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Cross-Field Ion Transport and Heating Due to Parametric Decay of Lower Hybrid Waves

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Parametric decay of lower hybrid pump waves into daughter lower hybrid waves and electrostatic ion-cyclotron waves was observed above instability threshold power levels in a nearly hot-electron plasma. The ion velocity distribution function was measured in time and space by the nonperturbing techniques of laser-induced fluorescence and ion optical tagging. Significant ion heating, \( T_i \) up to \( 6T_e \), and cross-field transport were observed in the regime \( \omega_p \approx 12\omega_{pi} \).

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Many experiments that study the interaction of radio-frequency waves with plasmas are reaching power levels where the interaction of waves and particles can produce hot ions via nonlinear mechanisms. Previous works in the regime where the rf pump frequency lies between the ion and the electron cyclotron frequencies (e.g., ACT-1, Alcator A', ATC, Doublet II-A, H-1, JFT-2, PETULA, and WEGA) show evidence of the parametric decay instability. There is concern that nonlinear interactions, such as ponderomotive effects or parametric processes at the edge of plasmas, can reduce the amount of wave energy available to ions in the plasma core. On the other hand, parametric processes which occur in the plasma core may produce useful ion heating.

In this paper we present data showing significant changes in the ion distribution function in the presence of electrostatic ion-cyclotron waves driven parametrically by nearly electrostatic lower hybrid waves. In particular, using a recently developed nonperturbing laser diagnostic, we have been able to measure directly, for the first time, both the evolution of the ion distribution function, \( f_i(\mathbf{k}, \mathbf{v}, \omega, \ell) \), and the trajectories of tagged ions in the presence of parametric decay. Substantial ion perturbations occurred only above the instability threshold. Three distinct effects were observed: (i) ion temperatures increased by as much as a factor of 6, (ii) cross-field diffusion was enhanced well above collisional levels, and (iii) an asymmetric ion velocity tail developed 0.4 msec after instability onset.

For the regime \( \omega_{ci}, \omega_{pi} \ll \omega_0, \omega_2 \ll \omega_{pe} \ll \omega_{ci} \), where \( \omega_0 \) is the pump wave frequency and \( \omega_2 \) is the lower sideband frequency, the nearly electrostatic lower-hybrid-wave dispersion relation simplifies to \( \omega \approx \omega_{pe} k_{\parallel} / \ell_{\perp} \), where \( k_{\parallel} / \ell_{\perp} \) is the wave number parallel (perpendicular) to the confining magnetic field. Electrostatic ion-cyclotron waves, \( \omega = \omega_1 \), follow the dispersion relation \( \omega = \omega_{ci} + (T_e / T_i)\Gamma_i (k_{\perp} \rho_i^2) \), for \( v_e \approx \omega / k_{\parallel} \approx v_i \), where \( v_e \) (\( v_i \)) is the electron (ion) thermal speed, \( (2T_e/m_i)^{1/2} \), and \( \Gamma_i (\omega) = e^{-\omega / \theta_i} \). The theory of parametric decay has been applied to lower hybrid waves by several authors for a dipole pump approximation, \( \theta_i = 0 \), and some finite pump effects. From Wong, Wilson, and Perlak we estimate the parametric coupling coefficient to be dominated by the \( \mathbf{E} \times \mathbf{B} \) drift. The decay threshold is modified also by convection.

The experiments reported here were performed in a single-ended \( Q \) machine (see Fig. 1) which provided a low-density \((5 \times 10^{15} < n_e < 2 \times 10^{16} \text{ cm}^{-3})\), low-temperature \((T_i \approx T_e \approx 0.2 \text{ eV})\), nearly completely ionized potassium, barium, and/or cesium plasma 1.0 m long and 5 cm in diameter. The confining magnetic field was 2–6 kG. The lower hybrid waves were launched from a slow-wave antenna consisting of eight coaxial loops with the 30-MHz pump signal applied to the loops so that unidirectional waves of principal wavelength 12 cm were launched. Plasma density was estimated both from the angle of propagation of the pump wave with respect to \( \mathbf{B}_0 \) (\( \theta^2 = \omega / \omega_{pe} \)) and from a Langmuir probe. Electron temperature was estimated with a Langmuir probe. The radial

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**FIG. 1.** Schematic of experiment showing laser-beam geometry. Antenna launches waves towards hot plate.
wavelength and resonance cone width were measured and found to be consistent with the dispersion relation.22

Ion velocity distributions were measured with use of laser-induced fluorescence (LIF), which uses a tunable dye laser to induce transitions to an excited state of the target plasma ion. The laser beam, collimated to 1 mm diameter, entered the plasma either perpendicular or parallel to the magnetic field (Fig. 1). Thus, both \( f(\mathbf{v} \perp \mathbf{B}) \) and \( f(\mathbf{v} \parallel \mathbf{B}) \) could be measured. The velocity resolution for either case was limited only by the natural linewidth of the absorption line, corresponding to an uncertainty of \( 10^3 \) cm/sec, or 0.03 \( v_{th} \) for cold ions (\( T_i \approx 0.2 \) eV).

In Fig. 2 we show the fundamental elements which identify the ion-cyclotron waves and daughter lower hybrid waves as resulting from the parametric decay of the pump wave. Frequency conservation is well satisfied, as demonstrated by Fig. 2(a), in which we plot the daughter wave frequencies (actually \( \omega_i \) and \( \omega_o - \omega_i \)) versus magnetic field. Qualitatively, the Manley-Rowe condition \( \omega_i \approx f(\mathbf{v} \parallel \mathbf{B}) \) could be measured. The velocity resolution for either case was limited only by the natural linewidth of the absorption line, corresponding to an uncertainty of \( 10^3 \) cm/sec, or 0.03 \( v_{th} \) for cold ions (\( T_i \approx 0.2 \) eV).

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transfer of ion wave energy to the ions. The initial ion heating rate for the data in Fig. 3 is $5.8 	imes 10^{-3} \text{ eV}$ per ion cyclotron period. From kinetic theory we calculate

$$F(v_f) = \frac{\partial T_i}{\partial (\omega_{ci} t)} \approx \left[ 4\pi^2 / T_i \left( \omega_{ci} / T_i \right)^4 \sum_{j=1}^3 \left( \frac{m_j}{n} \right)^2 j \right] T_i,$$

where $J_i$ is essentially a Maxwellian integrated over weakly-Landau-damped resonant particles. From Eq. (1) a heating rate of $8 \times 10^{-3} \text{ eV}$ per ion cyclotron period is found for the experiment. Scaling Eq. (1) to the WEGA regime yields a predicted heating rate of $15 \text{ eV/msec}$, only slightly larger than the observed value. For Alcator $A$ the predicted heating rate is $26 \text{ eV/msec}$, whereas Schuss notes that a ripple-trapped ion tail of energies above $5 \text{ keV}$ occurred in less than $1 \text{ msec}$.

Measurements of cross-field ion motion were made with the technique of optical tagging. Essentially, barium ions are tagged optically when they pass through the laser beam labeled $T$ in Fig. 1, which optically pumps them to a long-lived quantum level $L$. A second laser beam (labeled $D$), spatially separated from the first by $18.5 \text{ cm}$ along the magnetic field and which is tuned to produce fluorescence from ions in state $L$, is used to detect the tagged ions. By translating the location of the $D$-beam optics in a plane perpendicular to $B$, cross-field ion motion can be followed. Typical results of such a measurement are reproduced in Fig. 4, where we show the number density of tagged ions versus radial position of the detection optics for two different rf levels, above and below threshold. Below threshold (solid curve) the full width at half maximum corresponds to instrumental resolution, the finite gyroradius $\rho_{ic}$ (1.2 mm) of the cold ions, and effects from the tagging geometry. So, we presently cannot interpret data for diffusion coefficients less than $D \approx 80 \text{ cm}^2/\text{sec}$, which is greater than the expected collisional coefficients (self-diffusion and ion-electron). The dashed curve (rf power just above threshold at beam $D$, but well above threshold in the focal region near beam $T$) shows enhancement of cross-field transport by $D \approx 70 \text{ cm}^2/\text{sec}$. Cross-field transport was observed to increase with increasing rf power to the point where, for power levels $10 \text{ dB}$ above threshold, cross-field diffusion was enhanced by $D \approx 480 \text{ cm}^2/\text{sec}$. After Dupree, at these power levels the diffusion enhancement might go as $D \approx c 78 / 2 e V$. With use of $n/n$ of about $5\%$ for $10 \text{ dB}$ above threshold this predicts $D \approx 120 \text{ cm}^2/\text{sec}$. Our estimate of $n/n$ is probably low as it was measured at the beam $D$ and not over the entire ion path from the beam $T$.

In summary, we have examined the parametric decay of lower hybrid waves into other lower hybrid waves and ion-cyclotron waves. With use of a newly developed laser-induced fluorescence diagnostic the time-resolved ion distribution function was measured, from which it is clear that substantial ion heating and asymmetries in the distribution function occur in the presence of this decay process. By following the trajectory of tagged ions we observe, in a direct manner, cross-field transport due to lower-hybrid-wave heating.

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Mean-Field Theory for Diffusion-Limited Cluster Formation

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A mean-field theory for the diffusion-controlled cluster formation is presented by considering the competition among the different portions of a growing cluster for the incoming diffusive particles. This competition is shown to introduce a screening length which depends inversely on the density of the cluster. The Hausdorff dimensionality $\delta$ of these clusters is shown to be $(d^2 + 1)/(d + 1)$ where $d$ is the Euclidean dimensionality. This result is in excellent agreement with that of the computer simulations of Witten and Sander and of Meakin.

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In an attempt to describe the growth of clusters of small particles, Witten and Sander recently simulated a diffusion-limited aggregation in $d = 2$ on a computer and compared with other models such as Eden growth, dendritic growth, random animals, and percolating clusters. Meakin also has independently performed simulations of diffusion-controlled cluster growth similar to those of Witten and Sander for $d = 2, 3$, and 4. These simulations start with a single seed particle at the origin of a lattice. A second particle is added at some random site at a large distance from the origin. This particle undergoes a random walk on the lattice until it reaches a site adjacent to the seed and becomes part of the growing cluster. A third particle is then introduced at a random