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Fast-Wave Heating of Two-Ion Plasmas in the Princeton Large Torus through Minority-Cyclotron-Resonance Damping

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Strong minority proton heating is produced in the Princeton Large Torus through ion-cyclotron resonance damping of fast waves at moderate rf power levels. In addition to demonstrating good proton confinement, the proton energy distribution is consistent with Fokker-Planck theory which provides the prescription for extrapolation of this heating regime to higher rf power levels and other minority species.

Earlier attempts to heat relatively small, low-current tokamaks with waves generated at frequencies in the vicinity of the second-harmonic cyclotron frequency of the majority ion species of a two-ion plasma have resulted in heating efficiencies in the range of 20–40% and an enhancement of particle recycling into the plasma.[1-3] These results have been attributed to poor confinement of energetic ions and to surface heating by the excitation of wave modes with large electric fields and field gradients in the plasma periphery.[4] In higher current tokamaks, improved energetic ion confinement and proper selection of propagating modes should reduce considerably the surface heating.[4] In this Letter, we present heating results for the two-ion regime obtained at moderate rf powers ($\lesssim$70 kW) in the Princeton Large Torus (PLT) which demonstrate the expected improvement in ion confinement and, furthermore, support the prospect that the minority-ion cyclotron damping can be employed to heat large-scale plasmas in accordance with theory.

In recent years, the importance of the two-ion hybrid resonance on fast-wave damping has been observed in several tokamaks[2,3,5] and has received considerable theoretical analysis.[6-9] When the minority ion concentration is sufficiently high, mode conversion occurs at the two-ion hybrid resonance and leads to wave damping by both the electrons and resonant ion species. For example, for minority hydrogen in deuterium, mode conversion occurs when[9]

$$\eta_h \gtrsim (\beta_e T_h/2T_e)^{1/2} S_{\parallel}(4/3 + S_\varphi^2),$$

or for helium-3, we find

$$\eta_h \gtrsim (\beta_e T_h/2T_e)^{1/2} S_{\parallel}(12/5 + S_\varphi^2),$$

where $\eta_h = n_h/n_e$, $S \equiv kc/\omega_{pd}$, with ω_{pd} the plasma frequency in deuterium, and k_φ and $k_\parallel$ are wave numbers along the toroidal and total magnetic field, respectively. At lower concentrations, mode conversion is absent, but the residual effect in the two-ion hybrid zone on wave polarization enhances minority fundamental damping and shifts the peak of the damping toward this zone.[10] Even for minority concentrations and k_φ values which lead to mode conversion at low rf power levels, it is clear that there will be a tendency for direct damping to dominate at high power levels as the proton β increases, which in turn depends on the division of the mode-converted wave energy among the plasma species.

In the initial heating experiments on PLT, we have employed a single half-turn antenna located at the larger major radius perimeter of the plasma to generate waves having dominantly $m = 0, \pm 1$ azimuthal mode numbers. Although this antenna gives a broad spectrum of k_φ, the wave dispersion properties in the plasma[11] favor excitation of intermediate k_φ($\sim 5 - 15$ m^{-1}) values for the moderate densities studied—$\bar{n}_e \approx (1-1.5)\times 10^{13}$ cm^{-3}. An excitation frequency of 25 MHz has been used and the resonances have been positioned at selected major radii by choosing the level of the toroidal magnetic field on axis, $B_\varphi(R_0)$.

The first observations of heating were made for a deuterium plasma with a few percent (~3%) of hydrogen concentration which resulted in relatively strong wave damping at low rf power. The equilibrium discharge characteristics were $I_\varphi = 230$ kA, $V_\varphi = 1.3$ V, $\bar{n}_e = 1\times 10^{13}$ cm^{-3}, $n_e(0) \approx 2\times 10^{13}$ cm^{-3}, $T_e(0) = 1.4$ keV, $T_d(0) \approx T_h(0) = 0.4$ keV, $\tau_{E_e} \sim 16$ msec, $Z_{\rm eff} \sim 2-2.5$, and $B_\varphi(R_0) = 16.4$ kG which places the cyclotron layers on axis. Upon application of a 60-msec, 30–35-kW average rf wave power pulse, an increase in β_φ of 5–10% was observed on the diamagnetic loop and no perceptible changes occurred in $\bar{n}_e$, v_φ, and the light and heavy impurity concentrations. The heating characteristics observed for the plasma species are shown in Fig. 1. Electron cyclotron-emission measurements (supported by soft-x-ray data) showed strong initial increase in electron temperature ($\Delta T_e \sim 140$ eV) which diminished considerably during the remainder of the pulse. This electron temperature increase was observed for $r \lesssim 15$ cm, while for $r > 20$ cm, T_e stayed roughly constant or fell slightly. Mass-sensitive charge-exchange and neutron-flux measurements indicated a deuteron temperature increase of ~80 eV. The deuteron spectra had no energetic ion tail, indicating the absence of second-harmonic cyclotron damping. However, the hydrogen charge-exchange spectra reveal that the protons were strongly heated as indicated in Fig. 1 by the average temperature of the energetic hydrogen spectra between 5 and 40 keV (Fig. 2). Such strong heating of the hydrogen

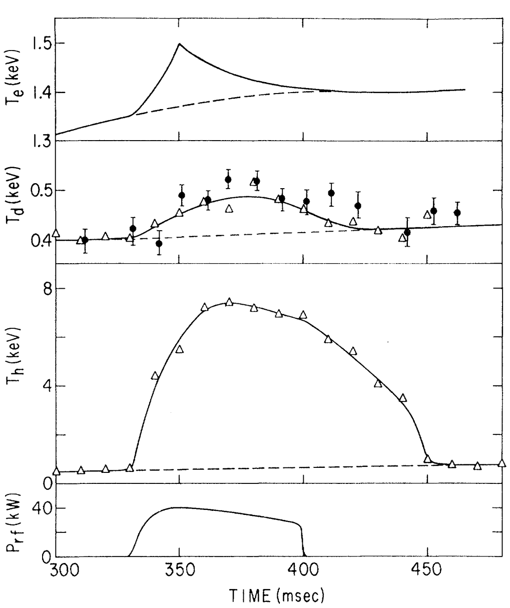

FIG. 1. Time evolution of central values of electron ($r \sim 10$ cm), deuterium (Δ charge exchange, I neutrons), and hydrogen (charge exchange for $E > 5$ keV) temperatures for application of the rf wave power pulse shown and the discharge conditions noted in the text.

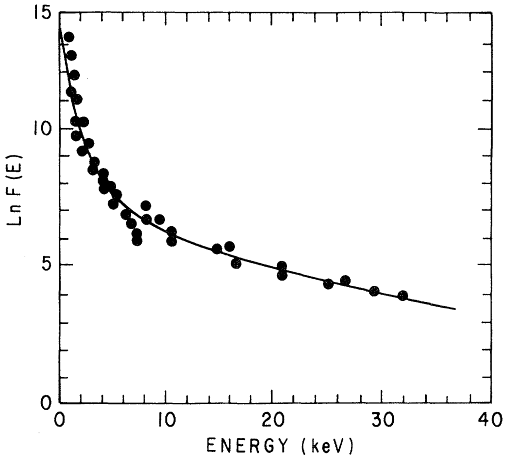

FIG. 2. Hydrogen charge-exchange spectrum at 370 msec of Fig. 1. The theoretical curve shown is for $Z_{eff} = 2.2$, $E_j = 1.8$ keV, and $\xi = 13.8$.

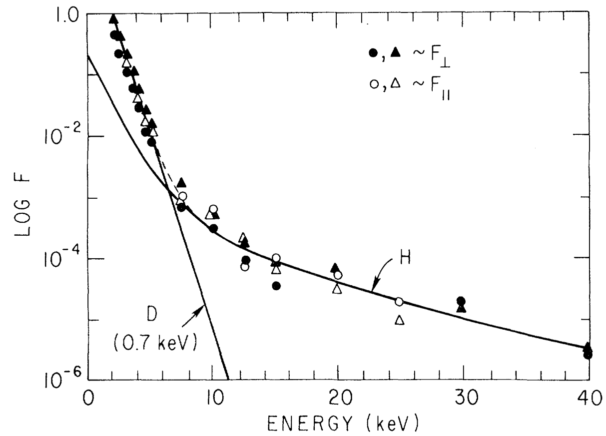

FIG. 3. Hydrogen plus deuterium spectra for directions approximately perpendicular and parallel to the plasma axis averaged over the latter 50 msec of a 60–70-kW, 70-msec rf wave power pulse. ($\bar{n}_e = 1.5 \times 10^{13}$ cm^{-3}, $Z_{eff} \approx 3$, and $\Delta T_d \approx 140$ eV.) For the theoretical hydrogen curve shown, $E_j = 3.3$ and $\xi = 10.4$.

can account for both the electron and deuteron heating characteristics. Mode conversion disappears for a broad range of k_φ when the hydrogen temperature rises to a high value, such that the protons dominate the wave damping (maintaining the absence of toroidal eigenmodes). The reduction of mode conversion results in a strong reduction of direct electron heating, and the deuterons are heated primarily via ion-ion coupling with the hydrogen.

The decay of this energetic hydrogen distribution after the rf pulse occurs over a period of ~50 msec which is ~200 times longer than for the decay of the energetic distribution in the ST tokamak and is consistent with the thermalization time for the energetic ions to equilibrate with the deuterons. Thus the expectation that the energetic ion confinement should no longer be plagued by severe banana-orbit loss cones is validated on PLT up to 40 keV.

Since the rf fields damp out before reaching the mass-discriminating analyzer location ($\varphi = 160°$ from the antenna), the energetic ions cannot result from local rf acceleration and are therefore toroidally precessing (banana trapped) ions. Spectra obtained with a horizontally scanning charge-exchange analyzer (without mass discrimination), located in the vicinity of the antenna and viewing approximately perpendicular and parallel to the plasma axis, are given in Fig. 3 for a ~60-msec, 60–70-kW average rf wave power pulse and somewhat higher $\bar{n}_e$ as noted. The low-energy regions of the spectra are attributable to deuterons and the high-energy regions to protons as determined from simultaneous spectra from the mass-discriminating analyzer.[12] To within the sensitivity of the analyzer (parallel energy up to $E = 25$ keV) the parallel and perpendicular energetic proton distributions are essentially identical, revealing a very nearly isotropic velocity distribution.

The heating of passing particles is augmented by the fact that the fundamental cyclotron damping peaks in the two-ion hybrid region, away from the cyclotron layer, where finite $v_\parallel$ is required for resonance with the wave frequency. However, the isotropic distribution is a consequence of collisional pitch-angle scattering and the quasilinear diffusion effects for wave damping on the protons. The Fokker-Planck analysis of Stix[13] for minority damping can be applied directly to characterize the experimental velocity distribution[14] and to prescribe its extrapolation to other plasma conditions.

Noting that the treatment of Stix is evaluated in terms of the local rf power density $\langle P \rangle$ so that the shift in the location of the peak damping does not alter the formalism (even with mode conversion present) and ignoring the effect of charge exchange loss, we find that the equilibrium distribution in the isotropic regime is given by Eq. (34) of Ref. 13 and is characterized by the parameters

$$\xi \equiv \frac{m_h \langle P \rangle}{8\pi^{1/2} n_e n_h e^4 \ln\Lambda} \left(\frac{2kT_e}{m_e}\right)^{1/2} \qquad (1)$$

and

$$E_d \equiv \frac{m_h k T_d}{m_d}\left[\frac{1+R_d+\xi}{(4/3\pi^{1/2})(1+\xi)}\right]^{2/3}, \qquad (2)$$

where $R_d \equiv Z_{\rm eff}(m_h T_e/m_e T_d)$ is assumed. E_d and $T_e(1+\xi)$ are best determined experimentally in the case where $R_d \gg 1+\xi$ (when ion-ion coupling to the deuterons dominates the proton energy loss) by employing the measurements of $Z_{\rm eff}$, T_e, and T_d to give one relation between E_d and $T_e(1+\xi)$,

$$\left(\frac{E_d}{k}\right)^{3/2} T_e(1+\xi) \approx \frac{m_h{}^2 3\pi^{1/2}}{m_d{}^{3/2} m_e{}^{1/2} 4}\, T_d T_e{}^{3/2} Z_{\rm eff}, \qquad (3)$$

and by using the effective temperature $T_{\rm eff}$ measured at a large energy, to give a second relation,[13]

$$T_{\rm eff} \approx T_e(1+\xi)\left\{1+\frac{(T_e/T_d)(1+\xi)-1}{1+(E/E_d)^{3/2}}\right\}^{-1}. \qquad (4)$$

Distributions obtained in this manner are compared with the experimental spectra in Figs. 2 and 3. This characterization appears to be valid out to ~40 keV for the conditions studied, although the theory of Ref. 13 predicts that the distributions should begin to deviate significantly from isotropic at energies higher than ~20 keV.

In the comparison of Fig. 3, the proton distribution is separated from that for deuterium. This permits the calculation of the proton concentration with the result $n_h/n_d \approx 7\%$ (in reasonable agreement with rough estimates based on mass spectrometry). From this value of concentration and the ξ parameter of Fig. 3, $\langle \Delta P \rangle \sim 0.09$ W/cm^3. It is not possible to specify the power deposition profile or the deuteron heating efficiency prior to making radial scans of the proton and deuteron spectra. However, assuming that all the delivered rf power (~70 kW) is deposited within uniform $\langle \Delta P \rangle$ within a power deposition radius r_0, we obtain $r_0 \approx 18$ cm, suggesting relatively strong localization (a parabolic squared profile gives $r_0 = 23$ cm). Under these conditions, approximately 30% of the rf power is coupled into the deuterons with the remainder being accounted for by losses through charge exchange and through the electron loss channel.

The parameter ξ, Eq. (1), can be experimentally adjusted by choosing the electron and minority densities for a given level of rf power and electron temperature to favor majority-ion heating through ion-ion coupling ($\langle T_{\rm eff}\rangle \lesssim 15\ T_e$). Such control has been maintained up to a power level of ~100 kW, and additional injection of hydrogen gas has been observed to decrease the effective proton temperature as predicted.

With regard to plasma species relevant to reactor operation, the wave-heating physics for T-D operation can be simulated on PLT with ^{3}He-H and approximately with ^{3}He-D. An energetic proton distribution has also been produced in a ^{3}He discharge (D in T) in the absence of a second-harmonic layer. Thus, minority deuterium cyclotron damping is shown to be a possible heating mechanism for use in T-D operation.

No similar energetic deuterium distribution has been produced for fundamental heating of a minority concentration of deuterium in a ^{3}He discharge (T in a D discharge) at the prevailing higher residual levels of D and with the modest powers applied. This may be due to the, for this case, different wave-dispersion topology. However, further experimentation is required to discern the true importance of the changes in the wave properties from the ^{3}He-H case.

In conclusion, direct minority cyclotron damping is found to dominate the two-ion ion cyclotron-resonance frequency heating regime in D-H and ^{3}He-H majority-minority plasma at moderate minority concentrations and rf power levels in PLT. Well confined, approximately isotropic minority distributions have been produced and controlled with the level of the minority concentration to produce significant majority-ion and electron heating through ion-ion coupling and electron drag and/or Landau damping, respectively. The results indicate that this heating process can be applied to heating via D, H, ^{3}He, and ^{4}He minorities in tritium plasmas.

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