Progress on the Development of a Direct Evaporation Bismuth Hall Thruster

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Abstract: **Thrust, I_{sp} and efficiency measurements were taken on a segmented Hall thruster designed to run on both bismuth and xenon in order to ascertain the effect anode current attachment as well as anode power density. Overall, very little change in thrust, specific impulse and efficiency were measured across the operating spectrum when running on xenon. Using a unique dual-propellant distributor, this work reports on experiments to use a xenon discharge as a "jump start" mechanism to provide waste heat necessary to initiate direct bismuth evaporation. Using the shim electrodes and magnetic fields for temperature control, the thruster is operated entirely on bismuth after a xenon warm-up stage.**

I. Introduction

BISMUTH has many attributes that make it well suited for development as a propellant. When compared to more traditional propellants such as xenon, bismuth holds significant advantages both from an energetics[1] and cost standpoint. There are significant ground-test facility cost savings as bismuth doesn't require the use of expensive cryogenic pumps. Since bismuth is a solid at room temperature, any exhausted bismuth will hit the tank wall and solidify, turning the entire vacuum chamber into an effective pumping surface. 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. Soviet work performed in the 1980's and only recently reported in the open literature 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%. Papers reporting on this early work give few details on bismuth flow control method or apparatus.

While physically superior in the discharge chamber, the obvious engineering challenge associated with bismuth is how to produce and deliver a metered flow of vapor to the thruster in an energy efficient method. Early Soviet work was based on handling bismuth in gas phase throughout the thruster[2, 3]. Besides the material difficulties associated with high-temperature propellant isolators, valves, and flow control devices, such a system is energetically unfavorable. Any power that is used to drive the evaporation heater

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and to maintain the temperature of the transfer plumbing is non-propulsive and reduces the overall system efficiency of the thruster.

II. Description of Concept

In the method proposed here, bismuth is supplied to an anode/reservoir within the thruster discharge chamber in solid or liquid form. Naturally occurring thruster waste heat is used to drive direct evaporation from the anode/reservoir into the discharge chamber. The evaporation rate is controlled through the reservoir temperature and the permeated vapor escape area.

Since it is not feasible to mechanically vary the vapor escape area through the reservoir, the mass flow rate is controlled by varying the reservoir temperature within the thruster. The evaporation rate, then, is governed by the equilibrium vapor pressure of the liquid metal and the goal is to maintain the proper reservoir temperature that, when combined with the vapor escape area, yields the correct value of mass flow (see Ref. 4 for a more detailed derivation).

Obviously, designing a thruster that dissipates exactly the right amount of power into the anode represents an unfeasible open-loop control system. The concept reported here uses a segmented-anode design to achieve closed-loop control of the bismuth reservoir temperature. Our design utilizes three separate anodes: the traditional main anode and two inert "shim" anodes - one inner and one outer –electrically and thermally isolated from the main anode. Figure 1 shows a cross section of the Isp Lab development thruster. The main anode serves dual use as a propellant diffuser and accelerating electrode very similar to traditional gas fed Hall thrusters. However, in this design the hollow main anode also serves as a reservoir of liquid bismuth. Electron current from the discharge plasma heats this anode/reservoir at a rate of approximately 10% of the total thruster power, driving the direct evaporation of propellant into the chamber.

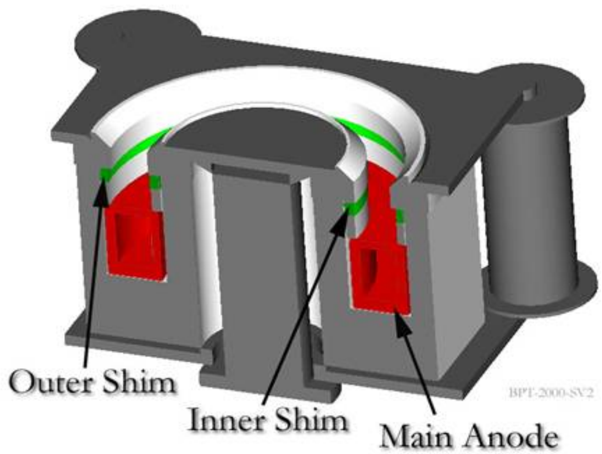

Figure 1. Cross section of the segmented anode hall thruster showing the three anodes and naming conventions. Discharge power can be shared between any combination of anodes by inducing voltage differences.

Main anode temperature is controlled by sharing the plasma discharge current with a set of electrically isolated shim anodes on the inner and outer wall. The shim anodes are inert and are not bismuth vapor sources. By varying the shim voltage with respect to the main anode, the plasma current and, hence, heating can be shared between the shims and main, thus controlling the main anode temperature and the evaporation rate. The mass flow rate is then bounded above by the equilibrium main anode temperature that is achieved when 100% of the discharge current is attached to the main, and bounded below by the temperature achieved when 100% of the current is attached to the shims.

While past work showed that it was possible to directly control the temperature of the main anode by using segmented electrodes to share the discharge current[4] and plume divergence was largely unaffected[5], researchers did not quantify the effect of current sharing on thruster performance. The goal of this study was to ascertain what if any effects using a segmented anode configuration for thermal control had on overall thruster performance. The first section of the paper reports the performance characteristics of the segmented anode Hall thruster running only on xenon and a look at how power density effects performance. The second section delves into the operation of the thruster on both xenon and bismuth concluding with some preliminary bismuth-only operation.

III. Xenon Performance

Using segmented anodes for thermal control has proven to be very effective. In this section we look beyond just thermal characteristics and cast an eye at how attaching current to different anodes effects thrust, specific impulse and anode efficiency. Higher power thermal measurements as well as the effects of changing anode power density are also presented.

A. Description of Apparatus

The Hall thruster employed by the Isp Lab for preliminary segmented anode tests uses the magnetic circuit from an Aerojet BPT-2000 which has been retrofitted with segmented anodes, the necessary power connections and instrumented for temperature measurements. As shown in Figure 1, adjustment of the current sharing properties of the anodes is accomplished by varying the voltage on either the shim anodes or the main anode. Electrical connections to the shim anodes were made through the use of high temperature wire welded directly to the anode and passed through the boron-nitride thruster body. Thermocouples were connected similarly.

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%. Thermal measurements of the thruster were taken using K-type thermocouples that were directly welded to the shim anodes and press fit against the back face of the main anode. However, since all thermocouples were at anode potential, temperatures were taken manually through the use of electrically isolated thermocouple monitors at approximately one-minute intervals. The thermocouple monitors have an uncertainty of ±1 percent. Voltage and current measurements were taken by a computer controlled data acquisition system which polled the power supplies at approximately one second intervals.

All xenon tests were performed in the Isp Lab's Xenon Test Facility on the campus of Michigan Technological University. 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 cubic-feet-per-minute. High vacuum is achieved through two 48-inch-diameter cryopumps, capable of pumping 120,000 liters-per-second on nitrogen. The background pressure was maintained below 2.6×10^{-5} Torr (corrected for xenon) during all tests. A xenon-fed LaB_6 cathode was used to sustain plasma discharge.

B. Results

Performance measurements were taken at anode voltages of 300, 350 and 400 volts and at xenon mass flows of 4, 5, 6 mg/sec to ascertain performance trends. At each operating point, the magnetic field was adjusted to minimize the total discharge current when the shim and main anode voltages were equal. This value of magnet current was then sustained as discharge current was shifted from the shim anode to the main anode. When the shim and main anodes were at the same potential, the majority of current would attach to the shims. In all cases, the shift in current was obtained by leaving the main anode potential fixed and lowering the shim anode potential. The shim anodes never needed to be lowered more then 40 volts below the main anode for complete main anode current attachment.

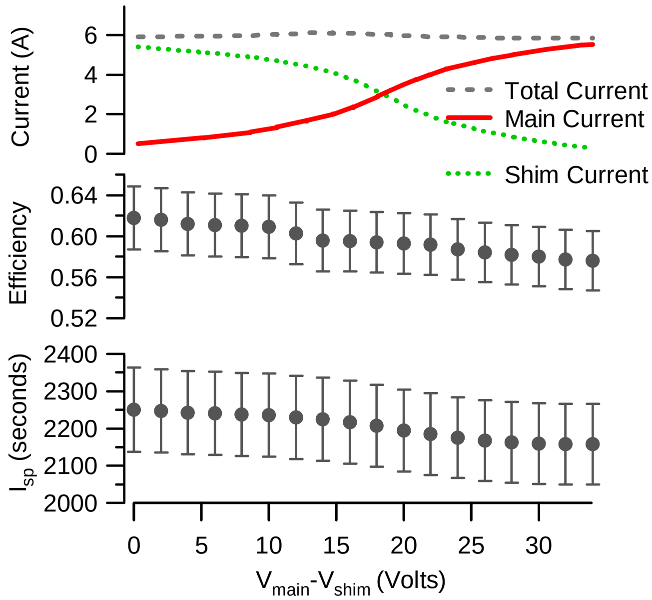

Figure 2. Results from a typical operating point. Main anode voltage is Vmain= 400 volts and flow is 6mg/sec of xenon. Experimental error for efficiency and I_{sp} is +/- 5%.

Figure 2 illustrates a typical case. In this figure, the main anode is held at 400 volts and the flow rate is 6mg/sec of xenon. The efficiency reported is anode efficiency. As can be seen I_{sp} and efficiency all decrease slightly as current is shifted from the shim anodes to the main anode while the total discharge current and power remains largely unchanged. The changes in I_{sp} and efficiency at all operating points examined is illustrated in Figure 3.

After completion of performance testing, the variation in anode/shim temperature as a function of current attachment was investigated. To establish the range over which the temperatures could be controlled, the thruster was allowed to come to thermal equilibrium with the current completely attached to each anode. Figure 4 shows how the thruster responds to both current shifting and mass flow increases with the main anode voltage fixed at 400 volts.

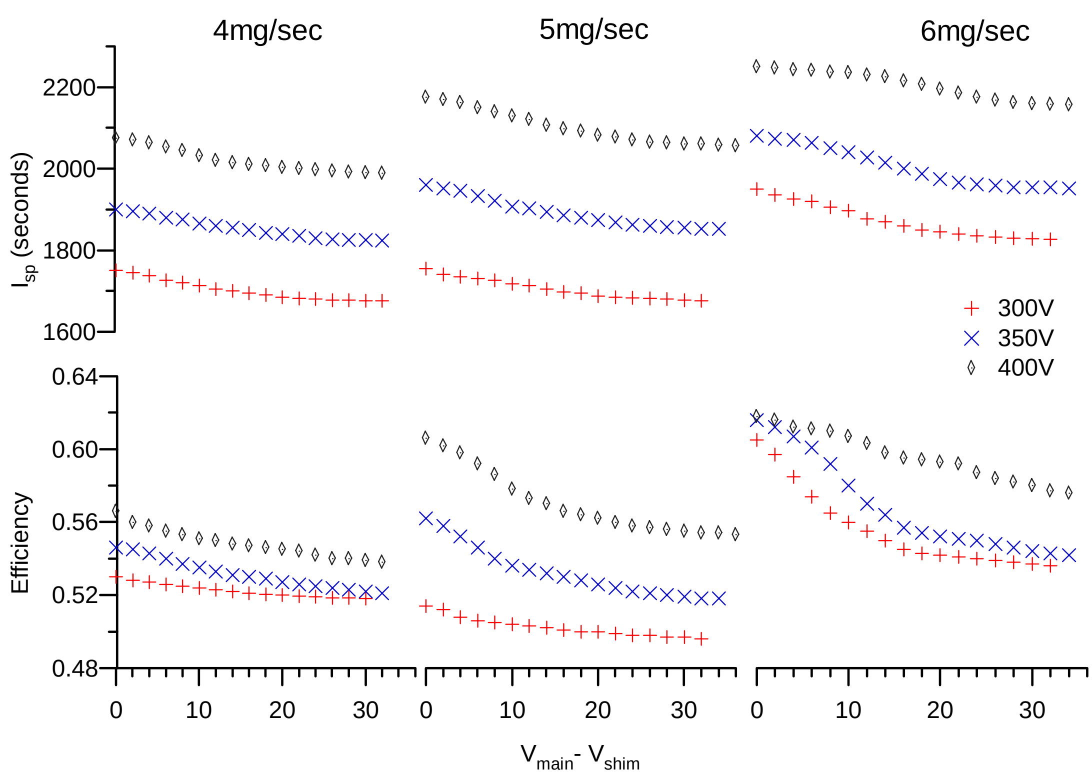

Figure 3. Thruster performance results showing the variation in anode efficiency and specific impulse as the discharge current is shifted between main anode and shims. Experimental error for efficiency and I_{sp} is +/- 5%.

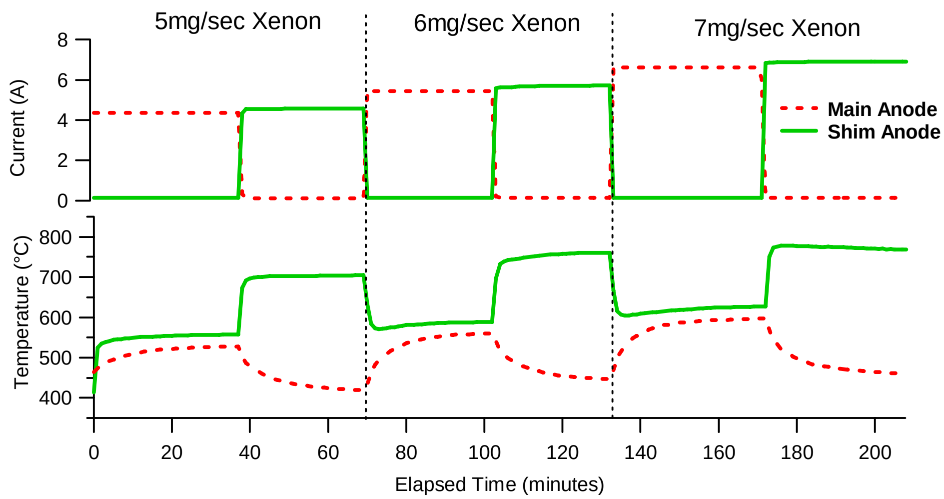

Figure 4. Thruster thermal variation due to varying current attachment. Main anode voltage was held constant at 400 volts.

C. Discussion

Performance testing demonstrated that operating with segmented anodes does not significantly alter thruster performance. Shifting current attachment from shims to main anode neither affects stability nor requires significant modifications to the magnetic field. Varying the current attachment causes less then a 10 % change in shim voltage and 5 % change in specific impulse. During testing no effort was made to optimize the magnetic field as the current attachment point was moved for a fixed main anode voltage. It may be possible to recover the slight efficiency loss seen as the shim voltage was reduced by adjusting the magnetic field at each value of current sharing fraction

It is interesting to note that there is evidence that the ionization region is upstream of the shims. The required reduction in shim voltage and subsequent reduction in Isp is consistent with the ion velocity loss one would expect by lowering the accelerating voltage. At 400 volts and 6mg/sec of xenon flow with all the anodes at the same potential the specific impulse was 2,250 seconds corresponding to an effective accelerating voltage of 332 volts. When the shim voltage was lowered to 366 volts (to shift current to the main anode) the specific impulse decreased by 93 seconds to 2,157 seconds corresponding to an effective accelerating voltage of 305 volts. So by reducing the shim voltage by 34 volts the effective accelerating voltage was reduced by 27 volts which is well within the experimental uncertainty.

In this application, the goal of using segmented anodes is to enable thermal control of the main anode for use in bismuth evaporation. In each of the cases presented in Figure 4, a 50+ degree variation in temperature can be obtained in a matter of minutes for the main anode, and seconds for the shim anode. This temperature swing would cause a 63% change in the bismuth evaporation rate, providing a wide range of throttleability. Moreover, at the tested power levels the anodes are both thermally stable and well within the working temperature of the constituent materials. From these results, it is clear that using segmented anodes for thermal control is a valid approach.

Although thermal testing showed the ability to substantially vary the anode temperature, the maximum temperature achieved was well below that required for sufficient bismuth evaporation for self sustaining operation. It was previously determined that a reservoir temperature of 750°C was required[4] but even running at 2.4kW the main anode temperature reached a maximum 597°C. To gain the additional 150 degrees, thruster power could be further increased at the expense of thruster lifetime. A better option was deemed to be a reduction in anode face area thereby increasing the power density as well as improving thermal insulation. During xenon testing a power density of 0.5 W/mm^2 achieved 597°C. Thermal modeling suggested that a power density of 1 W/mm^2 would be sufficient to achieve the goal of 750°C.

Subsequently, a new anode with approximately half the face area was fabricated to meet the estimated power density requirements. The smaller anode left significant physical gaps in the discharge chamber which could potentially affect thruster performance. In order to quantify the effects of the change, thruster performance was again evaluated. Figure 5 is plot of a typical case. The changes in efficiency and specific impulse were within the realm of experimental error and were therefore deemed as inconsequential.

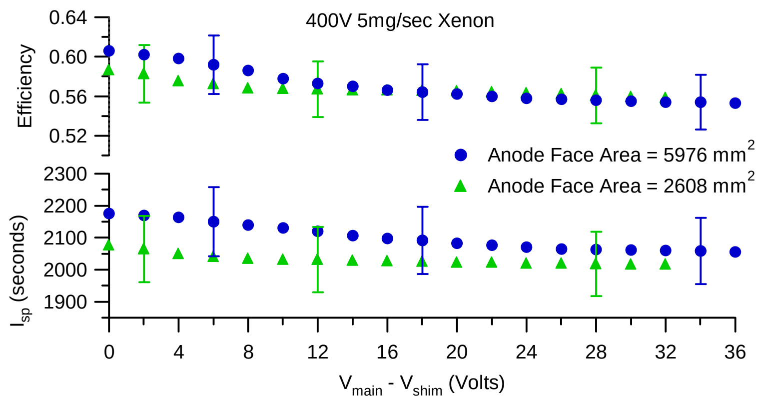

Figure 5. Full face anode and Reduced face anode typical performance and representative error bars. Main anode was held at a constant 400 volts. Experimental error for anode efficiency and I_{sp} is +/- 5%.

IV. Bismuth Operation

Xenon testing made it clear that using segmented anodes for thermal control is a very viable method as it works very well and doesn't negatively impact thruster performance. Traditional xenon design rules called for an anode that has insufficient power density for use with bismuth so the anode face area was reduced by about half, again without adverse impact on thruster performance.

D. Description of Apparatus

A unique dual-propellant anode was designed for bismuth development and testing. The anode was designed to accommodate gaseous xenon and bismuth simultaneously. The ability to run on xenon allows the thruster to achieve the high temperatures required for bismuth evaporation without the need for resistive heating. Figure 6 is an illustration of the anode cross section. Xenon is fed into the lower chamber where it then flows out the gas diffuser holes. Bismuth is contained in a separate chamber and is delivered to the anode via a hydrostatic reservoir external to the thruster. The bismuth vapors leave through a gas diffusing plate on the top of the anode which prevents liquid intrusion into the discharge chamber.

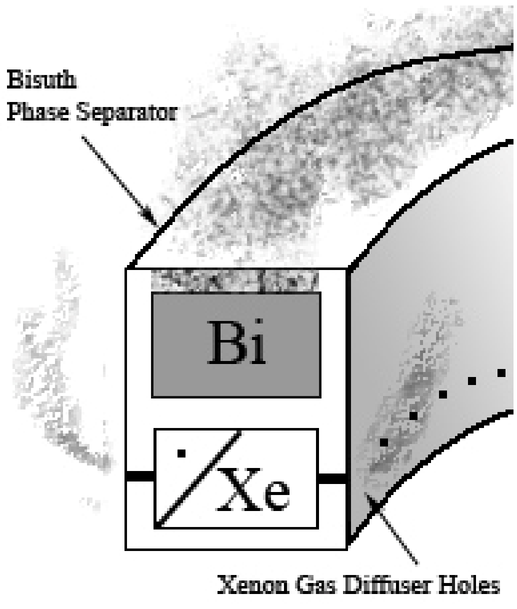

Figure 6. The combination xenon-bismuth anode

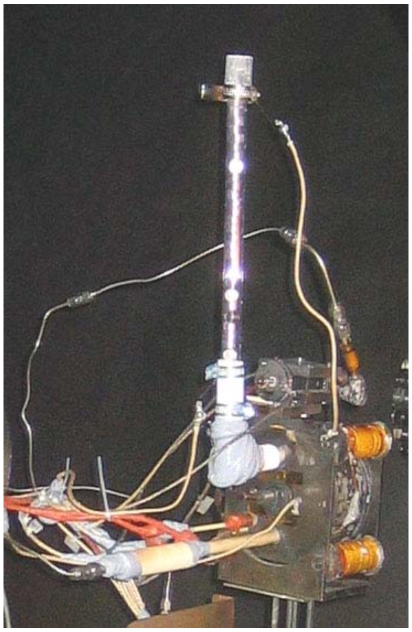

Figure 7. Photo of a typical bismuth reservoir in the back of the thruster. Only a modest level of resistive heating is required to keep the bismuth liquid.

The external bismuth reservoir is simply a welded stainless steel tube that is filled with bismuth prior to testing and uses hydrostatic pressure to ensure that the anode reservoir is full at all times. During operation, external resistive heating is applied to the external reservoir to ensure that the bismuth is liquid throughout the entire feed system. The power required to keep the bismuth liquid during operation was quite modest, ranging from 25 to 100 watts depending on reservoir size. Figure 7 is a photo of a typical reservoir attached to the thruster.

One drawback of the simplistic external reservoir approach is the difficulty in ascertaining mass flow. Bismuth mass flow can be estimated by measuring reservoir levels before and after a testing session. If the thruster operates consistently for a significant amount of time, a reasonably accurate estimate of mass flow can be obtained. For instance, the reservoir pictured in Figure 7 was a tube with an inner diameter of 15mm. For a mass flow rate of 7mg/sec, the bismuth level in the tube will drop by 14.54 mm/hour; a quantity that is easily measurable.

Bismuth tests were performed in the Isp Lab's one-of-a-kind Condensable Propellant Facility on the campus of Michigan Technological University. 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 cubic-feet-per-minute. High vacuum is achieved using three 28,000-RPM magnetically levitated turbo-molecular pumps capable of pumping 2,000 l/sec each providing a robust, oil free vacuum. Anode and cathode xenon flow into the tank was controlled via 100 and 20 SCCM MKS mass flow controllers respectively.

E. Results

In order to induce direct bismuth evaporation, the thruster was "jump-started" on xenon. The thruster was operated on 40 SCCM of xenon at 400 volts and 4.42 amps.

As the anode bismuth reservoir heated up, the discharge current began to slowly climb indicating bismuth evaporation. The current was allowed to rise until reaching about 8 amps. By this time, current was increasing at a rate of approximately 1-2 amps per minute so xenon mass flow was reduced to keep the current in an 8 to 10 amp window. Eventually all the xenon gas flow was removed and the power supplies were reconfigured to run in constant current mode. If the discharge current began to drop (indicating evaporation was slowing), the supply automatically increased voltage to maintain the current. The increased voltage subsequently increased the power deposition to the main anode, which in turn increased the bismuth

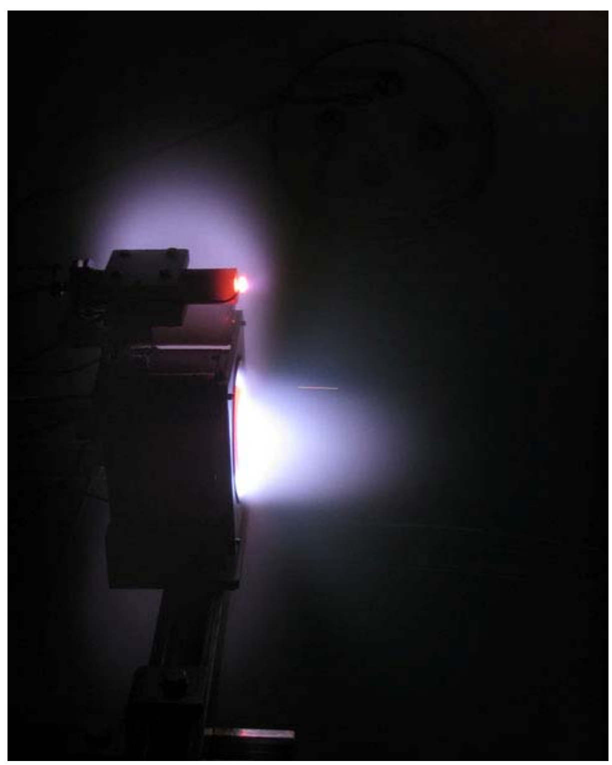

Figure 8. A 4kW Hall thruster running on bismuth.

evaporation rate. The bismuth thruster ran for approximately 45 minutes in a completely self-sustaining mode before being voluntarily extinguished. When the thruster was running at 4kW and 12 amps on bismuth (no xenon except 0.3mg/sec cathode flow), the facility pressure was 8.5×10^{-6} Torr. The thermocouple was reading a reservoir temperature of 756°C. Figure 8 is a photo during bismuth only operation.

At the time of writing, comprehensive bismuth mass flow and performance measurements were unavailable but will be orally presented during the conference proceedings.

F. Discussion

"Jump-starting" the thruster on xenon is a very effective way of initiating bismuth mass flow. Although the direct evaporation scheme is inherently unstable (high power induces high evaporation which induces even higher power), the slow instability time renders manual control possible. Figure 9 is a plot of a manually controlled transition from xenon to bismuth. In future work the shim-controlled evaporation will be brought under closed-loop computer control.

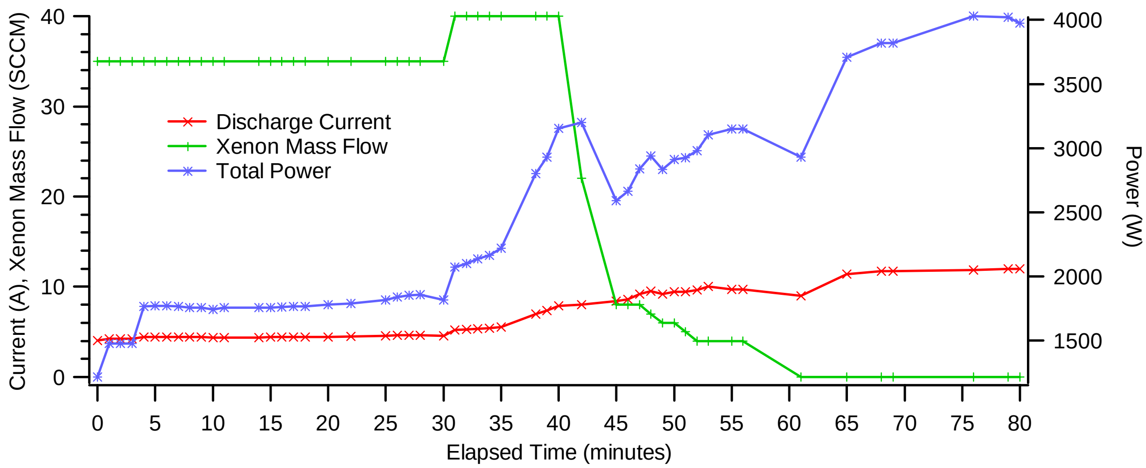

Figure 9. Current, power and xenon flow during a transition. Voltage was initially held at 400 volts until xenon flow was removed and the discharge was held at a constant current.

Attempts are currently underway to quantify the bismuth mass flow rate which will allow for efficiency and specific impulse calculations.

V. Conclusions

Operating a xenon thruster with segmented anodes has very little impact on performance. No attempt was made to minimize discharge current while shifting from shims to the main anode so slight decrease in efficiency could possibly be recovered by magnetic field tuning. Using the shim anodes for thermal control worked well to obtain temperature variations, but using a traditional 0.5Watt/mm^2 xenon anode the maximum temperature obtained was 150°C below what was required for bismuth operation. To achieve the required 1Watt/mm^2 power density, the anode face area was reduced by approximately 50%. Performance measurements of the reduced face anode did not show adverse effects on overall thruster performance.

Using xenon to "jump-start" the bismuth thruster is relatively easy and works very well. Although it requires significant operator interaction, the response time of the system is slow enough that it is not an unmanageable burden to operate manually. Detuning the magnetic field to increase waste heat by electron heating in the anode is also a very effective way to gain the necessary temperatures for bismuth evaporation. If efficient thruster operation is a concern during the bismuth transition, increasing discharge current via extra xenon flow also works as well.

Current work is focusing on obtaining bismuth mass flow rates so performance numbers can be calculated. ExB probe measurements are also being taken to get a grasp on how multiply charged ion populations change with respect to xenon and bismuth operation.

Acknowledgements

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