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Transverse ion acceleration and ion conic formation in a divergent-field laboratory plasma

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The results of laboratory experiments at the University of California at Irvine are presented in which multidimensional ion velocity distributions in the presence of radio-frequency (RF) waves and a spatially divergent external magnetic field are observed. A plasma volume is subjected to either local or nonlocal electrostatic turbulence, which in turn is responsible for accelerating the ions transverse to the confining magnetic field. The ions flow away from the source of turbulence in a spatially decreasing magnetic field, where the $\mu \nabla B$ force and magnetic-moment conservation work to distort the heated distribution. Laser-induced-fluorescence (LIF) signals, measured downstream from the plasma source with the aid of optical tomography techniques, reveal substantial ion heating and conic formation. © 1995 American Institute of Physics.

I. INTRODUCTION

An ongoing theme in basic plasma research is the simulation or modeling of space-related phenomena in a laboratory plasma device. Such research is useful for many reasons. Specifically, laboratory models may be used to bridge the often sizable gap between the theoretical interpretation of an effect, and the ability of a space satellite to measure the effect adequately in an environment that is often subject to constantly changing or nonrepeatable conditions. Among countless examples, laboratory experiments have been used to model auroral hiss,¹ large-amplitude electrostatic ion cyclotron (EIC) waves in conjunction with auroral arcs,² lower hybrid ion acceleration processes,³ double layers,^{4,5} and ion upwelling in a divergent magnetic field.^{6,7} More recently, experimental measurements of energy-density-driven instabilities⁸ may have new implications for ion acceleration processes in the low-altitude ionosphere.⁹

In the present work we consider specifically the evolution of plasma velocity distributions consisting of charges born in the upper atmosphere that are accelerated predominantly transverse to the magnetic field, and flow upward toward the ionosphere and beyond. These distributions are known generically as “ion conics,” which are velocity-space distribution functions that have a nonzero velocity pitch angle other than normal to the confining magnetic field. A surface of constant ion flux for this distribution takes on the general shape of a cone in velocity space whose vertex points along the magnetic field axis in the direction of the acceleration region, hence its given name.

Since the first satellite observation of ion conics,¹⁰ several mechanisms for their initial discovery have been proposed. In most models a low-temperature (~ 1 eV) ion plasma is accelerated normal to the geomagnetic field by any of a number of possible heating mechanisms, followed by an adiabatic upwelling of the heated distribution as it moves

into regions of weaker magnetic field, where the charge motion perpendicular to the field is slowed by conservation of magnetic moment, and the charges are accelerated in the direction of the field by the $\mu \nabla B$ force. The ion heating and upwelling (often called “folding”) of the distribution may often occur in tandem, i.e. the constituent charges must find a middle ground between the separate demands of the wave field and the magnetic confinement. Other mechanisms have also been suggested as alternatives to conventional adiabatic folding, such as interaction with double layers¹¹ and velocity-filter mechanisms.¹² Several ion heating mechanisms have been proposed, such as electrostatic ion cyclotron (EIC) waves,^{13,14} lower hybrid waves,¹⁵ electromagnetic ion cyclotron (EMIC) waves,¹⁶ large-amplitude EIC waves,¹⁷ stochastic acceleration,¹⁸ double-cyclotron absorption,¹⁹ and velocity-shear waves.²⁰ Some recent sounding-rocket observations²¹ in the topside auroral ionosphere cite an extremely strong “cause-and-effect” relation between transverse ion acceleration and “spikelets,” which are believed to be localized regions of intense lower hybrid turbulence. Prior satellite and rocket measurements have only been able to show simultaneity between electrostatic waves and energetic ion populations.

While the proposed ion conic formation mechanism of perpendicular heating and adiabatic upwelling of the plasma along auroral field lines is by far the most popular, it is difficult to demonstrate conclusively by satellite measurements. The reason is that magnetospheric conics are sufficiently localized spatially that the satellite can only measure the distribution on time scales much shorter than the evolution time of the conic. While multiple satellite measurements have shown the trend of increasing pitch angle with increasing altitude,^{22,23} those trends are inconsistent with adiabatic theory, most likely since wave-particle interaction may occur anywhere along the path of the upflowing plasma.

Previous laboratory studies related to this work have shed considerable light on the subjects of wave propagation and/or ion evolution in a nonuniform B field, in particular, those at Tohoku University,⁷ and the University of Iowa.^{4-6,24} Hatakeyama *et al.*⁷ measured ion energy distribution functions of an unheated plasma parallel to a divergent

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field and found deformations in the distributions that were discussed in the context of a simple adiabatic plasma model. Of particular interest are the results of Cartier *et al.*,²⁴ who measured ion temperatures perpendicular and parallel to a nonuniform magnetic field, when the plasma was subjected to narrow-band EIC waves. In the case of approximately fixed input power to the plasma, they established that the heated ions transfer their energy from perpendicular motion to parallel motion, in quantitative agreement with a straightforward theoretical model, which accounts for conservation of magnetic moment and energy of the constituent plasma ions.

In this paper we report recent laboratory measurements of ion conics in a Q-machine plasma. The conics are obtained in a manner consistent with the earlier discussion of the most likely process of conic evolution in space. Ions are heated by electrostatic waves nearest the plasma source, in regions of maximum magnetic field, and the plasma flows into regions of a smaller magnetic field. Laser-induced fluorescence (LIF)²⁵ and optical tomography^{26,27} measurements in the small-field region were used to obtain the plasma distribution function. The results shown in this paper build on the previous research discussed above as follows.

- (1) The complete two-dimensional structure of the plasma is measured. This is particularly important for identifying ion conics, as the angle of preferred velocity pitch (hereafter referred to as the "cone angle") may not be determined from a single measurement of the distribution either perpendicular or parallel to the magnetic field.
- (2) In one set of measurements, the absorbed power by the plasma is varied for a fixed magnetic field ratio. This has the added benefit of measuring a variety of possible distribution characteristics over a fixed flux tube, including cone angle and axial drift.

II. EXPERIMENTAL ARRANGEMENT

A. Plasma source and magnetic field geometry

The experiments described here were performed in a divergent-field plasma device, with the magnet coils at the plasma source set at higher current than the coils at the opposite end of the machine. This provided magnetic field geometries that were divergent, rather than mirror, in configuration; typical on-axis magnetic field configurations are shown in Fig. 1. The peak field near the plasma source was fixed at about 4.3 kG, while the field in the region of the optical diagnostics was varied between 0.85 and 2.7 kG. This gives a ratio between the magnetic field at the source compared to the field at the optical detection (denoted R_m , the magnetic field ratio) a range from 1.6 to 5.0. The plasma in the experiments was produced by contact ionization of barium metal on a tungsten hot plate. Barium was chosen for its ease of ionization and its useful optical properties. The source is similar to the usual Q-machine source,^{28,29} either modified by an annular oven³⁰ surrounding the hot plate or a traditional stainless steel oven mounted to the machine. Once ionized, the barium flows along magnetic field lines and terminates at the cold, electrically floating endplate, approxi-

FIG. 1. Plots of an on-axis magnetic field as a function of axial distance. The plasma source is located at approximately 0 cm and the optical tomography diagnostic is located at approximately 105 cm.

mately 150 cm from the plasma source. When radio-frequency (RF) excitation was desired, a dielectrically shielded eight-ring antenna³¹ placed approximately 30 cm from the hot plate, and aligned coaxially with the plasma column, was used. Broadband electrostatic ion-cyclotron (EIC) waves were generated by parametric decay of lower hybrid waves³² that were launched by a 30 MHz signal from the antenna. The EIC waves were used to heat the plasma ions perpendicular to the local magnetic field. To obtain time-evolution characteristics of heated plasmas, and to avoid measuring artificial temperature enhancements due to the presence of the wave field, the power to the antenna was pulsed for the duration of an ion transit time (approximately 900 μ s), and the distribution function was sampled with a boxcar averager and gated integrator assembly triggered to view the plasma distribution immediately after the antenna was turned off.

A variety of plasma diagnostics was used to obtain relevant information about plasma characteristics. Ion density, electron temperature, and radial density profiles were inferred from movable Langmuir-probe measurements made downstream from the antenna. Wavelength and frequency spectra were observed with RF probes placed in proximity of the antenna. Because of the broadband nature of the low-frequency wave response, the conventional method of measuring wavelengths by an interferogram was not possible; thus wave-spectral information was obtained by digitally sampling the frequency response of two probes placed at various relative radial separations, then cross-correlating the data.³³ Ion-velocity distribution, temperature, and drift measurements were taken using laser-induced-fluorescence (LIF)^{25,34} techniques. Typical measured plasma parameters at the source were as follows: $n_i \approx n_e \approx 5 \times 10^8 - 8.0 \times 10^9 \text{ cm}^{-3}$, $T_i \approx T_e \approx 0.2 \text{ eV}$. Figure 2 shows the arrangement of the source, antenna, and diagnostics in more detail.

B. Laser-induced fluorescence and optical tomography

Laser-induced fluorescence (LIF)^{25,34,35} is used in the laboratory to measure velocity distribution functions in one

FIG. 2. Diagram of the experimental arrangement. The plasma spreads radially as a function of distance from the source due to the decrease in magnetic field from plasma source to observation site.

dimension. A narrow-band ($\delta\omega < 1$ MHz) laser beam introduced into the plasma may excite atomic transitions of the constituent ions. For an ion moving with velocity $\mathbf{v}_i$ and electronic transition frequency ω_0 , excitation and fluorescence will occur when

$$\omega_l - \mathbf{k}_l \cdot \mathbf{v}_i = \omega_0, \quad (1)$$

where ω_l , $\mathbf{k}_l$ are the frequency and wave number of the laser, respectively. The fluorescent photon flux (which is measured by a collection-optics array and photomultiplier tube mounted outside of the plasma device) is proportional to the number of ions at that velocity (within the bandwidth of the laser). By sweeping out the appropriate range of laser frequencies, one obtains the one-dimensional velocity distribution $f(v)$ for ions with a velocity component in the direction of the laser-beam propagation.

The optical tomography diagnostic^{26,27} is based on the principle that one may think of the distribution obtained by a laser scan as the line integral of the full velocity distribution, i.e. $f(v_x, v_z)$ is integrated over the velocity component(s) orthogonal to $\mathbf{k}_l$ to obtain $f(v_\theta)$, where θ represents the angle between the laser direction and the x axis, defined as the direction normal to the magnetic field. Expressing this result mathematically yields $f(v_\theta)$ as a velocity-space "projection" of the distribution $f(v_x, v_z)$:

$$f(v_\theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(v_x, v_z) \times \delta(v_x \cos \theta + v_z \sin \theta - v_\theta) dv_x dv_z. \quad (2)$$

From a collection of line integrals, one may invoke the reverse process, known as filtered back-projection, to obtain the complete distribution,

$$f(v_x, v_z) = \int_0^\pi \int_{-\infty}^{\infty} h(v_\theta) \times \delta(v_x \cos \theta + v_z \sin \theta - v_\theta) dv_\theta d\theta, \quad (3)$$

where $h(v_\theta)$ is a one-dimensional velocity distribution convolved with a filter function designed to compensate for "smearing" of the higher velocity-space Fourier harmonics, a natural effect of conventional back-projection.³⁶

III. EXPERIMENTAL RESULTS

A. Wave propagation measurements

In principle, one may choose from a variety of wave-generation methods, including direct launching, unstable excitation driven by a current drawn from a biased button,³⁷⁻³⁹ or parametric decay.^{32,40} The first technique requires considerable input power since the antenna coupling to the plasma is extremely poor. The second technique generates an extremely narrow-band signal. It is preferred that a broadband signal be generated when modeling space plasmas, as satellite observations of energetic ion distributions are often observed in tandem with a broadband frequency spectrum. Further, the biased button generates an "uphill" electrostatic potential,² which slows the entire ion distribution down; the structure of the potential hill has the effect of decelerating small-gyroradius ions more than large-gyroradius ions, causing a stretching of the velocity contours into a conical shape,⁴¹ even when the magnetic field is uniform. This is an important consideration if one wants to isolate the causes for laboratory conic formation to the presence of the divergent magnetic field. Note also that supauroral plasmas are often observed by satellites to have electric fields that point away from the Earth's poles; if anything, this would accelerate, rather than decelerate, a plasma from its lower-altitude origin.

Thus, it was decided to use parametric decay techniques for generating low-frequency electrostatic turbulence. The details of similar measurements at Irvine have been documented previously,^{32,40} so we only highlight the important points here.

Figure 3 is a graph of wave amplitude versus detected frequency for both the pump signal and decay signal, for a typical nonuniform magnetic field configuration. The center pump frequency is 30 MHz and is shown off scale to emphasize the daughter lower hybrid waves approximately ± 50 kHz away from the pump frequency. The second sidebands, at ± 100 kHz begin to appear just beyond the measurement range. The decay frequency is also at 50 kHz, and three harmonics are shown here. The number of harmonics ranged from one at amplitudes near the decay threshold⁴² to five for large amplitudes. Ratios of the EIC frequency to the gyro-frequency (ω/ω_{ci}) ranged between 1.15 and 1.5.

For most of the measurements, the frequency bandwidth was on the order of 10 kHz, or roughly 20%, of the frequency of the first harmonic. Moreover, attempts to correlate digitally the RF probe response proved futile after approximately one-half wavelength. Given these two points, it was reasonable to conclude that the spectrum was weakly turbulent. However, phase information could still be obtained numerically within the measurable correlation length, and a wave number inferred. The phase information, coupled with estimates for a typical gyroradius, placed values of $k_\perp \rho_i$ for several measurements between 1.1 and 1.4. Porkolab⁴³ pre-

FIG. 3. Graph of typical RF probe spectral response for parametric decay of lower hybrid waves. Top graph: pump-signal band, centered at 30 MHz. Only the first sideband is shown. Bottom graph: decay response, band centered at 0 kHz. The first three sidebands of the decay wave are shown, the third (at about 140 kHz) being only slightly above background on a linear scale.

dicts $k_{\perp} \rho_i$ to be approximately 1.23, which reflects the value for which the growth rate of the cyclotron mode in parametric decay is maximized.

B. Background parameters

Because it is possible for conics to exist in the ionosphere without the need for the nonuniform field,¹¹ and also because conics have been observed in the laboratory where the field is uniform,⁴¹ it is important to know whether such possibilities exist in this experiment. In order to establish a causal relationship between the final plasma distributions and the combination of ion heating and evolution in a nonuniform field, we must first examine circumstances in which this causality does not exist.

1. Ion dynamics of a quiet plasma in a nonuniform field

First we address empirically the motion of the plasma in the absence of an external power source that could energize ions. There are two objectives to this measurement. First, it should be shown that the plasma flow is adiabatic, i.e., we want to show that the magnetic moment (manifested as plasma magnetization for the measurement) does not vary with the magnetic field ratio between the source and detector. Second, it is necessary to establish whether or not the total energy of the distribution is conserved, and to consider the possible implications for laboratory conics should the ion energy change with changing magnetic field ratio. One ex-

FIG. 4. Graphs of plasma properties as a function of magnetic field ratio R_m . Top graph: (a) $T_{\perp}$ vs R_m ; bottom graph: (b) $T_{\parallel}$ vs R_m .

pects, in principle, that the total energy of the distribution should not change, since magnetic forces do no work on a plasma.

The following measurements were performed under conditions similar to the experimental arrangement shown in Fig. 2. The plasma density was low ($<10^{-9} \text{ cm}^{-3}$) to limit effects due to Coulomb collisions, and there was no external RF power source. The magnetic field was varied to establish a range of magnetic field ratios between 0.8 and 14. In all but a few cases the field at the detection site was less than the field at the source. In order to consider the effects of plasma acceleration due to variation in downstream potential, floating potential measurements were made at both the center of the plasma (between the antenna and optical detection) and at the endplate.

Figure 4(a) is a plot of perpendicular ion temperature versus magnetic field ratio. As the field ratio increases, the temperature decreases in a manner consistent with conservation of the magnetic moment. The line is a curve fit that assumes an inverse field-ratio relationship with temperature, i.e.,

$$T_{\perp} = \frac{T_0}{R_m}, \quad (4)$$

where R_m is the magnetic field ratio and where T_0 is optimized to fit the data. The best-fit curve for this data dictates that $T_0 = 0.21 \text{ eV}$, which is well within the experimental reproducibility of our expected temperature of 0.2 eV. While the appearance of a systematically higher temperature at larger magnetic field ratios suggests a nonadiabatic regime,

FIG. 5. Drift energy (a) and total energy (b) of the plasma plotted against the magnetic field ratio.

such circumstances are well beyond the range of magnetic field ratios used in the conic-formation portion of the experiment.

The parallel temperature is plotted in Fig. 4(b) as a function of magnetic field ratio. The downward trend in temperature with field ratio is the expected result, as the $\mu \nabla B$ force acting to accelerate charges axially should also generate an axial cooling, i.e., the axial velocity difference between any two charges is smaller when both are subject to the same acceleration, provided the effects of $\mu \nabla B$ acceleration are low. The larger error bars in these data are due principally to a reduced fluorescent photon flux when the laser is pointed toward the hot plate.

Figures 5(a) and 5(b) show the drift energy and the total energy of the plasma distribution, respectively. The drift energy is determined by squaring the average (peak) drift velocity, converted to units of electron volts. The drift energy rises with increasing field ratio, its rate of rise decreasing with increasing R_m . This is the expected result, since the drift energy of the distribution is increased at the expense of thermal (both perpendicular and parallel) energy; thus the asymptotic limit of drift energy can be obtained only at the expense of all of the perpendicular motion of the ions. As the field ratio increases, perpendicular motion must be surrendered to parallel motion (the magnetic field cannot be a source of free energy for the plasma), so that the drift increases.

In the absence of an external free energy source, the plasma distribution should conserve energy, regardless of the structure of the magnetic field. Figure 5(b) shows that, for our experimental arrangement, this is not the case; there is a slight increase in total energy over the range of measured magnetic field ratios. This is due most likely to a slight ob-

FIG. 6. Contour plot of heated velocity distribution function in the presence of a uniform magnetic field. Each contour is a fraction of the maximum value of f , decreasing in 11% intervals, down to 11%. The stretching of contours in the direction perpendicular to the field is indicative of ion heating in that direction, specifically in the form of a wave-particle interaction.

servable change in electrostatic potential that tends to accelerate ions axially away from the source. This change in electrostatic potential may be due to plasma electrons having a greater net $\mu \nabla B$ acceleration than the ions, which would cause electrons to escape from the plasma column more quickly than the ions. To counteract the charge imbalance, and to help maintain plasma quasineutrality, a negative electrostatic potential would be set up. One might expect the effect to be augmented for lower source densities, where the plasma tends to operate as "electron rich." Potential drops along a divergent magnetic field comparable in magnitude to the ones measured in this experiment (~ 0.2 V) have been reported by at least two different authors.^{7,24}

If we consider only the range of magnetic field ratios used to create and measure the ion conics ($1.6 < R_m < 5.0$), we see that the total energy increase with increasing R_m is no more than 0.2 eV (noting that the trend falls well within the repeatability of the measurement). This difference, though small relative to the energy of the background distribution, may influence some of the parameters of the more energetic ion conic, in particular, drift speed and total energy.

2. Observations of ion velocity distributions in a uniform magnetic field

Multidimensional distribution function measurements in a uniform magnetic field were done to ensure that unexpected anomalies in the plasma that would generate conics in a uniform field were absent. The experimental arrangement used for this series of measurements was similar to that in Fig. 2, with the exception that the magnetic field was uniform. The background plasma density was approximately 10^{10} cm^{-3} , and the magnetic field was 2.9 kG. EIC waves, formed by the parametric decay process discussed earlier, were used to heat the plasma perpendicular to the magnetic field.

Figure 6 shows the plasma distribution due to RF heating. The contours fall off in 11% intervals, starting at 88% of f_{max} , and decreasing to 11%. The stretching of the contours

in the direction perpendicular to the field is indicative of ion heating; there is a fourfold increase in $T_{\perp}$ over the unheated distribution; the heating in $T_{\parallel}$ is much less, approximately 25% of the original parallel temperature. The maximum stretch of the contours is directly perpendicular to the magnetic field (within the limits of the resolution of the reconstructed image), and there is no evidence of conic formation in the uniform magnetic field. We mention also that energization of the distribution appears predominantly to be a bulk heating process, one that gives the full velocity distribution a bi-Maxwellian shape. Any experimental evidence of Maxwellian "tails"³ was smaller than the observed hyperfine splitting of the distributions.

C. Laboratory generation of ion conics

Here we describe the generation of laboratory ion conics in the presence of EIC waves. The experimental setup is almost identical to that discussed in the previous section, except that the magnetic field is now nonuniform. Tomographic data were taken for a variety of magnetic field configurations and RF power levels.

1. Time evolution of a laboratory ion conic

The first series of distributions showing aspects of conic behavior are presented in Fig. 7. All three of the distributions were measured in the same divergent magnetic field (4.1 kG at the antenna and 1.1 kG at the optical detector). Figure 7(a) shows a distribution with no external RF power. There is no evidence of ion conic formation, since the velocity contours are not outlined in a triangular fashion.

Figure 7(b) is a velocity distribution heated initially by EIC waves at fixed input RF power, but measured 300 μ s after the power to the antenna is cut off. Here we see a very weak conic structure, and it is apparent that replenishment of the plasma with unheated source ions dominates the distribution's appearance, though comparing the distribution to Fig. 7(a), it is seen that some heated ions remain.

Figure 7(c) is a full ion conic, where the plasma ions sample the EIC waves for the full time of their transit from the plasma source to the optical detector. We can obtain the cone angle by specifying the angle of preferred velocity pitch relative to the point of maximum $f(v)$,

$$\alpha = \tan^{-1} \frac{v_{\perp}}{-(v_{\parallel} - v_{\parallel 0})}, \quad (5)$$

which is the angle between two lines whose intersection lies at the maximum $f(v)$ of the distribution, as exemplified by the two lines accompanying Fig. 7(c). In this experiment, conic angles range between 90° and 180°, consistent with conics that evolve in the Earth's northern hemisphere, in which the field direction points along its positive gradient; as an example, the conic shown in Fig. 7(c) is angled at about 122°.

2. Conic structure as a function of magnetic field profile

Next, we present several conics, all of which were heated with approximately the same amount of EIC wave power, but that arose in the different magnetic field configu-

FIG. 7. Observation of ion conic structure due to the presence of applied RF power in a nonuniform magnetic field. (a) shows the distribution for a plasma in the absence of external RF power. (b) is a plasma distribution measured 300 μ s after the RF power was turned off, and shows only a weak conic structure. (c) displays a full ion conic, measured immediately after turning off the pulsed RF power.

rations displayed in Fig. 1. These are shown in Figs. 8(a)–8(c). Several trends are evident. First, the perpendicular temperature increases as the field ratio approaches unity. Second, the drift speed increases slightly with increasing field ratio. Third, the cone angle increases (the distribution is more beam-like) as the magnetic field at the detection site decreases. Finally, as the magnetic field ratio between the an-

FIG. 8. Ion conic distributions for the magnetic field profiles described in Fig. 1 under conditions of fixed input power to the plasma. The magnetic field ratios from peak field to optical detection site for (a)–(c), respectively, are 4.9, 2.8, and 1.7.

tenna and the conic detection site approaches unity, we note that the lower percentile contours at the smallest axial velocities [i.e., the low velocity (v_z) cutoff] tend to broaden, making the appearance of the distribution less cone-like and more bowl-like (isotropic). There appears to be no particular trend in the magnitude of the low-energy cutoff with respect to the field; in fact, it appears that the cutoff is relatively constant. We note that most of the general trends in the dis-

FIG. 9. Conic parameters as a function of magnetic field. (a) $T_{\perp}$ and $T_{\parallel}$; (b) drift energy and total energy; (c) conic angle, estimated from visual evaluation of distribution contours.

tribution can be explained in the context of basic adiabatic particle motion; we discuss some of the trends more quantitatively below.

Let us consider several specific aspects of the conics shown in Fig. 8. We may reduce the parameters of interest to five quantities: parallel and perpendicular temperatures, axial drift energy, total energy (or energy density), and conic angle. While this selection does not provide a complete description of a given conic, it does give a quantitative basis for a physical description of the processes at work, and, if desired, one may use the parameters to quantify comparisons between theory (e.g., Monte Carlo models) and experiment.

Figure 9 shows various conic parameters as a function of magnetic field ratio. The top graph shows the parallel and perpendicular temperatures. There is no appreciable change in $T_{\parallel}$ with an increasing magnetic field ratio (within the repeatability of the measurements). Previous authors⁴⁴ have suggested that the parallel temperature of the distribution should experience a slight cooling due to the combined effects of $\mu \nabla B$ and electrostatic potential acceleration; the results for an unheated plasma in a divergent B field shown in Fig. 4(b) are consistent with this suggestion. There is a considerable increase in $T_{\perp}$ as the magnetic field ratio between the antenna and the optics decreases. That $T_{\perp}$ should increase as the field ratio approaches unity is reasonable, since the magnetic moment of the constituent charges is conserved. The temperature exhibits an approximate $1/R_m$ relationship, similar to the curves shown for magnetic moment conservation in Fig. 4. This suggests that, in this case, the evolution of the distribution may be a two-stage process, i.e.,

the plasma is heated locally near the antenna, then folds along a decreasing magnetic field, as opposed to a simultaneous heating/folding process.

Figure 9(b) shows a plot of drift energy and total energy varying with field ratio. The increase in drift energy is consistent with $\mu \nabla B$ acceleration of the distribution. The total energy is approximately constant within the repeatability of the measurement, though it is arguable that there may be a slight (0.1 eV) energy increase over the range of fields in which the conics were measured. However, one must be careful to acknowledge potential subtle differences in both in EIC wave propagation and electrostatic potential differences due to the magnetic field divergence. One may expect to see a small (perhaps 10%) ion energy increase with increasing field ratio, as shown in Fig. 5(b), but this is likely offset both by the higher ion density (lower electron free-energy density for axial acceleration of the ions), and a slightly longer axial range of EIC wave propagation for magnetic field configurations that are more uniform; this would result in more free energy being made available to the plasma.

Finally, Fig. 9(c) shows the conic angle as a function of field ratio. For the conics observed in this series of measurements, the angle of maximum flux ranged between 90° – 130° . In some cases, the angle changed slightly as a function of ion energy (or as a function of contour percentile that is a manifestation of the same thing), over as much as a nine degree range; in those cases we determined the conic angle from the outer two or three contours, since those contours most strongly manifested magnetic folding. Qualitatively, the trend of increasing conic angle with increasing field ratio is expected, since the greater axial motion and the smaller radial motion of the ions with increasing field ratio would tend to align the ions more with the direction of the magnetic field.

3. Variable-energy ion conics in a fixed nonuniform magnetic field

Now we consider the evolution of ion conics in a fixed nonuniform magnetic field subject to a variety of input RF power levels, as shown in Fig. 10. The general trends seen in the distributions resulting from *increasing* RF power are (1) an increase in perpendicular temperature; (2) an increase in axial drift; (3) a slight increase in parallel temperature; (4) greater flattening of the velocity contours in the low-energy cutoff, giving the distribution more of a “bowl-shaped” appearance; and (5) a decrease in velocity pitch. Figure 11 shows a plot of the variations of these plasma parameters as a function of modulated parametric decay input power. Figure 11(a) shows increasing perpendicular temperature versus input power; this is expected, since the greater the applied power, the greater the transverse acceleration. There is a slight increase in parallel temperature as well, approximately 30% over this range ($\sim 6\times$) of applied power. Ordinarily, one might expect the change in $T_{\parallel}$ to be relatively flat, since $\mu \nabla B$ acceleration and conversion of perpendicular to parallel energy do relatively little to adjust the parallel temperature appreciably. However, given the plasma density used in the experiment, it is likely that Coulomb collisions will tend to thermalize the distribution slightly toward a Maxwellian,

FIG. 10. Ion conic distributions for fixed magnetic field ratio and variable input power to the plasma. Modulated parametric decay input power for these data is -16 , -10 , and -8 dB m, from top to bottom.

and thus an increase in $T_{\perp}$ would result in a somewhat proportional increase in $T_{\parallel}$ as well. Figure 11(b) displays an increase in total distribution energy with increasing RF power and also an increase in drift energy. This is to be expected, since the bulk effect of having a larger magnetic moment for each ion (i.e., larger magnetization) is to have a larger overall $\mu \nabla B$ acceleration of the distribution.

Finally, we consider the evolution of the conic angle with energy (or energy density). Figure 11(c) shows a range

FIG. 11. Conic parameters as a function of input wave power. (a) $T_{\perp}$ and $T_{\parallel}$; (b) drift energy and total energy; (c) conic angle, estimated from visual evaluation of the contours.

of conic angles from 103° to 130° , decreasing monotonically with increasing input power. That this should occur is not immediately obvious, since one needs to consider the competing effects of increased $\mu \nabla B$ acceleration, which would tend to increase the cone angle (i.e., as the cone angle moves toward 180° , the distribution would appear to be more "beam" shaped), and the effects of increased perpendicular energy that would tend to decrease the cone angle.

Consider an ion with typical perpendicular speed and axial velocity close to the drift speed of the distribution; such a particle is a subset of the maximum ion flux, the region in the velocity distribution used to determine the angle of the conic. Prior to adiabatic upwelling of the ion, it has an initial perpendicular speed of $v_{\perp 0}$ and an initial axial speed of $v_{\parallel 0}$. At the small-field end, the velocity of the ion, based on conservation of magnetic moment and energy, is

$$v_{\perp f} = v_{\perp 0} / \sqrt{R_m}, \quad (6)$$

$$v_{\parallel f} = [v_{\parallel 0}^2 + v_{\perp 0}^2 (1 - 1/R_m)]^{1/2}. \quad (7)$$

Because $v_{\parallel 0}$ typically is considerably larger than $v_{\perp 0}$ in Eq. (7), the final axial speed will not be appreciably higher than the initial axial speed, even if the magnetic field ratio is large. However, the final perpendicular speed will decrease considerably (over a factor of 2 for a field ratio of 5.0). This means that for our expression for the cone angle equation (5), the numerator will increase proportionately more than the denominator with increasing energy, and therefore the

conic will tend toward angles closer to 90° with increasing energy as well. Our observation is consistent with this argument.

IV. SUMMARY

Ion conics have been observed time in a laboratory plasma in which the scaled-down experimental parameters model the processes believed to exist above the auroral oval. Ions heated near the plasma source by electrostatic turbulence flow into regions of spatially decreasing magnetic field, where downstream optical detection of the plasma reveals velocity distributions unambiguously conic in appearance. Specific conic parameters such as perpendicular and parallel temperature, drift speed, total energy, and preferred velocity angle (cone angle) change as a function of changing magnetic field profile and changing RF power applied to the plasma. These changes are consistent with expected variations based on energy and magnetic moment conservation.

The possibility of discussing further theoretical aspects of the results is beyond the scope of this paper. Monte Carlo models of the plasma evolution, using theoretical models in the spirit of previous authors,^{45,46} have been used to provide a useful comparison between theory and laboratory experiment. These will be the subject of another paper.

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