Development of a Single-orifice Retarding Potential Analyzer for Hall Thruster Plume Characterization

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Abstract

A retarding potential analyzer (RPA) was carefully designed to investigate the high energy tail often observed in the ion energy distribution measurements in the plumes of Hall thrusters. The probe was designed to operate in regions of the plume where the Debye length was 100 μm or greater. Probe design was assisted by the PIC code MAGIC to maximize the ratio of the effective ion retarding potential to the applied potential to ensure that ions were not being detected at artificially high ion energies. The probe was built and tested. The results verify the existence of ions that have been effectively accelerated through voltages in excess of the thruster discharge voltage. This paper thoroughly discusses the design of the probe and presents preliminary measurements in comparison with the ion energy distribution measurements taken with two other diagnostics.

Introduction

Retarding potential analyzers (RPAs) are used extensively in the field of electric propulsion to characterize the ion energy distributions in thruster plumes. This information is imperative to gain an understanding of the influence of high energy plasma plumes generated by electric propulsion systems on spacecraft lifetime and operation. Ion energy distributions have been used with ion current density measurements to indirectly determine the thrust generated by a Hall thruster, replacing more costly direct measurements made by an inverted pendulum thrust stand.[1] Measurements of the ion energy distribution at large angles from the thruster axis are also used to assess the impact of Hall thrusters on spacecraft solar arrays since material sputtered off of spacecraft surfaces by the ions can be deposited on the solar arrays to degrade their performance.[2] This paper provides a detailed explanation of a new RPA design used to measure ion energy distributions.

RPAs use a series of electrodes to selectively filter out ions of varying energy, yielding an ion current which varies as a function of the ion retarding electrode potential. While RPA operation is fairly straight forward, previous designs have a number of potential problems. Large probe entrance apertures in closed-back probes allow a large flux of particles to enter the probe cavity resulting in a high ram pressure build-up. High pressure inside the probe increases both momentum and charge exchange (CEX) collisions resulting in broadening of the ion energy distribution. Inappropriately large inter-electrode spacings are responsible for space charge limiting of the measured current. Inappropriately large apertures result in artificially high ion energy distribution measurements because of Debye shielding. In addition, a probe designed with the appropriate aperture sizes and interelectrode spacing will also support field saddle points with improper electrode thicknesses. Studies of ion energy distributions in Hall thruster plumes have consistently reported that there exists a significant ion current at and above ion retarding voltages equivalent to the discharge voltage of the thruster.[3,4,5,6] With a cathode potential around -21V with respect to ground, measured plasma potentials around 5 V, and discharge fluctuations of only ~+/-10 V out of 300 V, maximum dc accelerating voltages should be ~284 V. While recent investigations have been launched to determine if plasma instabilities are responsible for the high energy particles, this investigation was carried out to verify the existence of the high energy tail in the ion energy distribution of SPT-100 ions using an RPA.

Addressing the design issues inherent to the RPA, a single aperture probe was designed, built and tested at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL). The PIC code MAGIC, developed by Mission Research Corporation, was employed to determine the actual retarding potential of the probe for specified applied potentials, spacings, and aperture sizes. This paper describes the probe design and experimental configuration, presents the contour plots of equipotentials near the electrodes predicted by MAGIC, and includes the experimental results of the ion energy distribution measurements obtained by the probe in the plume of SPT-100 provided by Space Systems/Loral (SS/L).

Retarding potential analyzer design

The RPA was constructed as shown in Figure 1 from molybdenum and nickel electrodes, and a stainless steel hood. TEFLON insulation was used between the electrodes and hood, and NOMEX insulation between the electrodes. The probe was open in both the front and back to allow the ions in the direct flux to be captured and analyzed while preventing high pressure build-up in the probe by allowing the particles to escape through the back. The electrodes used to analyze the direct flux included the floating electrode (FE), the electron retarding electrode (ERE), the ion retarding electrodes (IRE), the secondary electron suppression electrode (SESE), and the ion collector. The body of the probe floated to minimize probe perturbance to the plume, and the ERE was used to filter out plasma electrons. The IRE was used to retard the plasma ions, and the SESE was employed to prevent electrons emitted from the ion collector to escape the probe. Molybdenum was used as the electrode material because of its low electron emission yield compared to other materials typically used, like stainless steel.

The wake flux into the back of the probe due to the stagnant ambient plasma in the vacuum chamber warranted a series of grids to filter out the charged particles that could artificially increase the collected current. These grids included the floating grid (FG), the electron retarding grid (ERG), and the ion retarding grid (IRG). These grids were fashioned from 31 wire/cm nickel mesh sandwiched between stainless steel washers with ~ 1.5 mm between grids.

The design of the probe was based on the principles of energy analyzers presented by Hutchinson.[7] Since the plasma sheath typically extends over several Debye lengths, the diameter of the apertures in the electrodes was limited to two Debye lengths at the operating point of interest. With this aperture size, the shielding effect of the electrodes by the plasma is minimized. This probe was designed to operate at 0.5 m axial distance on the thruster centerline where the electron temperature was approximated as 2.0 eV[4] and the number density was ~8E15 m^{-3} .[8] While the particle densities and electron temperatures are unknown inside of the probe, the conditions outside of the probe were used to calculate the minimum possible Debye length at the electrodes. The Debye length is approximated as 116 μm at this position. The electrodes were laser machined with 200 μm diameter apertures. Because of the nature of the Hall thruster plume, the particle number density decreases, the electron temperature increases and the Debye length in the plasma increases with angle off centerline. Consequently, the probe design is appropriate at any angle from the thruster centerline at radial distances of 0.5 m or greater.

The appropriate size spacings between the grids were determined using Hutchinson's design recommendation that the interelectrode spacing should be less than 4 Debye lengths. Therefore, it was chosen to be ~457 μm. This requirement arises from the space-charge limitations of energy analyzers. Figure 2 shows a potenial diagram for the RPA. However, after selectively removing the electrons from the flow, charge density between the electrodes can change the potential. If the potential between the electrodes is shifted to a higher potential than the ion retarding grid, the ions will experience a repulsive potential hill higher than that created by the electrodes. Considering the case when the potential has zero slope at the ion repeller so that higher density would lead to space-charge limitations, a relationship was derived between grid spacing, x, and the potential difference between the ion and electron retarding electrodes, V. The relationship as derived by Hutchinson[7] is

$$\frac{x}{\lambda_D} = 1.02\left(\frac{eV}{T_e}\right)^{\frac{3}{4}},$$

where λ_D is the Debye length, and Te is the electron temperature. The λ_D used here corresponds to the plasma density outside of the electron retarding electrode. With the probe design defined, where x is ~457 μm and the electron temperature is 2 eV, the voltage between the IRE and ERE at which the space-charge effects are significant is about 12 V. In the data plots shown in the experimental section of the paper, this voltage corresponds to -14.5 V with respect to plasma potential. The space charge limited operating regime of this probe is insignificant since the majority of particles are accelerated by the thruster through voltages greater than 200 V. However, in other RPAs used in the same plasma regime, the interelectrode spacing is a few mm. With x equal to ~20 λ_D ,space charge are significant below 100 V.

RPA design analysis by MAGIC

RPA design development was aided by the particle-in-cell (PIC) code MAGIC. This code, developed by Mission Research Corporation, provides interaction between space charge and electromagnetic fields. It is a two-dimensional, finite-difference, time-domain code that simulates plasma physics processes. Electromagnetic fields are determined using the full set of Maxwell's time-dependent equations. Current and charge densities for Maxwell's equations are obtained by solving the complete Lorenz force equations.

The simulation employed radial and axial dimensions with azimuthal symmetry. The grid was uniform in every dimension with 25 μm x 25 μm cells. MAGIC was used primarily to determine the electrode thicknesses required with the aperture size and electrode spacing recommended by Hutchinson to ensure that the effective decelerating potential of the ion retarding electrode was greater than 98% of the applied potential. The goal was achieved by using 51 μm thick foil for the electron retarding electrodes, and two 127 μm thick electrodes with a 150 μm gap to repel the ions.

Figures 3a and 3b show equipotentials generated by the probe with the ERE at cathode potential, -20V with respect to ground, and the IRE at 300 V, near the primary voltage of interest. The effective ion retarding potential, Vire_eff, and electron retarding potentials, Vere_eff, are shown in Table 1 for several applied voltages to the ion retarding electrode, Vire_app, and electron retarding electrode, Vere_app. The two numbers in the Vere_eff column represent the values of the ERE and then SESE. Note how the effective retarding potentials of the electrodes are mitigated by the other electrodes because of the close-spaced configuration. To minimize the potential saddle points in the electrode apertures, a thick IRE could have been used or, as was done for this configuration, two IREs were employed, separated by an insulator to produce the same effect. In the first design iteration of this probe a single IRE was used with the same thickness as the electron retarding electrodes. This design failed because there was a 10% drop in potential between the IRE and the center of the aperture at 495 V so that ions passing through this region would only experience a 445 V decelerating voltage.

Table 1. The effective retarding potentials of the grids for the applied voltages.

Vire_app	Vire_eff	Vere_app	Vere_eff
500	498	-21	-13/-13
450	448	-21	-13/-14
400	399	-21	-13/-14
350	349	-21	-14/-14
300	299	-21	-14/-15
250	249	-21	-15/-15
200	199	-21	-15/-15
150	149	-21	-16/-16
100	99	-21	-16/-17
50	49	-21	-17/-17
0	0	-21	-19/-19

Experimental methods

The experiments to measure the ion energy distribution of the plasma ions were conducted at the PEPL using the RPA and emissive probes in the SPT-100 plume. The SPT-100 was operated with an SS/L power processing unit to maintain the nominal operating point of the thruster; 300 V discharge voltage and 4.5 A discharge current. The emissive probe was employed to obtain plasma potential measurements that were used to determine the true decelerating potential of the RPA; i.e. the potential of the ion retarding electrode with respect to the plasma potential.

The emissive probes were constructed from 0.064 mm diameter tungsten wire with a 4 mm long single loop. The wire was connected electrically by larger tungsten and copper wires, which were mounted within a two hole ceramic insulator inside of a stainless steel jacket. The filament was heated to emission with a 60 Hz half wave rectified heating current. The probe bias voltage with respect to ground was swept at 500 Hz with measurements taken during the off phase cycle of the heater when the filament had a unipotential surface and a correction for longitudinal potential across the probe was unnecessary. The inflection point method with the current-voltage trace of a hot electron emitting filament was used to determine the plasma potential.[9]

The RPA circuit shown in Figure 4 employed power supplies for the ion retarding electrodes, the ion retarding grid for wake flux filtering (100V with respect to cathode), and electron retarding electrodes and grids (at cathode potential). For these measurements, it was determined that cathode potential on the EREs was sufficient to retard the electrons to maximize the collected current. An oscilloscope was employed to record ion retarding voltages measured with 100x voltage probes that were calibrated against a Fluke 87 multimeter and ion currents were measured with a picoammeter. The recordings included at least 500 data points per current-voltage curve and were saved to data files using LabVIEW.

Experimental results and discussion

The experiments were very conclusive in verifying the existence of ions that have effectively been accelerated through voltages greater than 284 V. Measurements were taken at several angles that verify the high energy tail in the ion energy distribution, however, only the 0.5 m centerline data set is presented in Figure 5. The plasma potential at this position was 5.5 V with respect to ground. These measurements satisfy the objective of the probe by showing the high energy tail in the data.

Energy distributions measured at the same location in the plume by three diagnostics produced three measurements of the ion energy distribution for comparison and validation of the existence of high energy ions. RPA-I, discussed in detail in a paper by Marrese et al.,[5] had a less than optimal design and was used to obtain one measurement of the ion energy distribution. It was speculated that the large interelectrode spacings in the stainless steel grids prevented accurate measurements because of space-charge effects, and large potential gradients at the grid wires mitigated effective retarding potentials.

An additional problem with RPA-I was high ram pressure build-up in the probe during measurements. RPA-I had an entrance aperture 7 mm in diameter with a floating grid, electron retarding grid, ion retarding grid, and collector at the back of the closed end of the probe. The pressure in such a configuration would be similar to that measured with the neutral particle flux probe developed by King and Gallimore,[2] ~20 mTorr. As discussed by King et. al[10] in a later paper, the high pressure inside of RPA-I causes momentum and charge exchange (CEX) collisions to occur between the high velocity plasma ions entering the probe and the ions that were neutralized from wall and collisions with the collector. 90% of the ions entering the probe would experience CEX collisions before being collected at the back of the probe. The effect of these collisions is broadening of the ion energy distribution. A singly charged ion that has undergone a CEX collision will be detected at an artificially low ion energy while a doubly charged ion that undergoes a CEX collision will be detected at either artificially high or low decelerating voltages depending on where the collision occurs. Since the new RPA, RPA-II, presented in this paper employs an open back configuration to decrease the pressure inside of the probe, the ion energy distribution measurement by the RPA-II is narrower than that measured by the original probe, as expected.

Further reduction in ion energy distribution broadening can be achieved to acquire more accurate measurements of ion energy distributions by reducing the pressure inside of the probe further, as King et al. showed with a molecular beam mass spectrometer (MBMS).[10] The results of the measurements obtained using the MBMS are also included in Figure 5, showing a much narrower energy distribution. The MBMS employs a set of orifice plates to skim off a small beam of plasma from the thruster plume which is then collimated and energy filtered using a 45 degree parallel plate electrostatic energy analyzer. The chambers of this energy analyzer were differentially pumped to maintain pressures less than 7E-6 Torr during measurements, so that CEX collision probabilities were reduced to 10% inside of the MBMS, as opposed to the 90% probability of collisions that occur in RPA-I. While the two methods and two RPAs measure different energy distributions due to the probe configurations, all three approaches verify the existence of the high energy tail in the distribution.

There are other probe issues that were not discussed in this paper that limit the accuracy of the distribution measurements. These problems include decreases in beam transmission due to space charge effects and current reduction due to electron transmission through to the collector. Defocusing of the beam by the series of grids that constitute an electrostatic lens is also a source of error in the probe measurements. However, each of the sources of error considered contribute to the reduction in the measured current: they would most likely not increase the ion current to produce the high current at the thruster discharge voltage that has been observed in several investigations of Hall thruster plumes.

Acknowledgments

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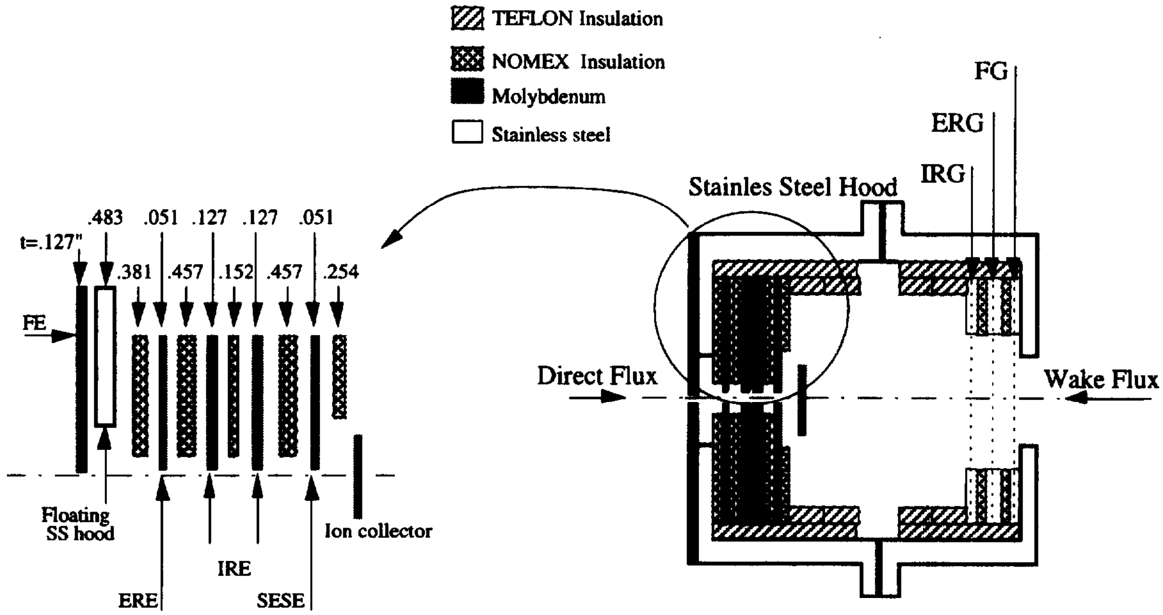

Figure 1. The single-orifice retarding potential analyzer configuration. Electrode thicknesses are given in millimeters.

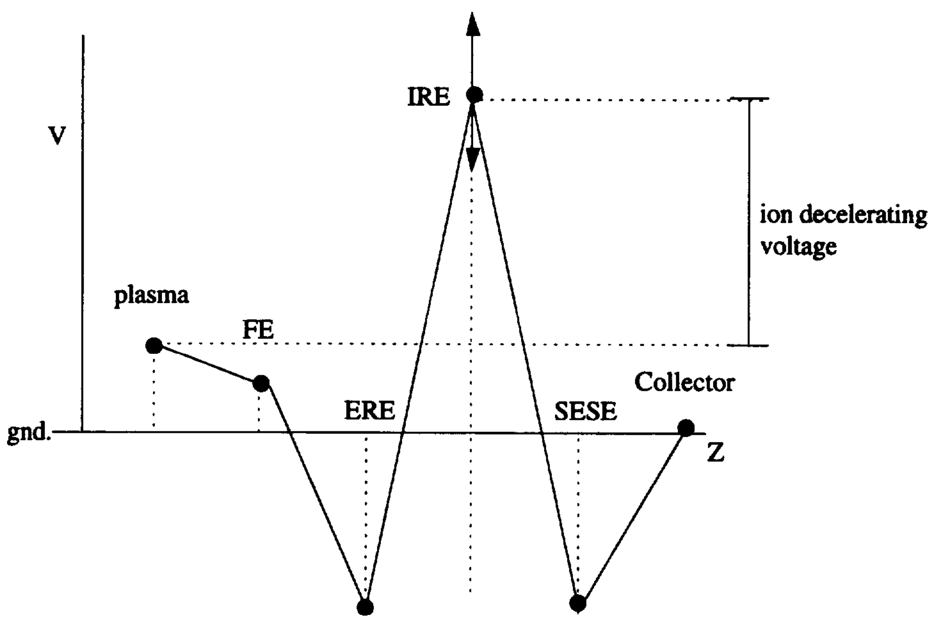

Figure 2. Potential diagram for the RPA.

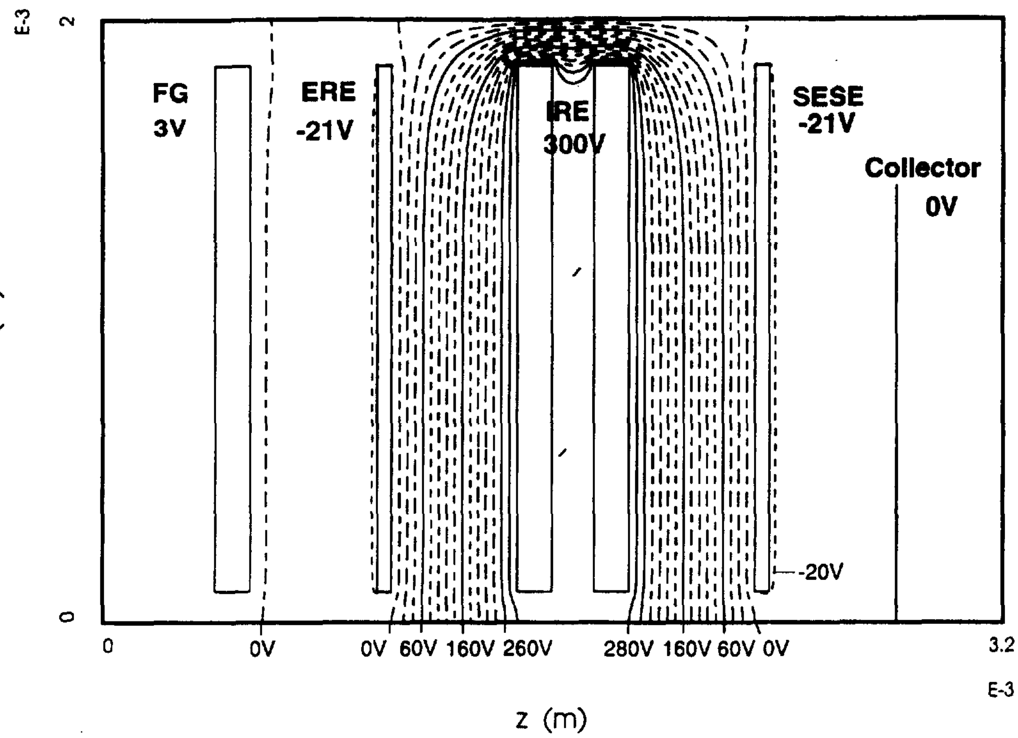

Figure 3a. Equipotentials in the RPA determined by MAGIC between -20 V and 300 V in 20 V increments.

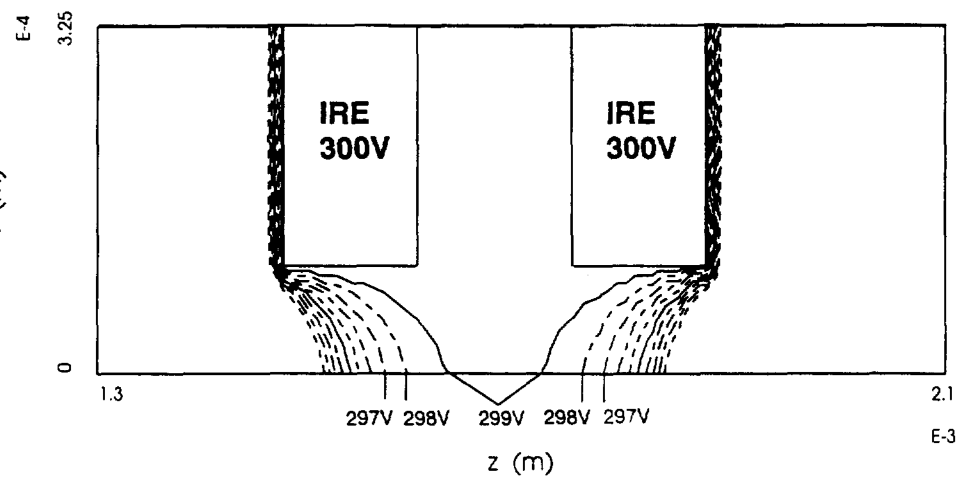

Figure 3b. Equipotentials in the ion retarding electrode aperture region between 290 V and 300 V in 1 V increments.

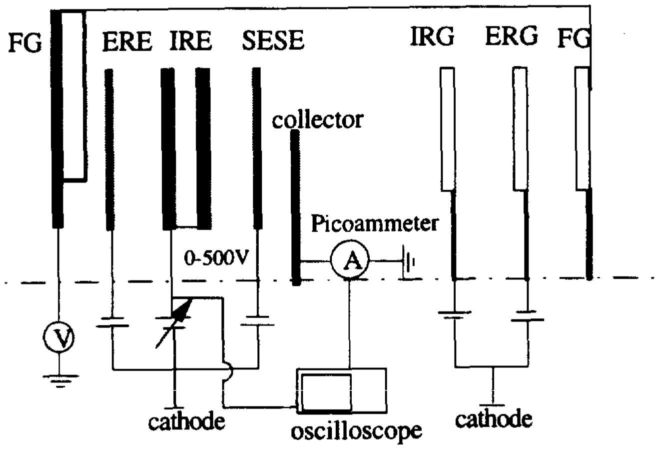

Figure 4. The electrical schematic of the RPA.

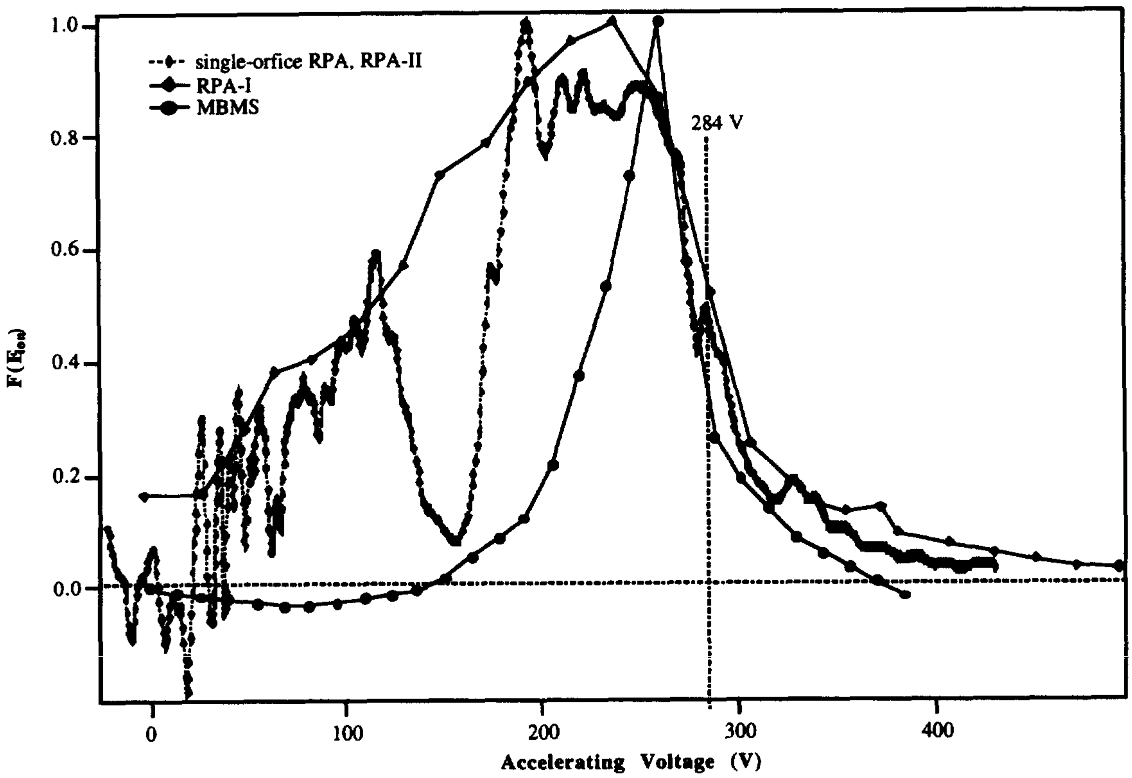

Figure 5. Ion energy distributions measured at 0.5 m axially on thruster centerline using two different RPAs and the MBMS. The data were normalized to the maximum values in each data set.