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Partial Stabilisation of NTMs with ECCD for standard scenarios in ITER

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Abstract

The performance of the ITER standard scenario can be reduced due to neoclassical tearing modes [1]. In particular 3/2 and 2/1 modes are predicted to lead to the main confinement degradation in ITER. Localised electron cyclotron current drive (ECCD) is proposed to fully stabilise these modes, however the power requirements are relatively large, about 20MW. Present experimental results confirm the efficient stabilisation with CW-ECCD down to an island width similar to the j_{eccd} characteristic width w_{cd}. In this paper we study the power requirements needed to partially stabilise the NTMs to sizes such that less than a 10% reduction in the confinement properties is expected. The required power is much lower than for full stabilisation, but it needs to be delivered continuously. We discuss the advantages and drawbacks of this new option, in particular concerning the influence on the maximum Q value that can be expected. An advantage of this new option is that the uncertainties in the predictions can be significantly reduced, since present experiments directly apply and can be scaled up to ITER. However it is shown that the optimum with respect to Q values depends on w_{cd} and the effective dependence of the CD term on island width. On the other hand, a finite saturated island can provide a unique actuator inside the plasma core for burn control. In addition it is easier to use this control if the island is continuously present, albeit at a small amplitude, since one can locate its position relatively accurately.

Introduction

Neoclassical tearing modes have been observed in many tokamaks. They are magnetic islands that lead to an increase in the local perpendicular transport. The confinement degradation can be relatively well modelled using the following simple expression from the belt-model [2]:

$$\frac{\Delta\tau}{\tau} = -\Delta_{\tau mn} w_{sat} \equiv -4\frac{w_{sat}}{a}\left(\frac{\rho_s}{a}\right)^3, \qquad (1)$$

with ρ_s the radius of the $q = m/n$ flux surface. According to the present estimations of the saturated island widths for the baseline ITER scenarios, degradations of the order of 15%-25% can be expected for the 3/2 and 2/1 modes, respectively. However less than a 10% confinement degradation, $HH > 0.9$, is admitted in the present ITER design in order to achieve the main goal of $Q = 10$. This is why a system of several launchers for electron cyclotron current drive (ECCD) is dedicated to stabilising these modes. Up to 20MW of power can be used for this purpose. The aim of this work is to study the dependence of the Q factor, $Q = P_f/P_{aux} = P_f/(P_{NBI} + P_{ec})$, on the ECCD power, P_{ec}, taking into account the effective island width and confinement degradation. Of course, NTMs need a seed island to be triggered unstable. However it has been shown that the marginal beta limit and marginal island width are expected to be very small in ITER, as they are in JET and AUG [3, 4]. In addition, fast particles stabilised sawteeth have been shown to easily trigger NTMs, therefore one can expect NTMs to be triggered at each sawtooth crash. The sawtooth period is expected to be of the order of 15s, thus it is reasonable to assume that NTMs are present in the ITER baseline scenario. It is possible of course to considerably lengthen the sawtooth period, using fast current ramp-up or localised ECCD just outside $q = 1$, however this is out of the scope of this study.

Burning plasma conditions

Let us first present our simplified model to determine the burning temperature and total pressure for a given auxiliary power. We start from the so-called scenario 2, which is one of the baseline scenarios for ITER, assuming a sawtoothing ELMy H-mode. The main parameters of interest are: $R_0 = 6.2m, a = 2m, I_p = 15MA, B_0 = 5.3T, V = 830m^3, \tau_{E0} = 3.7s, Z_{eff} = 1.7, P_{NBI} = 40MW, P_\alpha = 80MW, P_{Brem} = 21MW$. The scaling law assumed in this case yields $\tau_E \sim P_L^{-e_P}$ with $e_P = 0.69$ [1]. The fusion power is given by $P_f = 5P_\alpha$ with:

$$P_\alpha = \gamma_\alpha \, 1.5\,10^{-6} \, p_{keV}^2 \, R(T_{keV}) V \, [MW] \; ; \; R(T_{keV}) = 29.84 \, T_{keV}^{2.5} \, exp\left[- \frac{(T_{keV}+11)^{0.45}}{0.43} \right] \quad (2)$$

using a useful fit for the reactivity. The total thermal energy is given by:

$$W_E = \gamma_e \, \frac{3}{2} \, f_{pe} \, 1.6 n_{19} \, T_{keV} \, V \, 10^{-3} \, [MJ] = P_L \, \tau_E, \quad (3)$$

with $f_{pe} = p/p_e$ and where τ_E can be written as follows, using the baseline parameters: $\tau_E = \tau_{E0} \, P_{L0}^{e_P} / P_L^{e_P} \, (1 - \Delta_{\tau mn} w)$, with w the island width and $\Delta_{\tau mn}$ given by Eq. 1. For the effective total heating power, we take into account the Bremsstrahlung radiation and the fact that any off-axis additional power is located in a bad confinement region. Therefore we weight its contribution by a profile effect, ~ 0.5, at the 3/2 and 2/1 positions. Thus we use, assuming steady-state:

$$P_L = P_\alpha + P_{NBI} + (1 - \frac{\rho_s^2}{a^2}) \, P_{ec} - P_{Brem} \quad (4)$$

The radiation term is important to limit the benefits at large temperatures, and it is given by:

$$P_{Brem} = \gamma_B 47.4 \times 10^{-6} Z_{eff} n_{19}^2 \sqrt{T_{keV}} V \quad (5)$$

The parameters $\gamma_E, \gamma_\alpha, \gamma_B$ are introduced to take into account the profile effects. Assuming a flat density profile and $T(\rho) \sim (1 - \rho^2)$ one gets: $\gamma_E = 0.5, \gamma_\alpha = 0.19, \gamma_B = 0.67$. From Eq. 3 and τ_E one obtains:

$$P_L = \left[\frac{\gamma_e \frac{3}{2} f_{pe} 1.6 \times 10^{-3} n_{19} T_{keV} V}{\tau_{E0} P_{L0}^{e_P} \, (1 - \Delta_{\tau mn} w)} \right]^{\frac{1}{1-e_P}}, \quad (6)$$

which also shows the sensitivity on the power exponent in the scaling law. The burning temperature is then given by Eqs. 6 and 2. We have adjusted the factor $f_{pe} = p/p_e$ to 1.87, such as to recover the standard steady-state conditions, namely $P_\alpha = 80MW$, $Q = 10$, $T_{burn} \approx 20keV$, $\beta_N \approx 1.8$, $P_{Brem} \approx 20MW$ with $P_{NBI} = 40MW$, $P_{L0} = 99MW$, $\tau_{E0} = HH\,3.7$ and $HH = 1$. We see that with an additional 20MW of EC power, we obtain $P_\alpha = 83MW$ and $Q = 6.9$. In this way we can determine P_α for different HH values and additional P_{ec}, still assuming no NTMs. The results are shown in fig. 1a for HH values between 0.75 and 1.2. This is the operational diagram of interest for the present study. We also show the "anchor" points related to the 3/2 and 2/1 NTMs. If no ECCD is used to stabilise the modes, we expect $HH \approx 0.85$ for the 3/2 mode and $HH \approx 0.75$ for the 2/1, which yields $Q = 7$ and $Q = 5$ respectively. If the modes are fully stabilised with 20MW and this power needs to be kept continuously on, we have the operating point at $P_{ec} = 20MW$ and $HH = 1$, which gives $Q = 7.3$. Therefore, while increasing the EC power to stabilise the mode, one will move from points A or B to point C with a path to be determined as sketched with the dashed lines. Depending on the dependence of w_{sat} on P_{ec}, one could find an optimum at lower values of P_{ec}.

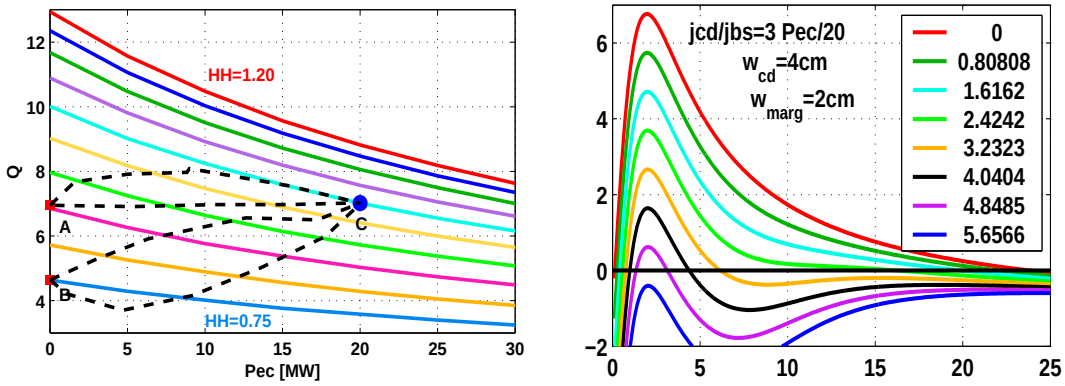

Figure 1: a) Q vs P_{ec} for HH in [0.75:0.05:1.2]. The points A and B mark the 3/2 and 2/1 modes, C assumes full stabilisation with 20MW. Dashed lines sketch possible operating points between A or B and C, with partial stabilisation. b) dw/dt, normalised (Eq.7), vs w using Eq.(20) of [5].

Island width as a function of P_{ec}

The island width is determined by the modified Rutherford equation (MRE). In order to minimise the number of parameters, it is best to normalise the equation by $\rho_s|\Delta'|$ and to define $w_{sat\infty}$ as the saturated island size with no stabilising term and using the non-perturbed plasma parameters [3]. In our case, using the parameters of the scenario 2 and evaluating the terms in the MRE as defined in [3], we obtain the values 23.5cm and 31.7cm for the 3/2 and 2/1 modes. The MRE is then written as:

$$\frac{dw}{dt} \sim -1 + (1 - \Delta_{\tau mn} w)\, \frac{w_{sat\infty}\, w}{w^2 + w_{marg}^2} - 1.1(1 - \Delta_{\tau mn} w)\, \frac{w_{sat\infty}}{w_{cd}} \frac{j_{cd}}{j_{bs}}\, 4\eta\left(\frac{w}{w_{cd}}\right), \qquad (7)$$

where the last term represents the effect of ECCD in the island. The notation and various options for η are discussed in Ref. [5] and refs. therein. The value of $4\eta \sim 1$ for $w \approx w_{cd}$. The predicted value of w_{marg} is 2-6cm, we use the pessimistic value of 2cm here. We neglected the polarisation model and the effect of ECCD on the equilibrium current density for simplicity. The main result do not depend significantly on the effective terms used. We still need to determine the terms related to ECCD. We define $j_{cd}/j_{bs} = f_{cd20} P_{ec}/20$, where f_{cd20} is the ratio with 20MW ECCD power. Typical values of f_{cd20} range from about 1 up to 3.5 using the optimised front steering launcher design [6]. The current density full $1/e$ width, w_{cd}, is of the order of 3-4cm for the FS launcher, up to 10cm for present designs. Finally we shall use two models for η, both assuming CW, one yielding a gaussian-type function (Eq. (20) of [5]) and one usually used in previous simulations ([7] in CW, Eq. (23) of [5]) yielding a more peaked function with lower values for $w > w_{cd}$. The effect of the first model on Eq. 7 is shown in fig. 1b. Due to the nonlinear dependence, there is a rapid change of w_{sat} between 2.4 and 3.2MW for these parameters.

Results

The results for four cases for the 2/1 mode are shown in fig. 2, two different models for $\eta_{aux}(w/w_{cd})$ as mentioned above and two different j_{cd} profiles such that $w_{cd} = 4$ or 8cm and $f_{cd20} = 3$ or 1.5 respectively. Thus these two current density characteristics correspond to a same total driven current. Fig. 2a shows the dependence of Q on P_{ec}. When Q "jumps" up, it means that the NTM has been fully stabilised and then the curve follows the HH=1 curve of Fig. 1. First the 2 cases with more localised ECCD fully stabilise the mode earlier, as expected. On the other hand, only the 2 curves with a larger w_{cd} exhibit a maximum before full stabilisation. In these

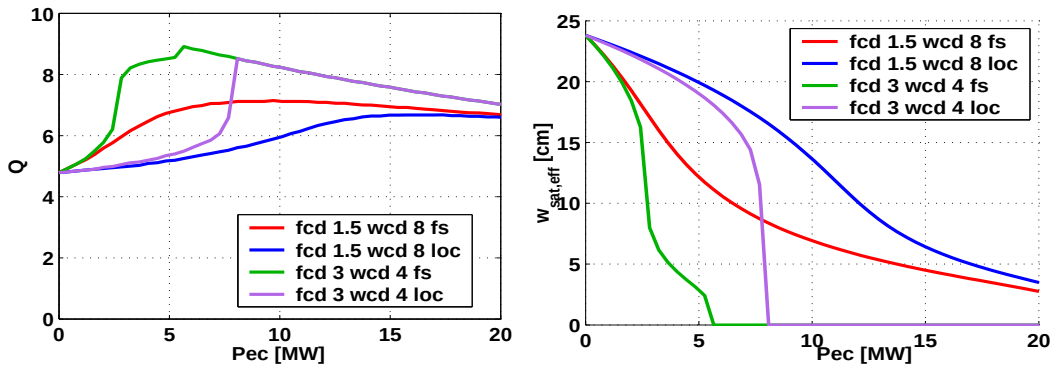

Figure 2: a) Q vs P_{ec} for a 2/1 mode in ITER. b) Corresponding saturated island width.

cases it would be better to keep P_{ec} at 8-14MW with a finite saturated island. This corresponds to $w_{sat} \approx 7$cm (fig. 2b). The dependence of w_{sat} on P_{ec} is quite interesting, in particular for the $w_{cd} = 4$cm case assuming flux-surface current density (green line). First it decreases "slowly" with increasing P_{ec}, similarly to the large w_{cd} case. Indeed, both have $w >> w_{cd}$ and it is $\eta_{aux} \sim (w_{cd}/w)^2$ which dominates. This is the same for the "local" approximation, albeit with a smaller coefficient. For $w \sim 2w_{cd}$ and a sufficient f_{cd20}, w_{sat} decreases rapidly because the right-hand side of the MRE turns out to be flat vs w, or even having a dip (fig. 1b). Thus a small change in power can have a large change in stabilisation efficiency. If $w_{sat} \geq 2w_{marg}$, one can still need a significant increase of power before the mode is fully stabilised. This in turns yields the s-shape for $Q(P_{ec})$ as shown in fig. 2a, green line. Nevertheless in the latter phase, the island is so small that the effective Q stays about constant between 4-8MW.

These few examples show that the effective dependence of the fusion performance on the partial stabilisation of NTMs can be quite complicated and is far from a simple linear dependence. This is due to the interplay between the $1/w$ dependence of the bootstrap drive at large island width and the $(w_{cd}/w)^2$ dependence of the ECCD stabilising term, and the modification of the ECCD term and the bootstrap drive (here due to finite perpendicular transport) at smaller island width. These effects depend on the relative values of w_{marg}, w_{cd} and w_{sat}, and on the value of j_{cd}/j_{bs}. This study also suggests that one might get new insight about the CD term experimentally by mapping the dependence of w_{sat} on P_{ec} with a slow ramp of EC power.

Even if there is no net gain in Q factor, partial stabilisation can be useful for burn control. Indeed one can increase or decrease the island size and therefore the global confinement from within the plasma core, simply by altering the alignment of the ECCD beam with the rational surface. This might also be useful for He ash removal. In addition, it is much easier to locate and control a finite amplitude mode. The present studies show that with 5-10MW, most of the possible performance recovery is obtained, even for the 2/1 mode, since $w_{sat,2/1} \leq 10$cm.

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