42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
9 - 12 July 2006, Sacramento, California

AIAA 2006-4638

Measurements in Stationary Reference Bi Discharge Cell for Diagnostics of a Bismuth Hall Thruster

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As development continues on the production of bismuth fueled Hall thrusters, there is a need for an accurate understanding of the nature of bismuth plasma. This includes both the ability to predict the electrical breakdown characteristics of a bismuth gas, as well as the design of tools necessary to make diagnostic measurements on a bismuth-fed electric thruster. A bismuth heat pipe apparatus capable of igniting an electrical discharge in a bismuth gas has been constructed for the purposes of such analysis. This paper will discuss the progress of using this chamber for preparing optical diagnostic techniques in a bismuth plasma, as well as measured current-voltage and Paschen curves for a bismuth gas mixed with Argon. While ion populations in the heat pipe are not yet strong enough to produce a measurable absorption or laser-induced fluorescence signal on the Bi II transition selected for thruster performance analysis, we have recorded significant effects on the electrical behavior of the argon gas due to the presence of bismuth vapor.

Nomenclature

Isp	=	specific impulse
$\delta\nu$	=	shift in linecenter frequency
ν_0	=	linecenter frequency
u	=	velocity (in direction of incoming laser beam)
c	=	speed of light
J	=	current
V	=	voltage between electrodes
V_b	=	breakdown voltage
P	=	pressure
P_0	=	normalized pressure
d	=	electrode separation distance

I. Introduction

In recent years, there have been a number of developments in the use of bismuth as a potential Hall thruster propellant. As the heaviest of the stable elements, bismuth has the unique property of producing the highest thrust per particle for an electric rocket with a given specific impulse (Isp). This maximum thrust per particle combined with the propellant usage efficiency of a high Isp electric thruster provides the potential for a minimization of the mass of propellant required for a given mission; the minimization of mass, in turn, translates to a reduced launch cost for the payload. Further, metal vapor electric thrusters, such as the TsNIIMASH-developed TAL 160 and TAL 200, have been demonstrated to operate at 25-140 kW with the potential to scale up to at least 500 kW; this significantly outpaces state of the art ion thrusters with power limits near 10 kW. As a result, a bismuth-fueled hall thruster shows strong potential for future higher-powered Nuclear-Electric Propulsion (NEP) missions to the outer planets.

Further, bismuth presents specific advantages that make it more desirable than the xenon propellant used for most existing Hall thrusters and ion engines. In addition to its higher mass, bismuth is also significantly more readily available and less expensive than is xenon. Further, the ionization potential of bismuth is only 7.3 eV compared to

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12.1 eV for xenon, so the propellant is more easily ionized and the thruster should run more efficiently. Finally, bismuth is condensable at room temperature, which allows for simpler testing on the ground in existing facilities as well as reduced spacecraft tankage fraction.

In the development of a bismuth hall thruster, as with any thruster, there will be a need for precise optimization of geometry and operating conditions, as well as accurate predictions of the potential for spacecraft contamination. In the process of thruster design, it will be useful to understand the nature of the dielectric breakdown of a bismuth gas. In addition to an understanding of the ionization process within the thruster channel, it will be necessary to prevent breakdown upstream of the channel between high voltage components along the propellant feed system of bismuth TAL thrusters. Additionally, it will be necessary to characterize the internal and near-field energy distributions, velocity fields, and particle fluxes of both neutral (Bi I) and ionized bismuth (Bi II); it will be useful to adapt optical diagnostic techniques, such as laser-induced fluorescence (LIF), to the bismuth spectrum so that these measurements can be made non-intrusively.

To these ends, a bismuth heat pipe cavity has been developed as a test bed for various thruster diagnostics, as a possible stationary spectral reference for use during optical measurements on a thruster exhaust plume, and as a facility for measuring the breakdown of bismuth vapor. This paper will present the developments in the use of this device for analyzing the dielectric nature of bismuth vapor and in preparing optical diagnostic techniques for use on a bismuth hall thruster.

II. Bismuth Heat Pipe Apparatus

A bismuth heat pipe apparatus, based on the design of Cappelli, et al.[1,2] and illustrated in Fig. 1 has been developed to produce and analyze a bismuth plasma. The apparatus consists of a small vacuum chamber, the top and bottom of which are lined with an electrically heated metal mesh. Two sides of the chamber are outfitted with quartz glass windows for optical measurements; the other two walls provide isolated electrical feedthroughs for the electrodes that are used to produce a plasma in the bismuth gas. The electrodes themselves are ¼ inch diameter stainless steel rods wrapped in ceramic tubes for insulation; one of the electrodes can be translated axially to vary the gap distance. Solid bismuth is placed in the center of the mesh where it is heated to produce a significant vapor pressure; the outer edges of the mesh are water cooled so that the bismuth vapor will condense out rather than coating the optical surfaces. A flow of argon through the chamber is also used to contain the bismuth in the center of the chamber; typically, the argon flow rate and the vacuum pump rate are simultaneously metered to produce the desired operating pressure. Pressure is measured via a baratron as well as a thermocouple pressure gauge mounted to the chamber.

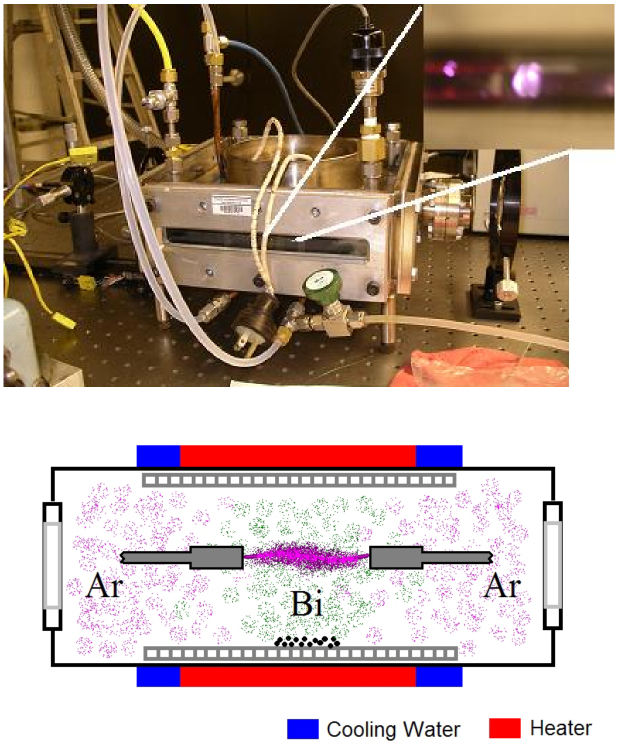

Figure 1. Bismuth Heat Pipe apparatus.

The ceramic electrical heaters used for the heat pipe have been measured via thermocouple to operate with surface temperatures in excess of 900ºC; IR measurements of the mesh surfaces inside the chamber also confirm temperatures as high as 900ºC. These temperatures should translate to a bismuth vapor pressure on the order of 1 torr (130 Pa)[3,4]. Due to the mixing of cold argon gas with the bismuth vapor (as well as errors due to conduction and radiation from the thermocouple bead), a thermocouple measurement of the gas near the center of the chamber typically reads a maximum temperature near 600ºC.

III. Optical Diagnostics

The most crucial measurement to be made in an electric thruster is the velocity of the ions in the exhaust stream; it is primarily the high ion velocity, and the ionization fraction, that define the performance of the thruster. In order to measure these quantities via non-intrusive optical diagnostics, it is necessary first to select electronic transitions for measurement, and to analyze the structure of each transition so that data can be properly interpreted. The general spectroscopy necessary to begin this analysis for bismuth has been discussed in previous conference proceedings,[5,6,7] and will not be repeated here.

A. Candidate Transitions

Previously,[5,6,7] several candidate Bi transitions were selected for analysis and discussed. The transition selected for ground state Bi I number density determination by atomic resonance absorption spectroscopy was the line at vacuum wavelength 306.86nm ($6p^3$ $^4S_{3/2}$ – 7s $^4P_{1/2}$). Candidate transitions for velocity determination via LIF analysis of ions were chosen based, in part, on accessibility to the New Focus Velocity line of lasers. Specifically, the New Focus TLB-6309, which can scan 680-690 nm, has been selected to probe the NIST-listed[8] 680.86 nm line of Bi II. Dolk et al., place this line at 680.91 nm with designation 6p7s $(1/2,1/2)_1$ – 6p7p $(1/2,1/2)_1$.[9,10]

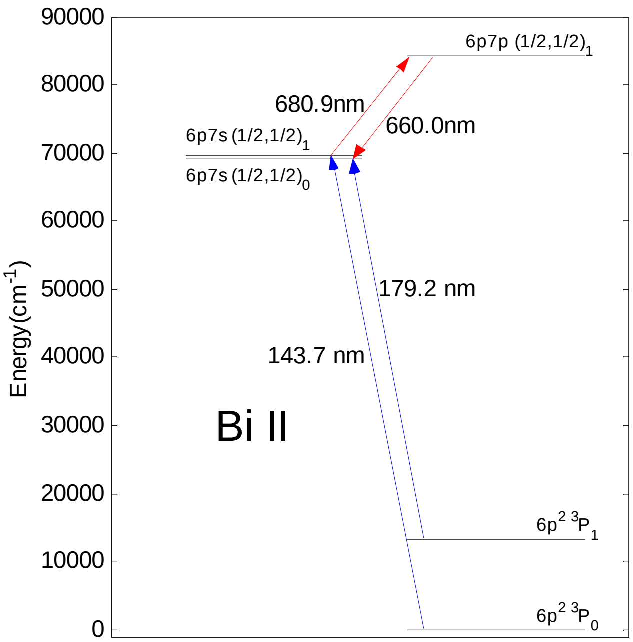

Figure 2. Partial Grotrian diagram for Bi II indicating the transitions of interest for LIF analysis.

The selection of the 680.9 nm transition provides several advantages. Aside from being accessible to a New Focus Velocity laser, the 680.9 nm line is a relatively strong transition according to NIST data;[8] in fact, it is the strongest Bi II line in the 600-900 nm region that is most useful for this work. Additionally, an analysis of the energy level structure of Bi II, depicted in Fig. 2, shows that the 680.9 nm transition shares an upper state with the 660.0 nm transition, which may be useful for non-resonant LIF collection. The 660.0 nm transition (configuration: $6p7s(1/2,1/2)_0$ – $6p7p(1/2,1/2)_1$)[9,10] is the second strongest Bi II line listed by NIST in the region of interest.[8] High intensity of both the probed transition and the collected transition should help to maximize signal strength in thruster measurements. Further, Dolk et al.[9] state that the “connection between the two lowest levels…of the ground configuration [of Bi II] and the excited configurations is established by the lines at 1436 Angstroms and 1791 Angstroms.” A further analysis of the energy level structure of Bi II, also illustrated in Fig. 2, shows that these ultra-violet transitions, which provide a bottleneck for the excitation and de-excitation of Bi II states, connect the ground configurations of Bi II with the lower levels of the 680.9 nm and 660.0 nm transitions. Therefore, the lower level of the 680.9 nm transition should be well populated, further maximizing the number of ions that can be excited by a laser at this wavelength and improving LIF signal strength.

B. Optical Diagnostics in Heat Pipe Chamber

Ideally, the heat pipe chamber should serve as both a medium for testing the optical diagnostic techniques intended for use on a bismuth fueled electric thruster, and as a stationary plasma reference to aid in the analysis of data recorded from such a thruster. The use of the heat pipe chamber for measurement of the 307 nm Bi I resonance transition has been previously discussed[7].

For LIF velocity determination using the 680.9 nm Bi II transition, a single laser beam should be split with one path directed toward the thruster plume and the other path passing through a reference cell, ideally utilizing an absorption measurement of the same transition for the spectroscopic reference. The absorption signal in such a cell should indicate the precise line position at zero velocity; the LIF signal from the thruster should show a Doppler shift of the measured feature. The Doppler shift in transition frequency, $\delta\nu$, due to a mean velocity component, u, in the direction of the incoming laser beam, is given by:

$$\delta\nu = \nu_0 \frac{u}{c}, \tag{1}$$

where v_0 is the unshifted linecenter frequency and c is the speed of light. A measurement of δv would be based on the difference in line position between the LIF signal and that of the stationary reference source; since the wavelength of a laser can drift with temperature, time, and other factors, and precise wavelengths of a scanning laser are difficult to measure in real time, data from a stationary absorption cell and the LIF signal should be recorded simultaneously while utilizing an etalon for measurement of the relative change in wavelength with time.

It was intended that the heat pipe cell discussed above would serve as both a test bed for LIF and absorption analysis using the TLB-6309 laser, as well as the reference cell while analyzing a thruster. However, we are as yet unable to produce a strong enough ion population in the cell to produce a measurable absorption or LIF signal from the 680.9 nm transition.

IV. Electrical Character of Bi Vapor

The secondary purpose of the heat pipe chamber is that it can be used to examine the electrical character of a bismuth gas. While electrical discharges in the heat pipe are not stable enough without the presence of some argon in the chamber, the analysis below will focus on the way the discharge changes as the argon pressure is reduced while holding the temperature (and therefore the bismuth vapor pressure) constant. In this way, the results should resemble the asymptotic behavior toward a pure bismuth gas. It should be noted, however, that there is significant error in the estimation of absolute bismuth vapor pressure. Slight adjustments in the positioning of the IR temperature detector result in a change of the measured temperature from tens to hundreds of degrees Celsius because different parts of the inner surface are at vastly different temperatures. It is nearly impossible to pinpoint the site of maximum temperature, and to be sure that that is the temperature controlling the bismuth vapor pressure; in the regime of 800-900ºC, the vapor pressure changes by a factor of 2-3 roughly every 50ºC[3,4], so errors here can be significant. It is also possible that the vapor pressure of the bismuth is not only influenced by the surface temperature of the mesh, but also by the temperature of the colder argon gas in the chamber. Although the absolute bismuth vapor pressure is difficult to precisely define with the current set up, the temperature measurements were kept consistent during each series of experiments. Therefore, the relative concentration of bismuth vapor should still be constant, though not precisely known, in each data set.

With the above in mind, the heat pipe chamber was used to construct current-voltage (*J-V)* curves with various argon backpressures. The results are shown in Figs. 3 and 4. This analysis was performed with a gap distance between the electrodes of 1.5 cm, an IR temperature reading of the mesh surface of roughly 850ºC, and a thermocouple reading near the center of the chamber of 610ºC. The voltage across the electrode gap versus current measurements were recorded for argon pressures ranging from 1-10 torr. According to the scaling laws[11,12,13], when the current, *J*, at each pressure is normalized by the square of the pressure, as in Fig. 4, the curves would collapse if only a single pure gas were present; instead, we see a shift in behavior due to an increasing influence of the bismuth vapor as the argon pressure was lowered. If there were a significant thermionic emission effect from the hot electrodes, the effect would be to produce a higher current density that was more pronounced at lower pressures; the opposite was observed in our recorded data, indicating a change in the electrical behavior of the gas that is most likely due to the increased bismuth vapor concentration.

Additionally, approximate Paschen curves were recorded for a variety of argon pressures and are shown in Figs. 5 and 6; the measurements listed with various pressures were recorded while the thermocouple inside the chamber

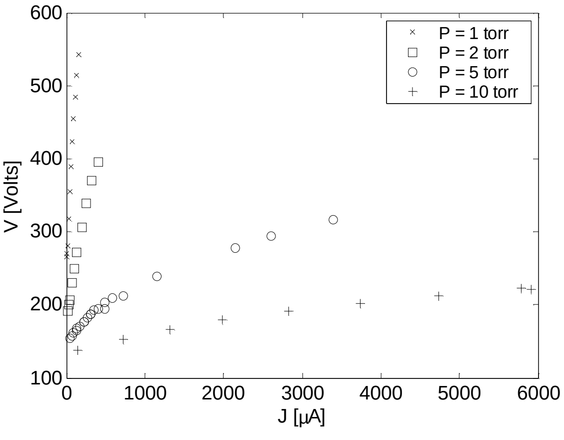

Figure 3. Current versus voltage for various bismuth concentrations at constant temperature.

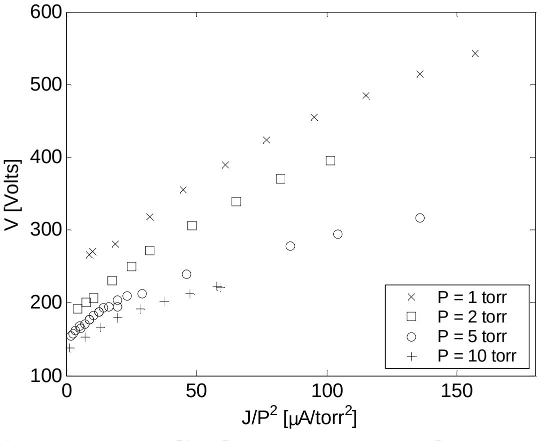

Figure 4. Normalized current versus voltage profiles.

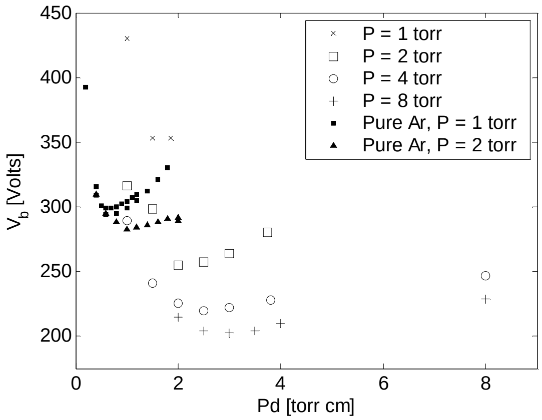

Figure 5. Paschen curves for various bismuth concentrations at 900ºC and for pure argon at 300ºC.

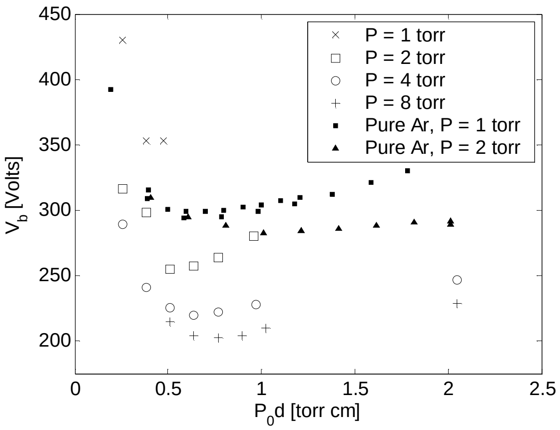

Figure 6. Temperature-normalized Paschen curve profiles.

read roughly 600ºC and the IR reading was 900ºC. The measurements for pure argon were recorded with a temperature of 300ºC. It should be noted that ideally, a breakdown study such as this should occur with very smooth and uniform electrodes so that there is a uniform electric field. In this case, however, soon after heating the chamber a visible amount of bismuth begins to plate out onto the electrode surfaces. The coating is rough and non-uniform, which would create sharp potential gradients and significantly affect data. For this reason, the data for pure argon was recorded after the high temperature data; the chamber was cooled and the electrodes were not cleaned, so results should reflect similar electrode geometry effects due to the plated out bismuth. Additionally, as the voltage was slowly increased for each pressure and *Pd* product (pressure times electrode separation distance), the breakdown voltage, V_b, was defined as the point at which the current flowing through both electrodes first reached a value of 1 μA or greater. The results of these measurements are shown in Figs. 5 and 6. The P_0 variable indicated in Fig. 6 represents a reduced pressure and is normalized from the IR wall temperature to 300 K using the ideal gas law; using this method of normalization, it should be valid to compare the results recorded at high temperatures to the data recorded at low temperatures for pure argon. Note that as the percentage of bismuth in the vapor was increased, the P_0d minimum shifted to a lower value while the voltage for a given P_0d increased. Strangely, the data recorded for pure argon appears at a significantly higher voltage than expected and does not seem to continue the trend illustrated at the higher temperatures. This may be the result of thermionic electron emission from the electrodes contributing to breakdown at the higher temperatures, and therefore lowering the breakdown voltage.

V. Conclusion and Future Work

In developing the optical diagnostics, we are still unable to find a suitable stationary bismuth plasma source with a high enough ion concentration for reasonable measurements of the 680.9 nm Bi II transition. At this stage, the stationary source will become a lower priority, and we will shift toward recording measurements on an existing hall thruster modified to run on bismuth propellant. It would still be useful to have a stationary spectroscopic reference near 680.9 nm for diagnostic purposes, so efforts in that area will not end, and may include further modification of the heat pipe apparatus, or the use of other species with stronger, precisely understood transitions of approximately the same wavelength.

The *J-V* and Paschen curves presented here represent a first approximation toward determining the nature of a pure bismuth gas. These measurements will be further refined, within the limits of the heat pipe apparatus, to provide a reasonably accurate picture of the electrical characteristics of bismuth vapor.

Acknowledgments

The research was conducted under a contract with the National Aeronautics and Space Administration. Support for D. Scharfe is provided through a fellowship from the Department of Defense and the American Society for Engineering Education.

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