Measurement of the Time Constants of Fast Electron Distributions in the Tore Supra Tokamak

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The fundamental phenomena governing the dynamics of anisotropic electron distributions in a tokamak plasma are investigated. A fast electron tail driven by modulated pulses of lower-hybrid waves is analyzed by a combination of three diagnostics, i.e., hard x rays, electron-cyclotron emission, and transmission. Three different time constants, characterizing radial diffusion, collisional friction, and pitch-angle scattering, respectively, are identified. Two distinct relaxation regimes are observed, related to the degree of anisotropy of the electron distribution.

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Several important regimes of tokamak operations involve non-Maxwellian plasmas [1–3], driven by dc electric fields or by high-power additional heating. One of the most typical examples of non-Maxwellian distributions of interest for controlled nuclear fusion research is the anisotropic tail of superthermal electrons with a large velocity component parallel to the confining magnetic field. Besides the specific driving force, the dynamics of such distributions is believed to be governed by both Coulomb collisions and fine-scale turbulence inducing radial transport. Effects due to these two classes of phenomena are usually difficult to separate. Global quantities (e.g., the runaway production rate or the total plasma current driven by rf waves) are often found to behave in general agreement with the kinetic theory of tail formation and sustainment [1,2]. More challenging is the experimental investigation of the elementary behavior of the distribution function due to the basic phenomena involved: radial diffusion and the different components of the collisional velocity-space flux, i.e., dynamical friction and pitch-angle scattering. Such measurements are difficult, since the phase space in which these phenomena occur is intrinsically three dimensional (in configuration space, the coordinate r corresponding to the minor radius of the torus; in momentum space, the parallel and perpendicular components with respect to the magnetic field, $p_\parallel$ and $p_\perp$). Therefore, measurements should be able to resolve simultaneously in time and in such a 3D phase space, while separating effects due to the driving force from the more basic collisional and diffusion processes. We describe here an experimental procedure used to realize such a program in the Tore Supra tokamak [4]. The method is based on rf-power modulations with pulses of variable lengths. The long pulses are used to study the radial diffusion time, which is measured by means of energy and space resolved hard x-ray spectrometry. The relaxation phase following the end of the power pulses yields information on short time scales (the collisional ones); this phase is observed by electron cyclotron emission (ECE) and absorption (ECA) diagnostics, at the second and first harmonic, respectively. For a long parallel tail, the emission and the absorption coefficients at the nth cyclotron harmonic are proportional to $F_\parallel T_\perp^n$ and $F_\parallel T_\perp^{n-1}$, respectively [5], where $F_\parallel(p_\parallel)$ is the parallel distribution function (i.e., integrated over the perpendicular momenta) and $T_\perp(p_\parallel)$ is the perpendicular energy. Thus, the simultaneous use of these two diagnostics yields information on both parallel and perpendicular momentum-space dynamics. By means of this set of diagnostics, it has been possible to measure all the relevant time constants of an anisotropic fast electron distribution, for the first time, in a tokamak plasma. The identification of the physical phenomena corresponding to each time scale implies a comparison with detailed theoretical models, in this case with the 3D kinetic theory of the tail formation and relaxation in the presence of Coulomb collisions, radial diffusion, rf waves, and dc electric field. This has been performed using a sophisticated computational model including a 3D time-dependent Fokker-Planck code (for the evaluation of the electron distribution function), coupled to a radiation code for the evaluation of the corresponding ECE and ECA outputs in a realistic geometry [6]. This comparison demonstrates that in a large machine the relaxation of fast electrons is dominated by Coulomb collisions, in contrast with small tokamaks, where radial diffusion plays a comparable or even dominant role [7]. The interest of this study goes well beyond the field of lower-hybrid current drive, from the point of view both of the experimental technique and of the physical results. The method of combined ECE-ECA for vertical propagation can be applied to other current drive schemes, such as fast wave or electron cyclotron current drive [2]. Furthermore, the peculiar behavior of superthermal electrons is often exploited to probe more general properties of the plasma. For instance, measurements of the radial diffusion of fast electrons have been used to determine the level of magnetic turbulence in the plasma [8], or to detect the presence of large-scale magnetic islands in strongly stochastic regimes [9]. The experimental validation of the basic kinetic theory of fast electron tails in hot plasmas

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is an important step for the further use and extension of such techniques. It is also of relevance for other fields in which superthermal electrons play a central role, such as, e.g., reversed-field pinch configurations [10], where Fokker-Planck models are the essential analysis and prediction tools of the plasma equilibrium [11].

These experiments have been carried out in Tore Supra [4], the largest existing tokamak device equipped with superconducting magnetic field coils ($R = 2.38$ m, $a = 0.78$ m, $B \approx 3.9$ T, circular cross section), in helium discharges ($Z_{\mathrm{eff}} \approx 2.5$ and radially constant). During the flattop of the plasma current ($I_p = 0.8$ MA for 12 s), the lower-hybrid (LH) power (two couplers globally delivering 2.2–2.5 MW at 3.7 GHz, wave spectrum centered at $n_{\parallel} \approx 1.8$) was modulated in two 4 s and five 250 ms pulses, separated by 100 ms intervals. The two couplers are switched on and off simultaneously, within a time shorter than the time resolution of the ECA and ECE diagnostics. During the LH phase, the loop voltage is as low as 0.1–0.2 V, undergoing oscillations of approximately a factor of 2 when the power is turned on and off. The most precise ECA measurements were performed at low-to-medium densities [$n_e(0) \approx (2-3) \times 10^{19}$ m^{-3}], corresponding to electron temperatures of the order of 6–8 keV during the LH phase. The electron density varies little during the power pulses; its measured variations at the switching on/off are slow compared to the relaxation phenomena measured by the ECE and ECA diagnostics [12]. The experimental setup now used on Tore Supra for diagnosing superthermal electrons is the most complete system of this type. It consists of the following: (i) hard x-ray emission (HXE) [13], probing a poloidal cross section of the plasma along five different chords, from the plasma center to $r/a \sim 0.7$ (multichannel spectrometers operating between 50 and 500 keV; time resolution $\gtrsim$20 ms); (ii) microwave transmission [12] at the electron gyrofrequency ω_{ce} (ordinary mode, vertical propagation through the magnetic axis, frequency range 77–109 GHz, corresponding to resonant energies below 180 keV; time resolution 0.5 ms); (iii) ECE [14] (extraordinary mode, second harmonic, six Fabry-Pérot interferometers, corresponding to six poloidal views; time resolution 0.5 ms).

The slowest time evolution is observed in the HXE, whose dynamics is closely linked to that of the pitch-angle integrated distribution function. Figure 1(a) shows the time evolution of the HXE signal at $E = 175$ keV on a central chord during a long power pulse, together with the values of the line-averaged density, LH power, and loop voltage. Figure 1(b) shows the HXE as a function of the radial position of the five chords, at $t \approx 5.5$ ms (when both density and loop voltage have become stationary) and 2 s later. After a short initial phase, a slow and persistent flattening of the radial HXE profile is observed. Although small, this effect is systematically found in many different plasma conditions, which allows us, by a statistical study, to rule out various possible interpretations. This slow relaxation cannot be attributed to a modification of the electron temperature or density profiles; it cannot be reconciled either with the diffusion of the residual electric field, since a temperature scan shows no correlation with the behavior of the resistivity. It is therefore attributed to radial diffusion of the fast electrons: The flattening of the measured profile is consistent with a radial diffusion time of 2 ± 1 s.

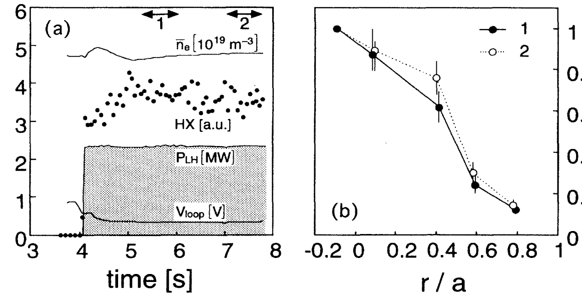

FIG. 1. (a) Time evolution of LH power, V_{loop}, line-averaged density, and HXE at $E = 175$ keV for a central chord. (b) HXE at $E = 175$ keV (normalized to the maximum value) for the five chords at $t \approx 5.5$ s (full circles) and $t \approx 7.5$ s (open circles).

The relaxation properties of $F_{\parallel}$ are measured by the ECA diagnostic at seven different frequencies, covering the energy range 60–165 keV. After correcting for refraction [12], the ratio of the transmitted power in the presence of the plasma and in vacuum P/P_v yields the optical depth τ_0 along the propagation chord. The quantity $F_{\parallel}^* = \tau_0[(\omega_{ce}/\omega)^2 - 1]^{1/2}$ is, with good approximation, proportional to the line-averaged value of $F_{\parallel}$ [5,12], at the resonant energy $E = mc^2(\omega_{ce}/\omega - 1)$. A typical example of $F_{\parallel}^*$ as a function of time, measured by the ECA diagnostic at $E = 124$ keV, is shown in Fig. 2(a). The signal is stationary for $t < 0$ and decays within 20 ms after the power is turned off (at $t = 0$). It is found that the signal can be fitted by a linear combination of two exponentials of the form $\exp(-t/\tau_r)$, with time constants equal to 2 and 6.5 ms, respectively, whereas no satisfactory fit can be found with a single time constant. Similar results (with different values of the constants) are obtained for lower energies, whereas a single time constant is unequivocally measured beyond 130 keV. These findings are summarized in Fig. 3(a), where τ_r is plotted versus energy. Two distinct regimes of relaxation are clearly observed, governed by two and one time constants, respectively, merging at $E \approx 130$ keV. A clue to the interpretation of this threshold is given by the full ECA spectrum, measured in the steady-state phase ($t < 0$) by sweeping the wave frequency, and shown in Fig. 3(b). This spectrum displays full absorption by both the thermal background plasma (below 60 keV) and an optically gray part (above 80 keV), due to absorption by the superthermal tail. As is known [12], the minimum of the

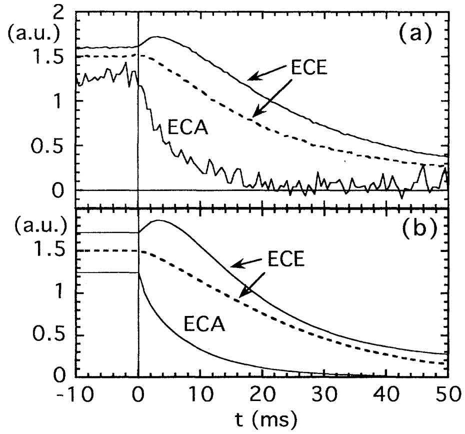

FIG. 2. Time evolution of the ECE (solid line: 160 GHz; dashed line: 120 GHz) and ECA ($E = 124$ keV) signals. (a) Experiment; (b) theory.

superthermal part of the spectrum corresponds to the transition between the plateau of $F_{\parallel}$ (namely, the part of the tail directly sustained by the LH waves) and the slowly decaying tail beyond it. The threshold between the two regimes appears related to such a transition.

A deeper insight into the relaxation problem is gained from the ECE measurements, performed in the frequency range 120–160 GHz. The energy resolution is rather coarse: At 160 GHz the resonant electrons are in the range 0–300 keV, whereas at 120 GHz the range is 200–500 keV. Because of wall reflections, the six poloidal views cannot be used to resolve the measurement radially: All of them give similar information, which is rather related to velocity-space effects. On the other hand, the excellent signal-to-noise ratio and time resolution of the Fabry-Pérot setup allow precise measurements of dynamical phenomena, which is the goal of this study. The ECE signals at 160 and 120 GHz are shown in Fig. 2(a) (solid and dashed lines, respectively), and appear to decay more slowly ($\tau_r \sim 20$ ms) than the ECA. Moreover, at 160 GHz the early phase of the relaxation, corresponding to the faster decay rate of the ECA signal, displays a systematic enhancement; in the worst cases, the increase is 10 times larger than the noise level. The effect is too fast to be attributed to changes in the density or in the loop voltage. At 120 GHz the resonant electrons are well beyond the maximum energy of interaction with the LH wave spectrum, and the enhancement is never observed. At intermediate frequencies, the signals are intermediate between those presented in Fig. 2(a). The evident correlation between the increase of the ECE signal (which is roughly proportional to $F_{\parallel}T_{\perp}^2$) and the rapid decay of $F_{\parallel}$ suggests a mechanism of fast redistribution of the kinetic energy from the parallel into the perpendicular degree of freedom.

In order to identify the phenomena governing the different time scales of the relaxation process, we have carried out extensive time-dependent Fokker-Planck simulations. A typical example of a distribution function in the stationary phase is shown by the dashed curves of Figs. 4(a) and 4(b) ($F_{\parallel}$ and $T_{\perp}$, respectively). This distribution is compatible with the injected LH spectrum and reproduces the measured values of both the total plasma current and the ECA spectrum. This distribution is taken as an initial condition and the relaxation due to Coulomb collisions is computed, in the presence of a radially constant dc electric field ($V_{\text{loop}} = 0.2$ V). Note that simple estimates based on the slowing-down equations show that the values of the electric field measured in steady state ($\sim 10^{-2}$ V/m), or those expected during the transient phases (up to a factor of 2 higher), are too low to have an impact on short time-scale phenomena (<30 ms). The computed $F_{\parallel}$ and $T_{\perp}$ are presented in Fig. 4, at different times. Figure 4(a) demonstrates that isotropization is the fastest process: In the first 10 ms the positive velocity side of the tail has relaxed, whereas the negative side is unchanged. The relaxation then continues on both sides at a slower rate. At the same time, the perpendicular temperature increases in

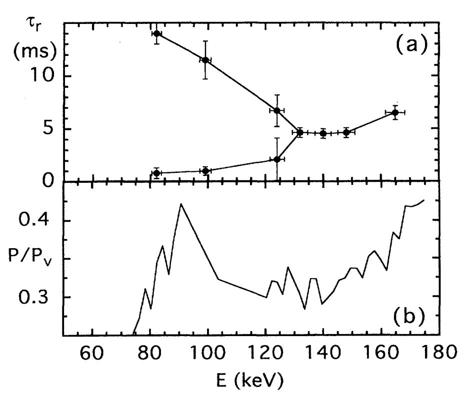

FIG. 3. (a) Measured relaxation time vs energy. (b) Measured ECA spectrum in steady state.

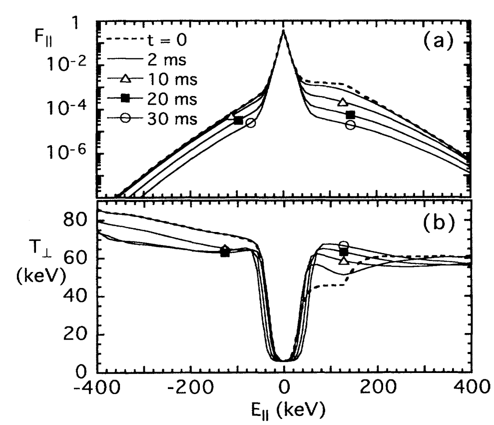

FIG. 4. Computed distribution function during the relaxation. (a) $F_{\parallel}$; (b) $T_{\perp}$.

the plateau region (where the anisotropy was maximum), but changes little beyond the plateau, where the distribution was already, to a large extent, isotropic. These results provide a qualitative explanation of all the features experimentally observed, i.e., (i) the presence of two time constants in the plateau region, clearly related to isotropization (due to pitch-angle scattering) and slowing down (due to dynamical friction); (ii) the single relaxation rate observed beyond the plateau, where, since the beginning, the distribution is nearly isotropic (being dominated by collisions); (iii) the enhancement of the ECE signal at 160 GHz, due to the increase of $T_\perp$ in the plateau region; and (iv) the lack of enhancement at 120 GHz, since in this case the resonant electrons are beyond the plateau. In order to show that the agreement is also quantitative, the computed distribution is used to evaluate both the emitted and the transmitted spectra, by means of a radiation code including ray tracing. Examples of the results are shown in Fig. 2(b), to be compared with the corresponding experimental curves of Fig. 2(a). A systematic agreement is found in the dynamical behavior of the ECA signals: The threshold between the two regimes is found at 130 keV, as in the experiments. The early phase of the relaxation of the ECE signals is also well reproduced; however, at later times ($t > 30$ ms), the theoretical curve drops somewhat faster than the experimental one. This is due to the increase of the electric field inside the plasma when the rf power is turned off. Using $V_{\rm loop} = 0.4$ V, excellent agreement is found during the whole relaxation phase ($0 < t < 100$ ms).

In conclusion, an experimental procedure has been developed to investigate the dynamics of a fast electron distribution in its natural phase space, i.e., in three dimensions (r, $p_\parallel$, and $p_\perp$). For a large tokamak, such as Tore Supra, the radial and momentum-space time scales turn out to be separated by at least an order of magnitude, which allows a clear identification of the different phenomena involved. The relaxation of the electron distribution is found to be governed by collective effects, since the relaxation times depend on the degree of anisotropy of the distribution itself. Two different relaxation regimes are observed for electrons in the plateau (namely, in direct interaction with the LH waves) and at higher energies, where the distribution is governed by collisions (with a weak effect of the electric field). As a consequence of such findings, some ideas and methods currently used in theoretical modeling should be revised: For instance, this investigation has revealed the importance of the perpendicular dynamics in the current drive process, which is often neglected in numerical simulations, although its importance was recognized since early theoretical works [2]. The theoretical models validated by these experiments have been used to investigate the applicability of the combined vertical ECA-ECE technique to other current drive schemes, more relevant to reactor applications, such as fast wave or electron-cyclotron current drive [2]. Such methods make use of lower resonant velocities (1–2 and 3–4 times the thermal velocity, respectively). Extensive Fokker-Planck simulations performed for typical Tore Supra parameters show that, by using the ordinary mode at the second harmonic, the contribution of such mildly superthermal electrons is predicted to be measurable and an analysis of the time constants similar to that discussed in this paper should be possible. More generally, the results of the present work constitute a firm basis for the use of experimental techniques involving transient fast electron phenomena.

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