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# Performance Characterization and Ion Energy Analysis of a 2-kW Hall Thruster with Segmented Anodes

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## Abstract

**The goal of this paper is to describe the change in performance and ion energy distribution in a 2-kW Hall thruster operated with segmented anodes. The effect on the performance and ion energy distribution as discharge current is shifted from the main anode to the shim electrodes is examined. Performance was largely unaffected by shifting current from the main anode to the shims. A water cooled ExB probe was utilized to determine the ion energy distribution. A change in the dominant singly charged ion energy was observed when the shim electrode voltage was varied. Measurable increases in singly charged xenon velocities correlated with slight performance gains. The thruster geometry examined here has been proposed for control of the temperature of a bismuth propellant feed system. No significant change in thrust, Isp, or efficiency indicates that a bismuth thruster could be operated and thermally controlled using segmented anodes without significant impact on the performance.**

## 1. Introduction

Current Hall thrusters utilize xenon gas as propellant. While xenon is effective, it may not be ideal for future high-power devices. First of these problems is the expense of xenon; extended testing of high-power Hall thrusters is very costly. Additionally, operation of a xenon thruster in a vacuum chamber requires very large pump throughput to efficiently remove the influx of propellant gas. One method of potentially reducing the cost of ground operations, while also improving the performance of a Hall thruster is to use condensable propellants such as bismuth. Bismuth offers two major advantages for ground testing: propellant cost and the condensible nature. Bismuth is much cheaper than xenon, and thus extended testing programs on large thrusters will cost much less with bismuth than with xenon. The condensible nature of bismuth aids in ground testing as propellant ions will condense on vacuum facility walls, effectively making bismuth 'self-pumping.' With that in mind, operating a 50-kW bismuth Hall thruster would require only enough pumping speed to keep up with the cathode mass flow (assuming a xenon cathode). Although immature as a Hall thruster propellant, the use of bismuth is not without precedent.[1,2] Soviet work performed in the 1970's and 1980's evaluated bismuth anode layer thrusters. TsNIIMASH researchers reported thrusters with power up to 140 kW and specific impulse as high as 8,000 seconds operating with anode efficiencies exceeding 70%. The thrusters tested were of the anode layer type, where the anode of the thruster was placed near the magnetic field poles. The thruster under consideration in this work is similar to the SPT-type thruster, in that the anode occupies the base of a ceramic discharge chamber. Bismuth also offers several performance advantages over xenon, which increase its attractiveness as a propellant.[3]

Bismuth presents its own engineering difficulties, however. In order for the thruster to operate, there must be a precisely controlled source of bismuth vapor. Previous work used a heated bismuth reservoir, which fed vapor directly into the thruster. The difficulty with this method was that the reservoir required significant resistive heating to maintain such a high temperature (more than 1,000 K). The temperature

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required for bismuth evaporation is a function of the vapor pressure, which increases exponentially with temperature. In order to reduce or eliminate the need for resistive heating during operation, the authors have developed a technique that utilizes the waste heat from the thruster to warm the bismuth reservoir to the required temperatures. Initial start-up of the thruster would require either resistive heating to reach the required temperature for bismuth operation, or initiation on xenon and conversion to bismuth operation once the desired temperature is reached. In this design, the main anode of the thruster functions as the bismuth reservoir. As the anode is heated by the thruster discharge plasma, this design has the potential to eliminate the need for resistive heaters, allowing the anode to be maintained at a temperature sufficient for bismuth evaporation purely from the discharge waste heat. The evaporation rate is controlled through the reservoir temperature and the permeated area through which the bismuth vapors diffuse into the discharge chamber. Since it is not feasible to mechanically vary the vapor escape area through the reservoir, the mass flow rate, $\dot{m}$, is controlled by varying the reservoir temperature within the thruster. The evaporation rate is governed by the equilibrium vapor pressure of the liquid metal with the resultant goal of maintaining the appropriate evaporator temperature, which when combined with the open area produces sufficient quantities of bismuth vapor. Previous studies have found that for an anode with a 10% open-area fraction in a thruster of the type investigated in this paper, a temperature of 750°C is sufficient to provide the necessary bismuth mass flow (5.5-6 mg/s in the examined thruster).[4]

Control of anode/reservoir temperature is necessary to provide a controllable flow of bismuth. In order to control the temperature of the main anode, a pair of inert shim electrodes was added to the discharge channel of the thruster, downstream of the main anode, as shown in Figure 1. By slightly varying the shim electrode voltage with respect to the main anode/reservoir, the discharge current can be shifted between the shim electrodes and the main anode. This shift in discharge current will then shift the discharge heating, with the result that shifting current to the shims will cool the main anode, and diverting current back to the anode will increase its temperature, and hence bismuth evaporation rate.[5]

While the segmented electrodes present a unique thermal control strategy, the non-traditional configuration may cause a change in the operating characteristics of the thruster. Any negative impact on beam divergence, efficiency, Isp, or thrust could negate the anticipated performance benefits of the bismuth scheme. Other experimental investigations have been performed on segmented-electrode Hall thrusters which showed a net decrease in beam divergence and an increase in thrust with addition of the segmented electrodes.[6,7,8] These investigations were performed on thrusters with largely different operating parameters than the design implemented in this paper. In many of the experiments the shim electrodes were held either at anode potential, cathode potential or just allowed to float as opposed to being forced to accept varying fractions of the discharge current. Some of the shim electrode configurations previously investigated were also emissive in nature. Between the differences in materials and the method of power application to the shim electrodes any attempt to predict the behavior of a candidate segmented anode bismuth thruster is necessarily precluded without experimental observation. Previous experiments on a similar thruster design intended for bismuth operation showed little change in the beam profile.[9]

Determination of the ion energy distribution can be of significant benefit to the analysis of a thruster. As the shifting of current from the shims to the main anode requires a change in voltage, the ionization and acceleration processes in the thruster may change. Determination of a change in ion energy (if any) as the shim voltage is adjusted will determine if any change in the performance of the thruster is due to different ion acceleration potentials or other factors.

# 2. Goal of Research

The goal of the research reported here is to determine the effect, if any, the addition of shim electrodes has on the performance of a 2 kW Hall thruster. Additionally, the effect the shim electrodes have on the ion energy distribution will be examined through use of an ExB probe.

# 3. Experimental Apparatus

## 3.1. Hall Thruster

The Hall thruster employed for segmented anode tests uses the magnetic circuit from an Aerojet BPT-2000,[10] which has been retrofitted with segmented anodes and the necessary power connections.

Adjustment of the current-sharing properties of the anodes is accomplished through independent adjustment of the voltage on either of the shim electrodes as shown in Figure 2 while keeping the main anode at a fixed potential. A single $LaB_6$ laboratory-grade cathode is employed as both neutralizer and discharge cathode.

### 3.2. Thruster Testing Facility

All tests were performed in the $I_{sp}$ Lab's Xenon Test Facility (XTF). The facility is comprised of a 2-m-diameter by 4-m-long vacuum tank. Rough pumping is accomplished by a two-stage rotary oil-sealed vacuum pump with a Roots blower, capable of pumping at 400 cfm. High vacuum is achieved through dual 48-inch-diameter cryopumps, capable of a combined pumping rate of 120,000 l/s on nitrogen as in Figure 3. Tank pressure was measured via a Bayard-Alpert ionization gauge.

### 3.3. Performance Measurements

Thrust measurements were taken using a NASA-Glenn-style inverted pendulum thrust stand and recorded via a computer controlled data acquisition system. Thrust measurements have an estimated experimental uncertainty of 5%. Voltage and current measurements were taken by a computer controlled data acquisition system which polled the power supplies at approximately one second intervals.

### 3.4. ExB Probe

An ExB probe utilizes perpendicular electric and magnetic fields to filter ions based on velocity. The magnetic field acts to divert ions away from an orifice, while the electric field provides an opposing force to push the ions back to their original path, as shown in Figure 4. The net force on an incident ion is given by:

$$\vec{F} = q\left[\left(\vec{v} \times \vec{B}\right) + \vec{E}\right]. \tag{1}$$

Where $\vec{F}$ if the force experienced by an ion, $q$ is the charge of the ion, $\vec{v}$ is the velocity of the ion, $\vec{B}$ is the magnetic field in the probe, and $\vec{E}$ is the electric field in the probe. The velocity for which an ion will experience no net electromagnetic force is:

$$\vec{v}_o = \frac{\vec{E}}{\vec{B}}. \tag{2}$$

This relation allows ions of a specific velocity to pass through the probe on a straight-line trajectory, as the magnetic Lorenz force will be equal and opposite to the applied electric force. Ions of other velocities will not be able to pass, as they will either be diverted too much by the magnetic field, or not enough to counteract the electric force. A more complete explanation of the construction and theory of an ExB probe is presented elsewhere.[11]

The ExB probe utilized has used has a 5-cm collimator and 23-cm filter. The collimator serves to reduce the allowable half-angle at which an ion can enter the filter. The orifices in the collimator are 1.6-mm in diameter. The orifice at the exit of the filter is 2.4-mm in diameter. All of the orifices have 90-degree chamfers on their downstream sides, to prevent ions from hitting the interiors of the orifices and unnecessarily reducing the measured current. The magnetic field is supplied by two 5 cm x 22.8 cm x 1.3 cm arrays of neodymium-iron-boron rare earth magnets, arrayed at the top and bottom of the probe, which provide an approximately 0.42 T field in the filter. The magnets are separated by Teflon spacers, which also hold and insulate the electrode plates from the structure of the probe. The current is detected by a K and M Electronics model 7550m channel electron multiplier. The multiplier was operated at supply voltages up to –2350 V, which correlates to a gain of up to $10^8$. The casing of the probe as well as the three orifice plates are fabricated of magnetic stainless steel, to direct and focus the magnetic field while preventing oxidation as is typical of magnetic iron or mild steels. The magnetic field outside the filter section of the probe is less than one gauss. The output current of the electron multiplier was converted to a voltage signal via a current amplifier and displayed on an oscilloscope. Total gain of the measurement system (multiplier and current amplifier) was on the order of $10^{13}$ volts per amp of ion current. Tuning of the electrodes and thus the electric field in the probe was performed a single utilizing a voltage divider to supply the bipolar voltage necessary for the electrode plates. The electrodes were swept through a 400-volt difference at a rate of 1 Hz, which with the estimated magnetic field corresponds to an ion with nearly 2,700 eV of energy, well above the 2,400 eV expected of a quadruply-charged ion accelerated through a 600 V potential. The ExB probe was enclosed in a watercooled copper shell. This allowed the probe to be used for extended periods of time in the thruster beam without excessive heat buildup.

# 4. Results and Discussion

Thrust and ExB probe measurements were taken at a mass flow of 5 mg/s, at anode voltages of 300, 350, 400, and 450 V, and at five levels of current sharing: all current on the shims, 75% on the shims, 50% on the shims, 25% on the shims, and less than 5% on the shims. Diversion of all discharge current to the anode was not possible: if less than 150 mA of the discharge current was on the shims, the thruster became unstable. In all cases, diversion of all current to the shims required increasing the shim voltage above the anode voltage by approximately 25 V, and diversion of all but 150 mA to the anode required lowering the shim voltage to approximately 40 V below anode potential. At all operating points, the efficiency was maximized through use of the magnet current.

The thrust, Isp, and efficiency all increased with higher anode voltage, as shown in Figure 5. The thrust generally decreased as current was shifted from the shims to the main anode (by reducing the shim voltage), however the trends were smaller than the estimated error in the measurements. This downwards trend in thrust indicates that the ions may have experienced a lower effective acceleration voltage than when all of the current was on the shims. Other factors such as beam divergence may also account for the change in thrust.

Specific Impulse also showed an increase with shim voltage, as shown in Figure 6, on the order of 100 s between the minimum and maximum shim voltages. Similarly to the thrust, however, these changes were on the order of the experimental error.

Efficiency showed much less variation than the thrust or Isp presented, as shown in Figure 7. The efficiencies at 350, 400, and 450 V showed a decrease of a few percent with reduction of the shim voltage, however these changes were small and well within the estimated error. The efficiency at 300 V showed an opposite trend, with an increase of almost 3% as the shim voltage was lowered. However this is also less than the experimental error.

Overall the performance of the thruster did not appear to change significantly as the shim voltage was adjusted to divert current from the shims to the main anode. This result is encouraging, as operation of a bismuth thruster utilizing diversion of discharge current from the main anode to the shims as a method of thermal control will require constant adjustments to the shim potential. No significant change in thrust, Isp, or efficiency indicates that a bismuth thruster could be operated and thermally controlled without significant impact on the performance.

Determination of the thrust, Isp, and efficiency can only provide some insight into changes taking place in the thruster as current is shifted from the shims to the main anode. Measurement of the ion velocity distribution (and thus, the ion energy distribution) with an ExB probe can provide further insight into the changes taking place in the thruster as the operating parameters are varied. Because the exact value of the magnetic field in the probe is not known, it must be calculated from an ion of known velocity and the applied electric field required for the ion to be detected. Determination of the velocity of ions passing through the ExB probe from the electrode voltage requires a calibration point. Usually this is accomplished by using a retarding potential analyzer to determine a most probable ion energy, which can be used as the known velocity. As ion energy data were not available during analysis of these data, results from previous thruster experiments were used for a crude calibration. The ion energy chosen as the peak of the singly charged ion distribution was 270 eV for a thruster of comparable performance operating at 300 V, as measured by King.[12] This energy corresponds to a velocity of 21,022 m/s. This velocity was fit to the peak of the ion distribution for the tested thruster at 300 V on the anode and 75% of the current on the shims, as shown in Figure 8. The peak of the singly-charged ions at this operating point was at 137 V on the electrodes, with the resulting calibration factor of 184.4 m/s/V. This calibration allows determination of whether a peak is singly-, doubly-, or triply charged based on the velocity. Doubly charged ions should display a velocity roughly $\sqrt{2}$ times as large as the singly-charged ion velocity (40% higher). This is due to doubly charged ions having twice the kinetic energy of the singles. Similarly, triply charged ions should display $\sqrt{3}$ times the velocity (70% higher). In the distribution in Figure 8, the velocity of the second peak in the distribution is only 30% higher than the single-ion peak. While this increased velocity is less than the approximately 40% higher expected of doubly charged ions, the velocity of the peak corresponds to a singly charged ion accelerated through a potential of 435 V. As this is 45% higher than the discharge voltage of the thruster, the peak cannot be singly charged xenon and thus must be doubly charged. This indicates that the doubly charged ions are not being accelerated by the same potential as the singly charged ions. The third peak has a velocity 57% higher than the singly charged ion peak, again indicating a smaller net acceleration potential on the triply charged ions. The velocity of the third peak corresponds to a singly charged ion accelerated through a potential of 665 V; well over twice the discharge voltage of the thruster. While these differences between the singly-, doubly- and triply- charged ions are smaller than expected, they are large enough to determine that the three peaks in the distribution are singly-, doubly-, and triply charged ions.

ExB measurements as current was shifted from the main anode to the shims showed an unexpected change in the ion populations, as shown in Figures 8-11. The magnitude of the large singly charged ion peak exhibited in the data when all of the discharge current on the shims was reduced and an additional singly charged ion peak appeared at lower velocities than the original singly charged ion peak. Further examination revealed that the low energy peak is always present, however when all of the current was on the shims the higher energy singly charged ion peak was significantly larger than the low energy peak. Due to the large difference in peak heights the distribution appeared to have only one singly charged ion population with a small shoulder on the low energy side of the peak. The mechanism behind this reduction in high energy singly charged ions as the shim voltage is reduced below the anode voltage is unknown at this time. The reduction in the number of high energy singly charged ions is likely a major contributing factor in the reduced thrust, Isp and efficiency seen in the thruster as current was shifted from the shims to the anode.

Additionally, the entire ion velocity distribution was shifted to lower velocities as the shim voltage was reduced below the anode voltage, as shown in Figure 12. The velocities of the peaks in both the doubly- and triply- charged ion distributions were lower when the shim voltage was reduced than they were with high shim voltage. The reduction in doubly charged ion velocity between the high shim voltage operating point (all current on the shims) and the low shim voltage operating point (<5% of the current on the shims) produces a calculated 57 eV reduction in ion energy, or a reduced acceleration voltage of 28.5 V. The triply charged ion velocity was reduced by 75 eV over the same shim voltage range, which corresponds to a reduction 25 V in the acceleration voltage. This reduction in the ion energy indicates that at least part of the ion acceleration is taking place downstream of the shims, as the anode potential did not change. If ion acceleration was dominated by the anode, no change should have been apparent in the velocities of the ions as the shim voltage was reduced.

# 5. Conclusions

The performance of the thruster was largely unchanged as discharge current was shifted from the main anode to the shims. As the shim voltage was decreased in order to force current attachment to the main anode, the thrust, Isp, and efficiency showed general decreases. These changes were smaller than the estimated measurement error, however, and cannot be verified without further experimentation and reduction of the error. No significant change in thrust, Isp, or efficiency indicates that a thruster utilizing shim anodes for thermal control of a bismuth evaporator could be operated and thermally controlled without significant impact on the performance.

The most interesting change in the thruster as the shim voltage was reduced was the large change in the ion energy distribution of the thruster. The large number of high energy singly charged ions that were present when all current was on the shims was reduced greatly as current was shifted to the main anode, yet a smaller, lower energy singly charged ion population was largely unaffected. A lower population of high energy singly charged ions will cause a corresponding decrease in thrust, specific impulse, and efficiency. Determination of the mechanism of the reduction in high energy singly charged ions could provide significant insight into the acceleration mechanisms in a Hall thruster with shim electrodes. Furthermore, the doubly- and triply- charged ions saw a reduction in effective acceleration voltage, indicating that the effective acceleration potential seen by the ions was reduced when the shim voltage was lowered. Both the reduction in high velocity singly charged ions and the reduction in doubly and triply charged ion velocities indicate that the reduced thrust, Isp and efficiency seen were caused by lower ion energy.

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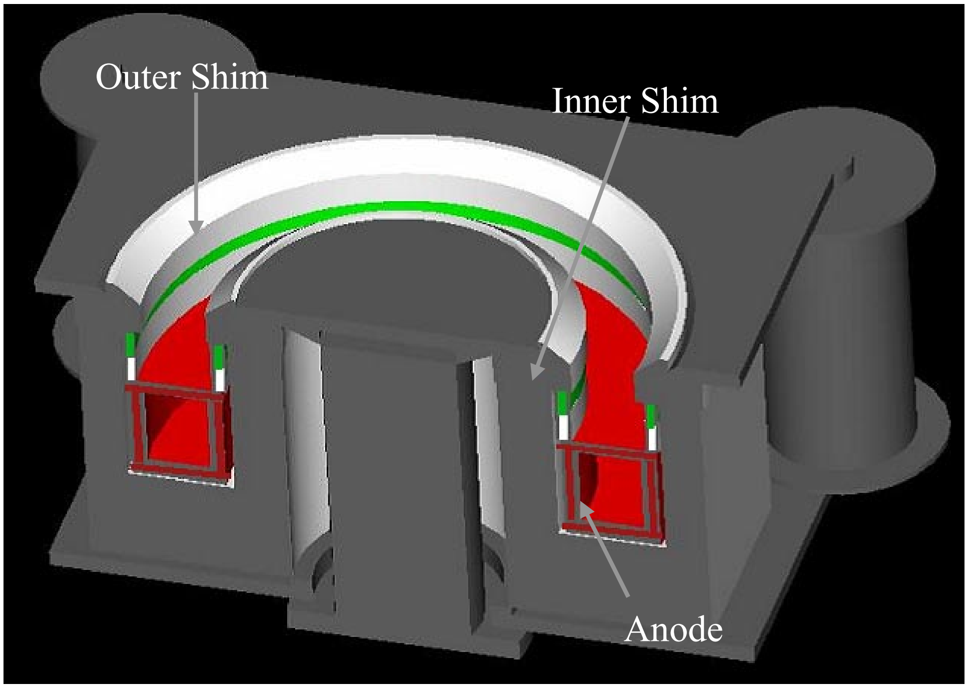


**Figure 1: Cross-Section View of the Segmented Anode Thruster.**

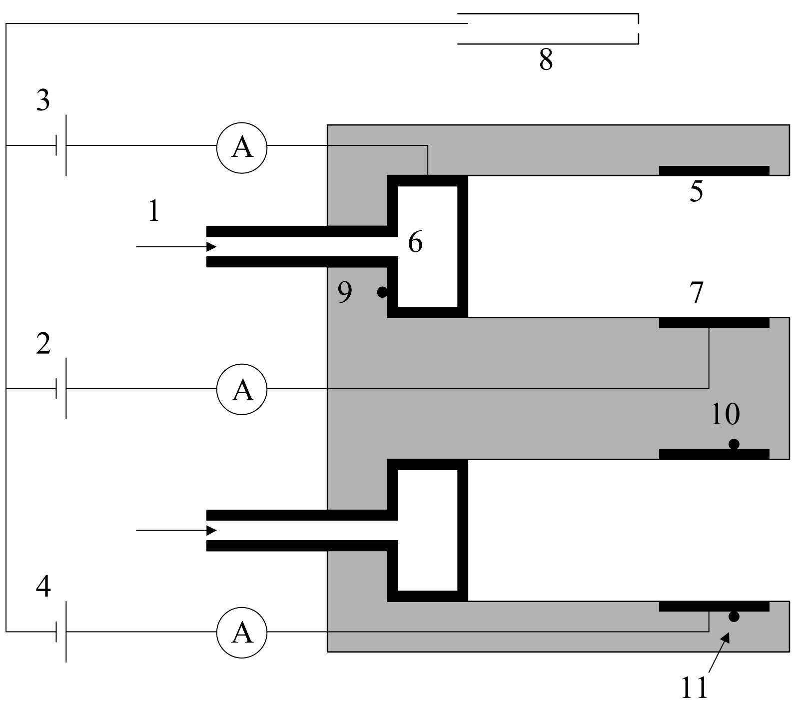


**Figure 2: Electrical schematic of thruster test apparatus. Numbered annotations are 1: xenon propellant flow, 2: inner shim power supply, 3: main anode power supply, 4: outer shim power supply, 5: outer shim electrode, 6: main anode and gas distributor, 7: inner shim electrode, 8: cathode, 9: anode thermocouple, 10: inner shim thermocouple, and 11: outer shim thermocouple**

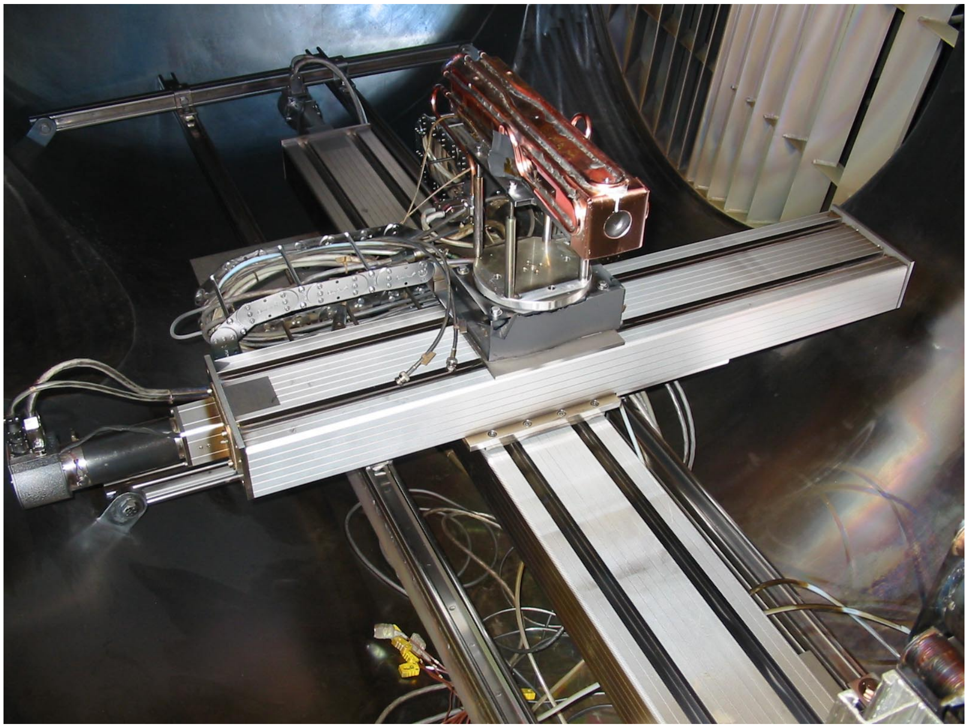

**Figure 3: Photograph of the ExB probe in the XTF.**

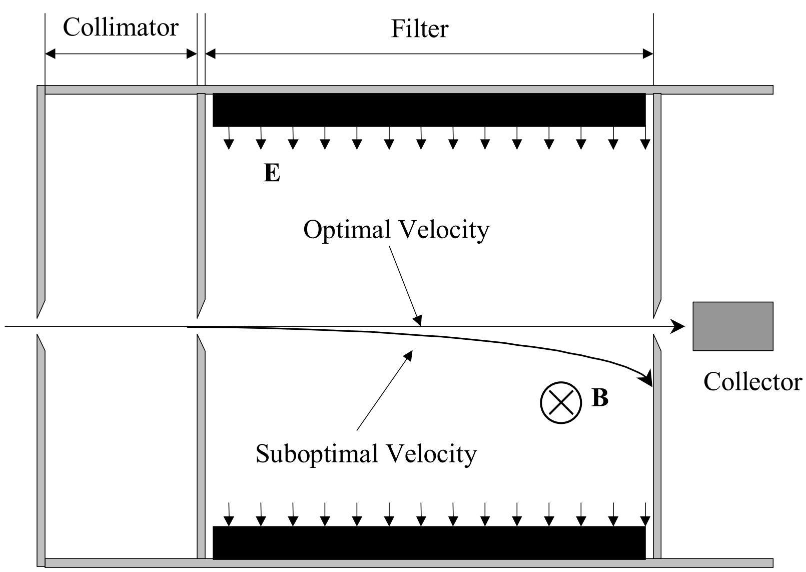


**Figure 4: Schematic view of ExB probe.**

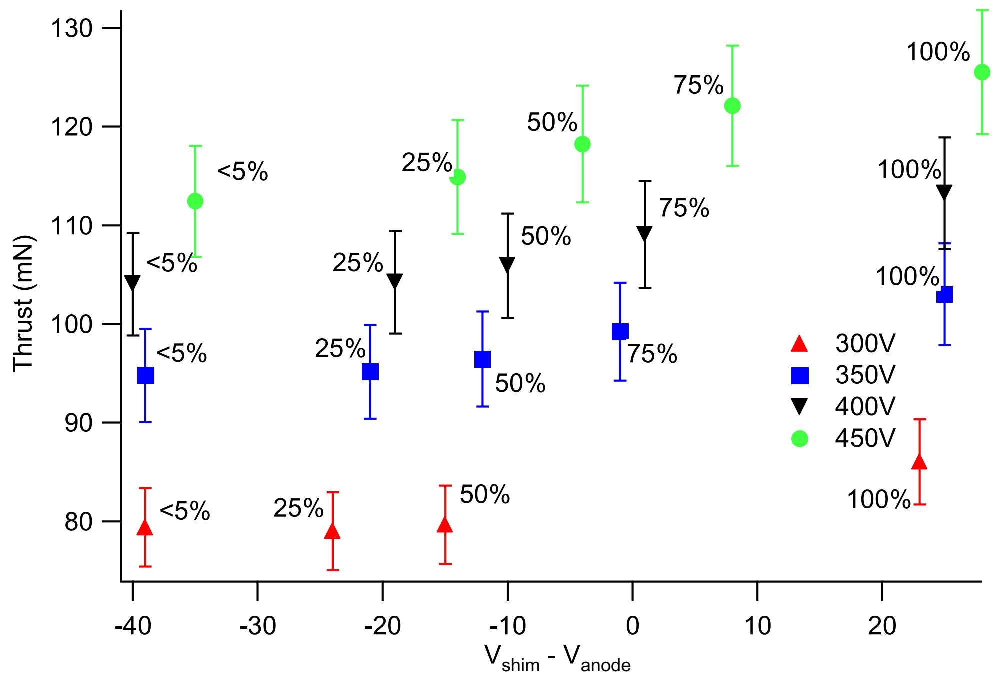


**Figure 5: Thrust produced as a function of the voltage difference between the shims and main anode, at four anode potentials. Error is estimated at 5%. Percentage notations indicate amount of discharge current on the shims.**

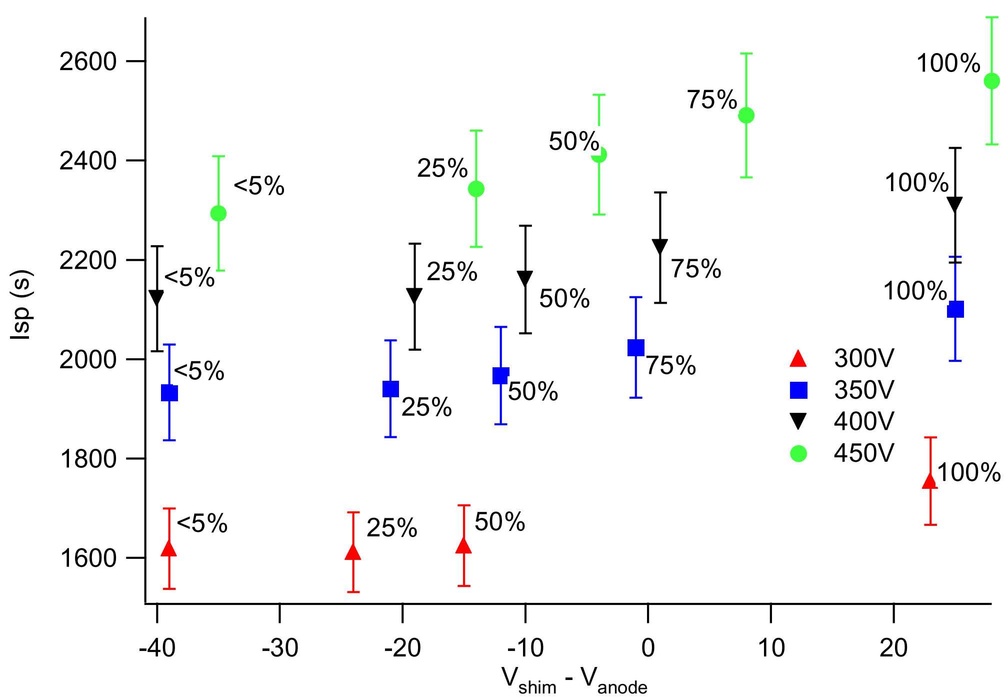


**Figure 6: Specific Impulse as a function of the voltage difference between the shims and main anode, at four anode potentials. Error is estimated at 5%. Percentage notations indicate amount of discharge current on the shims.**

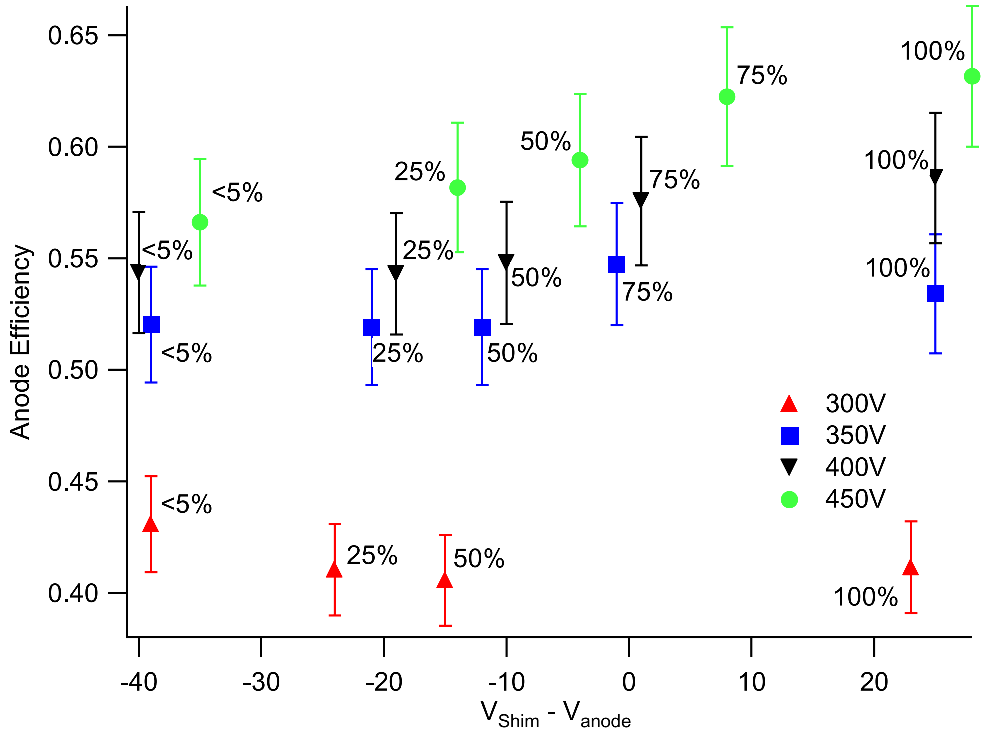


**Figure 7: Anode efficiency as a function of the voltage difference between the shims and main anode, at four anode potentials. Error is estimated at 5%. Percentage notations indicate amount of discharge current on the shims.**

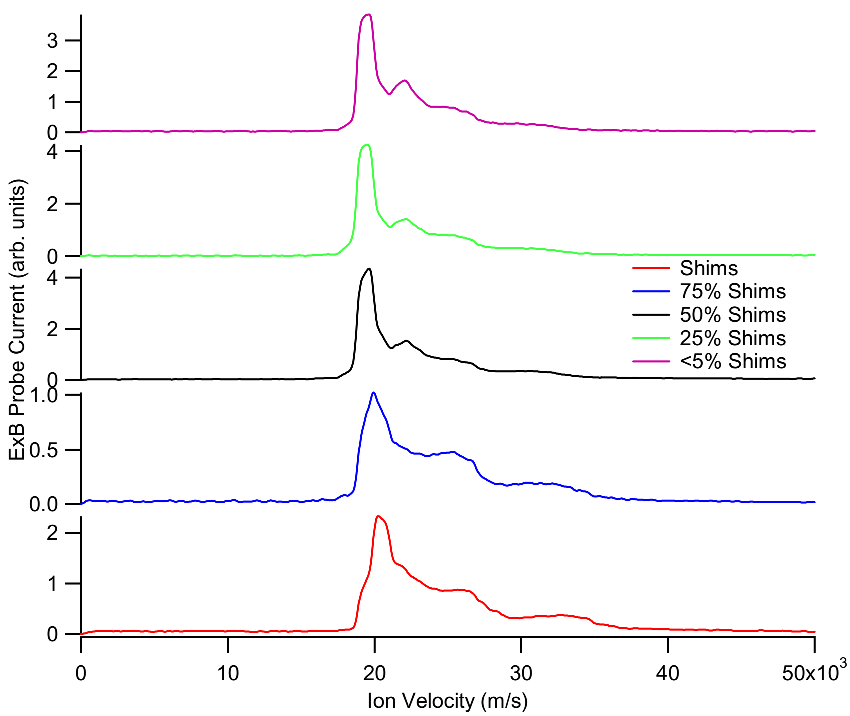


**Figure 8: ExB Traces acquired for 300 V on the anode at all shim current sharing levels.**

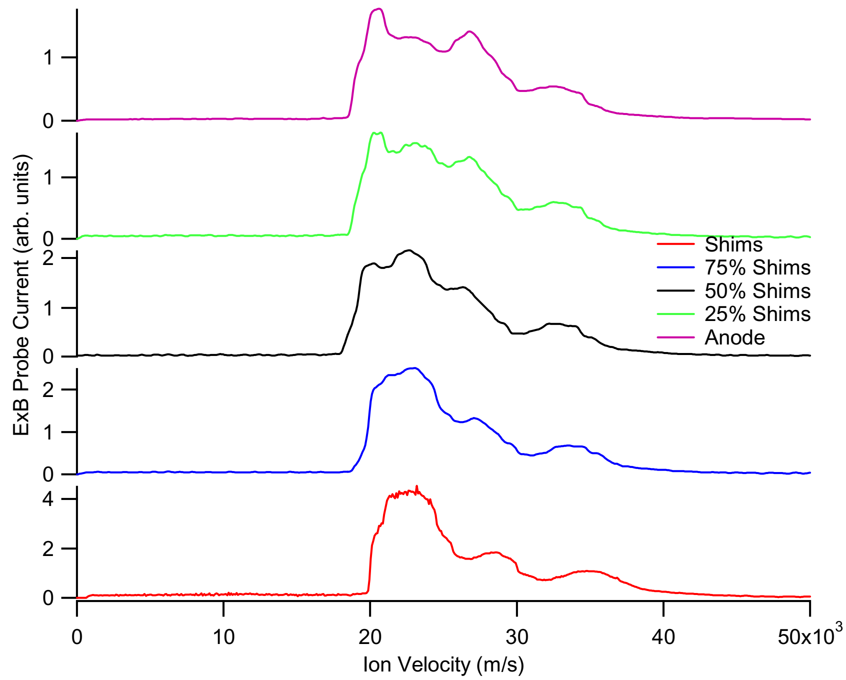


**Figure 9: ExB Traces acquired for 350 V on the anode at all shim current sharing levels.**

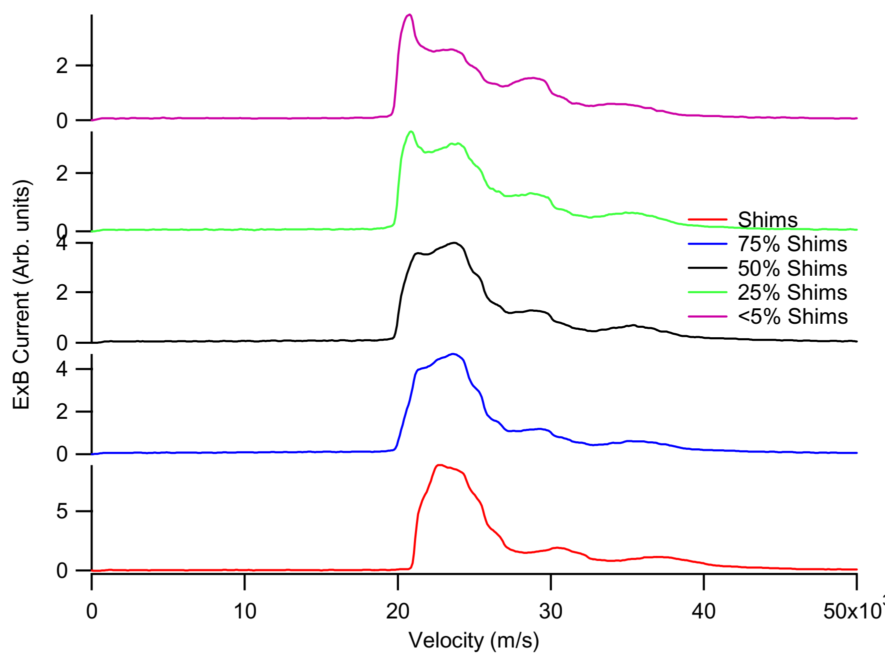


**Figure 10: ExB traces acquired for 400 V on the anode at all shim current sharing levels.**

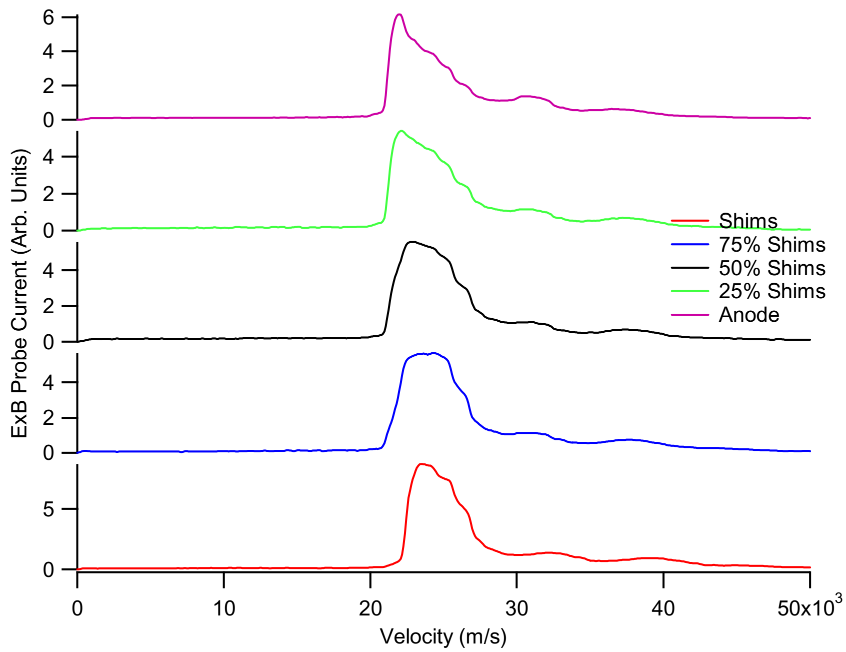


**Figure 11: ExB traces acquired for 450 V on the anode at all shim current sharing levels.**

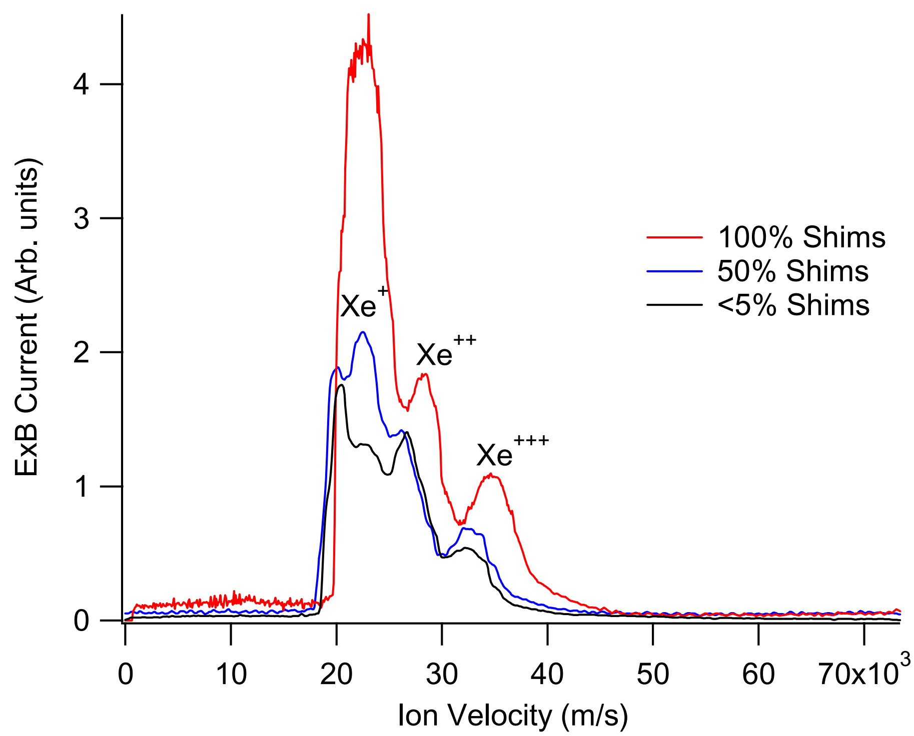


**Figure 12: ExB traces acquired with 350 V on the main anode at three shim current sharing levels.**