DEVELOPMENT OF A 45-DEGREE PARALLEL-PLATE ELECTROSTATIC ENERGY ANALYZER FOR HALL THRUSTER PLUME STUDIES: PRELIMINARY DATA

Richard R. Hofer[a], James M. Haas[a], and Alec D. Gallimore[b]
Plasmadynamics and Electric Propulsion Laboratory (PEPL)
Department of Aerospace Engineering
College of Engineering
University of Michigan
Ann Arbor, MI 48109 USA

ABSTRACT

Several successful Hall thruster plume studies have been conducted at the University of Michigan using a 45-degree parallel-plate electrostatic energy analyzer mounted externally to the vacuum chamber. This requires the thruster to be in close proximity to the chamber walls potentially resulting in some set-up induced inaccuracies of the ion voltage distributions. A new design has been developed that aims to mitigate these effects by substantially reducing the analyzer size and mounting it internally to the chamber. The device has an inter-slit distance of 66 mm, a plate separation of 18 mm, and a resolution of 1.4%. Existing data from the P5 laboratory Hall thruster on centerline was used to calibrate the spectrometer constant of the analyzer. The analyzer was tested with the P5 1 m downstream of the exit plane over angular positions from 0 to 80 degrees. The analyzer traces qualitatively match the existing data, but closer examination reveals that the spectrometer constant is variable over angular position. The variation is most likely attributed to high pressures being maintained inside the analyzer. Future work will concentrate on alleviating this problem so that the spectrometer constant does not vary over the density ranges encountered in a Hall thruster.

INTRODUCTION

In a Hall thruster ions are accelerated by an axial electric field established between a downstream cathode and an upstream anode. An applied radial magnetic field in an annular discharge chamber impedes the motion of migrating electrons due to the crossed electric and magnetic fields creating an azimuthal closed electron drift, the Hall current. Propellant is injected at the anode and collisions in the closed drift region create ions that are then accelerated producing thrust. Commercially developed Hall thrusters typically operate between 50–60% efficiency, achieving specific impulses between 1500–2500 seconds.[1]

In recent years, several plume studies of Hall thrusters have been conducted at the University of Michigan. These have included the use of a retarding potential analyzer (RPA)[2] and a parallel-plate electrostatic energy analyzer (ESA).[3-5] Although both devices yield data proportional to the ion voltage distribution function[3], RPAs are subject to numerical noise because the data must be differentiated. Parallel-plate energy analyzers do not require differentiation and the resulting traces are therefore more accurate representations of the distribution function.

A parallel-plate ESA consists of two plates, a grounded baseplate and a backplate held at some positive potential with respect to ground. An ion beam is passed through the entrance slit of the baseplate. By setting the voltage on the backplate, the ESA acts as an energy per charge filter, allowing only ions of a particular voltage to pass through the exit slit of the baseplate where they are then recorded as current on a detector.

The existing ESA at PEPL is a stationary device mounted externally to the main vacuum chamber. This leads to some important considerations, which will be discussed below, with the experimental set-up because the thruster must be mounted in close proximity to the chamber walls. The primary motivation for this new design was therefore to build a compact and mobile energy analyzer that could be mounted anywhere within a vacuum chamber and thereby minimize some of the set-up induced effects that the larger energy analyzer introduces.

In the following, the motivation for such an analyzer design is discussed. The theory of operation of electrostatic energy analyzers is reviewed and the design and set-up is also presented. Finally, the method of analyzer calibration and a preliminary set of data are also given.

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[a] Graduate Student, Aerospace Engineering.
[b] Associate Professor, Aerospace Engineering and Applied Physics, Laboratory Director.

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DESIGN MOTIVATION

The Molecular Beam Mass Spectrometer (MBMS) developed by King[3,4] is a 45° parallel-plate electrostatic energy analyzer combined with a time-of-flight (TOF) mass spectrometer. It was used successfully by King on the SPT-100 and by Gulczinksi[5] on the P5 laboratory Hall thruster, providing a wealth of information on the ion energy and species composition of Hall thruster plumes. The instrument is mounted externally to PEPLs main vacuum chamber (see Figure 5). This requires the thruster to be mounted in close proximity to the chamber walls since the MBMS sampling skimmer is within 25 cm of the chamber walls. In this configuration, successful measurements have been made in the far-field (50-100 cm beyond the thruster exit plane). An extension used by Gulczinksi allowed for near-field (10 cm) measurements by moving the skimmer approximately 75 cm from the walls.

Due to the proximity of the MBMS to the chamber walls some set-up induced effects are potentially encountered. These may include: 1) enhanced back-sputtering of material from the chamber wall and sampling skimmer onto the thruster, 2) thruster oscillations in the near-field or high power operation, 3) alterations of the measured distributions at high power levels due to the enhanced flow rates, and 4) artificially creating charge exchange (CEX) collision signatures due to the local increase in pressure. All of these effects result in a measured ion voltage distribution function that is not entirely representative of the unperturbed thruster plume.

In an attempt to mitigate these potential effects, the development of a smaller version of the ESA portion of the MBMS that could be used *in situ* has begun at PEPL. The device, dubbed the Miniaturized Ion Energy Analyzer (MIEA), has been constructed and some preliminary results are given later. The main goal of the design was to build a hand-held size device that could be mounted anywhere in a vacuum chamber without significant loss of resolution. Owing to the fact that time-of-flight mass spectroscopy requires long path lengths to achieve acceptable resolutions, the MIEA was never designed with TOF capabilities, operating strictly as an ESA.

THEORY OF OPERATION

Many examples of parallel-plate ESAs exist in the literature, particularly for injection angles of 30° and 45°.[3-9] A 45° analyzer was chosen because of its ease of construction and the experience gained at PEPL building the 45° MBMS. Figure 1 is a schematic of the ideal parallel-plate electrostatic energy analyzer for an arbitrary injection angle θ. Relevant parameters and the coordinate system are defined in the diagram. Such a device consists of two parallel-plates, one grounded and the other at some applied potential V_a. A vacuum is assumed to exist between the plates. Ions are admitted through the entrance slit of width w at some initial energy and charge state E_i/q_ie and subsequently decelerated by the constant electric field $-V_a/d$ between the plates. Only particles with a particular energy and charge state leave the device through the exit slit. The ESA is therefore an energy per charge filter and the derivation of the governing equations is presented below.

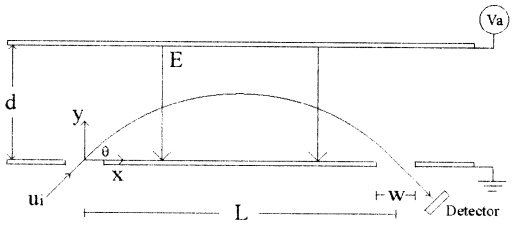

Figure 1 - Schematic of the ideal parallel-plate electrostatic energy analyzer with arbitrary injection angle.

A particle entering the field region is deflected due to the retarding potential applied at the backplate. The relevant differential equations are simply

$$\frac{d^2x}{dt^2} = 0 \qquad \frac{d^2y}{dt^2} = \frac{q_ie}{m}E \tag{1}$$

The particle trajectory in spatial coordinates for any injection angle is then given by

$$y = x\tan\theta - \frac{q_ie}{2m}\frac{V_a}{d}\frac{x^2}{u_i^2\cos^2\theta} \tag{2}$$

In a Hall thruster, ions are assumed to be created and simultaneously accelerated at some potential V_i. Applying conservation of energy

$$E_i = q_ieV_i = \frac{mu_i^2}{2} \tag{3}$$

Specializing to the case of a 45° injection angle the particle trajectory is then

$$y = x - \frac{1}{2d}\frac{V_a}{\left(E_i/q_ie\right)}x^2 \tag{4}$$

Setting the distance between the slits as L, the relationship between the applied voltage and the ion voltage for arbitrary injection angles is given by

$$\frac{E_i}{q_i e} = V_i = \left(\frac{L}{2d \sin 2\theta} \right) V_a \qquad (5)$$

The spectrometer constant K_{45} for the particular case of a 45° analyzer is then defined as

$$K_{45} \equiv \frac{L}{2d} \qquad (6)$$

Thus, for a given plate repelling voltage only ions with initial energy per charge ratios of

$$\frac{E_i}{q_i e} = V_i = K_{45} V_a \qquad (7)$$

reach the collector and are recorded as current. The above analysis assumes a point source of ions entering the field region. For a finite slit width w the resolution R for 45° analyzers is given by[9]

$$R \equiv \frac{\Delta E_i}{E_i} = \frac{w}{L} \sin\theta = \frac{\sqrt{2} w}{2L} \qquad (9)$$

Solving for the maximum height of the ion while in the field region, the correct condition to avoid impacting the backplate is

$$d > \frac{L}{4} \tan\theta \qquad (10)$$

which simplifies to d > L/4 in the case of a 45° analyzer.

As shown by King[3], the output current from the collector is proportional to the ion voltage distribution function in a ion beam with higher charge states according to

$$f(V_i) \propto \frac{I_i(V_i)}{\sqrt{q_i e V_i}} \qquad (11)$$

In a Hall thruster, approximately 90% of the flow consists of Xe^+ ions so the correction to Equation 11 due to higher ionization states is considered acceptable.[3]

ANALYZER DESIGN

The design of the MIEA was primarily driven by the need to significantly decrease the length L between the baseplate slits w. This would result in an overall decrease in the size of the device. The slit width was limited by manufacturing considerations using a standard mill. A slit width of 1.3 mm was achieved using this method. With that dimension set, the device resolution was relaxed so that the plate assembly could fit into a 35 mm inner diameter main body tube. This tube body size was chosen because it is a standard size that is readily available. Since Equation 10 requires d > L/4, setting the inner diameter of the main body tube ultimately sets the maximum length allowed. The final design resulted in a length L = 65.6 mm, a plate separation d = 17.6 mm and a corresponding resolution R = 1.4%. Table 1 summarizes the plate dimensions of the MIEA as well as listing those of the MBMS and a device constructed by Pollard[9] for ion engines. Pollard's device is also mounted interior to a vacuum chamber. The table indicates that the MIEA is the smallest device overall but is the least capable when resolution is considered.

Parameter	Pollard[9]	MBMS[3,4]	MIEA
d (mm)	76	160	17.6
L (mm)	152	584	65.6
w (mm)	0.25	3	1.3
K_{45}	1	1.82	1.86
R	0.1%	0.4%	1.4%

Table 1 - Comparison between three different 45° ESAs. The device used by Pollard was tested on an ion engine.

A schematic of the MIEA appears in Figure 2. All machined components are made from 304 stainless steel unless otherwise noted. The device consists of the entrance tube, main body, and collector housing. At the entrance tube, ions are admitted through a sampling orifice (9 in Figure 2) measuring 1.6 mm in diameter, countersunk on the inner side to reduce losses through the orifice. The entrance tube measures 102 mm long by 25 mm in diameter. The beam then passes into the main body where the plates are housed. The main body measures 230 mm long by 38 mm outer diameter. Solid Teflon rings (4 in Figure 2) support the plates. The baseplate is indicated as 8 in Figure 2 and the backplate by 3. The Teflon rings are held in place by an adjustment screw (1 in Figure 2) that allows for rotation and translation of the entire plate assembly. This capability is included so that the plates can be aligned correctly before testing. Facilitating this need, a screw on the backplate and a portion of the main body tube (2 in Figure 2) are removed and a laboratory laser is passed through the sampling orifice, through the entrance slit and out the holes left by the screw and removable portion of the main body. The screw in the baseplate is flush with the surface to minimize field perturbations. The backplate is biased by connecting it to an SHV connector (5 in Figure 2), which runs to a voltage supply exterior to the chamber. A Swagelok fitting (6 in Figure 2) leads to a turbopump that evacuates the interior of the entire analyzer. The turbopump is a Varian model Turbo-V70LP with a pumping speed of 68 l/s on nitrogen. Finally, ions that leave the field region through the

exit slit on the baseplate pass into the collector housing. The collector housing measures 111 mm long by 38 mm in diameter. As with the MBMS, a K&M Electronics model 7550m channel electron multiplier (CEM) is used to measure the incoming ion current (7 in Figure 2). The CEM is powered by a high voltage supply and grounded to the chamber. Output current from the CEM is sent via coaxial transmission cable. A thermocouple is attached to the CEM to monitor its temperature during testing. The CEM has a maximum operating temperature of 120 °C.

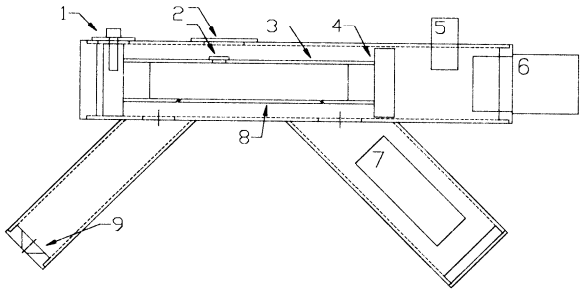

Figure 2 - The Miniaturized Ion Energy Analyzer (MIEA).

Experiments were performed that varied the size of the entrance orifice (1.6 vs. 3.2 mm) as well testing the MIEA with or without the turbopump attached. Without the turbopump, the Swagelok fitting was removed and the back end of the main body was exposed to the vacuum of the main chamber. These experiments indicated that the full width at half maximum (FWHM) of the main peak was minimized when the turbopump and the smallest orifice size were used and this configuration was used for the data presented in this paper.

Figure 3 is a photograph of the MIEA assembly with the turbopump attached. A graphite panel shields the turbopump from incoming ions. Another graphite panel is mounted parallel to the main body to protect the analyzer itself. Figure 4 is a close-up view of the MIEA as it appears in the vacuum chamber. A cylindrical Langmuir probe used to measure the local plasma potential is also indicated. The entrance orifice is covered in a graphite paint manufactured by Aremco (Pyro-paint, 634-GR) to reduce back-sputtering to the thruster.

The entire analyzer body, except the backplate, is grounded to the chamber. This introduces some disturbance to the local plasma environment since the plasma potential is positive with respect to ground for the P5 Hall thruster. Experiments by Pollard on an ion engine[8] have shown that there is no noticeable difference in the data whether or not the device is allowed to float or is grounded. The MBMS is also a grounded device. Based on these results, it was decided to ground the MIEA also.

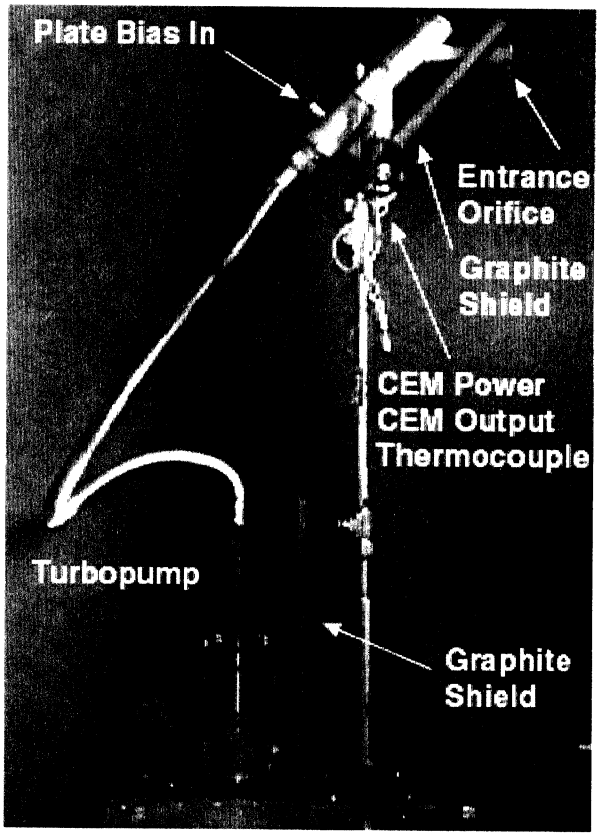

Figure 3 - The MIEA mounted to its stand with turbopump attached. Electrical cables and the Langmuir probe are not shown here.

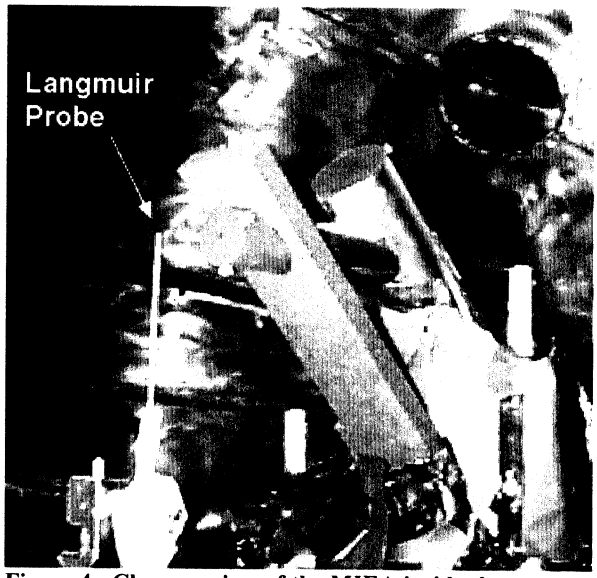

Figure 4 - Close-up view of the MIEA inside the vacuum chamber. The Langmuir probe is indicated in the figure. The entrance cap is coated with graphite to reduce back-sputtering to the thruster.

Note also that the 25 mm diameter cap to the entrance tube is a planar surface perpendicular to the flow direction. This configuration will create a local neutral cloud which decreases the mean free path. Accordingly, the FWHM should increase due to this effect. However, calculations by King[3,4] have

shown that this effect is negligible for the MBMS which uses a 152 mm diameter planar entrance cap. It was therefore decided that a similar configuration would be acceptable on the MIEA since the entrance cap was much smaller.

EXPERIMENTAL SET-UP

All experiments were conducted in the University of Michigan's 6 m diameter by 9 m long Large Vacuum Test Facility (LVTF). The pumping system consists of four CVI model TM-1200 Re-Entrant Cryopumps providing a measured xenon pumping speed of 140,000 l/s and an ultimate base pressure of $2x10^{-7}$ Torr. The operating pressure for these experiments was $5.1x10^{-6}$ Torr when corrected for Xenon. The facilities have been described in detail in a previous work.[1]

The LVTF is shown schematically in Figure 5. The thruster was mounted near the center of the chamber on a pair of X-Y linear translational tables with a rotary table also installed. The rotational axis of the thruster exit plane coincided with that of the rotary table. The thruster was pointed away from the cryopumps when testing on the axial centerline of the thruster. The MIEA itself was one meter downstream of the thruster position.

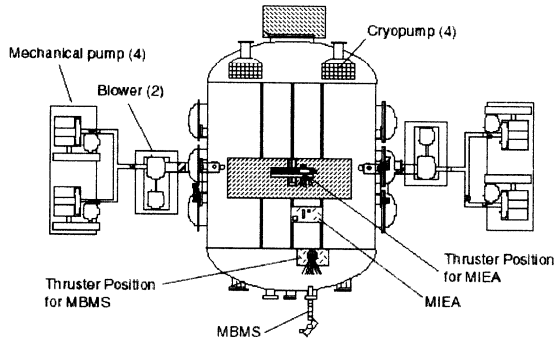

Figure 5 - Schematic of the vacuum chamber used in these experiments. Thruster positioning for the MBMS and the MIEA are indicated.

The thruster used was the University of Michigan – Air Force Research Laboratory P5 5 kW class laboratory model Hall thruster. The thruster has been thoroughly characterized and its performance closely matches that of commercially available 5 kW thrusters. Thrust, specific impulse, efficiency, and plasma parameter profiles in the plume are presented in a previous work.[1] To date, the P5 has accrued over two hundred hours of stable run time and continues to operate exceptionally well. The hollow cathode used, provided by the Moscow Aviation Institute (MAI), employs a small disk of lanthanum hexaboride as a thermionic emitter.

For these experiments the thruster was operated at 300 V, 5.4 A with a 60/6 sccm split between the thruster and the cathode. Prior to taking measurements, the thruster was allowed to operate 30 minutes to reach thermal equilibrium. The cathode was mounted at approximately the 2 o'clock position when an observer faces the thruster. Rotation of the thruster was in the clockwise sense when viewed from above the thruster. Thus, as the thruster rotated towards the left side of the chamber (see Figure 5) the cathode rotated closer to the MIEA. Samples were collected from 0-80° in 10° increments. The 80° position resulted in loss of signal. For every angular position the cathode potential was recorded. The cathode potential was found to be -21 ± 1 V with respect to ground.

The MIEA and a cylindrical Langmuir probe were mounted 1 meter downstream of the thruster exit plane. The MIEA backplate was connected to a Keithley Model 2410 sourcemeter which biased the plate between 0-500 V with respect to the baseplate which was maintained at chamber ground. The CEM was powered using a high voltage power supply over the range of –1.8 to –2.0 kV. Current from the CEM was collected using a Keithley Model 486 picoammeter. The current versus voltage trace was sent to a computer and collected via LabView. The CEM temperature was monitored using a thermocouple and was allowed to vary over the range 25-35 °C.

Since the MIEA is grounded the ions experience an acceleration as they enter the entrance orifice because the plasma potential for the P5 is positive with respect to ground. The Langmuir probe is then used to compute the plasma potential that is later subtracted from the analyzer traces to yield the correct energy per charge relationship. The Langmuir probe was located 6 cm radially away from the MIEA (see Figure 4), requiring the thruster to be moved for those measurements. The cylindrical probe measured 2.5 mm in diameter and 38 mm in length, mounted with the longitudinal axis perpendicular to the flow direction. The probe was biased using the same Keithley Model 2410 sourcemeter, which simultaneously measured the current collected. Data from the sourcemeter was sent to a computer and collected via LabView.

ANALYZER CALIBRATION

Experiments with the P5 operating at 300 V and 5.4 A using the MBMS indicated that the most probable voltage on centerline of the thruster between 50-100 cm axial position was 262 V with respect to ground. This value was used to calibrate the spectrometer constant of the MIEA. It is worth noting that the MBMS is a self-calibrating device because it can operate as an ESA and as a TOF mass spectrometer.

Data from the TOF mode confirms that the flight time of a Xe^+ ion is consistent with the path length induced by the particular pass voltage from the ESA.

Five sweeps were used from the MIEA on centerline at 1 m downstream to find an average value of the spectrometer constant K_{45}. This value was found to be 2.33± 0.05, which differed substantially from the theoretical value of 1.86. As will be discussed below, it was later found that the spectrometer constant was not constant over the range of angular positions tested here.

EXPERIMENTAL RESULTS

Data from the MIEA are presented in Figures 6 and 7. In all of the traces, the measured plasma potential from the Langmuir probe has been subtracted from the data. A boxcar average was performed over a three point span to smooth the data to remove some of the noise induced by the large line lengths separating the CEM and the Keithley picoammeter. A three point average was chosen since this range did not change the location of the peak nor change the overall structure of the trace. The measurements span the range 0-80°, in 10° increments. One additional trace was taken at 5° and loss of signal occurred between 70-80°.

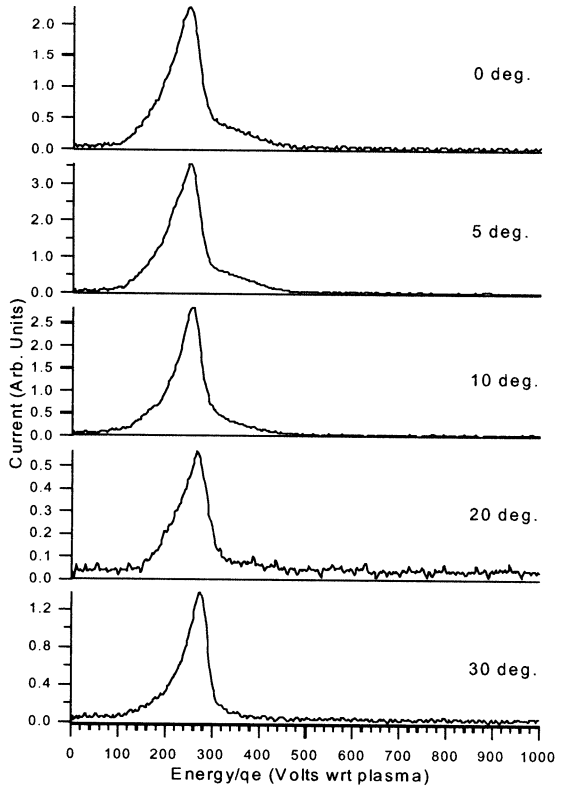

Figure 6 - Ion energy per charge distributions recorded at 1 m downstream of the P5 exit plane for angles of 0°, 5°, 10°, 20°, and 30° off the thrusters axis of symmetry.

DISCUSSION

The distributions shown in Figures 6 and 7 are qualitatively representative of the traces obtained by the MBMS on this thruster[5]. The dramatic shift to lower main peak voltage show at 70° was also seen with the MBMS at high angles. An immediate difference with the MBMS is the lack of CEX collision signatures in the data. A CEX collision will appear as two smaller peaks on either side of the main peak at discrete multiples of the main peak voltage. Elastic collisions, which appear as either a high or low voltage "tail" to the main peak, seem to dominate in the MIEA traces. However, closer examination of the data indicate that conclusions such as these may not be warranted.

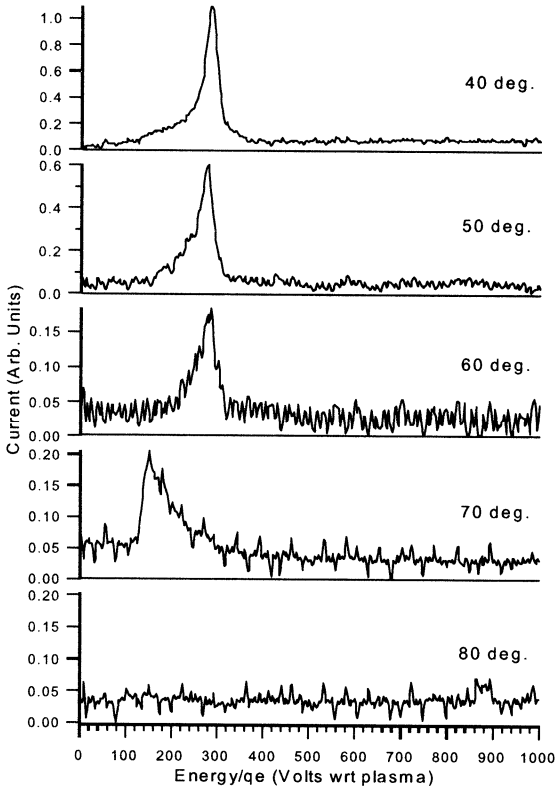

Figure 7 - Ion energy per charge distributions recorded at 1 m downstream of the P5 exit plane for angles of 40°, 50°, 60°, 70°, and 80° off the thrusters axis of symmetry. Loss of signal occurred between 70° and 80°.

Figure 8 is a plot of the FWHM for the analyzer traces at each angular position. No FWHM is computed at 80° since this represented loss of signal. The data spans the range of 36–77 V, where the FWHM on centerline was 77 V. Data taken by the MBMS on centerline at 75 cm indicate a FWHM of 35 V. A larger FWHM in ESAs than expected is usually indicative of signal broadening due to high pressures inside the analyzer. The data from Figure 8 is one indication that the pressure inside the MIEA is not being maintained at a sufficiently low level to

accurately capture the ion voltage distribution. Thus, it seems that the broadening in Figures 6 and 7 is partially attributed to a pressure effect and not solely to elastic collisions. If this is the case, any CEX collisions that may be present would be obscured by the pressure broadening.

Since the cathode potential V_c was monitored at each angular position and the discharge voltage V_D was also monitored it is possible to calculate a theoretical maximum accelerating voltage V_{max} that an ion would "see" in the discharge chamber of the P5. The theoretical value is simply

$$V_{\max} = V_D - |V_C| - V_P \qquad (11)$$

where V_p is the plasma potential obtained from the Langmuir probe measurements. The theoretical maximum is plotted in Figure 9 with the peak value from the MIEA traces after correcting for the plasma potential. The figure indicates that between 20° and 30° on centerline the data returned from the MIEA becomes unphysical since the measured peak is not likely to exceed the theoretical maximum. Since the peak value from the MIEA are obtained assuming a constant spectrometer constant, the likely explanation for this discrepancy is that the spectrometer constant is varying over the range of angles tested. As the analyzer is moving away from centerline the ion flux significantly decreases. This would tend to lower the internal pressure of the analyzer. Conditions closer to vacuum would result and the spectrometer constant should then approach the theoretical value. The trend in the data from Figure 9 supports this explanation.

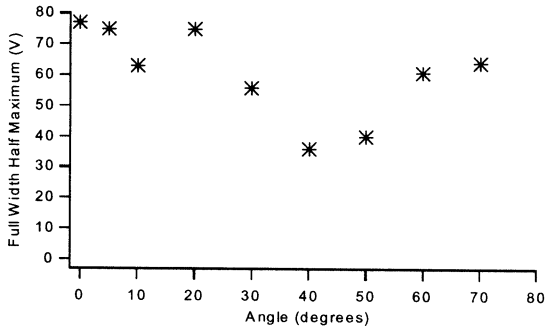

Figure 8 - The FWHM from the analyzer traces as a function of angular position.

Attributing the discrepancies in the data solely to a pressure effect may not be justified. It is also possible that the design of the plates is resulting in an electric field that is not constant across the plate gap. This could result in defocusing of the beam and other changes to the ion trajectories that make the calculation of K_{45} inaccurate. Another possible explanation is that the high pressure inside the analyzer is interfering with the operation of the CEM. The CEM manufacturer indicates that the CEM should only be operated below 3 x 10^{-4} Torr. Use above that pressure would produce erroneous and erratic behavior in the CEM output.

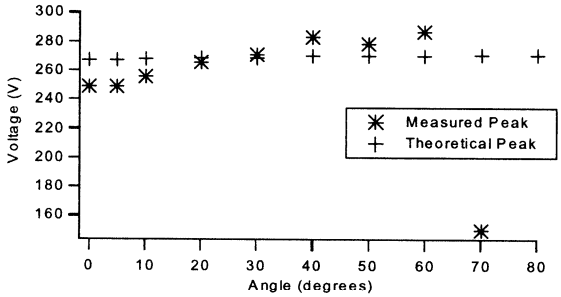

Figure 9 - The measured voltage peak from the analyzer traces corrected for the plasma potential and the theoretical maximum peak of the P5 versus angular position. Note that the measured peak crosses the theoretical maximum between 20° and 30°, indicating that the spectrometer constant is varying as the plasma density decreases.

FUTURE WORK

The data presented in Figures 6 and 7 are a promising first step in developing a small and mobile ESA. However, as indicated by Figures 8 and 9 the pressure being maintained inside the analyzer is apparently much higher than anticipated and steps need to be taken to correct for this problem. Other factors have also been considered, including a non-uniform electric field or erratic CEM output.

Work in the immediate future will focus on determining the root cause of the variations in the spectrometer constant. If the pressure inside the analyzer is found to be the cause there are several possible solutions. These include using a smaller entrance orifice, using a turbopump with a higher pumping speed, reducing conductance losses by shortening the flexible tubing connecting the analyzer and the turbopump, or simply sealing the analyzer better from the ambient plasma. A redesign of the plates may be in order if it is instead determined that the field structure between the plates is inducing the variations in the spectrometer constant.

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analyzer and for the actual machining and assembly of the device.

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