

The Physics Base for NTM Stabilization by ECCD in ITER

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Abstract. The requirements for NTM stabilization by ECCD in ITER comprise access to the resonant surfaces of interest, a steering speed sufficient to follow radial variations of these surfaces and the capability to drive sufficient current at the resonant surfaces to completely stabilize the NTMs. The paper focuses on the latter requirement, reviewing the previously derived criterion $\eta_{\text{NTM}} = j_{\text{ECCD}}/j_{\text{bs}} > 1.2$. An analysis of a multi-machine database using experimental data from ASDEX Upgrade, DIII-D, JET, and JT-60U using an alternative approach to that done previously basically confirms this number. We point out further work that is needed to refine the validity of this criterion. In addition, the analysis of the requirements highlights the need for injection of ECCD in phase with the NTM, suggesting that modulation capability should be retained in the design of the ITER ECCD system.

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INTRODUCTION

One of the main tasks of ECCD in ITER is the stabilization of Neoclassical Tearing Modes (NTMs). It is the main driver for the design of the Upper Launcher system. The requirements for NTM stabilization in ITER have been defined as

- steering range sufficient to access the (3,2) and (2,1) surface in scenarii 2, 3 and 5 including a variation of β and ℓ_i .
- steering speed sufficient to scan half the scanning range within 3 s.
- beam geometry such that for all the surfaces mentioned above, NTMs can be fully stabilized, assuming that this means $\eta_{\text{NTM}} = j_{\text{ECCD}}/j_{\text{bs}} > 1.2$, at $P_{\text{ECCD}} \leq 20$ MW.

While the first and second point are based on relatively well understood physics assumptions, the third point is based on an analysis using the modified Rutherford equation with the difficulty that the physics at small island width is not unambiguously clear. Recent progress in this field includes an analysis of the impact of NTMs on Q [1] and an approach to benchmark the modified Rutherford equation to experimental data from NTM stabilization in ASDEX Upgrade, DIII-D and JT-60U

[2]. It is the aim of this paper to review the predictions of the generalized Rutherford equation for ITER, to point out the open questions and to discuss the implications of these uncertainties for the ITER requirements.

THE POWER BALANCE OF NTM STABILISATION IN ITER

The main goal of NTM stabilization in ITER is to recover a loss in fusion gain $Q=P_{\text{fus}}/P_{\text{AUX}}$ due to NTMs. This has been analyzed [1] using a 0-d burn model together with the belt model to estimate the loss of confinement [3]. The result for the ITER scenario 2 (standard $Q=10$ scenario) is shown in Fig. 1:

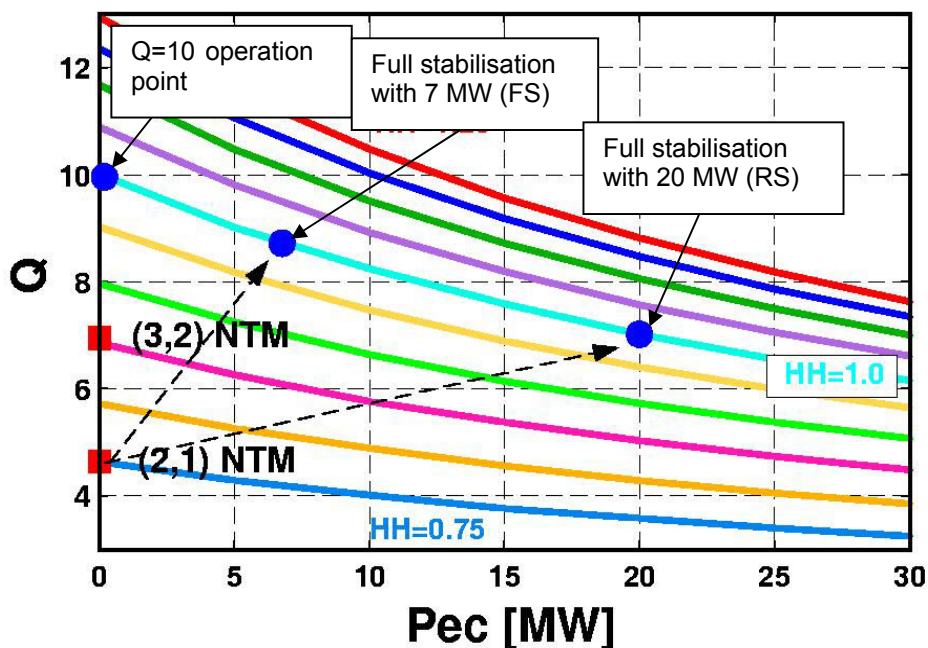


FIGURE 1. ITER burn curves for scenario 2 in the presence of additional ECCD power at the (3,2) or (2,1) resonant surface. The curve parameter is the confinement quality $H_H = \tau_E/\tau_{E,\text{scal}}$. The red squares mark the performance reduction without ECCD, the blue dots are the operation points without NTM assuming no ECCD necessary ($Q=10$), stabilization using the front steering (FS) launcher and the remote steering (RS) launcher.

It can be seen in Fig. 1 that in the presence of a (3,2) NTM, Q is predicted to fall from 10 to 7, with a (2,1) NTM the value is halved ($Q=5$) assuming no wall locking and no subsequent loss of H-mode. Using ECCD to restore normal confinement ($H_H = 1$) brings Q back to 7 for a required power of 20 MW (typical for the present remote steering (RS) launcher design) or to 9 for a required power of 7 MW (typical for the present front steering (FS) launcher design). The fact that adding ECCD power leads to a loss of Q even at $H_H = 1$ comes from the fact that in order to stabilize NTMs, the ECCD power is deposited in the periphery and is thus not expected to heat the plasma with the same efficiency than in the case of central deposition. In the model, this has been accounted for by using only a fraction of $P_{\text{ECCD}}(1-(r_{\text{res}}/a)^2)$ as effective additional

heating power. It is clear from Fig. 1 that a required power in excess of 20 MW cannot increase Q for the (3,2) mode and also for the (2,1) mode, the gain becomes marginal. It is thus not recommended to increase the installed power to accommodate full stabilization. On the other hand, we note that the main plasma physics argument for Q=10 operation is that the α -heating power should dominate the external power (by a factor of 2 at Q=10), allowing a true study of the nonlinear interaction between stored energy and α -heating power. Thus, one could argue that P_{ECCD} should only be counted in Q to the amount that it also contributes to plasma heating which, according to the argument above, is substantially reduced when ECCD is deposited in the periphery.

Another crucial point in the power balance is that NTMs, after full stabilization, are expected to be re-excited, e.g. by a sawtooth crash. It is however not clear at present how frequently this will happen. In the case of long NTM-free periods, this could potentially lead to a much reduced impact on Q, but it requires the ability to completely suppress the NTM to take advantage of it. In the other limit of very frequent NTM occurrence, it may be beneficial to only partially stabilize the NTM under some circumstances [1].

THE CRITERION FOR COMPLETE NTM STABILIZATION

The criterion for complete NTM stabilization has been derived previously from the generalised Rutherford equation

$$\frac{\tau_R}{r_s} \frac{dW}{dt} = r_s \Delta'_0 + r_s \delta \Delta' + a \frac{j_{bs}}{j_{||}} \frac{L_q}{W} \left(1 - \frac{W_{marg}^2}{3W^2} - K_1 \frac{j_{ECCD}}{j_{bs}} \right) \quad (1)$$

where a is a constant of proportionality of order unity. Here, the difficulty comes from the correct treatment of the physics at small island width, which involves several competing effects that lead to a marginal island width W_{marg} below which the NTM is no longer supported by the plasma and decays naturally. The previously derived criterion

$$\eta_{NTM} = \frac{j_{ECCD}}{j_{bs}} > 1.2 \quad (2)$$

assumed that W_{marg} is of the order of the ion banana width [4], consistent with various theoretical small island terms as well as with experimental results. We note that by using the $1/W^3$ dependence for the stabilizing term in (1), the W_{marg} term follows the functional dependence of the polarization current model.

In order to validate this criterion experimentally, a recent initiative on several fusion devices, namely ASDEX Upgrade, DIII-D, JET and JT-60U, produced a database of NTM stabilization experiments ([2], details about the experimental input data can be found there). First, a fit of the saturated island width without ECCD can be done to obtain the free coefficient a in Eqn. (1). Then, the ECCD current can be added in Eqn. (1) to check on the stabilization efficiency. This is shown in the left graph of

Fig. 2. As can be seen, all three experiments (JET does not have ECCD, but was included to obtain the coefficient a) are predicted to achieve full stabilization, consistent with the experimental results, but Eqn. 1 actually predicts a large 'overstabilization', indicating that the power could be largely reduced in the experiments. Since this is generally not the case, we conclude that another physics element has to be introduced to account for the experimental results. In [2], this was done by assuming that there is a mismatch between the deposition and the resonant surface, leading to reduced stabilization efficiency through a reduction of K_J . Since this mismatch has not been determined experimentally, we propose here another approach, namely to insert another free coefficient c_j in the Rutherford equation, which then reads

$$\frac{\tau_R}{r_s} \frac{dW}{dt} = r_s \Delta'_0 + r_s \delta \Delta' + a \frac{j_{bs}}{j_{||}} \frac{L_q}{W} \left(1 - \frac{W_{marg}^2}{3W^2} - c_j K_1 \frac{j_{ECCD}}{j_{bs}} \right) \quad (3).$$

There are a number of physics effects other than deposition mismatch which could lead to such a numerical correction, such as e.g. the averaging process over the exact island geometry as opposed to the presently employed constant ψ , parabolic helical flux approximation. On the right part of Fig. 2, one can see that $c_j < 1$ shifts the curves closer to the marginal point, consistent with the experimental results. We chose here a value of $c_j = 0.7$, but assume no deposition mismatch in K_J , bringing the JT-60U point close to the marginal point.

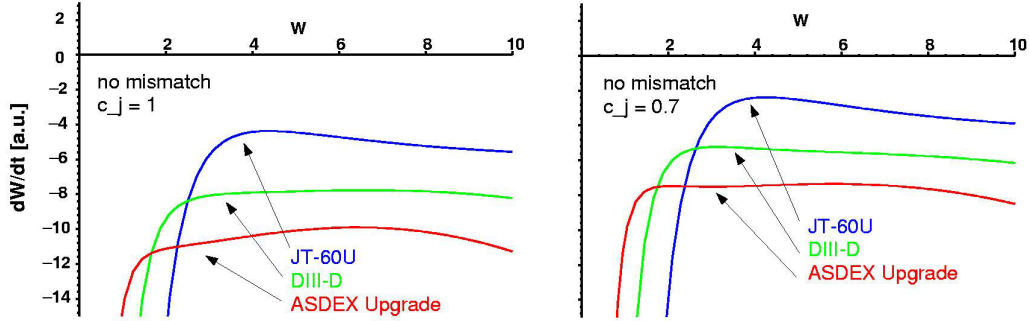


FIGURE 2. Predicted NTM growth rate in the presence of ECCD for the data points from ASDEX Upgrade, DIII-D and JT-60U. Consistent with the experiment, dW/dt is negative, but without further correction (left) too negative. With $c_j = 0.7$ (right), the fit becomes much better.

While it is not possible to distinguish between the two approaches from the present experimental database, we note here that their predictions for ITER are quite different: assuming $c_j = 1$ and no mismatch in ITER (i.e. a situation better than in present day experiments) leads to $\eta_{NTM} = 0.9$ for the (2,1) NTM in scenario 2, while $\eta_{NTM} = 1.3$ with $c_j = 0.7$ and without mismatch. We therefore propose to do further experiments to map out precisely the minimum power requirement in a given situation, thus also ensuring that there is no mismatch.

THE EFFECT OF MODULATED ECCD INJECTION

Finally, we note that in evaluating the ITER data point above, we have assumed in the generalized Rutherford equation that the power is injected in phase with the island O-point (50% duty cycle, 100% modulation depth). It has been shown before that this will be beneficial for generating helical current within the island [5]. However, taking into account that one loses half of the current by the modulation, there is a reduction in $\delta\Delta'$ which partly offsets this advantage. We therefore evaluate the stabilizing term due to ECCD taking into account both contributions as

$$r_s \Delta'_{ECCD} = a_{mn} L_q r_s \frac{I_{ECCD}}{I_p(r_s)} \eta_{mn} \left(\frac{W}{d} \right) \frac{1}{W^2} + a_{00} \frac{L_q r_s}{d^2} \frac{I_{ECCD}}{I_p(r_s)} \quad (3)$$

The function η_{mn} must be calculated by averaging the RF source profile $j(r, \zeta) = j_{ECCD} \exp(-(r/d)^2) \Theta(\zeta)$, where $\Theta(\zeta)$ characterizes the modulation in helical angle, over the island flux surfaces as in [5]. In Fig. 3, we plot the function $I_{ECCD}(a_{mn} \eta_{cd} (d/W)^2 + a_{00})$ as function of W/d for the modulated and the unmodulated case using the literature values $a_{mn}=32$ [5] and $a_{00} = 2$ [6]:

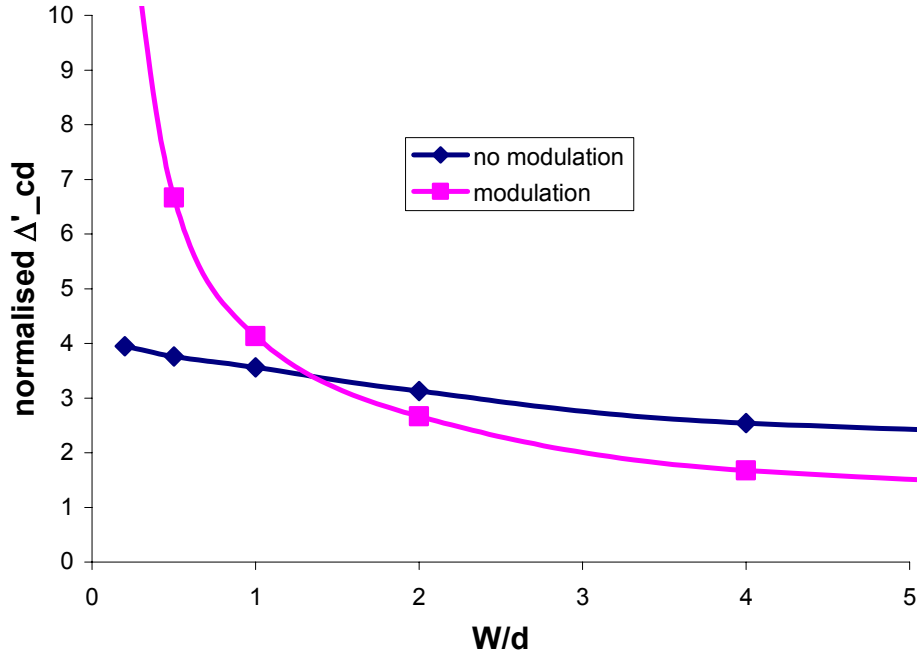


FIGURE 3. The function $I_{ECCD}(a_{mn} \eta_{cd} (d/W)^2 + a_{00})$, relating to the stabilizing term $r_s \Delta'_{cd}$ plotted for modulated ($I_{ECCD} = 0.5$) and unmodulated ($I_{ECCD}=1$) current drive.

Due to the assumption that the (0,0) term is independent of W , it dominates for large W and actually makes the unmodulated case exceed the modulated case, whereas

for small W/d , the (m,n) component dominates and consequently the benefits of modulation become evident. This means that for $W < d$, as is presently predicted for ITER, the modulation capability of the system should be retained.

CONCLUSIONS

In this paper, we have reviewed the physics base for the prediction of required current drive for NTM stabilization in ITER. First, we show that for required power in excess of 20 MW, the recovery in Q is small. Then, we use experimental data from an international database to obtain the required ECCD current density in the form $\eta_{NTM} = j_{ECCD}/j_{bs}$, as suggested by the Rutherford equation. The criterion previously derived $\eta_{NTM} > 1.2$ is confirmed, but we point out that more experimental work is needed to ensure that no mismatch between deposition radius and resonant surface is present in the experiment. Finally, an analysis of the CD term in the Rutherford equation taking into account the $\delta A'$, the effect of the change of equilibrium current profile, confirms that modulation should be beneficial in ITER once W becomes smaller than d .

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