An Energy Distribution and Charge State Analyzer for Hall Thruster Measurements

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Abstract

An energy analyzer has been constructed that is appropriate for measuring the energy profile and charge state distribution of the exhaust plume of a xenon-driven Hall thruster. The analyzer consists of a decelerating lens stage, a hemispherical energy selector stage, and quadrupole spectrometer stage that has the capability of separating charge states. The system has a theoretical energy resolution of 1.7 eV and is theoretically capable of separating singly, doubly, triply, and quadruply charged xenon ions. The device has been calibrated using an ion thruster as a known source.

Introduction

Electromagnetic thrusters can produce exhaust beams with very complex ion energy profiles. Accurate characterization of the spatial distribution of ion energies would provide valuable information about thruster performance. To perform these measurements, JPL's Advanced Propulsion Technology Group has developed a compact energy analyzer that has a hemispherical electrostatic energy selector as its central feature. The hemispherical segment passes ions that have a specific energy/charge ratio. By measuring the beam current downstream of the hemispheres, an accurate picture of the energy distribution can be obtained. The analyzer also includes an electrodynamic quadrupole spectrometer that can distinguish between different ion charge states. Thus the analyzer system not only has the ability to characterize an ion energy profile but can also determine which charge states are present.

The system is designed to measure ion energies in the range of 50 to 650 eV with a resolution of approximately 2 eV and distinguish between singly, doubly, triply, and quadruply charged xenon ions. While primarily intended for use with Hall thrusters, the device can be used to characterize any similar plasma within its energy range. The analyzer can be tuned to measure gases other than xenon by adjusting the frequencies employed by the quadrupole spectrometer.

The hemispherical energy analyzer is a relatively well-known device. Purcell [1] described using a spherical electrostatic deflector to measure the kinetic energies of charged particles as early as 1938. Hemispherical deflectors used in tandem with cylindrical decelerating lenses are currently available commercially [2]. The use of a quadrupole spectrometer with this type of system has not been done before to the best of the authors' knowledge.

Experimental

Apparatus

Figure 1 is a schematic of the system. The system consists of the hemispherical segment, a beam collimator, two sets of cylindrical electrostatic lenses — one of which decelerates the ion beam while the other exclusively focuses it — a quadrupole mass spectrometer and a Faraday Cup current collector. The collimator, which is located at the analyzer's entrance aperture, has a 0.25 inch diameter and is 6 inches in length. The decelerating lens is made up of three coaxial aluminum cylinders each with a diameter 1.1 inches with lengths of 1.65 inches, 1.1 inches, and 2.6 inches. The cylinders are separated by gaps of 0.11 inches and are biased to voltages in the range of -200 to 600 V. The hemispherical segment consists of two concentric aluminum

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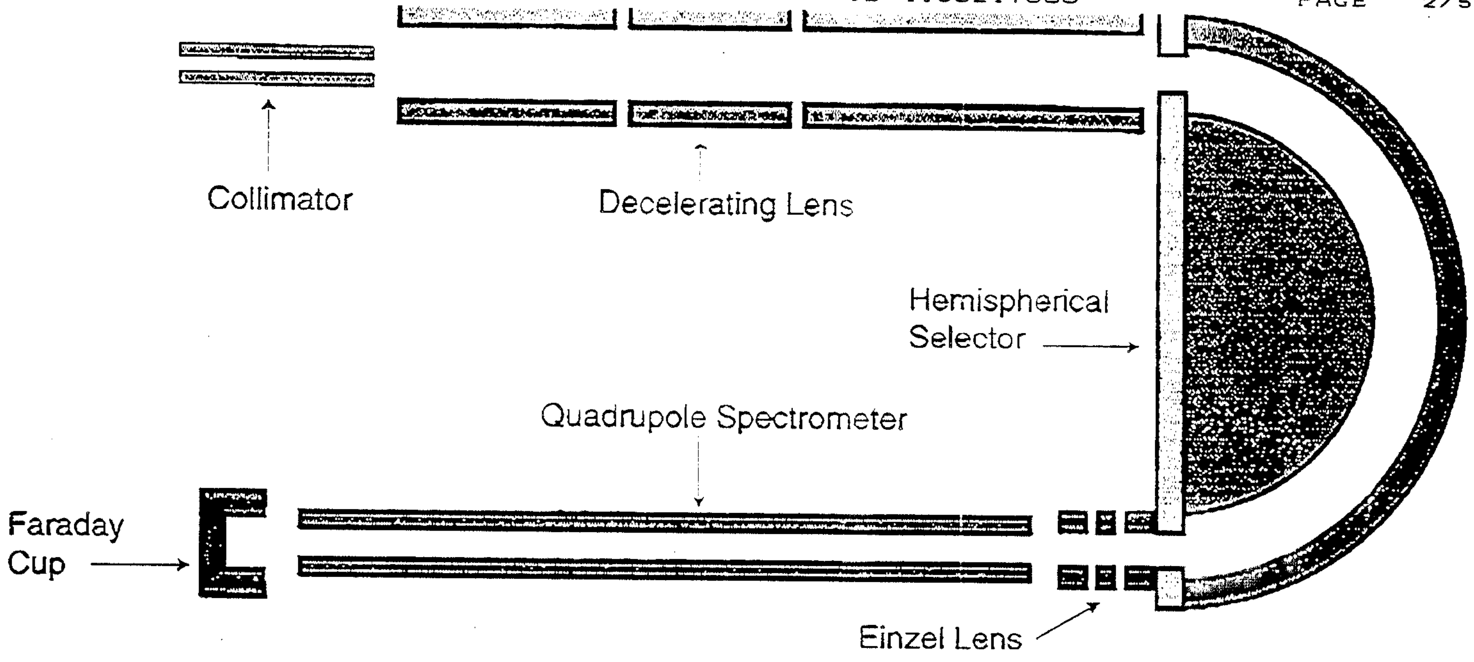

Figure 1: Schematic of the analyzer system

hemispheres of radii 1.47 inches and 1.69 inches. The hemispheres maintain a constant potential difference of 8.3 V relative to each other but float at a reference potential that varies with the decelerating voltage. At the exit aperture of the hemispheres is a 0.25 inch diameter Einzel lens made up of three aluminum cylinders of 0.25 inch lengths. This lens uses a focusing potential around -90 V to image the ion beam into the Faraday Cup seven inches away. The quadrupole spectrometer consists of four 0.25 inch diameter stainless steel rods arranged with a central channel of diameter 0.25 inches.

Operation

The analyzer is oriented so that the ion beam is directed into the collimator. The beam then passes through the collimator and enters the decelerating lens. The three-cylinder configuration of the lens allows for the beam to be decelerated by a varying amount while maintaining a constant imaging point at the entrance aperture of the hemispheres. All ion energy scanning is carried out in the decelerating stage. The hemispheres are maintained at a constant potential difference which allows ions of exactly 50 eV per unit charge to pass through. By varying the decelerating voltage on the lens, any energy value can be measured, but ions will always be decelerated to 50 eV before passing through the hemispheres. After emerging from the selector, the ions are focused by the Einzel lens to a point downstream of the quadrupole. Once the beam enters the region of the oscillating quadrupole field, ions without a certain charge state are selectively removed from the analyzer. Thus, the beam current collected in the Faraday cup is entirely monoenergetic and made up of a single charge species.

Theoretical Design Considerations

The Hemispherical Selector

There are several types of electrostatic energy selector geometries including parallel plates, cylindrical electrodes, and hemispherical electrodes. The hemispherical selector was chosen because its spherical symmetry gives it superior focusing properties. This analyzer is the only electrostatic selector that has the ability to image a diverging beam onto a single point, which makes collection and manipulation of the beam easier. The hemispherical electrostatic energy selector consists of two concentric hemispheres of different radii with a gap between them. A spherically symmetric electric field is produced in the gap by applying a voltage between the two hemispheres. The field strength decreases proportionally to the inverse of the square of the radius. Much as a satellite in the presence of a massive body will balance the gravitational pull with the centrifugal force of orbit, so will a charged particle assume a stable 'orbit' if it has the appropriate velocity for its radius. Thus, ions with a specified energy/charge ratio will maintain an orbit and be emitted from the other side of the selector. Particles without the necessary energy/charge will quickly collide with one of the hemispheres and be removed from the ion beam. For a given orbital radius a and voltage V the energy U_{pass} per unit charge q of an ion that will be transmitted through the analyzer is:

$$\frac{U_{pass}}{q} = \frac{R_i R_o}{R_o \quad R_I} V a$$

Where R_i and R_o are the radii of the inner and outer hemispheres respectively. It is important to note that the hemispherical selector only has the ability to separate out ions in terms of their energy per unit charge, not their energy alone. This means that a doubly charged ion will look the same to the hemispheres as a singly charged ion with half of the energy.

An important phenomenon to consider is the effect of space charge. The ion beam entering the analyzer will likely be quasi-neutral, but the decelerating optics will separate most of the electrons from the ions. Any electrons that do enter the analyzer will quickly be drawn to the walls and removed from the beam. Thus, the plasma inside the hemispherical selector will carry a net charge that will induce space charge effects. Kuyatt et al. [3] have worked out the space charge limited current allowed in the selector by essentially modeling the hemispherical gap as a straight tube with diameter d and length l. The maximum beam current that the analyzer can support, I_{max} is given by:

$$I_{max} = 38.5 U^{3/2} (\frac{d^2}{l^2})$$

Where U is the kinetic energy of the beam. The selector described here has a space charge limited current around 17 nA. Since currents less that 1nA were observed, this selector is considered to operate well within space charge limits.

In order for an ion to assume a stable orbit around the hemispheres, it will have to enter the selector normal to the plane of the entrance aperture, even if the ion has the correct velocity. Ideally, all particles that enter the hemispheres with the desired energy should pass through the analyzer. It is possible for a particle to traverse the hemispheres without actually being in a stable orbit. Purcell [1] worked out an approximation for the trajectory of an ion as it enters the analyzer with angular deviation α. This equation is quite useful in deriving some other practical quantities. The exact expression is:

$$r(\varphi) = a + \frac{2a}{2sec^2\alpha + (cos2\alpha \quad 1)sec^2\alpha cos\varphi \quad 2tan\alpha sin\varphi}$$

Where a is again the orbital radius and φ is an azimuthal angle along the trajectory. From this expression, a value can be calculated for the maximum beam divergence angle at the entrance aperture.

$$\Delta\alpha = cos^{\ 1}(2\sqrt{\frac{2(a+w)}{2a+w}})$$

where w is the width of the gap between the hemispheres. In other words, if there is a beam of particles that appears to emanate from a point at the entrance aperture of the analyzer, then as long as that beam doesn't diverge by more than the angle $\Delta\alpha$, the entire beam will be transmitted. With the dimensions described above, the hemispherical selector has an acceptance angle of 2 degrees. The decelerating optics were designed accordingly.

Another very useful relation that can be derived from the particle trajectory equation is the energy resolution [6].

$$\frac{\Delta E}{E} = \frac{w}{2a} + \frac{1}{2}(\Delta\alpha)^2$$

The quantity ΔE is the range of ion energies that will be transmitted through the selector. The smaller this value is, the more accurately an energy distribution can be described. Notice that ΔE is proportional to the ion energy being examined. This means that as the beam energy increases, the accuracy with which it can be resolved decreases. This presents a challenge for the designer since the uncertainty in the measurement will be a function of the energy being measured. At 50 eV, the dimensions of the hemispheres yield a theoretical energy resolution of 1.7 eV. Error in the resolution is most likely to come from imperfections in the fabrication of the hemispherical segment.

The Decelerating Electrostatic Lens

To overcome the problem of variable energy resolution, it was decided that all ions of a desired energy would be decelerated to 50 eV before entering the hemispherical segment. This task can best be accomplished by a cylindrical electrostatic lens system. Not only can it decelerate the ions, but it can also focus the beam to an image point on the entrance aperture of the hemispheres. Three coaxial cylinders are biased at different potentials. As an ion passes down the axis, it will be decelerated if the final potential it sees is higher than the potential at which it was initially accelerated. Two cylinders could sufficiently decelerate and focus an ion beam, but for a two-cylinder lens, the position of focus varies with the energy. Three lenses are required to fix the image point while varying the deceleration potential. This device is similar to an Einzel lens, which is a three-cylinder lens that maintains its first and third cylinders at the accelerating potential, thus focusing a beam of charged particles without accelerating or decelerating it. An Einzel lens is used after the hemispherical segment to focus the beam into the quadrupole spectrometer. The properties of electrostatic lenses have been worked out in the past, most notably by Harting and Read [4], who did numerical analyses of several kinds of lenses to be used for electron beams. The modeling of the electrostatic lens was extended for the present study through an analysis of the undertaken with the ion simulation software Simion. Using this program, it was shown that an xenon ion beam that varies in energy from 50 to 650 eV could be appropriately decelerated and focused to the necessary 2 degrees if the lens has the dimensions described earlier.

The Quadrupole Charge Spectrometer

As previously mentioned, the hemispherical selector only has the capability to separate ions in terms of their energy/charge ratio. Thus, this device alone cannot provide a complete picture of the energy distribution in an ion beam since ions carrying multiple charges will appear to have different energies than they actually do. In general, the production of higher charge states represents an inefficiency in thruster performance. Being able to distinguish between these states is therefore an important feature for the analyzer. It was therefore decided that an electrodynamic quadrupole spectrometer segment should be added to the hemispherical analyzer. Such a device is normally used as a mass spectrometer for measurement of a purely singly ionized ion beam. However, since it works to separate out ions in terms of the charge/mass ratio, it could just as well be used on a monoelemental beam with varying charge states as a sort of 'charge spectrometer'.

Four cylindrical electrodes were arranged with two in each of two perpendicular planes (Figure 3). The time varying voltage across opposite electrodes takes the form of a direct voltage U with a sinusoidal voltage of peak amplitude V and frequency f. That is:

$$\begin{aligned}\Phi_x(t) &= U \quad Vsin(2\pi ft)\\ \Phi_y(t) &= U + Vsin(2\pi ft)\end{aligned}$$

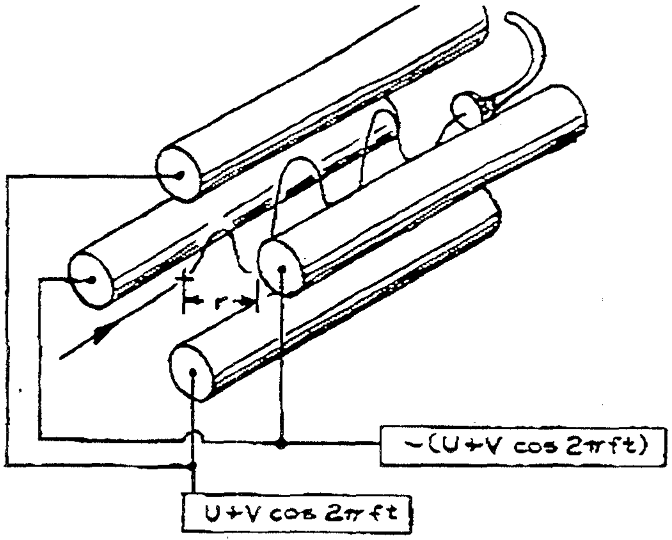

Figure 2: The quadrupole spectrometer

As an ion enters the quadrupole region, it oscillates according to the electric field. Most of the time, that oscillation is unstable and the amplitude quickly increases. Thus the particles will be removed from the spectrometer if allowed to stay in the field for a few cycles. However, for each voltage U, there is a specific mass/charge ratio for which an ion will assume a stable oscillation and maintain its amplitude. These particles will traverse the distance of the spectrometer and be collected at the end. Thus, by varying U one can measure the beam current corresponding to ions of a given charge state.

The most important consideration in designing a quadrupole spectrometer is the resolution. Since the determining factor in whether or not an unwanted particle will be removed is the number of cycles it spends in the field, the resolution is a function of the length L, frequency f, and initial kinetic energy V_z. The resolution is [5]:

$$\frac{\Delta m}{q} = \frac{40V_z}{f^2L^2}$$

The quadrupole described above has the ability to distinguish between singly, doubly, triply, and quadruply charged ions of xenon at an injection energy of 50 eV.

Results and Conclusions

The hemispherical segment was calibrated using an ion thruster that produced a relatively monoenergetic

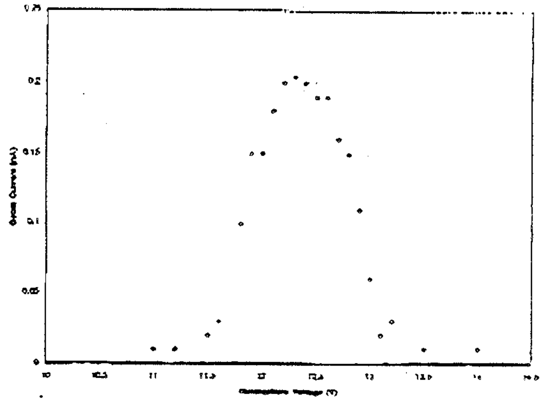

Figure 3: Hemispherical selector scan of monoenergetic ion beam

ion beam of relatively well-known energy. Since the energy of the ion plume was not known to within the theoretical resolution of the analyzer, a calibration technique was used which assumed a well-characterized deceleration stage and a linear relationship between the voltage across the hemispheres and the energy of an ion that was allowed to pass. Figure 4 is a sample plot of the data taken from one of the calibration tests. In this test, the voltage across the spheres was varied while the lens decelerated the ions by a fixed amount. The ion thruster was estimated to produce an ion beam of about 300 eV which corresponded to a theoretical voltage across the spheres of 12.3 V. It is difficult to accurately determine the resolution of the hemispheres using this kind of experiment since the ion thruster itself does not produce a completely monoenergetic beam.

As of the writing of this paper, the complete analyzer system with the quadrupole spectrometer intact has not been tested. Upon completion of the calibration and testing of the spectrometer segment, the analyzer should be ready to take energy measurements of a Hall thruster or similar electromagnetic accelerator.

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