Anomalous Doppler Resonance of Relativistic Electrons with Lower Hybrid Waves Launched in the Frascati Tokamak

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Relativistic runaway electrons are detected by hard-x-ray and (photo)neutron emissions in low-density experiments with lower hybrid waves. During the rf pulse these signals can be explained in terms of the anomalous Doppler resonance on the primary lower hybrid waves which is effective on electrons having energy > 10 MeV. This effect is present independently of the density limit which determines the efficiency of the other resonance $\omega = k_{\parallel} v_{\parallel}$; the latter is responsible for electron tail enhancement (up to 300 keV) and for wave absorption, heating, and current-drive effects.

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Experiments of noninductive current drive and electron heating by lower hybrid (LH) waves have shown the enhancement of a fast tail in the electron distribution function.[1,2] The typical energy of the electron resonating with the waves extends up to a few hundred kiloelectronvolts for the Landau resonance $\omega = k_{\parallel} v_{\parallel}$. This interaction, which is responsible for the occurrence of current drive,[3] is the basic mechanism for bulk electron heating in the Frascati tokamak (FT),[2,4] where the launched LH wave spectrum is symmetric in the toroidal direction and the electric field is also maintained during the rf pulse. This interaction is quite effective only below a density limit $\bar{n}_{\rm limit} \simeq 5\times 10^{13}$ cm^{-3} for the FT experimental conditions.

Experiments in FT have shown also the presence of a weak population of faster electrons (with energy $\gg 500$ keV) which interacts with the LH waves. This paper is devoted to presenting and discussing a theoretical interpretation of the observed behavior of this relativistic component. The model is based on the anomalous Doppler (AD) resonances $\omega \pm \omega_{ce} = k_{\parallel} v_{\parallel}$ and the quasilinear diffusion analysis. This resonance, which is also responsible for wave instabilities[5,6] in connection with LH current drive, here is considered to act on the primary LH waves.

The typical discharges under consideration are characterized by $B_0 = 80$ kG, $I_p \simeq 350$ kA, and $\hat{T}_e \simeq 1.5$ keV, while the rf power is launched by a two-waveguide grill at 2.45 GHz with power up to 200 kW and $n_{\parallel}$ spectrum in the range[2] 1.2–3. For $n_e < \bar{n}_{\rm limit} \simeq 5\times 10^{13}$ cm^{-3} the evidence of strong interaction[2,4] of the waves with the tail electrons up to ~ 300 keV consists of a strong enhancement of the ω_{ce}-range emission, a drop of loop voltage, the start of an increase in plasma current, and an increase of bulk peak temperature $\Delta T_e \lesssim 500$ eV as measured by Thomson scattering. On the contrary, all these phenomena are not observed when $\bar{n}_e > n_{\rm limit}$. A wide analysis of these results is reported also by Alladio *et al.*[7,8]

Measurements indicating the presence and the behavior of fast relativistic electrons are shown in Fig. 1. Here, measurements of hard-x-ray emis-

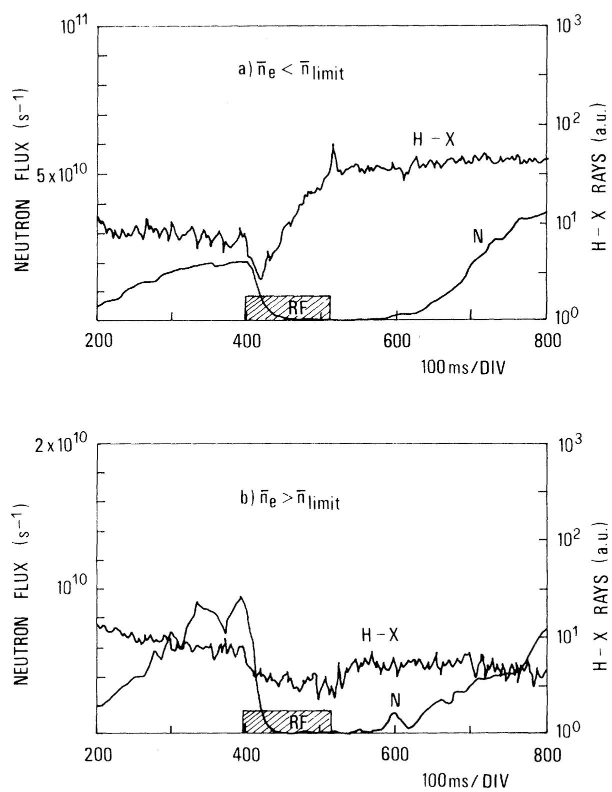

FIG. 1. Temporal behavior of photonuclear neutron emission and hard x rays in H discharge. (a) $\bar{n}_e = 3\times 10^{13}$ cm^{-3} and (b) $\bar{n}_e = 6\times 10^{13}$ cm^{-3}.

sion ($h\nu > 500$ keV) and of the photonuclear neutron flux are reported versus time for two discharges at $\bar{n}_e \simeq 3\times 10^{13}$ cm^{-3} and at $\bar{n}_e$ slightly above $\bar{n}_{\rm limit}$ in a H plasma. Similar discharges in D plasma show the same behavior, only with a background in the neutron signal present as a result of d-d and e-d reactions, which are rare in these conditions. Hard-x-ray flux has been measured out of the machine with a 2×2 in. NaI detector facing the limiter and the electron drift direction. The neutron production has been observed to be much larger for the detector closer to the stainless-steel limiter. For $\bar{n}_e < \bar{n}_{\rm limit}$, Fig. 1 shows an extinction of the neutron emission as rf is switched on, while the x-ray signal first decays and then increases again by about one order of magnitude. Slightly above the density limit, the neutron signal, whose intensity is weaker, shows the same behavior while the hard-x-ray emission decreases appreciably during the rf pulse. The two emissions are due to electrons of different energies accelerated by the dc electric field and escaping from the plasma column. For an appreciable photoneutron production, electrons with energy ϵ_e in the range 14 to 25 MeV are requested[9] while for hard x rays lower energies (>500 keV) are sufficient.

The different behavior of the two signals can be explained if for $\epsilon_e \sim 15$ MeV a mechanism is present which depletes the higher-energy population and avoids further acceleration by the inductive dc electric field. Indeed, the anomalous Doppler resonance on the primary LH waves is acting on the relativistic electrons at this energy. In fact, the resonance

$$\omega - l\omega_{ce} = k_\parallel v_\parallel ,$$

when we take $l = -\mathrm{sgn}(k_\parallel)$, $\omega_{ce} = \omega_{co}/\gamma$ with γ the relativistic enhancement factor, and $v \simeq c$, becomes

$$\gamma = (\omega_{co}/\omega)(|n_\parallel| \pm 1)^{-1} \tag{1}$$

with $n_\parallel = k_\parallel c/\omega$. For the $l = +1$ resonance and the considered values of B_0 and ω, we obtain (for $\epsilon_e \simeq \frac{1}{2}\gamma$ MeV)

$$10 \lesssim \epsilon_e \lesssim 20 \quad \text{for} \quad 1.2 < n_\parallel < 3. \tag{2}$$

In order to study the effect of the relativistic anomalous Doppler resonance we use a model for velocity-space diffusion of quasilinear type. Since the high-energy electron population is very weak, **the effect on the primary LH waves by this mechanism is negligible. The quasilinear model instead is** used to describe the perpendicular scattering of the relativistic electrons. In the relativistic velocity space $\vec{u} = \vec{P}/m_0 = \vec{v}\gamma$ with $\gamma = (1 = u^2/c^2)^{1/2}$, the following relativistic diffusion equation is derived:

$$\frac{\partial f}{\partial t} = \int dk_\parallel \left[\frac{\omega_{co}}{u_\perp}\frac{\partial}{\partial u_\perp} - k_\parallel \frac{\partial}{\partial u_\parallel}\right] \mathscr{D} \left[\frac{\omega_{co}}{u_\perp}\frac{\partial f}{\partial u_\perp} - k_\parallel \frac{\partial f}{\partial u_\parallel}\right] \tag{3}$$

with

$$\mathscr{D} = \sum_{l=\pm 1} \frac{\pi}{k_\perp^2} \frac{e^2|\tilde{E}|^2}{m_o^2} W(k_\parallel) J_1^2\left(\frac{k_\perp u_\perp}{\omega_{co}}\right) \delta\left(\omega - k_\parallel v_\parallel - \frac{l\omega_{co}}{\gamma}\right). \tag{4}$$

In this equation $|\tilde{E}|$ is the wave field intensity and $W(k_\parallel)$ the $k_\parallel$ spectrum normalized as $\int dk_\parallel\, W(k_\parallel) = 1$. The index o refers to the electron rest mass and $k_\perp$ is related to $k_\parallel$ via the dispersion relation for LH waves in a cold plasma.

By solving numerically Eq. (3) in the region of the $l = 1$ resonance, we study the time evolution of the distribution f. Initially, when rf is switched on, f is taken constant with $u_\parallel$ in the range of interest, i.e., $20c < u_\parallel < 40c$ according to Eq. (2) for the $l = 1$ resonance. The perpendicular spread of f is taken initially as $\Delta u_\perp \ll u_\parallel$. Equation (3) describes the increase of this spread in time and the depletion of f at $u_\parallel \gtrsim 30c$, having kept constant f for $u_\parallel < 20c$. The effect of momentum scattering and energy isotropization is represented by the tendency of f to become constant on the diffusion curves

$$\eta \equiv \gamma - (\omega/\omega_{co})(u_\perp^2/2c^2) = \text{const}, \tag{5}$$

where η commutates with the operator $[\omega_{co}\partial/u_\perp \partial u_\perp - k_\parallel \partial/\partial u_\parallel]$ in Eq. (3).

Numerical calculations of Eq. (3) show the time evolution of the constant-f curve in Fig. 2(a) in the $u_\perp, u_\parallel$ plane. The corresponding behavior of $F(u_\parallel) = \int du_\perp u_\perp f(u_\perp, u_\parallel)$ is shown in Fig. 2(b) at different times.

In the above calculation the $\eta_\parallel$ spectrum is assumed to have a triangular shape between $n_\parallel = 1.2$ and 3 with its maximum at $n_\parallel = 1.2$. The typical electrostatic wave field $\tilde{E}$ is taken to be 3 kV/cm. This figure for $\tilde{E}$ is consistent with the expectations

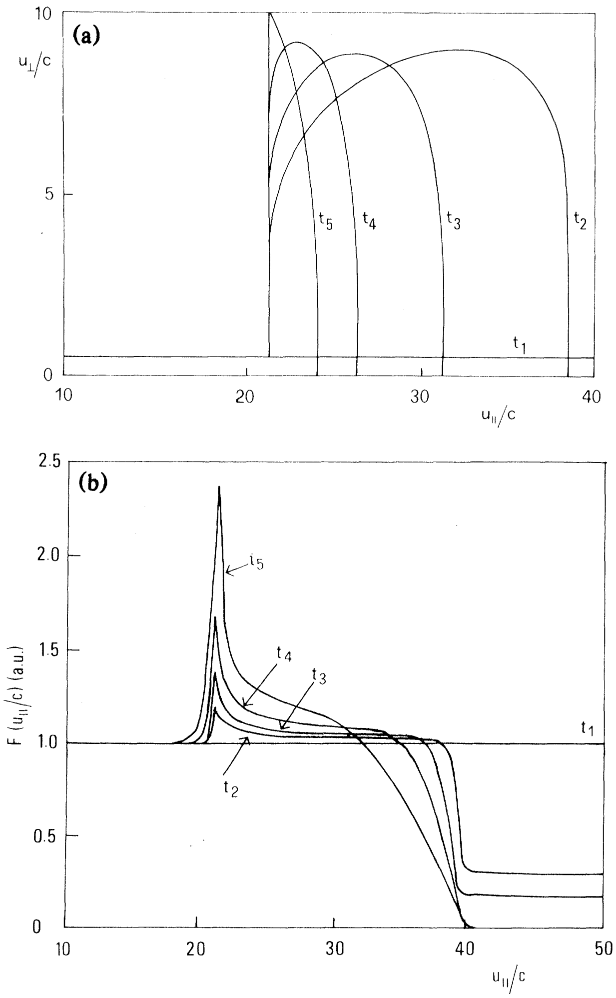

FIG. 2. Time evolution of the electron distribution function for resonating relativistic electrons. (a) Level curves of $f = \text{const}$. (b) Behavior of $F(u_\parallel) = \int du_\perp u_\perp f$. The labels 1 to 5 correspond to time $t = 0$ (rf switch on time), 0.3, 1.2, 5.0, and 20 ms.

of the wave field in the FT plasma, for a coupled rf power ~ 150 kW. If higher $\tilde{E}$ fields are present as a result of convergence of the wave trajectories,[10] the effect described here is even faster. The above numerical results show that the effect of perpendicular pitch-angle scattering described by Eq. (3) is sufficiently strong after 5 ms [Fig. 2(b)]. Thus having neglected the dc E_0 term in Eq. (3) is justified, the typical free-fall acceleration being in FT about (1 MeV)/(12 ms).

The results of Fig. 1 can be interpreted as follows: In both cases of Fig. 1 the anomalous Doppler resonance on the launched LH waves strongly reduces the number of electrons with energy larger than 15 MeV (where $u_\parallel/c = 30$). Consequently the neutron emission is extinguished when rf is switched on. This also is responsible for the initial fall of the hard-x-ray signal in Fig. 1(a) and for the reduction of the same signal in Fig. 1(b) during the rf pulse. Moreover, when $\bar{n}_e < \bar{n}_{\text{limit}}$, the resonance $l = 0$ is also very effective in producing an electron tail up to ~ 300 keV. This value is calculated from the accessibility limit of the $n_\parallel$ spectrum and it agrees with the relativistic shift of the $2\omega_{ce}$ enhanced emission.[2,8] Also an enhancement of the runaway population at higher energy is produced by the dc field E_0 since the critical Dreicer energy is much below 300 keV. This enhancement can justify the further increase of hard-x-ray signal during the rf pulse shown in Fig. 1(a) whose rise time is consistent with the free-fall acceleration time up to energy ~ 10 MeV. When n_e is above the threshold, the $l = 0$ resonance becomes very weak[7] (a typical feature of current-drive experiments not yet understood). The total number of runaways is not affected by this interaction while the $l = 1$ resonance is still effective as observed in Fig. 1(b).

In conclusion, the experimentally different behavior of hard-x-ray and neutron emissions is interpreted by a mechanism based on the anomalous Doppler resonance. This has been shown to agree with the characteristic time and the energy range resulting from the experiments and to be efficient also above the density limit for electron heating or current-drive interactions.

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