Nonlocal Effects in the Electrostatic Ion-Cyclotron Instability

R. A. Stern
Bell Laboratoires, Murray Hill, New Jersey 07974

and

D. L. Correll, H. Böhmer,* and N. Rynn
Department of Physics, University of California,† Irvine, California 92717
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High-resolution tunable laser resonance diagnostics reveal ion density decreases within the unstable region of an ion-cyclotron wave as well as hot-ion transport out of the unstable region, showing that instability and heating are dominated by a nonlocal process combining ion transport with heating.

We report the observation of nonlocal heating of ions by the electrostatic ion-cyclotron instability (i.e., the heating and subsequent transport of the hot ions away from the local region of heating).

Recent measurements of the ion temperature, T_i, have demonstrated that the current-driven electrostatic ion-cyclotron wave (EICW) instability[1] leads to ion heating.[2] We note that, in such experiments, the ion Larmor radius $r_L \propto T_i^{1/2}$ readily reaches values in excess of the current-perturbed plasma radius, R. It is evident that ion transport across the field, which increases rapidly as $r_L/R \rightarrow 1$, should become an important factor. To seek out this effect, we have carried out the first measurements of the local ion density within the unstable plasma, together with the associated local ion temperature. Using a novel diagnostic technique of general interest, our observations reveal both (i) large density decreases within the unstable region and (ii) selective hot-ion migration out of the unstable region, yielding a temperature increase (rather than decrease) transverse to the magnetic field, and also (iii) temperatures much higher than previously reported, localized in a cylindrical annulus around the unstable plasma. We show that these results are quantitatively consistent and indicate a new, nonlocal process which dominates the EICW instability. Besides its basic interest, this process may be responsible for some previously explained filamentary instabilities[3] and the EICW ionospheric instability[4]; and it may have a bearing on plasma heating schemes.[5]

A novel version of the laser resonance fluorescence technique[6] was developed, which permits detailed measurement of ion density and temperature changes within very small, localized volumes in magnetized plasmas. Our plasma [Fig. 1(a)] consisted of Ba II ions in a single-ended collisionless, fully ionized Q machine,[2] with equal ion and electron densities $10^9 < n < 10^{10}$ cm^{-3} at background pressures $\sim 10^{-6}$ Torr and magnetic fields between 2 and 7 kG. Under these conditions, about 10% of ions are in the $5^2D_{3/2}$ metastable state (energy 0.6 eV $\sim T_{i0}$). Our scheme used a low-power cw dye laser in π polarization, tuned near 5854 Å to populate the $6^2P_{3/2}$ $m=\frac{3}{2}$ sublevel selectively, as indicated in Fig. 1(b). It decays, with 6-nsec lifetime, to the ground state, emitting σ polarized radiation in one line only, from whose line shape we obtain n and T_i. The volume viewed, defined by the intersection of the high-f-number optics along an axis normal to both laser beam and magnetic field, had dimensions of about 1 mm^3, much less than r_L^3. We note that the previously used optical techniques,[2,7] besides having inadequate spatial reso-

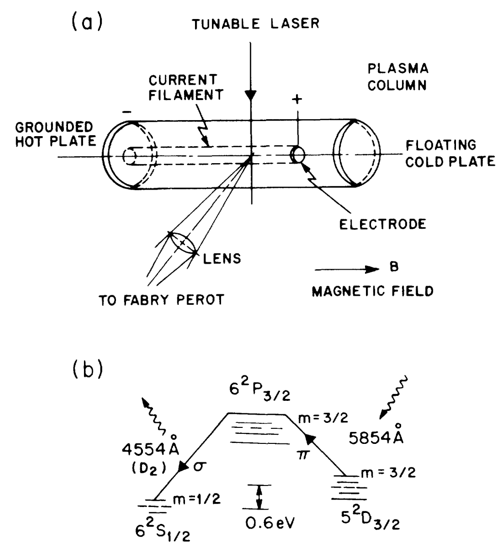

FIG. 1. (a) Schematic setup of the experiment. (b) Optical diagnostic technique. Dashed lines indicate line center for $B=0$.

lution, cannot avoid a Zeeman-component overlap, rendering measurements under our conditions—low n and high T_i—nearly impossible.[8] As a check, D_2 linewidths excited directly using continuum radiation showed no significant difference from our scheme, whenever comparison was possible.

The plasma column size, determined by the hot-plate diameter, was 5 cm. To excite instabilities, a 6-mm-diam electrode was inserted into the column center and an axial current j parallel to B maintained to the hot plate, using a power supply in the constant-current mode, as in Ref. 2. The small electron Larmor radius (less than 0.1 mm) confines the current radially to the size of the electrode. Low current densities, $j \sim 2$ mA/cm^2, triggered the well-known EICW bands near the ion cyclotron frequency and its harmonics.[2] The oscillating field amplitude peaks at the current filament center, decreasing radially to 10% of peak value at a radial position 4 mm from center, and becomes unobservable at positions much smaller than the plasma column radius, 25 mm.

Plasma property changes caused by the instability are illustrated in Fig. 2. Figure 2(a) shows the laser-excited 4554-Å fluorescence originating near the current filament center, for increasing j. Two effects are apparent: The linewidth, proportional to $T_i^{1/2}$, increases, while the total line intensity (peak amplitude and integral under the line, proportional to n) decreases. Figure 2(b) displays the fluorescence originating at points

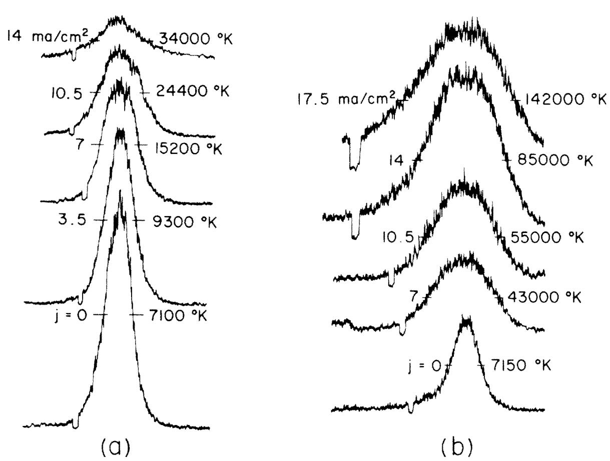

FIG. 2. Fluorescent line shapes with constant sensitivity. Laser beam positioned at (a) current filament center and (b) 5 mm from center. A blocked-laser glitch showing background level is given on the left-hand side of each trace.

about 5 mm away from the filament center, i.e., outside the interaction region. Here both n and T_i increase with j. Combining these observations, it appears that the saturated configuration of the EICW instability consists of a low-density, relatively warm core, surrounded by a denser, hot ion cloud which extends considerably beyond the original interaction region boundary. An independent check is provided by Langmuir probe measurements which show a sharp dip in the ion radial profile over the central 6 mm, where the current is localized, up to a 0.8 decrease in n, close to the value determined optically.

The dominant role of wave-particle interactions in this process is verified by studies of the temporal evolution of the ion density and temperature using sampling techniques.[8] These measurements show that the changes in T_i occurred on time scales of ~ 100 μsec or longer, which is many times greater than a typical cyclotron wave period, ~ 10 μsec. This eliminates the possibility that collective ion cyclotron motion is responsible for the line broadening; and it indicates that the temperature increase is due to multiple scattering between particles and waves, as expected theoretically. Similarly, the density depression at the plasma column center was found to require time scales longer than 200 μsec. This excludes changes in potential difference between ionizer and plasma as a factor, since they occur at the electron transit time, ~ 1 μsec. Local steady-state variations in the sheath at the hot plate, due to the filament current, are inhibited by fast radial diffusion of ions from the surrounding unperturbed region of the hot plate.

The quantitative relationships between n, T_i, and j are plotted in Fig. 3. Curves a and b show the density variation with j inside the current filament [data of Fig. 2(a)], based on the D_2 line peak amplitude (n_p), representing the cold ions, and the line integral ($\bar{n}$), respectively, while curve c shows T_i. Both the n and T_i dependences appear to be exponential,[9] i.e., much stronger than theory, which predicts[10] that T_i should increase with electron drift velocity u only as $T_i \propto u^{2/3}$ if constant density is assumed.[11]

Using the actually observed density $\bar{n}$, the true u, obtained from $u = j/\bar{n}e$ and plotted in Fig. 3, curve d, is seen to increase much faster with j than if n were constant, as in Fig. 3, curve e. The data are fitted by $u = j\,\exp(0.06j) \cong j(1+0.06j)$, and is linear in j initially, explaining why observations of EICW instabilities[12] at low j (~ 0.9 mA/cm^2) appear to agree with theory.

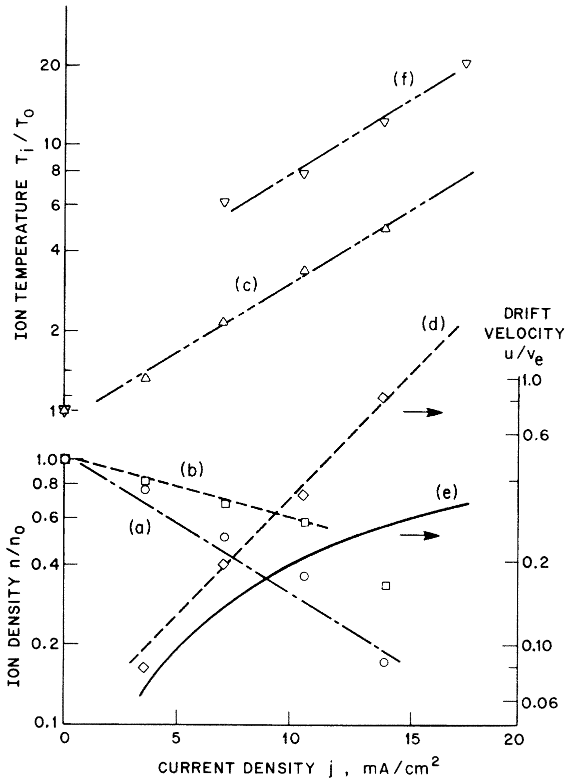

FIG. 3. Ion property changes with current. Curves a–d, at filament center, data of Fig. 2(a). Curve a, ○, normalized density n_p, based on line peak intensity. Curve b, □, normalized density $\bar{n}$, based on line integral. Lines are data fits, $\exp(-0.12j)$ for curve a and $\exp(0.06j)$ for curve b, with j in mA/cm^2. Curve c, △, temperature. Curve d, ◇, corrected drift velocity $u \equiv j/\bar{n}e$, normalized to electron thermal speed v_e. Curve e, theoretical drift velocity, without density correction. Curve f, ▽, temperature 5 mm from center, data of Fig. 2(b) ($T_{i0} = 7150$°K).

A cross plot yields $T_i \propto u^{0.6 \pm 0.1}$, Fig. 4(a), remarkably close to the theoretical $T_i \propto u^{2/3}$. This suggests that, once the density decrease is properly taken into account, the homogeneous plasma model realistically represents EICW heating. Figure 4(b) shows $n \propto u^{-0.6 \pm 0.15} \propto T_i^{-1}$; thus $nr_L^2 = \text{const}$. Since ions are localized within a field-aligned volume $\propto r_L^2$, the n decrease appears internally consistent with the T_i increase. Finally, at the peak T_i inside the region, $r_L/R = 1.3$. Thus, the warmest ions have orbits with minimum residence time within the region. This may constitute a self-limiting process which determines the maximum T_i and n within the interaction region, while allowing transport of hot ions beyond the current filament.

Figure 3, curve f, plots T_i outside the interaction region, from the data of Fig. 2(b). The critical value $r_L/R = 1$ is exceeded over the entire range, consistent with the requirement that the hot ions be transported across field lines.

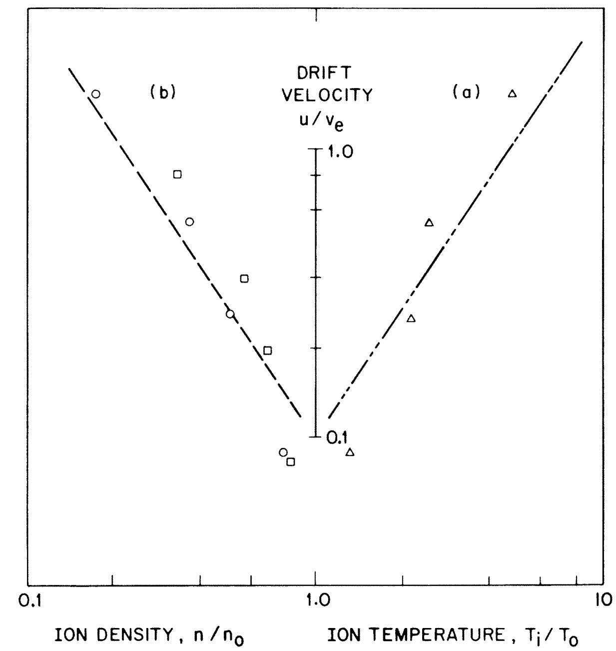

FIG. 4. Cross plot of (a) △, ion temperature and (b) ○ and □, density versus corrected drift velocity, data of Fig. 2(a). Lines represent $u^{\pm 2/3}$ dependences for T_i/T_0 and n/n_0, respectively.

We suggest that current filaments are inherently unstable, and form spontaneously even without geometric constraints because of slight irregularities in electrodes, end plates, etc. Similar effects may exist in injected-particle instabilities in the ionosphere,[4] in plasma heating schemes,[5] or in any situation involving electron drifts. Our results may explain the filamentation observations of Buchelnikova and Salimov.[3]

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*On leave from the Physics Department, University of Illinois, Urbana, Ill. 61801.

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[9]The laser linewidth ≤ 0.03 Å is broader for all but the last point ($T_i \leq 2.4\times 10^4$°K) in Fig. 3, curves *a* and *b*, rendering intensity corrections for Doppler broadening unnecessary. For the last point, less than 30% of the ions lie outside the laser linewidth. This correction brings the density closer to the dashed line.

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Preheat by Fast Electrons in Laser-Fusion Experiments

B. Yaakobi, I. Pelah,* and J. Hoose
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627
(Received 24 March 1976)

Neon-filled glass spherical shell targets were irradiated by a four-beam laser system of incident power 0.6–0.8 TW. By measuring $K\alpha$ x-ray lines of neon and silicon we are able to determine the number of fast (nonthermal) electrons and their preheating effect. Correlation is made with fast ion measurements.

Premature heating of the interior of laser-irradiated targets by either fast electrons or x rays has long been recognized as one of the most serious difficulties to contend with in fusion experiments.[1] For example, preheat of the gas enclosed in glass spherical shells should make it more difficult to compress it; preheat of the inner part of the glass shell would cause it to explode inwards and the "pusher" action is thereby impaired. We have studied preheat *experimentally* by measuring the intensity of $K\alpha$ radiation from the glass elements as well as from a heavy fill gas, neon. Electrons or x rays of sufficient energy traveling into cold un-ionized material can eject K-shell electrons before the outer electrons are removed through heating. A K-shell vacancy has a probability ω (the fluorescence yield) to decay by emitting a $K\alpha$ photon. The fraction $1-\omega$ of the absorbed energy is mostly converted into heat, either through Auger cascades or through the emission of softer radiation which has a high probability of being reabsorbed. If preheat continues as the target core is being heated and ionized through compression, $K\alpha$ lines will shift to shorter wavelengths one step for each additional removed electron.[2]

The targets used in this study were glass spherical shells of diameter about 90 μm and wall thickness 1 μm filled with neon of pressures 2 and 10 atm. $K\alpha$ lines of neon can be excited by electrons of energies higher than 0.87 keV. A heavier atom fill gas (e.g., argon) would detect electrons above a higher threshold. Since fast electrons are believed to be produced near the critical surface these results should apply to other gas fills, such as D-D or D-T. Other experimental parameters were total incident power in four beams 0.6–0.8 TW, power density (2–3) $\times 10^{15}$ W/cm^2, pulse width 0.2–0.4 nsec, and energy absorbed 5–10 J. For more details on the laser system and interaction diagnostics see Soures, Goldman, and Lubin.[3] A saturable dye