DYNAMIC MODELLING OF TEARING MODE STABILIZATION BY RF CURRENT DRIVE

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1. Introduction

The localized absorption of radio-frequency waves has been proposed by a number of authors as an effective means of controlling tearing modes in tokamak plasmas. Here, the potentially most efficient method of this kind is investigated, i.e., modulated current drive inside the magnetic islands. Since power modulations are expected to be an important factor of optimization, the study of the impact of time-dependent phenomena on the stabilization efficiency is justified. At least three basic effects of this type can be identified. First, non-inductive current drive is not an instantaneous effect, because the driven current is due to a superthermal electron tail that builds up as a consequence of velocity-space diffusion induced by the RF waves. This takes at least a typical kinetic time τ_c, related to the collision time of the current-carrying electrons, which can easily be of the same order as the island rotation period (a fraction of, or a few ms). A second effect is related to the inductive response of the plasma (back emf). On short time scales, the back emf provides the stabilizing mechanism, but in general this induced electric field must be evaluated self-consistently with the fast electron distribution function. The third effect is related to the dynamic interplay of power modulations and island rotation.

2. Dynamic model

The stabilization problem is addressed by numerically solving the appropriate time-dependent kinetic equation for the electron distribution function $f(p_{||}, p_{\perp}, \rho, t)$ (**p** is the electron momentum, ρ the normalized radial coordinate and t the time). Since the back emf plays a central role, the kinetic equation must be coupled to an evolution equation for the induced electric field (resistive diffusion equation). This procedure yields the appropriate, time-dependent source term to be used in the island evolution equation [1,2]:

$$\frac{dw}{dt} = \frac{k_R}{\sigma\mu_0}\left[\Delta' + \Delta'_\beta + \Delta'_{CD}\right] , \quad \text{where} \quad \Delta'_{CD} = \frac{16\,\Delta'_{vac}}{n s_s q_a}\,\frac{I_{CD}}{I_p}\,\frac{a^2}{\Delta r^2}\,\frac{1}{\overline{w}^2}\,\eta_{CD} , \qquad (1)$$

w is the island width, k_R is a dimensionless numerical constant of order 1, and $\Delta'(w)$ is the conventional stability index for current driven tearing modes [1]. The finite-β term Δ'_β accounts for pressure effects (neoclassical modes). $\Delta'_{vac} = -2m/r_s$ is the *vacuum* Δ', m and n

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are the poloidal (θ) and toroidal (ϕ) mode number, respectively, s_s is the magnetic shear on the resonant surface $r = r_s$ where $q = m/n$, q_a is the safety factor at the plasma surface $r = a$, I_p is the total plasma current, I_{CD} is the time-dependent RF-driven current, Δr is the radial width of the RF-driven current channel and $\overline{w} = w/\Delta r$. The function η_{CD} has a complicated structure, depending both on the space and time behaviour of the rf source term and on the island width and rotation frequency. It is discussed in detail in Ref. [3].

3. Numerical results

Calculations are performed in a standard ITER equilibrium, for both Lower Hybrid (LH) and Electron Cyclotron Current Drive (ECCD), with assumptions of good coupling properties at the plasma edge (which for LH waves is non-trivial), a launching geometry inspired by the present version of the ITER antennas design [4], and the following parameters [5]: T_{e0} = 22 keV, $n_{e0} = 1.3 \times 10^{20}$ m^{-3}, R_0 = 8.14 m, a = 2.8 m, elongation κ = 1.6, I_p = 21 MA, B_0 = 5.7 T, Z = 1.6, P_{rf} = 50 MW. The m = 2 surface is assumed to be at $\rho_s \approx 0.8$, where $n_e(\rho_s) \approx 1.1 \times 10^{20}$ m^{-3}, $T_e(\rho_s) \approx 7.5$ keV. The wave propagation is computed by means of toroidal ray-tracing codes. The main wave parameters are: f = 5 GHz, $n_{||} \approx 2$, $\Delta n_{||} \approx 0.1$ (LH); f = 140 GHz, toroidal injection angle $\approx 30°$ (EC). Figure 1 illustrates the time evolution of the driven current, computed by means of a 3-D Fokker-Planck code [6], for LHCD (a) and ECCD (b), respectively. Note the large difference in efficiency (a factor of 7, mainly due to trapped electrons), the difference in time scale (a factor of 5, due to the different resonance velocities) and the different behaviour in the beginning of the evolution (the ECCD starts with the negative sign because of the Ohkawa current).

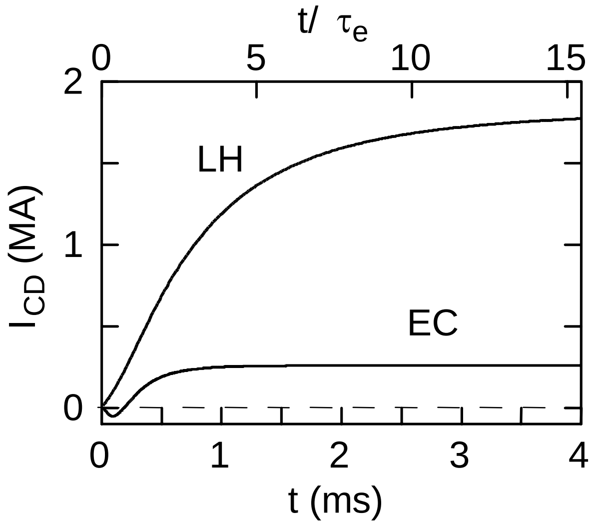

Fig. 1. time dependent non-inductive current, neglecting inductance effects, for 50 MW of LH or EC power. τ_e is the thermal electron colision time

The simultaneous solution of the Fokker-Planck and the electric field diffusion equations yields the space and time dependence of the induced electric field. In contrast with the results of Fig. 1, obtained without an electric field, the total current and also the current density profile now remain essentially constant. On the other hand, a large hole in the parallel electric field profile, initially constant, appears on a time scale much shorter than the resistive diffusion time, in the region where the waves are absorbed. For an ITER plasma, the island rotation frequency is expected to be of the order of the diamagnetic frequency in ohmic plasmas, i.e., 0.1 - 0.2 kHz, and much higher (of the order of a few kHz) in Neutral-Beam heated discharges. The computed electric field at ρ = 0.8, during a few modulation cycles at various values of the modulation frequency f_{mod}, is shown in Fig.2, in the case of LHCD. As the modulation frequency increases, the excursions of $E_{||}$ around an average value become smaller and smaller. If $f_{mod} > \tau_c^{-1}$, the stabilizing current perturbation would not attain its maximum value for a given wave power during the heating pulse. Thus, for high island rotation frequency, it is not possible to profit of the available power completely, in order to drive an as large as possible current at the island O-point.

The island width evolution equation (Eq. 1) is then solved, evaluating the current perturbation from the computed induced electric field and describing the angular dependence of the current source term by means of the model discussed in Ref. [3]. Neoclassical effects are neglected, and the case of a positive Δ' tearing mode is considered. Values of $\Delta' = (10/a)(1 - w/w_s)$ and $s_s = 1$ are considered, where w_s is the saturated island width (here, $w_s/a = 0.2$ is used). For both kind of waves, the current perturbation is assumed to be exactly centred at the resonant surface (i.e., at $\rho = \rho_s$), with a full radial width $\Delta\rho \approx 0.1$, in agreement with ray-tracing calculations. The island width evolution for 50 MW of LHCD, 50 % duty cycle square power modulations, is shown in Fig. 3. Complete stabilization of the m = 2 mode is eventually achieved; however, the model considered here is not strictly applicable to the vanishing island width limit, in which saturation effects related to transverse diffusion are expected to take place [3]. The dashed curve represents the ideal limit, in which the wave power stays centred at the island O-point: it is obtained by neglecting island rotation effects. If the island is allowed to rotate at the frequency f_{mod}, the stabilization becomes slower and dependent on f_{mod}, as shown by the two solid curves.

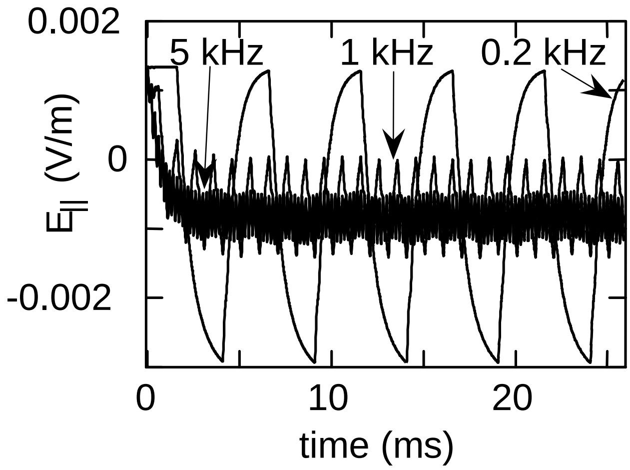

Fig. 2. computed electric field at ρ = 0.8, for LHCD at three different modulation

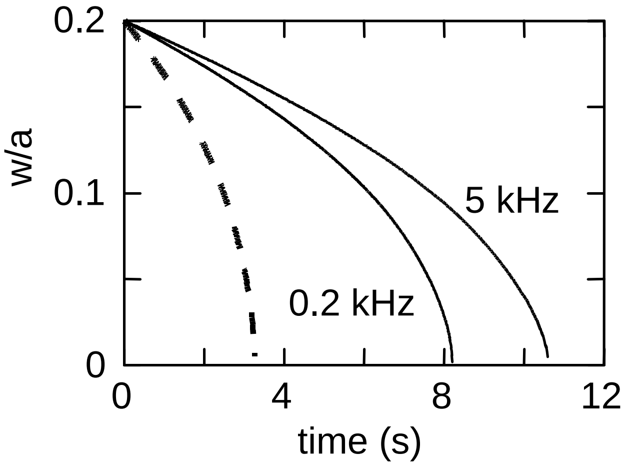

Fig. 3: time evolution of the normalized island for the parameters of Fig. 3. Ideal case no island rotation effects (dashed line); cases with different modulation (solid lines)

A comparison between ECCD and LHCD for the same wave power, modulation characteristics and f_{mod} = 0.2 kHz is shown in Fig. 4, assuming the same radial power deposition width. Despite the advantage related to the better angular localization of the ECCD, the time required for a full stabilization of the mode is much longer, because of the large difference in the CD efficiency. This suggests the possibility of using LHCD at a lower power level, in order to attain full stabilization in a time of the order of 30 to 40 s, comparable to the mode growth time.

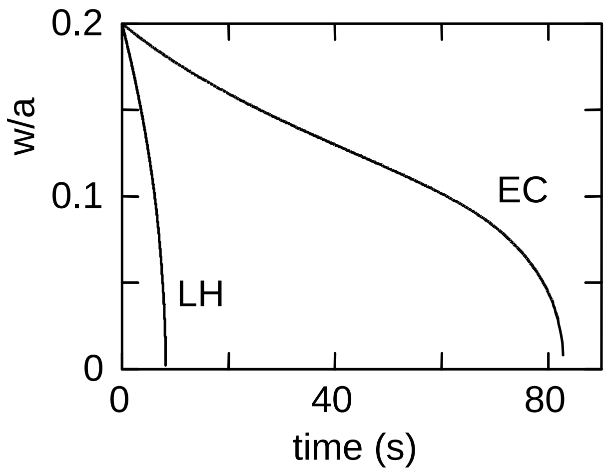

Fig. 4. time evolution of the normalized island width during LHCD and ECCD, for the same wave power (50 MW) and f_{mod} = 0.2 kHz

4. Conclusions

On the basis of the results presented in the previous sections, the potential of using RF current drive for tearing mode stabilization in a tokamak reactor can be discussed. As far as the comparison between LHCD and ECCD is concerned, a clear advantage in using LHCD (a factor of 7 in the CD efficiency), at least for ITER parameters, exists. Although in principle LHCD appears a more suitable method [7], its use in a reactor for this function is subject to many more uncertainties than ECCD. The main problem is that first-pass absorption in the region $\rho \approx \rho_s$ is critically dependent on the density and temperature profiles and the useful window is rather narrow for very flat density profiles. Moreover, a very narrow $n_{||}$ spectrum is required and must be accurately controlled, in order to centre the power deposition on the resonant surface with a good precision. These requirements are probably more easily satisfied by an ECCD system specifically dedicated to this task. In addition, the power deposition profile of EC waves is virtually independent of the density profile and the time response of ECCD, in the case of a modulated power input, is faster by a factor of 4-5.

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