31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-5.126 (2004)

On electron cyclotron current drive near low order rational magnetic surfaces in tokamaks *

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1. Introduction

One of the main scenarii for the stabilization of neoclassical tearing modes (NTM) in tokamaks uses electron cyclotron resonance heating (ECRH) or electron cyclotron current drive (ECCD) localized around the low order rational magnetic surface where the NTM is developing. As it has been pointed out in Ref. [1], ECRH and ECCD in the vicinity of low order rational magnetic surfaces have a peculiarity which can be summarized as follows: In the usual case where the cyclotron interaction is localized over toroidal and poloidal angles in a narrow region of the microwave beam, the relaxation of the distribution function due to the parallel motion of electrons along field lines is not anymore much faster than the relaxation of the distribution function in velocity space. As a result, the distribution function remains inhomogeneous on the magnetic surface even if it is expressed through the integrals of motion. This means, in particular, that the usual two-dimensional bounce-averaged quasilinear kinetic equation cannot be applied in a certain vicinity of the rational magnetic surface.

2. Formulation of the problem

The dominance of velocity space relaxation over parallel relaxation is especially strong in the case of microwave beams propagating in the tokamak mid-plane. The width of the resonance zone in velocity space is determined either by the spectral broadening of the resonance line due to the finite parallel beam width, L_b, or due to the nonlinear effects coming from the change of the relativistic gyro-frequency caused by electron energy modification by the wave. This gives, respectively, the following estimates of the resonance zone width over the perpendicular velocity, $v_\perp$,

$$\Delta v_{\perp,L} \sim \frac{c^2 v_\parallel}{\omega L_b v_\perp}, \qquad \Delta v_{\perp,NL} \sim c\sqrt{\frac{E_0}{B_0}}. \tag{1}$$

Here, c, E_0 and B_0 are the speed of light, the amplitude of the wave electric field and of the main magnetic field, respectively, and the relation for $\Delta v_{\perp,NL}$ is valid for the 2-nd harmonic resonance with the extraordinary mode (X-mode). Practically, both values (1) are in the same range [2]. If $\Delta v_{\perp,L} \gg \Delta v_{\perp,NL}$, the change in the derivative of the distribution function, f, with respect to the energy of the perpendicular motion, $w_\perp = m_e v_\perp^2/2$, where m_e is the electron mass, is small, and,

*This work has been carried out within the Association EURATOM-ÖAW and under Contract No. P16157-N08 with the Austrian Science Foundation. The content of the publication is the sole responsibility of its authors and does not necessarily represent the views of the commission or its services

therefore, linear theory is applicable. In the opposite limiting case, this change is strong such that in the resonance zone f becomes symmetric around the resonant value of $w_\perp$, see Ref. [2]. Coulomb collisions destroy these changes and restore the Maxwellian distribution after a finite number of toroidal turns [1],

$$N_t \sim \frac{(\Delta v_\perp)^2 v_\parallel}{2\pi R \nu_c v^2}, \tag{2}$$

where R and ν_c are the tokamak big radius and the collision frequency, respectively. E.g., for parameters typical for ASDEX Upgrade, $R = 165$ cm, $B_0 = 22$ kG, $L_b = 3$ cm, density $n_e = 6 \cdot 10^{13}$ cm^{-3} and electron temperature $T_e = 5$ keV, assuming $v_\parallel \sim v_\perp \sim v \sim 2(T_e/m_e)^{1/2}$ one obtains $\nu_c \sim 5 \cdot 10^3$ s^{-1} and $N_t \sim 4$ when using $\Delta v_{\perp,L}$ or $N_t \sim 15$ when using $\Delta v_{\perp,NL}$ with an ECCD power $P_b = 500$ kW.
The number of toroidal turns on an irrational magnetic surface which an electron typically makes before re-entry into the beam is $N_r \sim 2\pi r/L_b$ where r is the small radius. For $r = 20$ cm one obtains $N_r \sim 40 > N_t$, i.e., the relaxation of the distribution function is strong. However, if the value of the safety factor is close to a low order rational number,

$$q = \frac{M}{N} + \Delta q, \qquad \Delta q \leq \Delta q_{cr} = \frac{q L_b}{2\pi r N}, \tag{3}$$

a significant fraction of particles leaving the beam can re-enter it at least once after $M \ll N_r$ turns with almost the same distribution function as they had when leaving the beam. Therefore, even if the wave-particle interaction is linear, but $\Delta q \ll \Delta q_{cr}$, small changes of f accumulate and may lead to the formation of a quasilinear plateau on the distribution function in the resonance zone, leading to a degradation of absorption. If the interaction is nonlinear, $\Delta v_{\perp,L} \leq \Delta v_{\perp,NL}$, the nonlinear plateau is formed with the same effect on absorption [2] immediately after a few first passings through the beam. The degradation of absorption does not require a strong inequality $\Delta q \ll \Delta q_{cr}$ in this case.

3. Computational results

For the computation of power absorption and current drive, the electron distribution function is modeled using the Monte Carlo method described in Ref. [2] for a simple geometry of the main magnetic field. In the present work, a more realistic geometry of a tokamak with circular magnetic surfaces is used for modeling test particle orbits outside the microwave beam. A Gaussian wave beam with circular cross-section propagating in the mid-plane is considered. Its parameters are calculated with the help of the beam-tracing code TORBEAM [3]. Whenever a test particle is crossing the beam, its perpendicular velocity is modified using the method of Ref. [2] ignoring the magnetic field inhomogeneity along the field lines within the beam. The values of the main magnetic field and of the wave amplitude are taken in the point where the maximum of the beam electric field is achieved along the orbit when crossing the beam. For all computations, off-axis second harmonic X-mode ECCD with beam launched in the mid-plane from the low field side at an angle $\phi_{inj} = -10^o$ is considered. The resonance region is located at the high field side. Beam and plasma parameters are those from ASDEX Upgrade, see above. In addition to that "high

density" case, also computations are done for the "low density" case with density being reduced by a factor of 6 and temperature being increased by a factor of 3.
The results of modeling shown in Fig. 1 demonstrate the reduction of the absorbed power density, p, and of the generated current density, $j_\|$, around a rational magnetic surface with $q = 3/2$. In the "high density" case the quasilinear distortion of the electron distribution function is small on irrational surfaces and the results there are close to those given by linear theory. As discussed above, in the region where q satisfies the inequality (3) (boundaries of this region are shown with dashed-dotted vertical lines in Fig. 1) the absorbed power and the current density are reduced. In the "low density" case the quasilinear degradation of the absorption and the current drive is significant also on irrational magnetic surfaces. Also in this case, the degradation is stronger around the rational magnetic surface.
As shown, e.g., in Ref. [4], current profile modifications by ECCD can have a strong effect on the tearing mode stability index, Δ'. To estimate this effect in case of ECCD current profiles shown in Fig 1b, the equation for the resonant harmonic of the perturbed poloidal flux, ψ_m, in zero order with respect to toroidicity [5],

$$\frac{\mathrm{d}}{\mathrm{d}r} r \frac{\mathrm{d}\psi_m}{\mathrm{d}r} - \frac{m^2}{r}\psi_m - \frac{mq\psi_m}{m - nq}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\frac{r^2}{q}\right) = 0, \tag{4}$$

is solved numerically. The following function can be constructed from two solutions of Eq. (4) which satisfy boundary conditions on the plasma axis and on the infinitely conducting wall, respectively,

$$D'(x) = \frac{\psi'_m(r_s + x)}{\psi_m(r_s + x)} - \frac{\psi'_m(r_s - x)}{\psi_m(r_s - x)}, \tag{5}$$

where r_s is the small radius of the resonant magnetic surface. The tearing mode stability index is given as $\Delta' = D'(0)$. The dependence of D' on x demonstrates the influence of different regions on the current profile on the value of Δ'. As Fig. 2 shows, the presence of a relatively small dip on the current profile near the rational surface changes the sign of Δ' to the opposite as compared to the profile following from linear theory which is without a dip. Thus, co-current drive becomes destabilizing and counter-current drive becomes stabilizing. This conclusion, however, shows only the tendency in the considered parameter range because the effect of the cross-field radial transport of current-carrying electrons is not taken into account in the computation. Roughly, radial transport would smear the current over the radial scale $\delta r \sim (D_\perp/\nu_c)^{1/2}$ where ν_c is the collision frequency for supra-thermal resonant electrons. The process of radial relaxation of current carriers occurs on a much longer time scale (of the order of the current destruction time) than the process of plateau formation which takes place on a time scale of the order of collisional diffusion time across the narrow resonance zone in velocity space.

4. Conclusions

The modeling for ASDEX Upgrade parameters shows that, in the vicinity of low order rational magnetic surfaces, the quasilinear effect leads to the formation of a plateau on the electron distribution function and a consequent reduction of power absorption and generated current there. The presence of a resulting dip on current profiles can change the sign of the tearing mode stability index, Δ', to the opposite as compared to the profile following from linear theory which is without a dip. However, practically interesting cases where the effect of the reduction of ECCD current near rational surfaces can influence the tearing mode stability index are still to be found. The possible existence of such cases could provide a method for NTM stabilization which does not need an active control of the ECCD current profile. Indeed, if a rather broad radial profile of the ECCD current is created, it can cover the whole region where the low order rational surface is expected, and the dip on the current profile is automatically formed around this surface with no need of an accurate current profile control.

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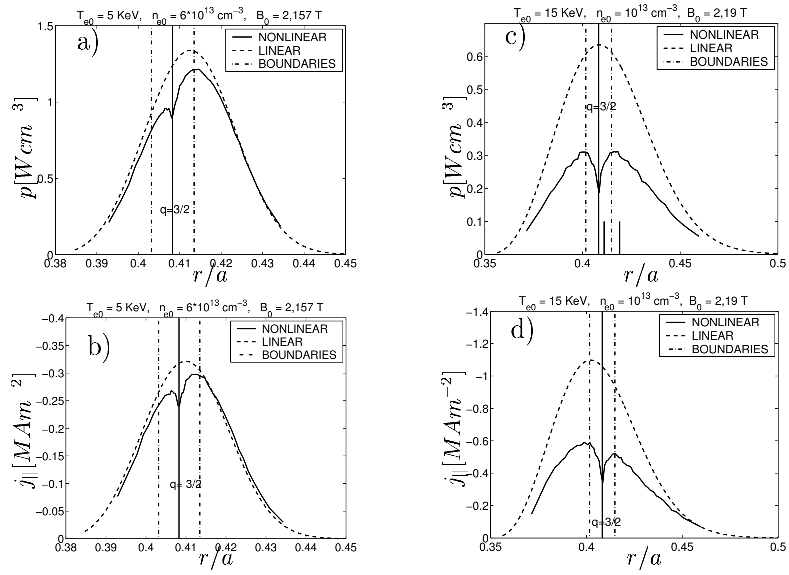

Figure 1: Absorbed power density p (a and c) and parallel current density $j_{\parallel}$ (b and d) versus dimensionless radius r/a.

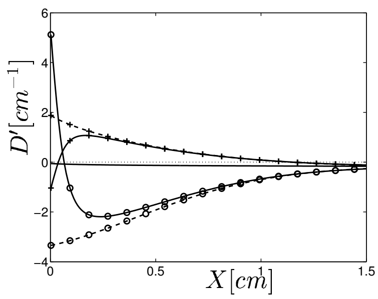

Figure 2: Function $D'(x)$ for the linear model (dashed) and the nonlinear model (solid) without current drive (no marker), with co-current drive (circles) and with counter-current drive (crosses).