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Technical Notes

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Ion-Energy Plume Diagnostics on the BHT-600 Hall Thruster Cluster

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I. Introduction

ELECTRIC propulsion (EP) offers power-efficient, high specific impulse (I_{sp}) options for deep-space missions as well as stationkeeping, orbital transfer, and attitude control requirements for near-Earth spacecraft. Hall thrusters are a type of EP system that uses electric and magnetic fields to produce thrust. Currently, midpower Hall thrusters achieve specific impulses between 1500–2500 s and electrical power efficiencies between 50–60% [1]. For high-powered engines being developed in the near future, plume characterization is imperative for determining their effect on spacecraft systems. Plasma transport properties, ionic charge state, and ion energy distributions are also important for understanding how Hall thrusters work and for improving their performance [2]. One technique for determining the energy-to-charge distribution of plasma is to use an electrostatic analyzer [3]. A specific geometry for the electrostatic analyzer, which allows for a wide field of view, is the top-hat analyzer [4]. This electrostatic analyzer consists of a sphere and a concentric shell with an aperture at the apex of the outer shell. The inner sphere is set to a specific voltage to allow for a narrow energy band of particles to pass through the aperture. By virtue of its geometry, the top-hat analyzer is capable of having a wide azimuthal field of view. Steering electric fields above the aperture allow for a field of view in the vertical direction as well.

The damaging effect of high-energy plasma exhaust particles on spacecraft surfaces has driven efforts in Hall thruster plume characterization. Electrostatic analyzers are capable of measuring ion energy-to-charge distributions and angular trajectories of plasma exhaust particles, therefore, they are particularly well suited for Hall thruster plume diagnostics. Unlike a retarding potential analyzer (RPA), the current profile does not require differentiation [5], which induces increased inaccuracies, and the energy-per-charge distribution is directly measured. The true charge state of the measured ions remains unknown; however, previous measurements on anode layer type Hall thruster plumes reveal a majority of plume ions are singularly charged [2].

II. Analyzer Design

TOPAZ has been designed to have a high energy measurement capability, up to 15 keV. The nature of a top-hat analyzer allows for the lower bound to be close to 0 eV, because the plate potentials correspond directly with the measured energy. The lower energy bound, therefore, is set by the accuracy of the power supplies used. Because TOPAZ is a far-field plume-diagnostics instrument, an adequate field of view of the thruster is required to "image" the ions projected from the entire discharge channel. A 30-deg vertical field of view allows for 57.7 cm of an object to be viewed from 1 m away, well within the size range of most thrusters. Structural constraints prevent exploiting the full axisymmetric geometry of the instrument and yield a field of view of 112 deg in the azimuthal direction.

The top-hat analyzer uses a radial electric field to guide ions through a spherical shell-shaped channel between a grounded outer plate and a negatively charged inner deflection plate that are concentrically aligned. Figure 1 displays the key dimensions and plates for a top-hat analyzer. The most important criterion is the ratio of the channel radius R_C (the average of the inner and outer radii for the gap, that is, $R_C = (R_1 + R_2)/2$) to the gap distance $\Delta R(\Delta R = R_2 - R_1)$, which sets the analyzer constant [Eq. (1)].

$$K \equiv \frac{R_C}{\Delta R} \qquad (1)$$

The analyzer constant K determines the energy resolution, energy-to-voltage ratio, and other properties of the analyzer and is 100 for TOPAZ. Further discussion of the analyzer constant and its relationship to other parameters can be found in [4].

A. Analyzer Design and Characterization through SIMION

SIMION is a computer code that is capable of modeling ion optics problems with electrostatic potential arrays, by solving for the electric potential φ around the instrument through the Laplace equation [6]. SIMION assumes a zero charge volume density (no space charge). Experimental characterization and SIMION simulation of TOPAZ revealed the correlation between the deflection and guiding plate potentials, elevation angle, and ion-energy-to-charge ratio E/q (in eV$/e_c$). A monoenergetic ion beam was used to experimentally characterize the plate voltage–ion acceptance relationships. The ion beam energy was held constant, and the deflection plate voltage V_D was varied to maximize the transmission of ions to the detector. The plate voltage, which maximized the counts, was found to vary linearly with the energy of the ions being measured. In a similar fashion, TOPAZ was rotated vertically with respect to the ion beam, and the optimum guiding plate voltage V_G, which maximized the counts at a particular elevation angle α, was determined. Equations (2) and (3) display these relationships, with the units in brackets.

$$V_D = -0.02083(E/q) \qquad (2)$$

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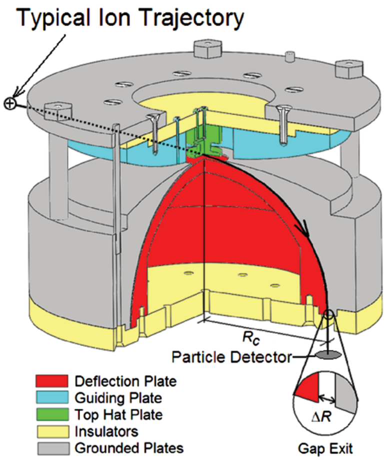

Fig. 1 Major components and a typical ion trajectory for a top-hat analyzer.

$$V_G = -\left(\frac{E/q}{262.4}\right)(\alpha[\text{deg}] + 1.871) \tag{3}$$

The energy and angular resolutions were determined by calculating the full-width half-maximum (FWHM) of the count profiles for a particular setting of TOPAZ and varying the ion beam energy and elevation angles. SIMION is used to determine the transmissivity of TOPAZ as well. Because the transmissivity varies as a function of the elevation angle, the measured current I is normalized (as I_n) across all elevation angles through Eq. (4).

$$I_n = \frac{I}{-[(E/q)/241.4](\alpha[\text{deg}] + 1.871) + 51.51} \tag{4}$$

The final design specifications and performance parameters are summarized in Table 1, and a detailed description of the design and characterization of TOPAZ is discussed in [7].

The geometric factor $G(E)$ describes the total ion acceptance of the instrument for particular plate voltage setting through the product of the effective collection area (horizontal by vertical), solid angle (azimuthal by elevation angle), and energy range per average energy (energy resolution) being measured. Through SIMION, TOPAZ was found to have a small geometric factor of 2.4×10^{-5} cm^2-sr-eV/eV, meaning the instrument is highly selective. The resolutions in the vertical α and horizontal β are 2 deg, with a total simultaneous field of view of 112×30 deg. Delrin® and glass mica provide insulation between the aluminum plates, which are either electrically biased or grounded.

III. Measurements on the BHT-600 Cluster

To verify the operation of TOPAZ, as well as to characterize the plume of a cluster of Hall thrusters, TOPAZ was placed 1 m downstream of a cluster of four 600-W BHT-600 Hall thrusters [8] (see Fig. 2). Energy measurements through TOPAZ have been validated through use of the NASA-173 mV1 Hall effect thruster. Profiles on the plume yielded a similar energy-to-charge peak and distribution shape to previous measurements on the same thruster and similar power-level thrusters [9,10]. Each thruster operates on xenon propellant at 300 V and 2 A. Measurements were conducted at thruster plume angles of 0 and 60 deg to the left of the cluster (from the vantage point of being downstream looking upstream to the cluster).

Table 1 Physical characteristics of TOPAZ

Parameter	Value
Analyzer constant, K	100
Inner gap radius, R_1	9.95 cm
Outer gap radius, R_2	10.05 cm
Gap distance, ΔR	1 mm
Instrument size, diameter	24.6 cm
Geometric factor, $G(E)$	2.4×10^{-5} cm^2-sr-eV/eV
Angular resolution $\beta \times \alpha$	2×2 deg
Field of view $\Delta\beta \times \Delta\alpha$	112×30 deg
Plate material	Aluminum 6061-T6
Insulator material	Delrin® and glass mica

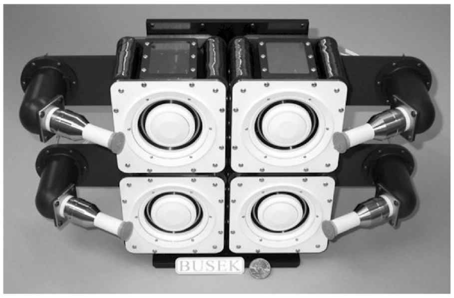

Fig. 2 The 600 W BHT-600 Hall thruster cluster.

A. Experimental Setup

All measurements were conducted in a 6-m-diam by 9-m-long cylindrical stainless-steel vacuum chamber [11]. Four of the seven model TM-1200 Re-Entrant Cryopumps are used to create an ultimate base pressure of 3×10^{-7} torr. The corrected pressure for these measurements during cluster and single thruster operation were 5.0×10^{-6} torr and 1.96×10^{-6} torr, respectively. The pressure correction approach used for xenon is presented in [12].

TOPAZ was placed 1 m downstream along the centerline from a cluster of the four BHT-600 Hall thrusters (see Fig. 3). The BHT-600 cluster was acquired for basic research on Hall thruster cluster characterization, cluster facility effects, and plume diagnostics. Cluster measurements were performed with all four thrusters running. For single thruster measurements, only the lower-right thruster (from the perspective of TOPAZ) was operated. Each thruster has a 6-cm outside-channel diameter and a centerline-to-centerline separation of 11 cm in the square-cluster configuration. Four hollow cathodes are placed at the 9 o'clock position for the two thrusters on the left and at the 3 o'clock position for the two thrusters on the right. Each thruster is operated at 300 V and 2 A with anode and cathode flow rates of 2.5 mg/s and 0.5 mg/s, respectively. Single thruster measurements were conducted on the bottom-left thruster. A graphite box with a slit entrance is used to protect TOPAZ from the ion beam flux. The cluster is mounted on two linear tables that are positioned perpendicularly to each other. This configuration allows for measurements by TOPAZ to be taken from different angles from the cluster centerline.

A K&M Electronics model 7550 m channel electron multiplier (CEM) is employed to detect ions after they have passed through TOPAZ. A Keithley picoammeter is used to measure the current generated by the CEM outside of the LVTF. To measure different azimuthal angles, TOPAZ and the CEM are rotated about the

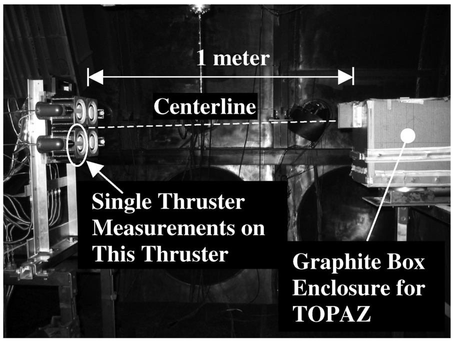

Fig. 3 TOPAZ (enclosed in a protective graphite box) placed 1 m downstream of the BHT-600 cluster.

centerline of the analyzer by using a Daedal 20600RT rotary table. A thermocouple was placed on TOPAZ to monitor the temperature of the instrument. During all tests the temperature remained between 20–55°C.

B. Experimental Results and Discussion

Data sweeps were taken by either varying the deflection plate voltage to generate energy profiles or by sweeping through elevation and azimuthal angles at constant plate voltages to piece together images of the thruster(s) at a particular energy. Figure 4 displays the energy-to-charge profile of the cluster down the centerline at a thruster angle of 0 deg. The peak energy-to-charge ratio is 275 eV$/q$. Ions with energies down to 230 eV$/q$ and up to 500 eV$/q$ were measured as well. The peak ion voltage exists slightly below the discharge voltage due to the decrease in plasma potential near the anode. Ions accelerated in this region do not realize the full potential drop from the anode voltage to ground, because there is a voltage spread near the discharge chamber [13]. Ions above and below this peak are measured due to charge-exchange (CEX) and momentum-exchange collisions with low-energy particles. CEX can decrease the charge state of an ion while maintaining its energy, thereby creating energy-to-charge ratios that are significantly higher than the discharge voltage in the plume [14].

Figure 5 presents the azimuthal distribution of beam ions of 275 eV$/q$ that are detected from the horizontal centerline of the cluster. The two peaks in the profile of Fig. 4 are spaced 5.54 deg apart. The image of 275 eV$/q$ ions from the cluster indicates the beam ions from each thruster are not blurred together. Their trajectory is maintained into the far-field plume and beam ions from each thruster are easily discerned. A slight dip is also noticed at each peak, which is indicative of the annular geometry of the Hall thruster.

Measurements of a single BHT-600 thruster were made on the bottom-left thruster (approximately -3 deg in both the α and β directions). Energy-to-charge profiles were generated over a range of guiding plate potentials. The relationship between ion energy and elevation angle is discerned by combining the profiles into a contour plot. Figure 6 displays this contour plot. Ions with energies below 275 eV/q are measured at lower elevation angles. The energy profile for the cluster is equivalent to a horizontal "slice" taken along $\alpha = -3$ deg. At this angle for the single thruster, there are fewer ions with energies below 275 eV as well. The data in both plots indicate that higher-energy ions tend to travel more in line with the thruster centerline, whereas lower-energy ions diverge at larger elevation angles. Ions with energies below 275 eV/q tend to arrive from the left of the thruster near the cathode. Higher-energy ions are detected from the right side. A similar contour plot of the energy-per-charge and azimuthal angle is displayed in Fig. 7. Ions emanating from below the thruster centerline tend to have lower energies. The cathode plume extends in front of the thruster. Ions with apparent elevation angles from below the thruster centerline represent ions that have traveled from the cathode plume. The two angular-energy measurements suggest that beam ions emanating from the cathode plume on the left and the front of the thruster tend to have lower energies.

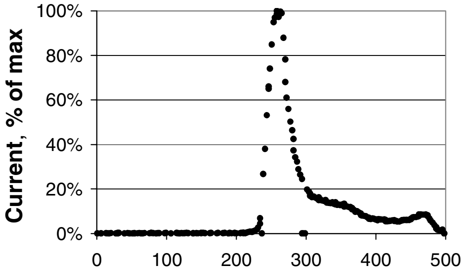

Fig. 4 Energy-to-charge profile of the BHT-600 cluster.

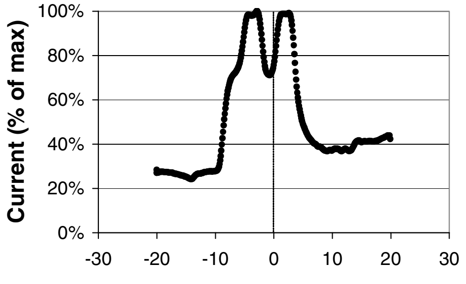

Fig. 5 Azimuthal profile of 275 eV ions for the top two thrusters in the BHT-600 cluster.

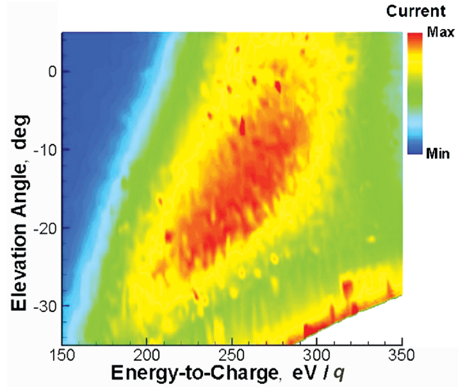

Fig. 6 Current as a function of elevation angle and energy-to-charge for a single BHT-600 thruster.

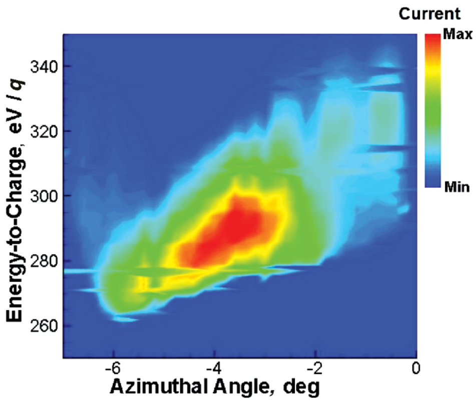

Fig. 7 Current as a function of azimuthal angle and energy-to-charge for a single BHT-600 thruster.

Figure 8 displays a beam ion image (275 eV) of a single thruster at a 60-deg plume angle. The oval shape of the image corresponds with the angle of the thruster with respect to TOPAZ. A higher current is detected from side of the thruster opposite of the cathode near the cluster centerline (see Fig. 3). Neutral particles and low-energy ions emitted by the cathode could decrease beam ion energy through elastic collisions. Because the cathode plume particles are released in front of the thruster and are heavily concentrated on the left of the thruster (near the cathode orifice), elastic and charge exchange collisions are more likely to occur in the lower-left area of the thrusters from the viewpoint of TOPAZ. In addition, ions that are created near the cathode and outside the discharge channel will have lower acceleration potentials and, hence, lower energies. The electron stream from the cathode to the anode could ionize neutral particles that accelerate only through part of the potential drop generated by the anode.

IV. Conclusions

Measurements on the BHT-600 Hall thruster cluster were conducted through TOPAZ. Energy profiles depicting ion energies

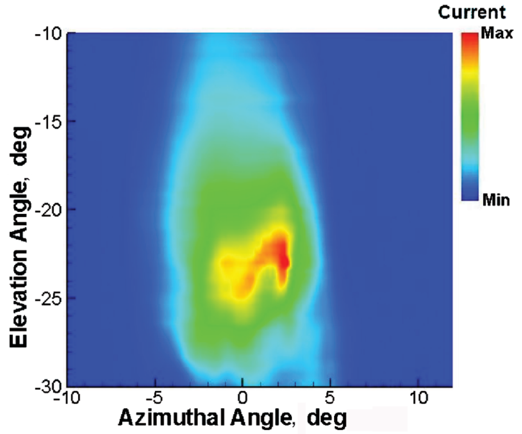

Fig. 8 An image of 275 eV/q ions emanating from a single BHT-600 thruster.

near the discharge voltage of the thrusters verify the instrument's utility for Hall thruster cluster plume characterization. Beam ions along the centerline of each thruster have energies closest to the discharge voltage. Ions emanating from near the cathode tend to have energies significantly lower than the discharge voltage. Either elastic and/or charge exchange collisions with low-energy particles or ion production at potentials lower than the anode potential are conjectured to be possible causes for this phenomenon. This relationship could also affect measurements of beam ions at off-axis plume angles as well.

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