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Electron Cyclotron Current Drive Control of Neoclassical Nonlinear Tearing Modes

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Abstract

An important role of ECCD is that of maintaining MHD-stable operation by a well localized current drive at the q = 2,3/2 surfaces to stabilize the m = 2, n = 1, m = 3, n = 2 tearing modes. In particular, we refer here to the Neoclassical Tearing Modes whose relevance for reactor-grade tokamaks has been pointed out as they could set the β limit of long pulse discharges well below the ideal limit. A way of controlling (or suppress) these modes could be to drive a non-inductive current in the island O-point replacing locally the missing bootstrap current and phasing the current relative to the rotating island by modulating the source. We address here this problem by retaining in the equation for island growth the stabilizing term of an auxiliary current and the associated heating. Evaluation of the driven current are made by a ray-tracing code as a result of the injection of focused multibeams. A quantitative assessment of the EC power required to keep the island width at a reasonable level is given. Consideration is given to different effects that may reduce the efficiency of the control and the benefits of the wall stabilization associated to the island rotation frequency.

Keywords:
tokamak, plasma instabilities, neoclassical tearing modes, electron cyclotron current drive

1. Introduction

In the present-day tokamak discharges the Neoclassical Tearing Modes (NTMs) with low number (m = 2, n = 1, m = 3, n = 2) can limit the high β operation scenarios and be disruption precursors [1,2]. Control and/or suppression of these modes are provided by using non-inductive off-axis current in the island O-point in order to replace locally the missing bootstrap current. The possible candidate is the Electron Cyclotron Current Drive (ECCD) because of its narrow and well localized power deposition profile, associated to an efficiency remaining acceptable also off-axis. Our objective here is to give a quantitative assessment of the EC power required to stabilize the NTM island width at a reasonable level below the saturated one. Evaluations for the ITER-Fusion Energy Advanced Tokamak (FEAT) and for a JET Enhanced (E)-like configuration, proposed as the machine closest to ITER plasma parameters, are given. Two launching schemes, through the equatorial and vertical ports, are considered for ITER, while only the equatorial rf injection is examined for JET, as shown in Fig. 1 [3]. Both the machines can match the key dimensionless parameters ε, β and q, being respectively the inverse aspect ratio, the poloidal beta and the safety factor.

2. Optimization of ECCD for ITER-FEAT and JET-E

The rf current, externally applied for the NTMs control, is provided by injection of EC waves, whose propagation and absorption are calculated by a 3D

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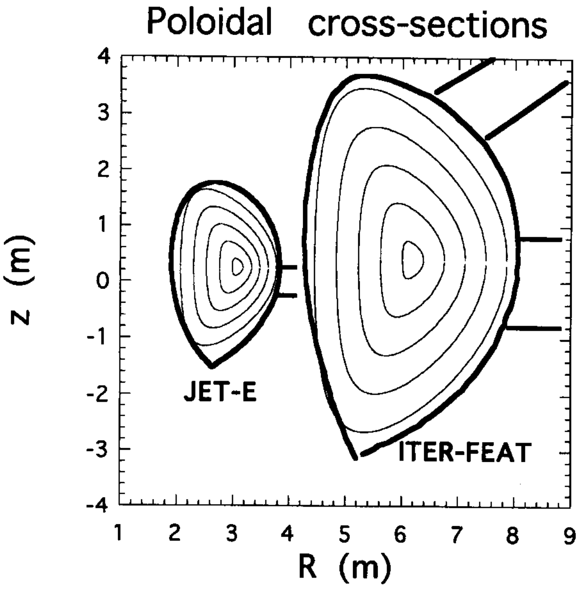

Fig. 1 Poloidal sections of JET-E and ITER-FEAT.

toroidal code [4]. The reconstructed magnetic equilibrium and the diffractive behaviour of the launched beams are both taken into account. The effects of trapped particles are included in the evaluations of driven current. It must be stressed that the optimization of the current drive efficiency by means of a best choice of launching conditions (frequency and injection angles) is strongly dependent on the considered equilibrium, in terms of central magnetic field B_0, electron density/ temperature and q profiles. In particular, small variations of B_0 (of order of half tesla) change the frequency range involved and slight modifications in the pressure and q gradients lead to sensitive variations of the tearing modes growth. For our calculations we refer to the the basic plasma parameters for ITER-FEAT and JET-E (see Table 1).

Total EC powers up to 30 and 10 MW are required for ITER-FEAT and JET-E, respectively. In ITER-FEAT the (m = 2, n = 1) and (m = 3, n = 2) modes, located at the normalized minor radius $\rho_s = 0.8$ and 0.7, can be simultaneously controlled by EC waves toroidally injected from the equatorial port at f = 140 GHz or f = 170 Ghz. In the latter case a poloidal steering has also to be given, providing a current density profile narrower than the former one by about 30%. A further width reduction (up to 33%) can be obtained by beams, still injected at 170 GHz, entering the plasma from the upper port (140 GHz being out of the absorption zone).

Table 1

Parameters	ITER-FEAT	JET-E
B_0, T	5.5	3.5–4
R_0, m	6.2	2.96
a, m	1.9	1.0
n_{e0}, $10^{19}m^{-3}$	10	10
T_{e0}, KeV	35	12
τ_E, s	3.2	1
Z_{eff}	1.8	1.8

The current radial full width Δj is about 0.13*a at 140 GHz, 0.08*a and 0.04*a at 170 GHz for launching from the equatorial and vertical ports, respectively. In JET-E the q = 3/2 and q = 2 rational surfaces are placed at $\rho_s = 0.5$ and 0.72. The central magnetic field of 3.5 T allows to use rf at 140 GHz at the fundamental Ordinary Mode with absorption on the high field side. The current profile width is between 0.18*a and 0.24*a. The 2nd Extraordinary Mode at higher frequencies (170 GHz at B_0 = 3.5 T, increasing up to 195 Ghz at 4 T), with absorption on the low field side, could be considered to optimize the current drive efficiency. In both cases Δj is about 0.08*a–0.1*a.

3. Control of (m = 2, n = 1) and (m = 3, n = 2) NTMs in ITER-FEAT and JET-E

The non-linear amplitude evolution of the magnetic islands is calculated [5] by a generalized Rutherford equation, including the stabilizing term of rf-current and associated heating. The term due to the driven current, more effective than the heating one for the considered machines, is proportional to $1/\Delta j^2$. This means that, among the current density profiles previously calculated, at comparable levels of driven currents, the profiles with smaller width increase the stabilizing effects. We consider island saturation width 0.15*a both for ITER-FEAT and JET-E calculations.

The control of the (m = 2, n = 1) mode is obtained in ITER-FEAT by injection of 20–30 MW. Stabilized levels, smaller of 35–50% than the saturated value, are obtained in ITER for (m = 2, n = 1) mode by injection of 20–30 MW of EC power, reached in 10–25 s with respect to the resistive time τ_R = 350 s.

Further level reduction are due to pressure gradient effects and Z_{eff} = 1 (Fig. 2).

A reduction of the (m = 3, n = 2) mode up to 60-70% is calculated for 20 MW of rf power (Fig. 3).

In JET 10 MW of ECRH power decrease the (m = 2, n = 1) mode width up to 70% in 3–5 s (Fig. 4) and

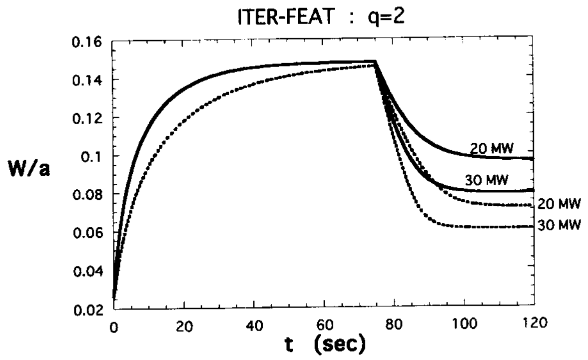

Fig. 2 Effects of 20–30 MW of rf power (injected from 75 s to 120 s) at q = 2 for Z_{eff} = 1 (dashed lines) and Z_{eff} = 1.8 (solid lines).

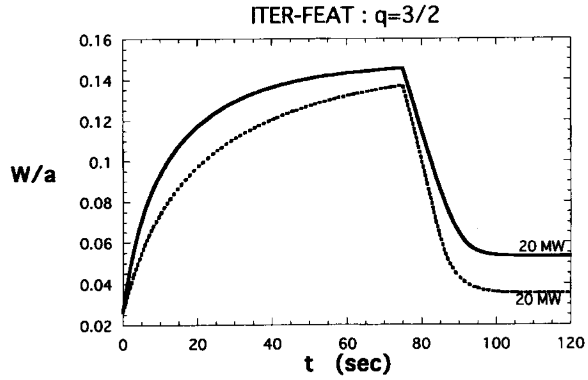

Fig. 3 Effects of 20 MW of rf power (injected from 75 s to 120 s) at q = 3/2 on the (m = 3, n = 2) mode amplitude for Z_{eff} = 1 (dashed lines) and Z_{eff} = 1.8 (solid lines).

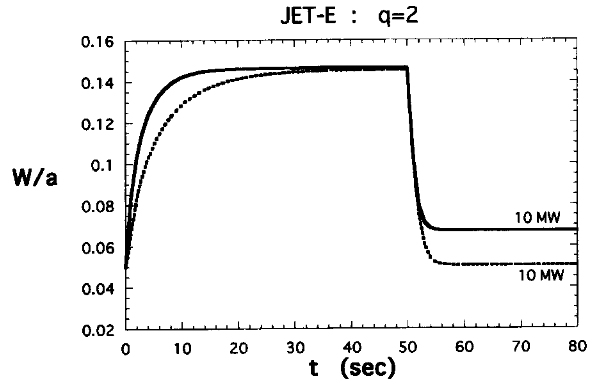

Fig. 4 Effects of 10 MW of EC power (injected from 50 s to 80 s) at q = 2 on (m = 2, n = 1) mode amplitude for Z_{eff} = 1 (dashed lines) and Z_{eff} = 1.8 (solid lines).

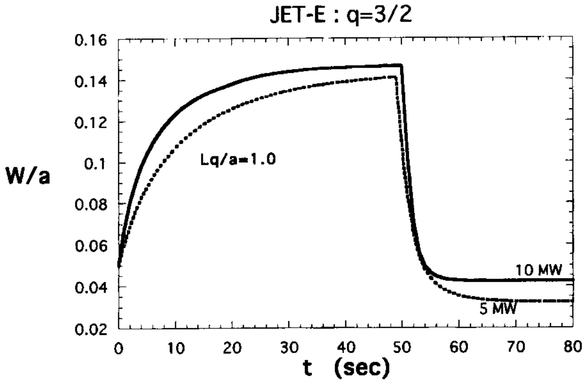

Fig. 5 Effects of 5–10 MW of EC power (injected from 50 s to 80 s) at q = 3/2 for Z_{eff} = 1 (dashed lines) and Z_{eff} = 1.8 (solid lines). In the former case the mode (m = 3, n = 2) is suppressed with 10 MW. The local gradient scale length of the safety factor, L_q, normalised to the minor radius a, is taken = 1.

suppress the (m = 3, n = 2) mode in plasmas with Z_{eff} = 1. This last mode is reduced by up to 75% with 5 MW of EC injected (Fig. 5), taking also advantage of wall stabilizing effect on the rotating mode. All the other cases, discussed above, are locked in a few seconds.

4. Conclusions

For ITER-FEAT and JET-E we gave a quantitative assessment of EC power required to stabilize the island width of the (m = 2, n = 1) and (m = 3, n = 2) tearing modes. In ITER-FEAT reduction up to 50% at q = 2 and 70% at q = 3/2 are obtained with 20 MW of EC power for f = 170 GHz. In JET-E width levels up to 70% (q = 2) and 90% (q = 3/2) smaller than the saturated value are calculated with 5–10 MW of rf power for f = 170–195 Ghz.

References

[1] Zohm H. *et al.*, Plasma Phys. and Contr. Fusion **39**, B237 (1997).

[2] JET Team, Nucl. Fusion **39**, 1223 (1999).

[3] J. Jacquinot *et al.*, JET-R (99) 12, Dec 99.

[4] S. Nowak, E. Lazzaro and G. Ramponi, Phys. Plasmas **3**, 4140 (1996).

[5] G. Ramponi, E. Lazzaro and S. Nowak, Phys. Plasmas **6**, 3561 (1999).