Stochastic Particle Acceleration in an Electrostatic Wave

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Stochastic acceleration of plasma ions is observed in the field of an intense electrostatic wave. Both electrostatic ion cyclotron and ion Bernstein waves are launched from antennas at the plasma boundary, and ion motions are observed by laser-induced fluorescence. The threshold for stochastic ion heating is observed for the first time. As anticipated, the ion distribution function changes rapidly above threshold (on a cyclotron-period time scale). Measurements of the wave electric field and the ion distribution function indicate that the ion Bernstein wave is responsible for the ion accelerations.

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Hamiltonian stochasticity has a recognized importance in the study of many classical systems.[1] That intrinsic stochasticity can arise in the motion of a single magnetized particle (ion) in a single electrostatic wave has been shown numerically by Smith and Kaufmann[2] and Karney and Bers.[3] Although the Hamiltonian for such a particle is conserved in a reference frame moving with the wave, the onset of stochasticity usually results in a change in particle energy in the laboratory frame. The experimental observation of stochastic electron heating in a standing plasma wave has been reported by Doveil[4] and stochasticity has been proposed as an explanation for tokamak ion heating in the presence of lower-hybrid waves[3,5] and ion Bernstein waves.[6] Stochasticity has also been proposed as an ion-heating mechanism in the magnetosphere.[7] This Letter reports the observation of a threshold for rapid ion heating in the field of an electrostatic wave where the conditions for stochasticity have been met. Observations of the wave electric field amplitude indicate that the ion Bernstein wave is above the stochasticity threshold given by Karney and Bers[3] when heating is observed.

For these experiments, an argon gas-discharge plasma with $n_e \sim 10^{-11}$ cm^{-3}, $T_e \sim 14$ eV, $T_i \sim 0.3$ eV was produced in the 5-m Linear Magnetized Plasma device.[8] The 5-cm-diam plasma was immersed in a steady, uniform ($\pm 0.3\%$ over the plasma volume) magnetic field $B_0 \leq 3$ kG. Electrostatic ion cyclotron waves (EICW) and neutralized ion Bernstein waves (NIBW) were launched between the third and fourth ion cyclotron harmonics by use of electrostatic plate antennas at the plasma radius.[9] The linear propagation and dispersion relation of these waves were measured and are compared with the electrostatic dispersion relation in Fig. 1. Certain aspects of the wave generation are important to note here. First, since $T_e/T_i \gg 1$ and $v_i/\Omega_{ci} \leq 0.02$, in the linear regime the waves are weakly damped over a wide range of frequency and parallel wavelength. Second, ring antennas which surround the plasma column are used so that the wave-induced $\mathbf{k}\times\mathbf{B}_0$ drift motion is in the azimuthal direction. This is done to avoid the rapid loss of accelerated particles.[2] Finally, we note that the wave envelope is observed to extend several parallel wavelengths along the magnetic field.

A complication arises because for a given choice of wave frequency and parallel wavelength, two different perpendicular wavelength-λ waves are launched. The EICW has $\lambda_\perp$ on the order of the plasma radius whereas

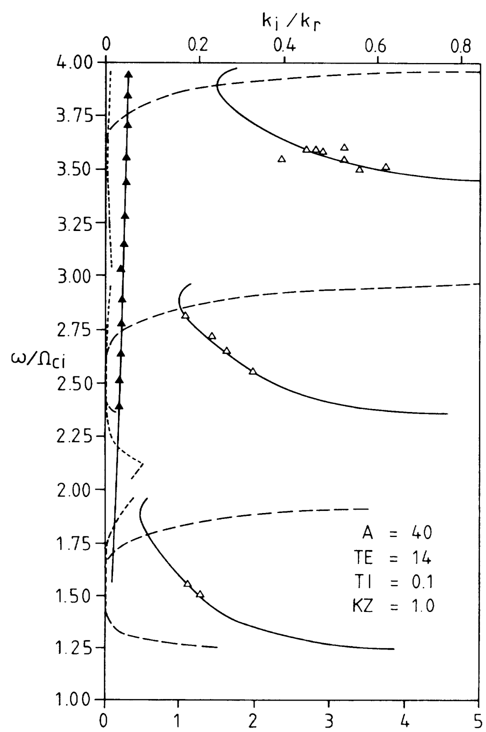

FIG. 1. Electrostatic dispersion relation. Theoretical dispersion curves (solid lines), EICW linear damping (short-dashed lines), NIBW linear damping (long-dashed lines), and data points (triangles) are shown for argon with $T_e = 14$ eV, $T_i = 1$ eV, and $k_z = 1$ cm^{-1}.

the NIBW has a much shorter $\lambda_\perp$ $[k_\perp \rho_{ci} = \sim O(\omega/\Omega_{ci})]$. The EICW can produce stochasticity through the overlap of cyclotron resonances and has a threshold of[2]

$$E_z/B_0 \sim 0.3(\Omega/\omega)(\omega/k_z c). \qquad (1)$$

On the other hand, the NIBW is described by the analysis in Ref. 3 for a nearly perpendicular propagating wave (involving different resonances) and has a threshold given by[3]

$$E_x/B_0 \sim \tfrac{1}{4}(\Omega/\omega)^{1/3}(\omega/k_\perp c). \qquad (2)$$

For the wave parameters of this experiment ($\omega/\Omega \approx 3.5$, $k_z \cong 1\ \text{cm}^{-1}$, $k^{\text{NIBW}} \cong 21\ \text{cm}^{-1}$), the latter threshold[2] is lower by a factor of 6 in wave electric field.

It has recently been shown that ion Bernstein waves can also be subject to strong nonlinear ion Landau damping.[10] We do not expect this mechanism to be involved here since the coupling would need to be at $m = 7 \sim (\omega/\Omega_{ci}) \times 2$ and the necessary wave power at $m = 5$ is already a factor of 10 above the stochasticity threshold for our experiment. Typically the EICW and NIBW are observed to have nearly the same electric field strength in our experiments. This indicates that stochastic heating from the NIBW is the easiest to achieve for the experimental conditions chosen.

Ion velocities are measured by use of laser-induced fluorescence on argon metastable states.[11] The perpendicular ion distribution function $f(v_\perp)$ is obtained from Doppler broadening after the broadening due to the laser linewidth and the multiple Zeeman components of the argon transition have been deconvolved. Temperatures as low as 0.1 eV and fluid drifts (from line shift) as low as $\sim 10^4$ cm/sec can be resolved with the current system. A 10-nsec laser-pulse length is what limits the velocity resolution but also provides for time resolution. Ion velocities are diagnosed at the intersection of the laser beam and the viewing volume. Argon metastable states, populated by the gas-discharge electron current, are selectively pumped to an excited state which has a small branching ratio for decay back into the metastable state. In this way the fluorescence light can be discriminated from directly scattered laser light.

Measurements of plasma-wave electric fields are generally a difficult task. With plate antennas, deductions of absolute wave amplitude from antenna loading are not feasible because much of the antenna power is lost to electrons at the plasma surface. Relative amplitude measurements, however, indicate a linear relationship between wave amplitude and antenna current. Probe measurements are an acceptable means of measuring wave potential as long as $e\phi/T_e < 1$, which is true even at the stochasticity threshold. For sufficiently large-amplitude waves, it is also possible to observe the wave electric field through the linear dielectric motion of the ions.[12] This method involves measurement of the ion velocity synchronous with the wave. An oscillatory motion of the distribution function can be expected due to the (hot plasma) dielectric response transverse to the electric field E_x and the static magnetic field B_0. For the chosen experimental conditions ($\omega/\Omega_{ci} \sim 3.5$, $B_0 = 2$ kG), this method provides for electric field measurements below 1 V/cm, depending on the signal-to-noise ratio.

Ion temperature as a function of rf antenna current is shown in Fig. 2(a). Above a certain threshold in antenna current, a sudden increase is observed in the ion temperature. Figure 2(b) shows raw data of the transition line shape both below and above threshold. The corresponding ion distribution functions are shown in Fig. 2(c). Although the heated distribution is slightly non-Maxwellian, the shape of the distribution indicates an interaction with particles near the thermal velocity implying an interaction with the NIBW as opposed to the EICW.[3] The changes in the distribution function occur very quickly as well. Figure 2(d) shows the time evolution of the observed heating (which is no less Maxwellian at early times). The heating is clearly much faster than any ion collision time and, therefore, cannot be attributed to a collisional mechanism.

In addition to probe measurements, the wave electric field was measured through the dielectric motion of plasma ions. Figure 3(a) shows a radial profile of wave electric field obtained in this way for a wave amplitude a factor of 2 above threshold. Also shown [Fig. 3(b)] is the theoretical prediction of the wave electric field profile. An indication of the EICW wavelength expected is given by the dashed curve. The NIBW perpendicular wavelength depends on the ion temperature, but very weakly on density or parallel wavelength. There is very good agreement between the ion temperature derived from the distribution function, and that of the NIBW dispersion relation. At threshold, the wave electric field is near the limit of detectability (with use of the laser). Detection below threshold is further complicated by the NIBW wavelength being comparable to the laser beam diameter. Extrapolation down from the laser data and measurement using probes indicate a threshold value of $c(E_x/B_0) \sim 3 \times 10^4$ cm/sec which is to be compared with the theoretical value of 1.3×10^4 cm/sec for the NIBW. Self-consistent effects are clearly necessary to explain the experiment fully. For instance, the NIBW wavelength depends on the ion temperature, and, therefore, so does the stochasticity threshold. This may be why the observed heating seems to saturate as a function of wave input power.

Measurements at other wave frequencies (range shown in Fig. 1) do not indicate a sharp resonance at the half harmonic, though there is a frequency dependence due to changes in wavelength (antenna coupling efficiency also changes). The absence of half-harmonic resonance is in contrast to tokamak ion Bernstein-wave heating experiments. This difference may be due to the fact that ion Bernstein waves in tokamaks are nonneu-

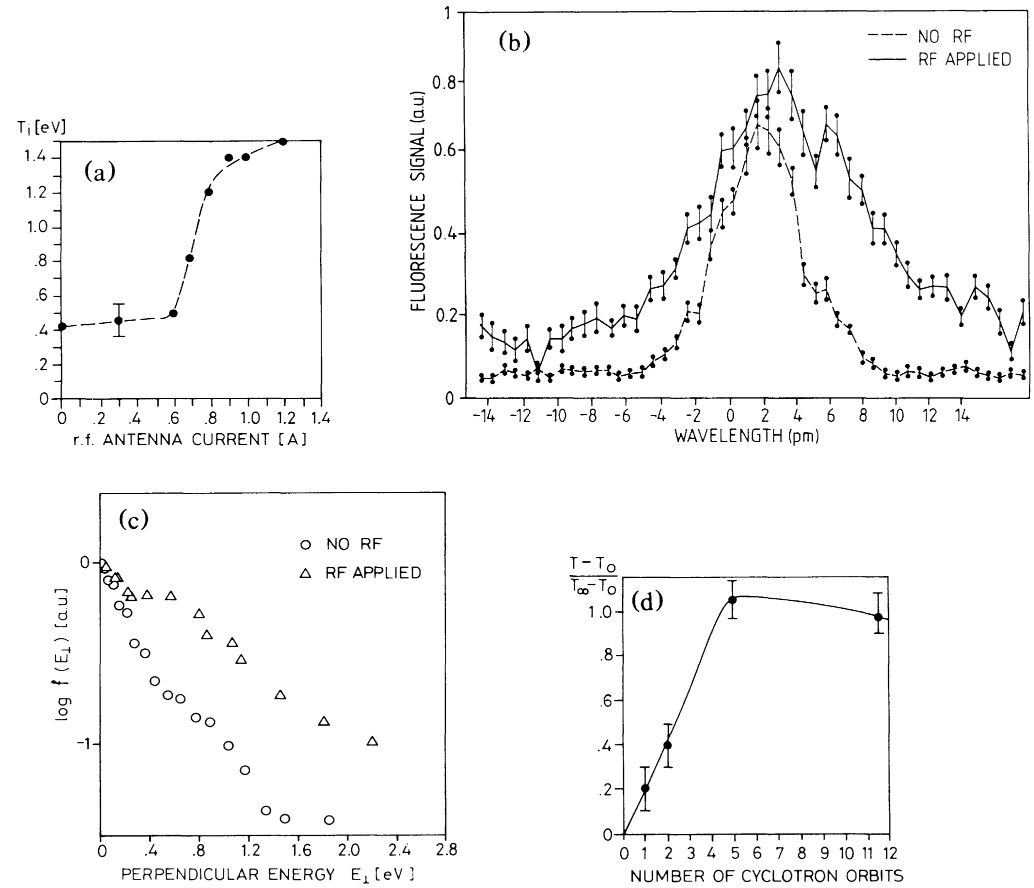

FIG. 2. Laser measurements of the perpendicular ion distribution function. (a) Temperature as a function of rf antenna current. (b) Transition line shape above (solid line) and below (dashed line) threshold. The latter is also identical to the one in absence of any wave in the plasma. (c) Ion energy distribution corresponding to (b). (d) Time evolution of the heating in units of the period of ion gyrotation.

tralized (i.e., $\omega/k_{\parallel}v_e > 1$) and therefore exhibit much sharper ion cyclotron resonances. The tokamak experiments may also involve a different mechanism.

In summary, we have observed the threshold for stochastic ion heating in the field of an electrostatic wave. Above threshold, the ion heating requires only a few ion gyroperiods. Both the threshold level and the ion distribution function indicate that the ion Bernstein wave is responsible for the heating. Further experiments are in progress to measure

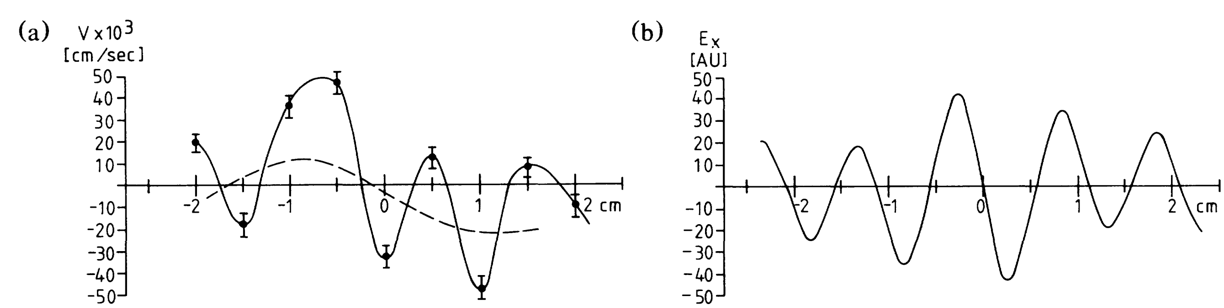

FIG. 3. Plasma dielectric response. (a) Observed dielectric motion implies wave electric field values. Dashed line indicates the acoustic wavelength. (b) Reconstruction of the wave electric field from linear theory, given the plasma and antenna parameters.

the parallel distribution function and to attempt to launch the different wave types more selectively. Experiments involving the selective "tagging" of ions are also planned.

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