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ABSTRACT

A mechanism, in which the wave-induced flux plays the key role, is proposed to explain the density rise observed during Alfvén wave heating in the TCA tokamak.

A density change is seen during the RF pulse in many plasma heating and current drive experiments. The nature and magnitude of this change seems to depend primarily on the injected wave spectrum [1-4]. In the TCA tokamak, where additional heating is achieved by the resonance absorption of fast magnetosonic waves, Collins et al. [5] have observed a remarkably large density increase, of the same order of magnitude as the target density.

In this note, we argue that the density rise in TCA is caused by a quasilinear radial electron flux generated by the resonant wave absorption. We propose a mechanism that predicts a density rise in order-of-magnitude agreement with the experimental results of Collins et al., and that is compatible with many features noted by them. The mechanism includes an enhancement of the wave amplitude due to the linear mode conversion, which could account for the fact that the density inrease has a comparatively large magnitude.

TCA is a small-sized tokamak (R = 61 cm, a = 18 cm) with a circular cross-section. Standard operating conditions are set at B_{tor} = 15 kG, I_p = 130 kA, with n ~ $2 \cdot 10^{13}$ cm^{-3}, T_e ~ 750 eV, T_i ~ 500 eV, for a hydrogen plasma. Up to 200 kW of RF power can be injected into the plasma, at a characteristic frequency of 2.5 MHz.

During the flat-top phase of the RF pulse (~ 20 ms), the plasma profile peaks sharply, while both n(o) and $\bar{n}$ increase linearly, where n(0) and $\bar{n}$ are the central and line averaged electron densities. As soon as the pulse ends, the plasma profile broadens, and $\bar{n}$, followed by n(o) begin to fall. Such behaviour has persisted since the earliest experiments on TCA, even though successive technological modifications have improved the plasma purity.

Collins et al. [5] have documented this density rise as a function of externally controllable parameters, e.g., RF power, target density, and antenna phasing. They show that the density increase is proportional to the injected RF power, and the target density (apart from a region of reduced increase, corresponding to the appearance of a new resonance surface in the center of the plasma). Power scans using different antenna phasings seem to indicate that the density rise diminishes when central power deposition increases.

For simplicity, let us neglect toroidal effects, and consider a slab geometry, where the radial, poloidal and toroidal directions are represented respectively by the x, y and z axes. The variation of the electron density in a uniformely magnetized inhomogeneous plasma due to a wave-induced flux is described by the equation of continuity,

$$\frac{\partial}{\partial t} n + \nabla_x \Gamma_x = 0, \tag{1}$$

where Γ_x is the quasilinear electron flux driven by the RF, and generally consists of both resonant and non-resonant contributions [6]. In the present case, the latter contributions may be neglected. Moreover, the conditions $\omega^* \equiv k_y \; \kappa(v_{te}^2/\omega_{ce}) \ll \omega \ll \omega_{ci}$, $\omega/k_\parallel \ll v_{te}$, and $k_x\rho_e \ll 1$ hold, where κ^{-1} is the inhomogeneity scale length, v_{te} and ρ_e are the electron thermal velocity and Larmor radius, and ω_{ci} is the ion cyclotron frequency. The resonant electron flux may then be written as,

$$\Gamma_x = -\frac{1}{|4\pi\omega_{ce} m_e|}\sqrt{\frac{\pi}{2}}\int \frac{d^3k}{(2\pi)^3}\frac{k_y}{k_z^2\lambda_{De}^2}\frac{\omega}{|k_z| v_{te}}\exp\left(-\frac{\omega^2}{2k_z^2 v_{te}^2}\right)\langle E_z^2\rangle, \qquad (2)$$

where E_z is the electric field perturbation parallel to the static magnetic field and λ_{De} is the electron Debye length. Expression (2) can also be deduced from the drift kinetic equation [7]. In this low frequency regime, no flux would result when $E_z = 0$. If we chose $\nabla_x n < 0$, an inward flux corresponds to $\Gamma_x < 0$, i.e. to $k_y > 0$; an outward flux (which would lead to a density decrease) corresponds to $k_y < 0$.

To be specific, let us assume that the antenna phasing is given by N = 1, M = 1. This corresponds rspectively to positive dominant toroidal and poloidal wavenumbers $k_z = N/R \approx 1.6 \cdot 10^{-2}$ cm^{-1} and $k_y = M/a \approx 5.6 \cdot 10^{-2}$ cm^{-1}. The antenna excites a spectrum of fast magnetosonic waves. Measurements in the shadow of the limiter indicate that the dominant poloidal magnetic component of these waves has a characteristic amplitude $B_y^{ext} \approx 2$ G [8]. At the Alfvén resonance, the fast waves undergo a linear mode conversion into kinetic Alfvén waves. Due to the mode conversion [7], the poloidal magnetic component B_y^A of the kinetic Alfvén waves is much larger than B_y^{ext},

$$|B_y^A| \sim (\kappa \rho_i)^{-\frac{1}{2}} \left(1 + k_x^2 \rho_i^2 \frac{T_e}{T_i}\right) |B_y^{ext}|. \qquad (3)$$

where ρ_i is the ion Larmor radius. The radial wavenumber k_x can be determined from the dispersion relation of the kinetic Alfvén wave

[7]. For the experimental parameters given here, $k_x \sim 3.6\ \mathrm{cm}^{-1}$. If we assume $\kappa^{-1} \sim 15$ cm, and insert the measured value of B_y^{ext} into (3), we find $B_y^A \sim 28$ G. The kinetic Alfvén wave has an electric field component E_z parallel to the static magnetic field. Its amplitude can be deduced from [7],

$$|E_z| \sim \left| \frac{\omega}{c k_x} \left(\frac{T_i}{T_e k_x^2 \rho_i^2} - 1 \right)^{-1} B_y^A \right| \simeq 0.9\ \mathrm{V\,cm}^{-1}. \tag{4}$$

It is precisely this electric field component that gives rise to the wave-induced flux (2), which can be evaluated approximately as,

$$\Gamma_x \simeq - \frac{1}{|4\pi\, \omega_{ce} m_e|} \frac{k_y}{k_z^2 \lambda_{De}^2} \frac{\omega}{|k_z| v_{te}} \exp\left(- \frac{\omega^2}{2 k_z^2 v_{te}^2} \right) E_z^2 \tag{5}$$

$$\simeq -1.7\ 10^{16}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

Inserting this value into the equation of continuity (1), which we approximate by

$$\frac{\Delta n}{\tau} + \kappa\, \Gamma_x = 0 \tag{6}$$

we obtain $\Delta n \simeq 2 \cdot 10^{13}\ \mathrm{cm}^{-3}$, for an RF pulse duration $\tau \simeq 20$ ms. This estimate is in order of magnitude agreement with the values reported in Ref. [5].

In the actual experiment, the antenna simultaneously excites waves with dominant poloidal wavenumbers $M = \pm 1$. We have neglected the waves corresponding to $M = -1$, which would lead to an outward flux. To justify this, let us note that in TCA, the resonant surface for the $M = +1$ (resp. -1) mode is known to be near the plasma boundary (resp. plasma center) [9]. The linear mode conversion of a fast into a kinetic Alfvén wave enhances the amplitude of the applied wave by a factor approximately $\simeq (\kappa\rho_i)^{-1/2}$, as mentioned earlier. Since the flux is proportional to $(B_y^A)^2$, the inward flux will dominate if the enhancement is larger near the boundary than near the center, i.e. if

$$(\kappa\rho_i)^{-1/2}_{\text{boundary}} \gg (\kappa\rho_i)^{-1/2}_{\text{center}}.$$

This inequality is satisfied in TCA: although the plasma profile is somewhat steeper near the boundary than in the central region, the temperature profile is such that ρ_i is substantially smaller near the boundary than near the center [10].

Consequently, the mechanism proposed here links the inward flux to power deposition near the boundary and an outward flux to central power deposition. This fact agrees with the experimental evidence that the density rise seems related to a phenomenon that is diminished when central power deposition increases [5].

Finally, let us stress that this mechanism also accounts for the linear power dependence of the density rise.

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