Partial Stabilization and Control of Neoclassical Tearing Modes in Burning Plasmas

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Abstract. Neoclassical tearing modes (NTMs) are magnetic islands which increase locally the radial transport and therefore degrade the plasma performance. They are self-sustained by the bootstrap current perturbed by the enhanced radial transport. The confinement degradation is proportional to the island width and to the position of the resonant surface. The q=2 NTMs are much more detrimental to the confinement than the 3/2 modes due to their larger radii. NTMs are metastable in typical scenarios with β_N>1 and in the region where the safety factor is increasing with radius. This is due to the fact that the local pressure gradient is sufficient to self-sustain an existing magnetic island. The main questions for burning plasmas are whether there is a trigger mechanism which will destabilize NTMs, and what is the best strategy to control/avoid the modes. The latter has to take into account the main aim which is to maximize the Q factor, but also the controllability of the scenario. In this paper we present different aspects of the above questions, in particular the role of partial stabilization of NTMs, the possibility to control NTMs at small size with little electron cyclotron heating (ECH) power and the differences between controlling NTMs at the resonant surface or controlling the main trigger source, that is the sawteeth.

1. Introduction

Neoclassical tearing modes (NTMs) have been observed in many tokamaks, in particular in H-mode scenarios. They are metastable with monotonic safety factor profile (q) with positive shear. It has been shown that the marginal beta limit is very low [1]. Therefore, ITER standard scenario is predicted to have a β value (ratio of total plasma pressure to magnetic pressure) about 10 times larger than the marginal value β_{marg}. It has also been shown on JET that crashes after long sawtooth period are the main trigger mechanism at low beta, similar to the expected value in ITER [2]. Since fast particles are known to stabilise efficiently the sawtooth activity and lead to long sawtooth periods [3], it is most likely that sawtooth crashes in burning plasmas will trigger large enough seed islands, such that $w_{seed}>w_{marg}$. If no external control methods are used, the island will then grow up to its saturated value, w_{sat}, yielding a confinement degradation proportional to w_{sat} [4]:

$$\frac{\Delta\tau}{\tau} = -\Delta_\tau w_{sat}\,, \qquad \text{with} \qquad \Delta_\tau = 4\frac{\rho_s^3}{a^4}. \tag{1}$$

The driving term sustaining the island is the perturbed bootstrap current [5]. In present and future burning plasma scenarios, the bootstrap contribution will be significant. This is why NTMs have to be considered seriously when analysing ITER-like scenarios.

The main control is obtained by "replacing" the missing parallel current within the island, using localised current drive. The best tool is therefore electron cyclotron current drive (ECCD). At present, a design for 20MW of ECCD, dedicated mainly to NTM stabilization is being developed for ITER [6]. The series of launchers are able to aim at the q=3/2 or q=2 surfaces, the two main resonant surfaces, with very localised current density. The current density deposition width is of the order of w_{cd}=2.5cm (1/e full width) [7] with a value of $\eta_{NTM}=j_{cd}/j_{bs}$=2.7 with 13.3MW [7, 8]. The stabilisation has been demonstrated in several tokamaks [9] and the efficiency depends both on the peaked current density j_{cd} related to the local bootstrap current density j_{bs}, and to the j_{cd} width (w_{cd}) [10-12]. Naturally, the extra EC power required to stabilize NTMs needs to be taken into account for calculating the global Q factor, where Q is the ratio of the fusion power to the auxiliary power needed to sustain the fusion reactions.

The main aim of ITER, for example, is to sustain a Q=10 scenario in stationary state. The design of ITER-FEAT is such that this can be obtained within some margins, in particular for confinement factors HH around 0.8-1.2 [13]. Using simple relations and usual confinement laws, as discussed below, one can derive the relation between the Q factor and the additional EC power for various HH values. This is shown in Fig. 1 for HH values between 0.75 (bottom curve) and 1.2 (top curve) by steps of 0.05. The standard operational point, Q=10, is obtained with HH=1 and P_{EC}=0. Using the predicted profiles for ITER standard scenarios, one can infer a saturated width of about $w_{sat\infty}$=32cm for the 2/1 mode, neglecting the confinement degradation. Taking into account the effect mentioned above, Eq. (1), the final island width is reduced by the factor $1/(1+\Delta_\tau w_{sat\infty})$, which yields a saturated island size of about 24cm (with q=2 surface at ρ_s=166cm and a=200cm). This gives a confinement degradation of more than 25%, thus would move the operating point to HH=0.75, P_{EC}=0 on Fig. 1 (point B), that is Q<5. For the 3/2 mode, we expect about 15% confinement degradation (point A, Q=7, in Fig. 1). If the modes can be fully stabilised with 20MW, then the operating point will be for both cases on HH=1, P_{EC}=20, that is point C in Fig. 1. Note that it yields only Q=7, thus, in particular for the 3/2 mode, it is not clear one can gain anything with EC stabilisation in terms of Q values. This is shown by the sketch of the possible trajectories between points A/B and C, while the saturated island is stabilised. The dependence of w_{sat} on P_{EC} and its effects on $Q(P_{EC})$ are presented in this paper. The various assumptions usual in NTM simulations are considered, in particular the cases with and without modulation are discussed in detail as well as the $\chi_\perp$ and polarisation models. The possibility that the optimum might be with partial stabilisation [14] or with pre-emptive ECCD around the time of expected sawtooth crashes are also discussed. Finally the effect of sawtooth control is also taken into account and discussed. The aim of this paper is to discuss all the various options in a consistent way, in order to evaluate the best strategy for controlling NTMs in burning plasmas.

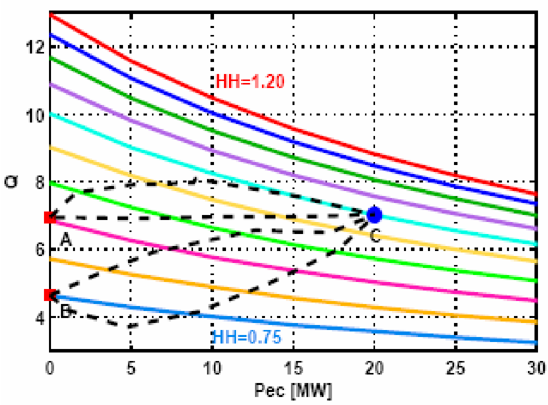


Fig. 1: $Q(P_{EC})$ for different HH factors between 0.75 and 1.2, by step of 0.05 (solid lines). Sketches of $Q(P_{EC})$ from stabilization in ITER of 3/2 (A) and 2/1 (B) NTMs.

2. Physics model

The goal of this study is to survey the range of parameters expected in ITER standard scenario. In order to limit the number of parameters, the best is to normalize the usual modified Rutherford equation (MRE) by ($\rho|\Delta_s'|$) and to define two island sizes:

$w_{sat\infty}$: the expected saturated island width neglecting stabilising terms ($\sim\beta_p$)

w_{marg}: the marginal island width without ECCD stabilization

Two types of stabilising terms, in addition to ECCD, are usually considered separately: the $\chi_\perp$ [15] and the polarisation [16] models. The latter was used for cross-machine comparison [9] and in turns to predict the minimum ratio of j_{cd}/j_{bs}: η_{NTM}=1.2 [17]. In order to extend these studies to the $\chi_\perp$ model and to different values of w_{cd}, we propose the following modified Rutherford equations [14]:

$\chi_\perp$ model:

$$\frac{\tau_R}{\rho_s^2|\Delta'|}\frac{dw}{dt} = -1 + (1-\Delta_\tau w)\frac{w_{sat\infty} w}{w^2 + w_{marg}^2} - c_j(1-\Delta_\tau w)\frac{w_{sat\infty}}{w_{cd}}\frac{j_{cd}}{j_{bs}}\eta_{aux}(w/w_{cd}), \tag{2}$$

pol model:

$$\frac{\tau_R}{\rho_s^2|\Delta'|}\frac{dw}{dt} = -1 + (1-\Delta_\tau w)\frac{w_{sat\infty}}{w}(1-\frac{w_{marg}^2}{3w^2}) - c_j(1-\Delta_\tau w)\frac{w_{sat\infty}}{w_{cd}}\frac{j_{cd}}{j_{bs}}\eta_{aux}(w/w_{cd}), \tag{3}$$

where c_j=1.1 is expected but is used here as a fit parameter as discussed below. Naturally, equating either right-hand side to zero yields the saturated island size. For example, without CD stabilization, we obtain at large enough β value, say β_∞, such that the polarisation or $\chi_\perp$ effects are negligible:

$$w_{sat} = \frac{w_{sat\infty}}{1+\Delta_\tau w_{sat\infty}} \quad , \tag{4}$$

which is the ratio mentioned before. This reduction factor applies to beta and the thermal energy as well. Since $w_{sat\infty}$ is proportional to β_p, reducing the input power results in reducing $w_{sat\infty}$. In particular the marginal β value (such that max(dw/dt)=0) is obtained with $w_{sat\infty}=2w_{marg}$ or $w_{sat\infty}=1.5w_{marg}$ (from Eq. (3) and (4) respectively with $j_{cd}=0$ and $\Delta_\tau\sim 0$). This means that the ratio between the β_∞ value and the marginal value β_{marg} can be directly evaluated from $2w_{marg}/w_{sat\infty}$ or $1.5w_{marg}/w_{sat\infty}$ depending on the model used. The comparison between ITER and present experiments will be discussed below. Nevertheless, one sees why it is difficult to discriminate experimentally between these two models. Indeed, w_{marg}, $w_{sat\infty}$ and $\beta_{marg}/\beta_\infty$ can be relatively well measured experimentally, but not with enough accuracy to separate these marginal values, $2w_{marg}/w_{sat\infty}$ or $1.5w_{marg}/w_{sat\infty}$, with $\beta_{marg}/\beta_\infty$, especially since $\beta_{marg}/\beta_\infty$ is a small number.

The ECCD efficiency is encapsulated in the last term of Eqs (2-3). We have neglected here the effect on the equilibrium current, $\delta\Delta'$ [9]. In this way the values predicted in this work are conservative. The two main assumptions for η_{aux} are either CW, assuming flux surface current densities [12], and 50% modulation with deposition localised within the O-point and with respect to the helical angle [10]. We use the fit proposed in [12], multiplied by 4 such that they are of order unity for $w=w_{cd}$:

$$\eta_{aux,cw}(x=\frac{w}{w_{cd}}) = \frac{12}{x^4+40}+\frac{2}{x^2+10}, \tag{5}$$

$$\eta_{aux,50\%}(x=\frac{w}{w_{cd}}) = \frac{1.8}{x^2}\tanh(\frac{x}{2.5}), \tag{6}$$

Note that a factor ½ has been added to both functions, with respect to [12], to take into account the effective driven current. In this paper, we shall only analyse the predictions for the 2/1 mode, because it is the main performance limiting mode. As mentioned before, the expected value of $w_{sat\infty}$ is about 32cm. The expected value of w_{marg} is between 2 and 6cm [1]. With these parameters, we shall analyse both Eqs (2) and (3) with either Eq. (5) or (6). We still need to determine the typical values of w_{cd} and $\eta_{NTM}=j_{cd}/j_{bs}$, which is done in Sec. 3. Note that the results obtained here with Eq. (5) would be similar if another model for CW deposition, as in [9], was used with $\eta_{aux,locCW}=1./(1+2/3/(w./w_{cd})^2)$. Of course near marginal cases, the differences could appear larger.

The latest design of the upper launcher dedicated mainly to NTM stabilisation [6] is such that very localised current density profiles can be driven. The latest simulations yield, for 13.3MW (2/3 of the EC power), $\eta_{NTM}=2.7$ for $d_A=2.9$cm and $r_A=2.1$m [7]. These dimensions are normalised with respect to an average radius proportional to the sqrt(Area). Since the island widths are usually normalised with respect to the average minor radius on the equatorial plane, we take $w_{cd}=d_A/\kappa^{1/2}=2.4$cm and $\rho_s=r_A/\kappa^{1/2}=170$cm in order to conserve the area and the total current. But before we apply these values to Eqs. (2) and (3), we need to compare these equations with the benchmarking performed in Ref. [9]. We shall use in Sec. 3 the same method as explained in [17] and extend it to the $\chi_\perp$ model as well as to CW case.

The experimental values of w_{marg}, w_{sat}, w_{cd} and η_{NTM} are used to match the experimental results with Eqs. (2) and (3). A free parameter is included in the ECCD term, c_j, which multiplies η_{NTM}. In this way we can fit the results such that Eqs.(2) and (3) predict marginal stability when the NTMs are fully stabilised experimentally. This is another way to take into account any misalignment. Assuming the *pol* model and local CW, a factor $c_j=0.7$ is found [17]. Assuming the form given in Eq. (5), we find $c_j\sim 1$ for the *pol* model, which gives an idea of the uncertainties in the number presented below. For the $\chi_\perp$ model, we have calculated the consistent values of $w_{sat\infty}$ to match w_{sat} without ECCD, assuming the same values of w_{marg}, and then we find that a factor $c_j=0.5$ is required in order to have not too negative values of dw/dt, in particular for JT-60U. This factor can be seen as a quite conservative approach to allow for safe predictions for ITER. It should also be noted that the ratio $2w_{marg}/w_{sat\infty}\sim\beta_{marg}/\beta_{onset}$ is 2-4 times larger in these experiments than predicted for ITER. This is because beta is not very large before the ECCD is applied in present stabilization experiments.

3. Predictions for η_{NTM}

Using a factor c_j=0.5 with Eq. (2) and 1.0 with Eq.(3) and assuming either CW or modulation, Eqs. (5-6), we have calculated the marginal value of η_{NTM} required to fully stabilise a large size NTM. We have also assumed w_{marg}=2, 4 and 6cm. The results, using rounded values, are summarized in the table below, assuming w_{cd}=2.5, 5 and 10cm:

CW case

w_{marg}	$\chi_\perp$, 2.5cm	*pol*, 2.5cm	$\chi_\perp$, 5cm	*pol*, 5cm	$\chi_\perp$, 10cm	*pol*, 10cm
2cm	2.8	1.5	4.2	2.9	8.5	4.3
4cm	2.2	1.3	1.8	1.3	3.5	1.8
6cm	1.7	1.2	1.0	0.8	1.8	0.9
η_{NTM} ; $\eta_{NTM}w_{cd}$	2.23 ; 5.58	1.33 ; 3.33	2.33 ; 11.65	1.67 ; 8.35	4.6 ; 46	2.33 ; 23.3
η_{NTM} ; $\eta_{NTM}w_{cd}$	**1.78 ; 4.5**		**2.0 ; 10.0**		**3.47 ; 34.7**	

50% modulation case:

w_{marg}	$\chi_\perp$, 2.5cm	*pol*, 2.5cm	$\chi_\perp$, 5cm	*pol*, 5cm	$\chi_\perp$, 10cm	*pol*, 10cm
2cm	2.9	1.5	2.0	1.1	1.9	1.1
4cm	2.4	1.4	1.6	1.0	1.4	0.9
6cm	2.0	1.3	1.3	0.9	1.3	0.7
η_{NTM} ; $\eta_{NTM}w_{cd}$	2.43 ; 6.1	1.4 ; 3.5	1.63 ; 8.15	1.0 ; 5.0	1.53 ; 15.3	0.9 ; 9.0
η_{NTM} ; $\eta_{NTM}w_{cd}$	**1.92 ; 4.8**		**1.32 ; 6.6**		**1.22 ; 12.2**	

Table 1: η_{NTM} values to fully stabilise the 2/1 NTM on ITER assuming (a) CW deposition and (b) modulation. Various model equations, w_{cd} and w_{marg} values are tested. The required $\eta_{NTM}w_{cd}$ increases rapidly with w_{cd}.

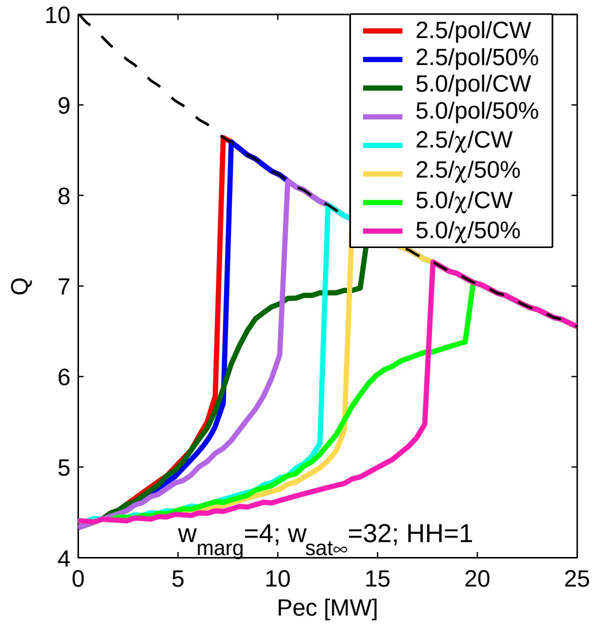
Usually, the total current that can be driven by a particular launcher is relatively constant with respect to the launcher design. It depends mainly on the launcher position and the local power deposition, decreasing with increasing minor radius due to the increased trapped particle fraction and the lower local plasma temperature. Since Icd~ $\eta_{NTM}w_{cd}$, we have also quoted these values in the table, for the averaged η_{NTM} values. Given the values of $w_{cd,min}$ and η_{NTM} of a particular launcher design, this table tells us if full stabilization is possible and in which cases.

A first observation is that the required values do not depend as much on w_{marg} for the modulation case as for the CW case. This is also why the 50% modulation is usually assumed, since the predicted η_{NTM} depends less on the model used. On the other hand, one sees that except for w_{marg}=2cm, the values for CW and 50% modulation are relatively similar for $w_{cd}\leq$5cm. Another clear result is that η_{NTM} increases rapidly with w_{cd} for the CW case, but not for the modulation case. Actually, since the real advantage of modulation is when w< w_{cd}, it is not better at the smallest w_{cd}, since $w_{cd}\sim w_{marg}$. In any case, the required $\eta_{NTM}w_{cd}$ increases with w_{cd}. This is why the launcher design needs to minimize the w_{cd} width achievable [6].

Using the value quoted above for the present design, at P=13.3MW, namely $\eta_{NTM}w_{cd}$=6.3 and $w_{cd}\geq$2.5cm, we see that we can fully stabilise the 2/1 mode using either CW or modulation if perfect alignment is achieved and even with an effective width of w_{cd}=5cm with 50% modulation. In the CW case with w_{cd}=5cm, one would rely on $w_{marg}\approx$6cm to be able to fully stabilize the 2/1 NTM.

4. Predictions of Q in the presence of NTMs and EC stabilisation

The standard operational regime used here is given by R_0=6.2m, a=2m, I_p=15MA, B_0=5.3T, V=830m3, τ_{E0}=3.7s, Z_{eff}=1.7, P_{NBI}=40MW, P_α=80MW, P_{Brem}=21MW, assuming a scaling law with $\tau_E\sim P_L$-0.69 [13]. The fusion power is given by $P_f=5P_\alpha$, yielding $Q=P_f/P_{aux}$=10. P_α depends on p^2 and the reactivity R(T). $P_L=P_\alpha+P_{NBI}+0.5P_{EC}-P_{Brem}$ and $W_E= P_L\ \tau_E$. We have used a reduced contribution from P_{EC} to take into account that it is aimed off-axis, where the local confinement is reduced. Other profile effects are considered [14]. These equations determine the burn temperature, which enables us to calculate P_α and Q. The results obtained with varying HH in the value of τ_E are shown in Fig. 1. For example, with 20MW EC, one obtains P_f=415MW and P_{aux}=60MW for Q=6.9 (point C). Adding a confinement degradation as given by Eq. (1) provides the link between Q, w_{sat} and P_{EC}.



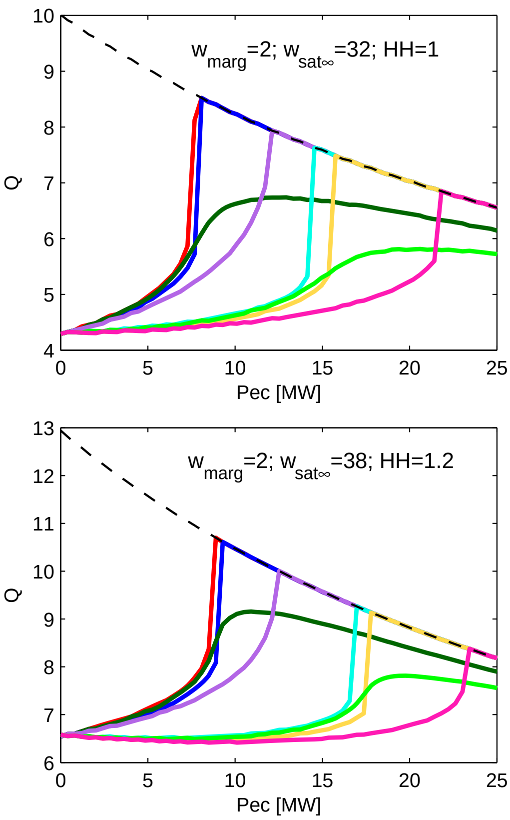


Fig. 2: Q(P_{EC}), taking into account the self-consistent confinement degradation due to a 2/1 NTM. The legend refers to w_{cd}, model type and CW/modulation 50%. The dashed line marks the HH=1 line. (a) w_{marg}=4cm; (b) w_{marg}=2cm, and (c) HH=1.2. Other values are on the Figs.

Since we expect w_{cd} between 2.5 and 5cm [7], we have used both to see the effect. In order to be consistent with the total current driven, we keep $\eta_{NTM}w_{cd}$=6.3*P_{EC}/13 fixed and vary η_{NTM} accordingly. Note that it corresponds to η_{NTM}=1.5 with w_{cd}=4.2cm and 13MW. We also have 2 options for the MRE, Eqs. (2) and (3), and for the use of EC: modulated or not. This gives 8 different cases which are shown in Fig. 2. Fig. 2a shows Q(P_{EC}) with the medium value of w_{marg}=4cm and with $w_{sat\infty}$=32cm. The value of $w_{sat\infty}$ is not significant, however the value of w_{marg} is important as can be seen by comparing Fig 2a and b. In particular for the cases with w_{cd}=5cm and CW. In these cases, if w_{marg}=2cm, the island is not fully stabilised within 25MW. However, due to the high relative efficiency near w=w_{cd}, the mode shrinks rapidly at small power and Q increases correspondingly. This yields a maximum for Q at P_{EC}~10-17MW. Thus in this case, partial stabilization would be beneficial. The effect is more pronounced in Fig. 2c where we have assumed a HH factor of 1.2. In this case, for example with the *pol* model, one can get Q=9.2 with 11MW, while Q<8 at full stabilization. It can also be advantageous to partially stabilise the mode, since it is easier to maintain an accurate aiming in this way. Otherwise, the correct aiming might be lost when the next mode is triggered. It can then lead to a larger mode before it is stabilised again. This increased variation in the Q value might not be desired. In addition, one has the possibility to increase the island size, through deliberate misalignment or reducing the EC power, in case a more precise Q control is required.

In the case of w_{marg}=6cm, the Q values stay relatively low until the mode is fully stabilised, which happens at low input power, between 6 and 13MW for the 8 cases. Therefore partial stabilisation might be useful in the case of a low w_{marg} value, but not in case of $w_{marg}\geq$5cm. The predicted value of w_{marg} is still not well determined. It is actually not yet well determined in present experiments, although a significant work to obtain these values in various machines has started [1, 18, 9]. In Ref. [9], a value of w_{marg}~2ρ_b~2cm is predicted following a cross-machine scaling law, where ρ_b is the banana width. In [1], a value 2-6cm is predicted, following observations on JET experiment. In the latter, it has been found that the rate at which the power is ramped down can influence significantly the inferred marginal island sizes. At large field and current, w_{marg}~4cm has been obtained with very slow ramp-down and for 3/2 modes. Since in JT-60U also a value of 4cm is quoted [9], we base our study here on a value between 2 and 6cm, with an average of 4cm.

Note that the power at which full stabilisation occurs can be checked with the values in Table 1. For example, for the most unstable curve in Fig. 2a, "5.0/$\chi_\perp$/CW" (light green), we need η_{NTM}=1.8 from table 1 (w_{marg}=4) which is obtained with a power P=13*1.8/(6.3/5.0)=18.5MW, consistent with the results in Fig. 2a.

5. Time evolution and link with sawteeth

In order to discuss the best strategy for NTM stabilisation, one needs also to take into account the time evolution of the island and the characteristic time constants. When the EC power is sufficient to fully stabilize the mode, it means that dw/dt<0 for all w. It turns out that the negative growth rate is relatively constant until it shrinks to below 3 w_{marg}. This translates into a relative linear time evolution of the island width with time, as shown in Fig. 3. We have chosen the five main cases of Fig. 2a which can provide full stabilisation at ~13MW. The parameters are the same as used for Fig. 2a. We show the 4 cases with w_{cd}=2.5cm and the case with w_{cd}=5.0cm/modulation/*pol* model. We assume that we have an island at t=0, w_{sat0}, when EC is turned on, of size 24cm, 16cm and 8cm.

Let us discuss first the 3 cases with the *pol* model, which can all fully stabilise the mode at P=7-10MW (Fig. 2a). If the EC is turned on and aligned when w_{sat0}=24cm, it takes ~25s for the 2 cases with w_{cd}=2.5cm and ~42s if w_{cd}=5cm to fully stabilize the mode. If w_{sat0}=16cm, it takes 10s and 24s respectively; and only 1.2s and 4.5s if w_{sat0}=8cm. In these cases, there is a clear advantage to catch the mode relatively early. Moreover, if the power available is marginal, then even if one can fully stabilize the mode completely, the negative growth rate will be relatively small in absolute value. This translates in a slow decay rate in Fig. 3. This is for example the case for the 4th case shown, "2.5/CW/$\chi_\perp$", which fully stabilizes the mode at 162s, 111s and 3s depending if w_{sat0}=24, 16 or 8cm respectively. In this case, the max(dw/dt) occurs at about $w_{max(dw/dt)}$=12cm, therefore it is only once w<10cm that the stabilization is fast, which explains why the time necessary for full stabilization goes from 111s to 3s when w_{sat0}=16 and 8cm. Finally the last case, "2.5/50%/ $\chi_\perp$", is just above marginality and thus has dw/dt=0 at 2 values close to max(dw/dt), at 10.5cm and 15cm. Therefore, if w_{sat0}>15cm, it will very slowly saturate to this value, but if w_{sat0}<10.5cm, it will very rapidly decay away, because the growth rate rapidly becomes very negative. Indeed it takes only 5.3s in this latter case to stabilize a mode with w_{sat0}=8cm.

These few examples show very well that the actual best strategy will depend on the effective efficiency of NTM stabilization in ITER and the value of w_{marg}. It also shows that one needs to be somewhat above marginal (>30%) to be able to stabilize a large mode quickly. This is also why we have chosen P=13MW, to keep some margins. Another reason is the results of the previous Section which show that the Q value is not really improved if more power is required to fully stabilize the mode. However, these results assume CW use of ECCD. Since the main trigger for NTMs in burning plasmas is expected to be the crashes after long sawtooth periods, one can use this knowledge to turn on the EC only around the ST crashes. The sawtooth period is expected to be around 15-20s [19]. If we wait for the mode to be triggered and observed, there will be some delay before the ECCD is well aligned on the island position. During that time the mode will grow and from the results shown in Fig. 3, a few extra seconds can lead to a much longer time for full stabilisation. This is illustrated in Fig.4 where a sawtooth crash is assumed to trigger a seed island of size 8cm at t=0. The same parameter (w_{marg}=4cm, $w_{sat\infty}$=32cm) as in Fig. 2a and 3 are used, but only 2 models are illustrated. The solid lines correspond to "2.5/CW/ $\chi_\perp$" and the dashed lines to "2.5/CW/*pol*". Note that "2.5/50%/*pol*" would yield similar results as the dashed lines, as inferred from Fig. 3. A delay before the ECCD effect is turned on is included. A delay of "0s" represents the case of pre-emptive ECCD, that is one would turn on the EC at the right location before the ST crash happens. A delay of 3s is representative of the case that the EC is turned on only once a mode is measured, but the launchers are kept aligned all along the discharge. Finally a delay of 10-20s can represent the case when a mode is observed and the launchers where not aimed correctly or where aimed at q=3/2 for example.

As expected from Fig. 3, the delay has a significant impact on the first case, which is just marginal to fully stabilise the mode (solid line). In this case, if the delay is more than about 5s, it will take more than 100s to fully stabilize the mode, because w_{sat} is larger than the value $w_{max(dw/dt)}$, that is the value which has the less negative growth rate. If we are significantly above marginal power to fully stabilize the mode, then the results corresponding to the dashed lines are expected. In this case, already with a delay of 3s, it takes 7.1s since the ST crash before the mode is fully stabilized, that is about half the ST period. This would mean that the EC is turned on about half of the time, on average, thus yielding a slightly better Q factor.

In the case of pre-emptive ECCD, delay=0s, the mode is stabilized very quickly because $w_{sat} < w_{max}$ and the growth rate is rapidly very negative. Assuming that we would be able to predict in real time the next sawtooth crash, or even to control its occurrence with local ECCD, we can turn on the EC power only when needed. Let us assume we can predict the crash within 3s, that is we would turn on EC about 3s before a crash on average. We would then leave it on typically 2s to fully stabilize the mode. This gives an effective duty cycle of 5s as compared to the sawtooth period of about 15s, thus a factor 1/3. This could be the best strategy if one cannot avoid the triggering of NTMs. It would also insured that the 2/1 mode is never larger than about 10cm, avoiding large drop in confinement and probably avoiding mode locking [9]. We have also calculated the modifications of the local shear at q=1 that can be obtained with the present launcher design (modified to reach q=1 [6]). We see that a factor of 3-4 is possible, thus controlling the sawtooth period between about 5s to 50s, which is similar to the early simulations obtained during the ITER-FEAT design [19]. In such a case, if the ST period is lengthened up to 50s, the effective duty cycle would drop to 1/10 for the NTM stabilization which is negligible. Thus the efficiency of this strategy would depend on the power required to stabilize the sawteeth. If only about 5MW is sufficient, then it could be worthwhile. However the best would be to destabilize the sawteeth, such that with periods of 5s or less NTMs would not be triggered. This has been proven useful in JET [2], although the minimum period required is hard to predict. Nevertheless, at least the triggering of 2/1 NTMs might be avoided. Indeed it is seen on JET that only very long sawtooth periods are related to the trigger of 2/1 modes at low beta, usually only 3/2 and 4/3 modes are triggered.

6. Conclusions

We have used the present experimental and theoretical understanding of the main physics effects controlling the trigger and sustainement of neoclassical tearing modes to predict the main strategies to be used for NTM control and/or avoidance in burning plasmas. We have used the predicted ITER parameters and the 2/1 NTM to show examples of the effects due to the various terms.

We have extended the analysis of present experimental results to the cases of the $\chi_\perp$ and polarisation models, assuming CW or modulation and varying the current deposition full 1/e width w_{cd}. All these combinations have been evaluated assuming a marginal island size on ITER of 2-6cm. The results are presented in Table 1 and they allow one to predict the power required to fully stabilize the mode, given the minimum value of w_{cd} achievable for a given design and the value of $\eta_{NTM}w_{cd}$. The main result is a rapid increase of the required $\eta_{NTM}w_{cd}$ with w_{cd}, as expected. Moreover, with this Table, one is able to analyse the effects of the various assumptions and therefore to understand better the range of applicability of a single specific criteria as used in present design work [8]. In particular one sees that with a value of $\eta_{NTM}w_{cd}$=6.3 and $w_{cd}\geq$2.5cm, as achieved in the present design [6, 7], the 2/1 mode can be fully stabilised using either CW or modulation, if w_{cd}=2.5cm is achieved (perfect alignment), and even with an effective width of w_{cd}=5cm with 50% modulation. In the CW case with w_{cd}=5cm, one would rely on $w_{marg}\approx$6cm to be able to fully stabilize the 2/1 NTM.

Using the dependence of the saturated island width on the EC power, one can infer the resulting Q factor. We have shown that with most models and with w_{marg}=4cm, full stabilisation is obtained at about 10MW, yielding an average Q factor of about 8, as compared to Q=4.5 without ECCD. A value of Q~9 is relatively easily obtained if w_{marg}=6cm. However if w_{marg} is small, as predicted in [9], w_{cd}=2.5 is required to achieve Q>8. It has also been shown that partial stabilization can maximize $Q(P_{EC})$ if w_{marg} is small. At larger values of w_{marg}, full stabilisation is always better. However the main benefits of partial stabilization would be in the possibility to control the factor Q and also to track the island position with EC launcher easier. The control of Q could become an important area of research if one obtains confinement properties better than expected in burning plasmas.

We have also presented the typical time evolution of 2/1 NTMs in ITER, assuming different initial saturated islands and various delays after a mode is triggered/observed. This study show that if one is not at least 30% above the marginal power required to fully stabilise the mode, then the time required to achieve full stabilization can be very long. Another result is the clear benefit of pre-emptive application of ECCD. If the stabilising contribution is present from the start, modes are quickly stabilised. This is mainly due to the w dependence of the Δ'_{CD} term, which cancels in a large part the 1/w dependence of the driving term. This leads to a shift of the island width at which dw/dt is maximum.

The simulations of the island time evolution also show that the sawtooth activity and in particular the sawtooth period has to be taken into account to define the best strategy for NTM control. Not only one might avoid in particular the triggering of 2/1 modes by destabilising the sawteeth, but an accurate control and/or prediction of the next sawtooth crash can optimise the use of pre-emptive ECCD.

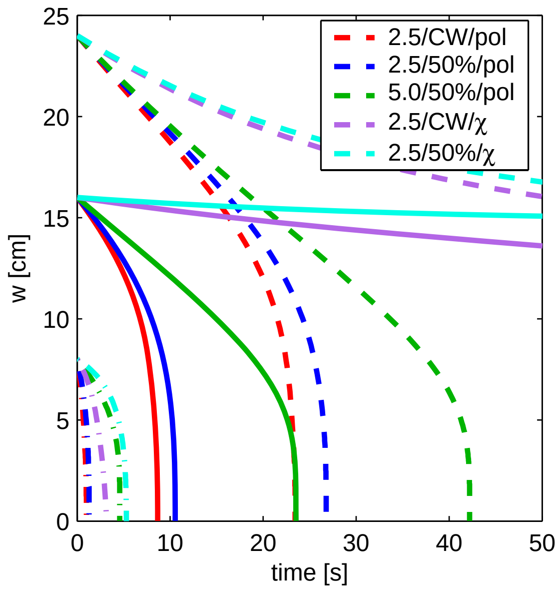


Fig. 3: w vs time for 3 different initial saturated island sizes and with various models

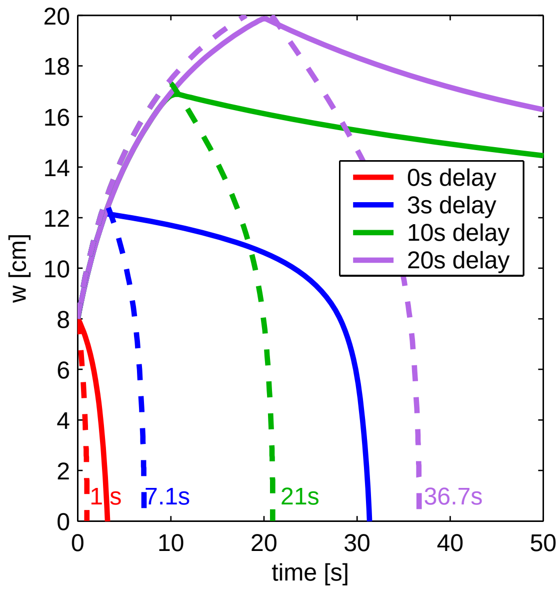


Fig. 4: Time evolution of a 8cm island, assuming some delay before EC is fully operative.

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