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HYBRID INSTABILITY AND
STOCHASTIC ION HEATING

BY

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Cross-Field-Current Driven Lower-Hybrid Instability
and Stochastic Ion Heating

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CROSS-FIELD-CURRENT DRIVEN LOWER-HYBRID INSTABILITY
AND STOCHASTIC ION HEATING*

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ABSTRACT

A suprathermal electron beam is injected parallel to $\vec{B}$ in a low- β plasma. The sharp space-potential drop across the surface of the beam generates a strong cross-field current which in turn drives a modified two-stream instability at the lower hybrid frequency. Intense stochastic ion heating is observed with the onset of the instability, and the heating rate is found to be proportional to the wave energy.

Heating a plasma by injecting high-energy charged or neutral-particle beams is a topic of major interest in fusion plasma physics. We have investigated a fundamental process in the interaction between an injected high energy electron beam and a target plasma.

In past years, cross-field-current driven microinstabilities have been intensively studied,^{1,2} particularly in connection with anomalous ion heating in plasmas produced by relativistic electron beam injection into mirror machines,³ theta pinches,⁴ and collisionless shock experiments.¹ Among these instabilities, a lower-hybrid instability, with frequency between the electron and ion cyclotron frequencies ($\omega_{ci} < \omega_{LH} < \omega_{ce}$), is easily destabilized by $\vec{E} \times \vec{B}$ current. This instability often occurs as a flute-type nonresonant mode and can play an important role in enhanced ion heating.⁵ In contrast to ion acoustic waves, lower-hybrid waves are not subject to strong ion Landau damping even in isothermal ($T_e \approx T_i$) plasmas and can have a large growth rate ($\gamma \sim \omega$).

In this letter, we report a new experimental identification of the modified two-stream lower-hybrid instability and the resultant stochastic ion heating in a laboratory plasma, not only in steady state but also in pulsed operation. A significant result of the present experiment is the first detailed study of the relation between the excited wave amplitude and the ion heating rate (time resolution: $t < 2 \mu\text{sec}$), elucidating the stochastic ion heating which is due to the lower-hybrid instability.

The experiments were performed on the thermally ionized potassium plasma of the Princeton Q-1 device,⁶ Fig. 1(a). The

plasma column (diameter 3.2 cm, confining field 2-6 kG, $T_{eo} \lesssim T_{io} = 0.35$ eV, and $n_{eo} \approx 10^9 \text{ cm}^{-3}$) is divided by a negatively biased mesh (grid spacing $< \lambda_{\text{Debye}}$). If the beam-source end-plate is biased at a potential somewhat higher than the mesh voltage and the target-plasma end-plate is grounded, electrons flow through the mesh with more than thermal velocity into the target plasma; high electron conductivity lowers the potential in the beam region. The beam, well defined by a mechanical aperture, has a velocity $v_b \approx (2e V_{\text{Bias}}/m)^{1/2}$ and density $n_b \approx n_o \cdot \exp [e(V_{\text{Bias}} - V_{\text{Mesh}})/T]$. The important feature is that the sharp drop in plasma potential, generated at the radial surface of the electron beam, creates a strong cross-field azimuthal electron current $[c(\vec{E} \times \vec{B})/B]$ at the surface, Fig. 1(b). Ion $\vec{E} \times \vec{B}$ motion is negligible because of the high ion inertia and $(1/\phi)(d\phi/dr) \gg 1/\rho_i$.

With the injection of a low density beam ($n_{eb}/n_{eo} \ll 1$, $eV_b \gg kT_e$) we observe the familiar electron-electron two-stream instability which has been well investigated.⁷ The peak frequency is somewhat below the electron plasma frequency, and neither fluctuations below the ion plasma frequency nor ion heating is detected in this condition.

On the other hand, with a high density beam ($n_{eb}/n_{eo} \gtrsim 1$), we observe a new instability ($\omega \approx \omega_{\text{LH}} \approx \omega_{\text{pi}}$) destabilized at the periphery of the injected beam. The identification of this instability and the resultant ion heating are the subject of this Letter. Fig. 1(b) depicts the floating potential profile and Fig. 1(c) presents the measured wave amplitude versus radial position. The amplitude of the instability peaks at a few cyclotron harmonics clustered around the lower-hybrid frequency, Fig. 2(a), and the

center of the spectrum shifts with the target plasma density. Propagation is predominantly azimuthal [in the slab model, $k_y > k_x \gg k_z \approx \pi/2L$; $L = \text{machine-length } (10^2 \text{ cm})$] in the direction of the $\vec{E} \times \vec{B}$ drift. Figure 2(b) presents the azimuthal phase velocity versus magnetic field strength B , showing $\omega/k_y \sim B^{-0.7}$. Since the parallel wavelength, λ_z , is longer than the machine-length, there is no parallel resonance effect⁸ between the injected beam velocity and the wave propagation. The observations are in agreement with numerical calculations of the modified two-stream instability.¹

Theoretically, we consider a low- β Maxwellian target plasma in a straight magnetic field $B\hat{z}$ with $T_e = T_i = T_0$ and an electron beam with streaming velocity $u = u_z\hat{z} + u_y\hat{y}$ and temperature $T_e \approx T_0$. The dispersion relation for electrostatic waves propagating nearly perpendicular to $\vec{B}$ ($k_\perp \gg k_z$ and $\omega/k_z v_e > 1$), for $k_\perp \rho_e \ll 1 \lesssim k_\perp \rho_i$ and $\omega_{pe} \ll \omega_{ce}$ is written at the beam surface,

$$1 - \frac{k_z^2}{k^2} \frac{\omega_{pe}^2}{(\omega - \vec{k} \cdot \vec{u})^2} + \frac{k_{Di}^2}{k^2} \left\{ 1 + \sum_{n=-\infty}^{\infty} I_n(\lambda) e^{-\lambda} \frac{\omega}{k_z v_i} Z\left(\frac{\omega - n\omega_{ci}}{k_z v_i}\right) \right\} = 0, \quad (1)$$

where $\lambda = k^2 \rho_i^2 / 2$, $\rho_i = (2T_i / M\omega_{ci}^2)^{1/2}$, $v_i = (2T_i / M)^{1/2}$, I_n is the modified Bessel function of n th order, and Z is the plasma dispersion function with conventional definitions.¹ We have neglected the electron diamagnetic drift since probe measurements indicate that the electron density gradient is small at the beam surface.⁹

We have also assumed that all electrons are drifting with the macroscopic azimuthal velocity at the beam surface.

In the present experiment, with $10^{-2} < (k_z^2/k^2)(M/m) \lesssim 1$ and $\omega_{pi}/\omega_{ci} \approx 3 \sim 10$, a numerical calculation of Eq. (1) predicts the most unstable modes somewhat below ω_{pi} , with a few cyclotron harmonics.^{1,10} The phase-velocity of the wave is close to the $\vec{E} \times \vec{B}$ drift velocity of the electrons at the beam surface. These features are compared with the experiment in Fig. 2.

In order to investigate in detail the relation between the wave amplitude and ion heating, a pulsed electron beam ($\tau_{\text{rise}} \lesssim 1 \mu\text{sec}$) is injected. The absolute value of the wave amplitude is measured with a probe calibrated by comparing DC and rf probe detection characteristics. The very large saturated amplitude ($e\tilde{\phi}/T_{e0} \sim 1$) is consistent with the notion that ion trapping in the potential troughs of the waves invokes nonlinear wave stabilization.¹ Parallel and perpendicular ion temperatures are measured using a small Faraday cup (size 2 mm, located outside of the electron beam) in which the separation between the electron shielding grid and collector is less than 0.2 mm. The collector current signal is analyzed with box-car sampling at a resolution time shorter than 2 μsec . In all cases, the wave amplitude saturates within a few microseconds ($\tau_{\text{growth}} \sim 3/\omega_{pi} \lesssim \tau_{\text{rise}}$), after which strong ion heating occurs, Fig. 3. The deviation from the computer simulation results¹ in which T_i increases with wave amplitude is considered to be due to the present large ion/electron mass ratio ($M/m \approx 8 \times 10^4$) and to the small electron beam radius ($r_{\text{beam}}/r_{\text{plasma}} \approx 1/5$). The ion temperature is observed to saturate at $\tau \lesssim 200 \mu\text{sec}$: Saturation is due to a balance between

the energy input and losses caused by large ion Larmor radii. The increase in parallel ion temperature is small as expected.¹ An increase in parallel electron temperature was not detected; the electron transit time is much shorter than the heating time.

According to renormalized quasi-linear theory,¹¹ the ion heating rate can be expressed as

$$\frac{dT_{i\parallel}}{dt} = \omega_{pi}^2 \left\{ \sum_k \frac{\langle |\tilde{E}_k|^2 \rangle}{4\pi n_0} \left[\frac{v_c(k)}{\omega^2} + (4\pi)^{1/2} \frac{\omega^2}{k^3 v_i^3} \exp\left(-\frac{\omega^2}{k^2 v_i^2}\right) \right] \right\}. (2)$$

Stochasticity of the fluctuation field is taken into account by introducing a correlation time $1/v_c(\vec{k})$, in the first term, since pumping from the $\vec{E} \times \vec{B}$ electron drift balances the damping due to ion-wave interaction even after wave amplitude saturation. The second term represents resonant ion heating ($\omega \gg \omega_{ci}$) and is much smaller than the first for the present conditions. An estimate of $v_c \approx \omega_{ci} \lesssim \gamma$ ^{12,13} is supported by the observed constant spectrum width, $\Delta\omega$, and the correlation of signals from two probes at different azimuthal positions. Substituting the measured values of $v_c(k) \approx 0.1 \omega_{pi}$, $\sum_k \tilde{E}_k^2 / 4\pi n_0 T_{i0} \approx 0.04$, $\omega_{peak} \approx 2/3 \omega_{pi}$, we obtain $(1/T_{i0})(dT/dt) = 0.009 \omega_{pi}$, corresponding to $\tau_{heating} \approx 20 \mu\text{sec}$, in agreement with Fig. 3.

To check the quasilinear heating rate, Fig. 4(a) presents the bulk perpendicular ion-temperature increase versus time for various saturated wave amplitudes. As seen in Fig. 4(b), the ion-heating rate is proportional to the square of the saturated

wave amplitude, quantitatively confirming the quasi-linear relation, Eq. (2); $v_c \approx \text{constant} \lesssim \omega_{ci}$. Furthermore, since we have observed a linear relation between the saturated wave energy and the radial voltage drop (pumping energy), the ion heating rate is proportional to the power input through the $\vec{E} \times \vec{B}$ motion of the electrons. A similar result is obtained for the electron heating rate in parametrically driven instabilities.¹⁴

In summary, cross-field electron current at the surface of an injected suprathermal electron beam was seen to destabilize lower-hybrid waves. With the onset of the instability a sharp increase in perpendicular ion temperature was observed. The ion-heating rate was measured to be proportional to the saturated wave energy.

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Fig. 1. (a) Schematic diagram of set-up; (b) radial floating potential profile; (c) wave amplitude profile.

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 Fig. 2. (a) Frequency spectrum vs target plasma density; solid curve denotes $f_{LH} \approx f_{pi}$, $B = 4$ kG. (b) Azimuthal phase velocity vs B , $eV_{Bias} = 8$ eV. Solid line is calculation in the fluid limit¹ for fixed $k_z = \pi/2L$.

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Mesh Bias
(Electron Beam Injection)

Instability Amplitude

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Fig. 3. Pulsed operation. From top, Mesh bias, instability amplitude and perpendicular ($\bullet T_{i\perp}$) and parallel ($\circ T_{i\parallel}$) ion temperature are plotted versus time. $B = 4$ kG.

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 Fig. 4. (a) $T_{i\perp}$ vs time for various $\vec{E} \times \vec{B}$ pumping energies. Waves saturate within a few μsec . (b) Ion heating rate vs the instability energy. $B = 4 \text{ kG}$, $n_{e0} = 1.2 \times 10^9 \text{ cm}^{-3}$.