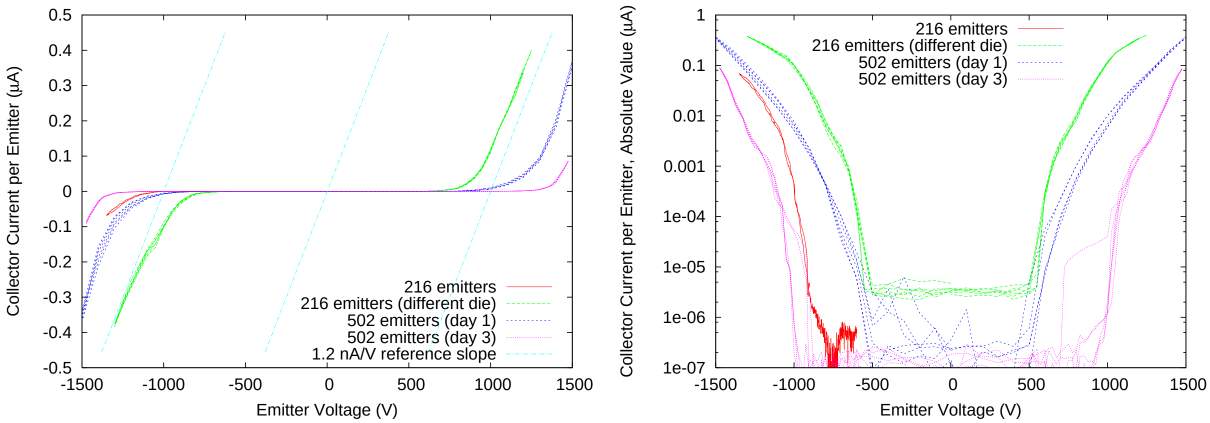
III.B.1. Stability of Operation

When a thruster was first started, a higher voltage was needed to start emission than during subsequent operation. This extra voltage may have been necessary to complete the wetting of the emitters. After this conditioning process, the thruster would go through three consecutive phases of operation. The *over-wet* phase was characterized by high interception on the collector electrode and unsteady emission. Then the thruster would transition to the *steady* phase with a repeatable I-V characteristic and very low current intercepted on the extractor. Finally, in the depletion phase, interception remains low, but higher and higher voltages are needed to maintain a given current level.

This paper focuses on steady the phase operation which is most interesting for propulsion. Observation of the emitters[12] suggests that the over-wet phase may be caused by excessive liquid present on the surface of the freshly wetted die. The depletion phase could be caused by insufficient liquid, or as a consequence of electrochemical reactions poisoning the emitter surface.[14]

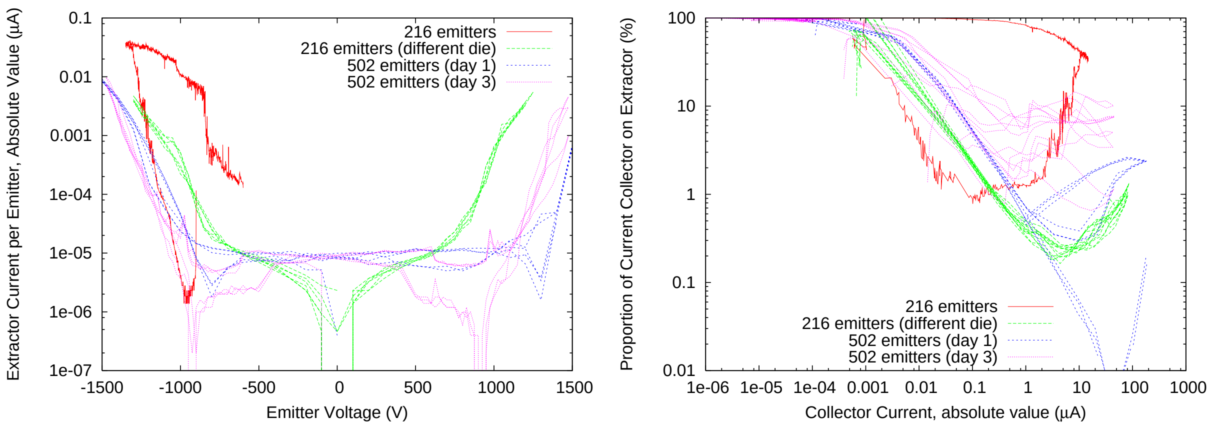
III.B.2. Emitted Current

Figures 3(a) and 3(b) shows the current per emitter for three different thrusters in the steady phase. One of the thrusters was tested on two different occasions, with the propellant being replenished between the firings.



(a) High current behavior (b) Low current behavior

Figure 3. Emitted current for different emitter dies, on different occasions.



(a) Intercepted Current (b) Interception Fraction

Figure 4. Current intercepted on the extractor. Interception much lower than 1% is possible, even at high currents.

The emitted current is symmetric to within a factor of 2 to changes in polarity. Different runs are not consistent with each other, but the overall shape of the characteristic remains similar, simply shifting up/down or left/right. The thruster seems to operate at lower voltages the first time an emitter die is used.

Unlike most electrospray experiments, we do not observe a distinct startup voltage. Instead emission starts below the noise floor and increases continuously from there. Computing startup voltage as in Ref. 15, yields a startup voltage of 475 V, slightly below the voltage at which the emitted current rises beyond the noise floor.

Initially, current increases exponentially with voltage. At current levels above about 100 nA, the dependence becomes linear with a 1.2 nA/V slope. The highest current we have observed is just over 1 μA per emitter, but at such high current levels, the thruster quickly enters the depletion phase preventing repeatable I-V traces like the ones presented here from being obtained.

III.B.3. Intercepted Current

Figure 4 shows the current intercepted by the extractor for the same set of experiments. There is a lot of variation from experiment to experiment. At very low currents, the interception signal is artificially high because the interception is below the noise floor. Once the interception becomes measurable, the proportion of interception slowly increases with current. Interception is often well below 1%, and rarely rises above 10%. For now there is very little consistency of the intercepted current between runs. Effects such as particulate contamination, broken emitter dies, position of the emitters relative to the extractor and emitter wetting procedure may partly explain these inconsistencies.

III.C. Time of Flight Measurements

We use time of flight to measure the velocity of the emitted particles, from which specific impulse can be deduced. The experimental apparatus[16] is depicted in Figure 5. Compared with the I-V experiment, the collector plate has been moved about 80 cm from the thruster, and a gate has been added to turn the emitted beam on or off. An Einzel lens collimates the beam onto the collector. The gate is repeatedly turned on and off, and the collector current follows the gate with a delay that is indicative of the beam particle velocities. The signal is averaged over 1024 gate switches to reduce noise.

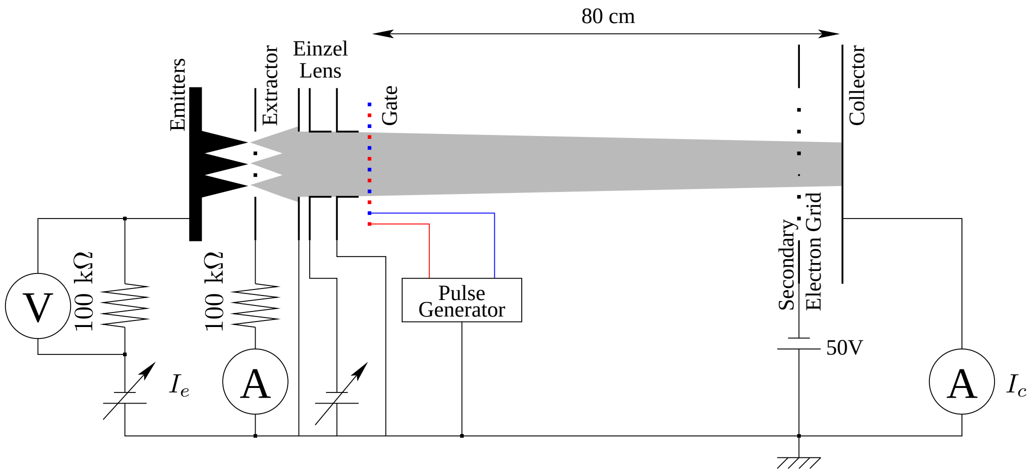
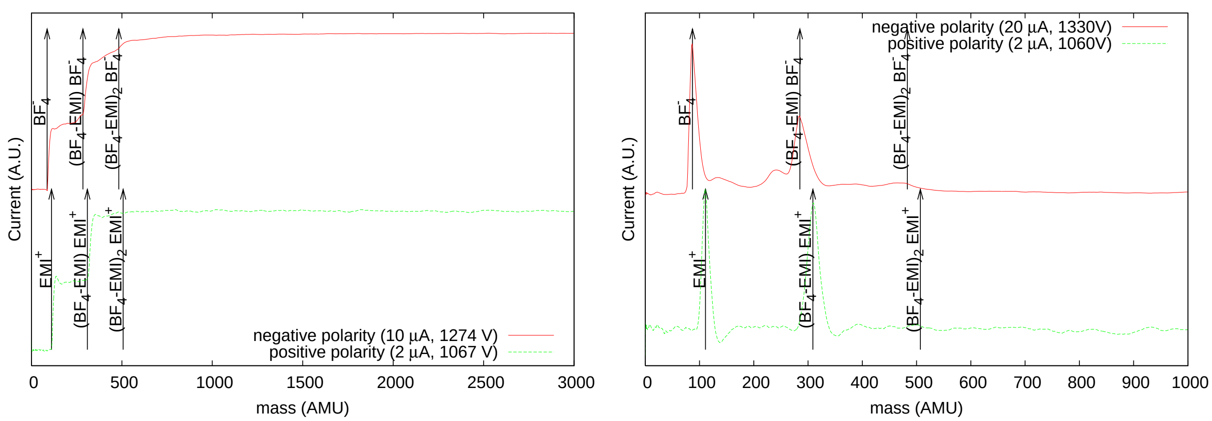


Figure 5. Diagram of the time of flight apparatus.



(a) Long exposure

(b) Pulsed Short exposure

Figure 6. Typical time-of-flight measurement with EMI-BF_4.

Figure 6 shows a typical time-of-flight plot for EMI-BF_4. The delay has been converted into particle mass, assuming singly charged particles accelerated by the full extractor voltage. The long exposure plot shows that there are no droplets present in the beam. The short exposure plot in which the gate underwent a 1 μs pulse, shows the details of the particles that are present (the pulsed operation makes the mass for each species easier to identify). In the figure, the monomers EMI and BF_4 are clearly visible at 111.2 and 86.8 AMU, as are the dimers (BF_4-EMI)BF_4^- and (BF_4-EMI)EMI^+, and the trimer (BF_4-EMI)$_2BF_4^-$. The proportions of the monomer, dimer and trimer were consistent across the various measurements we made to within 5 to 10%.

III.D. Visual Observation of Thruster Operation

At high currents, when the room was darkened, the thruster emitted a dimly visible plume shown in Figure 7. A bluish glow was visible, mainly in the area between the secondary electron suppression grid and the collector plate. In some cases, at high emitted currents (100 μA or more), small sparks were visible around the thruster, possibly due to gas emission from electrochemical reactions. In general, the pressure in the chamber increased during high-current thruster thruster operation, from about $5 \cdot 10^{-6}$ torr to $5 \cdot 10^{-5}$ torr.

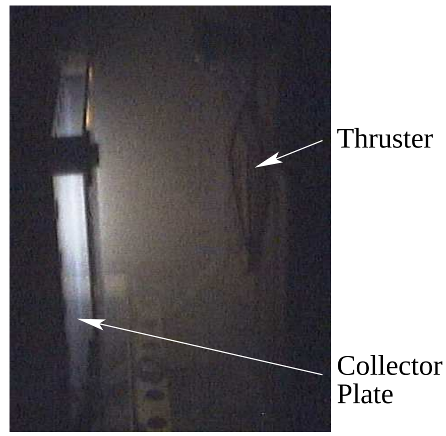


Figure 7. The thruster firing, as seen through the chamber window.

IV. Results and Discussion

To estimate the performance of the thruster, we first evaluate its thrust efficiency. Different sources of inefficiencies must be considered:

Polydispersity: The presence of different species in the emitted beam leads to a velocity spread, which is an inefficient distribution of kinetic energy between the particles. The polydispersity efficiency is around 94% with the mix of ions we are considering.[16,17] Details are given in Table 1.

Angular: Angular spreading of the beam implies wasteful use of kinetic energy for off-axis velocity components. We have measured an angular distribution of about 20° half-width half max,[12] which leads to an angular efficiency of 94%.

Extraction: About 7 to 8 eV is lost to ion extraction and vibrational excitation of the emitted ions.[2] This accounts for a loss of about 1% at 1 kV extraction voltage.

Electrical: Resistors and poor contacts account for an effective resistance of about 300 $k\Omega$. This loss is about 1% at 1 kV and 30 μA, and is proportional to current, and inversely proportional to applied voltage.

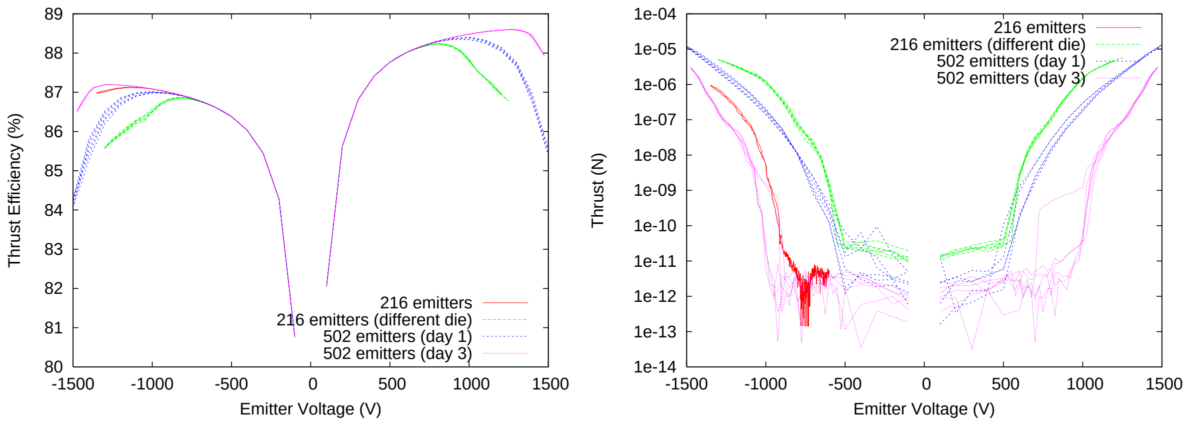
Thus inefficiency is dominated by beam divergence and polydispersity, with electrical losses becoming important at high currents, and extraction energy at low currents. At intermediate currents, the overall efficiency is around 87%. Figure 8(a) shows the efficiency for the usual set of runs.

Knowing the electrical power provided to the thruster, the thrust efficiency, and the mass flow rate (from the current and particle mass distribution), we can now deduce the thrust in Figure 8(b). The thrust can be varied over 6 orders of magnitude by varying the voltage. By hand it is easy to adjust the current to within 20% of a desired value, suggesting that a slow current control loop would be sufficient to control the thruster over the whole 6 orders of magnitude range, obviating the need for individually addressable clusters of emitters.[18] Direct thrust measurements are currently underway at Busek Co., Natick, MA, using a torsional thrust balance.[19] Hopefully these data will confirm our analytical thrust predictions.

The specific impulse is obtained directly from the time of flight data. At 1000 V it is about 3050 s in the positive polarity, and 3240 s in the negative polarity, and increases with the square root of the voltage. If an

Polarity	Negative		Positive	
Species	BF_4^- (monomer)	(BF_4-EMI) BF_4^- (dimer)	EMI^+ (monomer)	(BF_4-EMI) EMI^+ (dimer)
Monomer fraction (%)	60 to 65		55 to 60	
Mass (AMU)	86.8	284.8	111.2	309.2
Average mass (AMU)	156 to 166		190 to 200	
Dimer to monomer mass ratio	3.281		2.781	
Polydispersity efficiency (%)	93.3 to 94.0		94.4 to 94.8	

Table 1. Data used to compute polydispersity efficiency



(a) Thrust efficiency

(b) Thrust

Figure 8. Thrust efficiency and thrust as a function of applied voltage for some typical runs. A monomer fraction of 60% is assumed.

accelerator electrode were added to adjust the energy of the emitted beam, this specific impulse should be adjustable over a wide range, limited from above by the available power and maximum operating voltage, and from below by the energy spread of the ions.

The highest calculated thrust for our runs is 13 μN for a 502 emitter die in the positive polarity. The corresponding thrust density is 0.12 N/m^2, and the thrust per emitter is 26 nN. The power consumption at maximum thrust is 275 mW. Estimating the mass of the thruster at 5 g, and the mass of the power supply at 20 g (for example, the Q-series power supplies from EMCO High Voltage Co., Sutter Creek, CA, come in a 5 g package and can deliver $\pm$2000 V at 250 μA with better than 50% efficiency), a thrust-to-weight ratio of $4 \cdot 10^{-5}$ is possible (excluding the mass of the power source itself).

The reported thrust is not an absolute limit, and in fact, this same thruster was run at nearly twice the reported current level in one test for which the data acquisition failed. Currently, rapid depletion of the liquid on the emitter surface limits operation at high flow rates. In the future, erosion of the extractor may be a concern since interception increases with current. It may therefore be desirable to limit the thrust to levels where there is low interception. Interception exceeds 1% near the highest thrust levels we have reported. However, some dies had significantly higher interception near 10%. The causes of this higher interception need to be understood so that it can be reduced.

V. Conclusion

A fully integrated planar electrospray thruster has been demonstrated. It operates in the pure ion emission regime with the ionic liquid EMI-BF_4. In the steady operating phase, the thruster exhibits stable repeatable emission, with current interception on the extractor of less than 1% in many cases. The performance of the thruster is not consistent from emitter die to emitter or between refuellings of a given emitter die. Current and time of flight measurements indicate a specific impulse around 3000 s at 1 kV extractor voltage. The maximum recorded current was 186 μA at 1500 V, for a total thrust of 13 μN across the 113 mm^2 emitter area, and a power consumption of 275 mW. These results prove that the externally wetted planar array is a viable architecture for space propulsion, but there is still work needed to understand the difference in performance between runs.

Acknowledgments

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