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Technique for increasing dynamic range of space-borne ion composition instruments

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The dynamic range of ion composition spectrometers is limited by several factors, including saturation of particle counters and spillover of signals from highly dominant species into channels tuned to minor species. Instruments designed for composition measurements of hot plasmas in space can suffer greatly from both of these problems because of the wide energy range required and the wide disparity in fluxes encountered in various regions of interest. In order to detect minor ions in regions of very weak fluxes, geometry factors need to be as large as possible within the mass and volume resources available. As a result, problems with saturation by the dominant fluxes and spillover to minor-ion channels in plasma regions with intense fluxes become especially acute. This article reports on a technique for solving the dynamic-range problem in the few eV to several keV energy/charge range that is of central importance for space physics research where the dominant ion is of low mass/charge (typically H^+), and the minor ions are of higher mass/charge (typically O^+). The technique involves employing a radio-frequency modulation of the deflection electric field in the back section of an electrostatic analyzer in a time-of-flight instrument. This technique is shown to reduce H^+ counts by a controllable amount of up to factors of 1000 while reducing O^+ counts by only a few percent that can be calibrated. © *2005 American Institute of Physics.*
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I. INTRODUCTION

Hot plasmas resident in the magnetospheres of the Earth and other planets present a challenging target for space-borne particle detectors and particularly for ion composition instruments. These plasmas have source regions both in the solar wind and in planetary ionospheres, so there is typically a mixture of ions such as hydrogen, helium, oxygen, nitrogen, and other minor species with density ratios that are in some cases very different. As shown in Fig. 1, the proton fluxes are often extremely high while in the same part of the Earth's magnetosphere important minor ions will have fluxes of only a few percent of the proton flux. Because of thermalization by the bow shocks, which slow the solar wind in front of the magnetospheres, and wave turbulence within the magnetospheres, the ion distribution function covers a wide energy range with significant flux at all angles within the field of view.

Two major problems limit the dynamic range that can be achieved by space-borne ion composition instruments. The first is simply the requirement for very high counting rates that result when an instrument that is sensitive enough to detect minor species in a tenuous plasma region must also measure major species in a more intense flux region. This problem results in flux pileup or saturation in the detectors. The addition of a second analyzer to handle the higher fluxes is generally prohibited by available resources such as mass, volume, and power.

The second problem is the spillover from dense major species into channels tuned to minor species. In a time-of-flight (TOF) velocity analyzer this problem results from the occurrence of uncorrelated start and stop signals, generating a background rate that grows quadratically with the rate of the majority species. In addition to its occurrence in TOF systems, this problem will occur in any instrument using a coincidence technique.

Present-day composition instruments have been unable to measure minor-ion species such as O^+ unambiguously at the Earth's magnetopause—the boundary between the magnetosphere and the solar wind—because of high background levels caused by instrumental spillover effects from the intense and dominant proton fluxes. Specifically, this effect has precluded any meaningful TOF-based ion composition measurements at energies in the important keV ranged at the Earth's magnetopause.[1,2] To overcome this problem, we have developed a type of plasma composition instrument that can reduce the H^+ flux to extremely low levels while keeping the O^+ flux nearly unaffected.

II. CONCEPT

The technique reported here involves the incorporation of a radio-frequency (rf) deflection voltage in the exit segment of a toroidal tophat electrostatic analyzer (ESA). The technique will work equally well with other analyzer geometries (such as parallel-plate and spherical). As will be shown, the rf deflection voltage provides a low-pass velocity filter for incoming ions. Because the ion populations in the space environment often have broad energy distributions, for effective operation it is necessary to perform an energy pre-

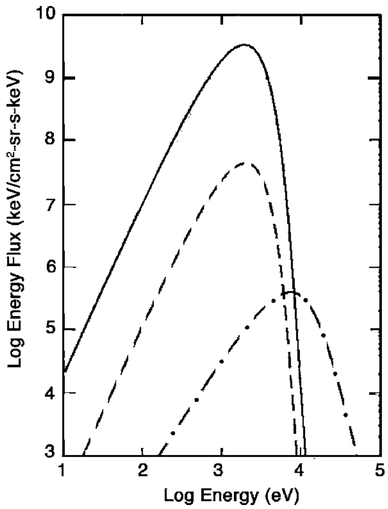

FIG. 1. Representative ion fluxes that are encountered in the Earth's magnetosphere. The H^+ fluxes (solid line) are typical for the dayside boundary region (the magnetopause) with density of $80\ \mathrm{cm}^{-3}$ and bulk flow of 400 km/s. The O^+ fluxes (dashed line) are modeled after the beams observed in the low latitude boundary layer (Ref. 6), which lies just inside the magnetopause. The magnetotail fluxes (dash-dot line) are modeled after plasma sheet encounters (Ref. 7), including the O^+ composition representative of disturbed magnetospheric conditions.

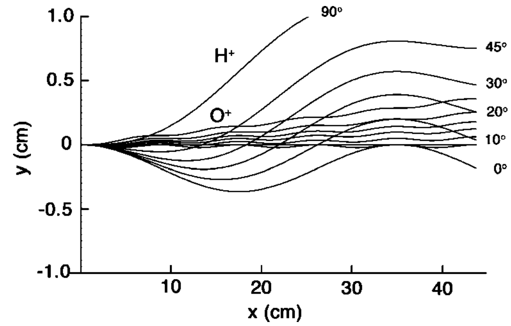

FIG. 2. Plot of the calculated path of H^+ and O^+ ions with energies/charge of 1 keV through a parallel-plate analyzer segment with no dc voltage applied but with a peak 5 MHz rf voltage of 150 V across a 4 mm analyzer gap. The phases of the rf voltage when the ions enter the analyzer are noted on the H^+ curves.

filtering using a dc deflection voltage applied to the entrance segment of the analyzer. The same dc deflection voltage is applied to the exit segment of the analyzer, but an additional rf voltage is superposed on it.

Light, fast-moving ions such as hydrogen will strike the deflection plates in a time short compared to the rf period of the deflection voltage. Slower-moving heavy ions such as oxygen will, for the most part, remain within the deflection plates during a rf period. Thus, the analyzer acts as a high-pass mass/charge (or equivalently, a low-pass velocity) filter. By varying the frequency and magnitude of the rf deflection voltage, the filtering can cover a fairly wide range of energies and can be tuned to transmit known fractions of ions at all masses. In this way it solves both of the dynamic-range problems (count saturation and major species spillover) mentioned above.

To illustrate the technique further, consider the effect of a peak rf voltage V_0 at frequency f applied across a deflection gap Δy in a parallel-plate analyzer, in which the dc applied deflection voltage is zero. The deflection from the central plane of the analyzer as a function of time is given by

$$y(t) = \int_0^t \left[\int_0^t a(t)dt \right] dt$$

$$= \int_0^t \left[\int_0^t \frac{qV_0}{2m\Delta y} \cos(\omega t + \theta) dt \right] dt \tag{1}$$

$$= \frac{qV_0}{2m\Delta y} \left[\frac{-\cos\theta + \omega t \sin\theta - \cos(\omega t + \theta)}{\omega^2} \right]. \tag{2}$$

Because of the difference in velocity between light and heavy ions with the same energy/charge (E), it is more relevant to examine the dependence of the deflection (y) from the central plane of the analyzer on the distance down the segment of the analyzer that has the rf voltage applied. Since $v_x = \sqrt{2E/m}$ is constant, we can substitute $t = x/v_x$ in Eq. (2). The result is displayed in Fig. 2, which shows plots of y as a function of distance (x) for H^+ and O^+ with equal energies/charge of 1 keV for the following selected analyzer parameters: $V_0 = 150$ V, $\Delta y = 4$ mm, and $f = \omega/2\pi = 5$ MHz. As shown in Fig. 2, the path of the ions through the analyzer depends on the phase of the rf deflection voltage at $t=0$. This effect is illustrated for phase angles between 0° and 90°, the results of which are representative of the full range of angles. It is evident from Fig. 2 that for most phase angles the H^+ ions will be deflected into the plates while the O^+ ions will not. Eventually, of course, the O^+ ions will also strike the plates if they are too long.

The actual performance, particularly of a curved-plate analyzer, is best evaluated by numerical simulations, as shown in Sec. III.

III. IMPLEMENTATION

Since their initial suggestion,[3] rf velocity filters have been used extensively for mass spectrometry applications, especially in quadrupoles. Typically these filters are employed for mass focusing of monoenergetic and highly directional beams. In the present context the rf field is used as a high-pass mass/charge filter within an electrostatic analyzer/TOF system designed to measure three-dimensional composition-resolved distribution functions of hot plasmas in space.

The specific electrostatic analyzer used is a variation on the original tophat analyzer.[4] Instead of spherically symmetric deflection plates, the analyzer has a toroidal geometry, which has been shown to be somewhat more efficient by volume but more importantly to have focusing characteristics that are better suited to coupling with TOF mass-analyzer systems.[5]

A drawing of the analyzer is shown in Fig. 3, which shows a planar section of a toroidal tophat analyzer with deflection plates that are divided into an entrance region and an exit region. The deflection-plate gap of 4.1 mm is constant throughout the analyzer. The entrance region, which contains a dc deflection electric field, serves to present a nearly monoenergetic beam ($\Delta E/E \sim 0.2$) to the exit region,

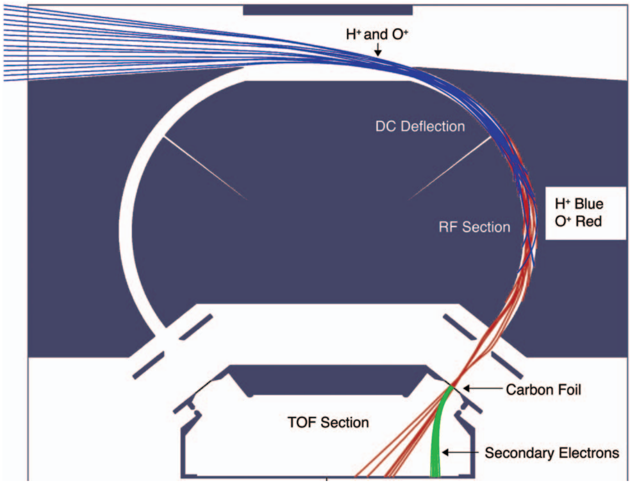

FIG. 3. (Color) Results of ray tracing using the SIMION program of a toroidal tophat electrostatic analyzer (Ref. 5) with a time-of-flight (TOF) mass analyzer. H^+ and O^+ ions at an energy/charge of 1 keV fill the field of view of the analyzer, which has a dc potential difference of 189 V across the deflection plates, which have a gap of 4.1 mm. In the rf section a 5 MHz, 150 V signal is added to the dc deflection potential. In the rf section the O^+ ions (shown in red) are transmitted by the analyzer and enter the TOF section, while the H^+ ions are almost completely absorbed by the deflection plates.

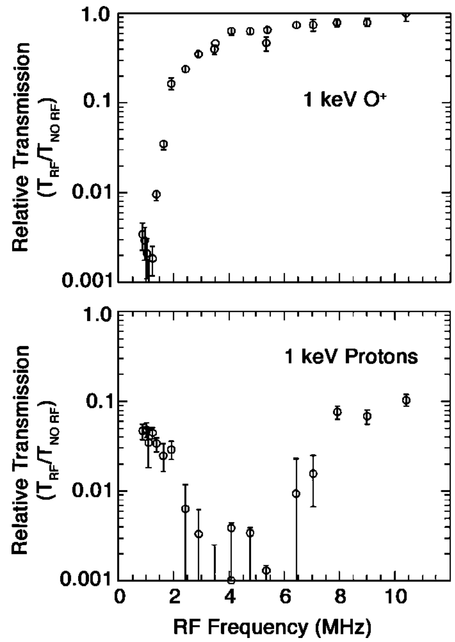

FIG. 4. Results of the laboratory test showing relative transmission of oxygen ions and protons as a function of applied rf.

which contains a rf-modulated deflection electric field. As discussed in Sec. II, the rf is chosen so that a heavy ion will undergo many cycles of low-amplitude spatial oscillation as it traverses the deflection plates while lighter ions will undergo a much smaller number of higher-amplitude oscillations along their paths (see Fig. 2). The result is a relatively high transmission of heavy ions (e.g., O^+) and a successively lower transmission as the ion mass decreases and the ions begin to strike the deflection plates.

Ray-tracing results obtained with the SIMION program are shown in Fig. 3. A uniform mixture of H^+ and O^+ ions enters the tophat from the left and is deflected into the entrance region of the ESA by the dc field. They then travel into the exit region where rf is applied. For the deflection voltage and rf used, the H^+ ions are seen to be totally absorbed by the analyzer plates, while the O^+ ions exhibit a high transmission fraction. By varying the rf and voltage, the filtering can be optimized for certain combinations of ions at various energies. For a fairly narrow energy range, such as that for H^+ at the Earth's magnetopause, a single frequency rf deflection voltage is sufficient to allow accurate O^+ measurements while reducing the H^+ count rate to a known and manageable level.

IV. VERIFICATION

The ray-tracing results were verified in the laboratory using a prototype toroidal tophat unit. Figure 4 shows the relative transmission of 1 keV singly-charged oxygen ions and protons as a function of applied rf as obtained in the laboratory tests. The optimum response is seen to be at about 5 MHz, where the proton counts are reduced by nearly three orders of magnitude while the O^+ counts are reduced by only about 25% as compared to the response with only dc deflection voltage applied.

Figure 5 shows laboratory data from an improved prototype showing reduction of 1 keV proton transmission as a function of rf peak-to-peak voltage at a frequency of 5 MHz. Figure 5 shows again the 1000-fold reduction in proton throughput that is possible and also shows how the throughput can be regulated to intermediate values.

V. DISCUSSION

A long-standing problem in space physics has been the spillover of major-ion signals in TOF mass analyzers resulting in serious contamination of minor-ion signals. In important regions near magnetospheric boundaries the problem is so severe that no meaningful composition measurements have been feasible in the important keV energy range. Previous attempts to solve this dynamic-range problem have involved mechanical constrictions that reduce the throughput

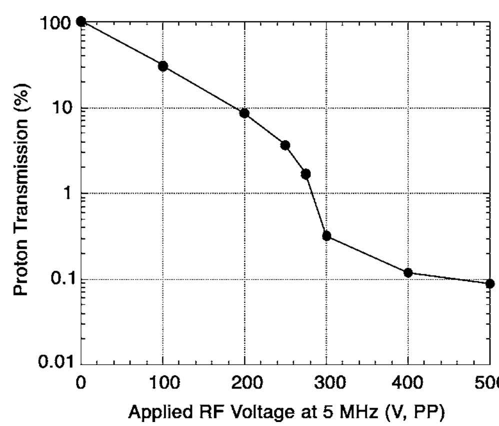

FIG. 5. Results of the laboratory test showing transmission factor of protons as a function of the peak-to-peak voltage of the rf deflection potential.

equally for all species, which can help the saturation and spillover problems, but reduce the minor-ion throughput to levels that are often undetectable.

A satisfactory solution requires the controllable reduction of major-ion throughput with little or no reduction in minor-ion throughput. The rf technique described here satisfies this requirement for the case in which the major ion is significantly lower in mass than the important minor ions. We anticipate that the basic approach can be tailored for effective use in many space and laboratory plasma environments.

ACKNOWLEDGMENTS

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