Partial Stabilization and Control of Neoclassical Tearing Modes in Burning Plasmas

O. Sauter, M.A. Henderson, H. Zohm[1] *, C. Zucca*

Ecole Polytechnique Fédérale de Lausanne – CRPP - EPFL
Association Euratom-Confédération Suisse - CH-1015 Lausanne, Switzerland
[1] IPP-Garching, Max Planck-Institute für Plasmaphysik, D-85748 Garching, Germany

First Author e-mail: olivier.sauter@epfl.ch

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 ρ_s^3, where ρ_s is the position of the resonant surface. Therefore the q=2 NTMs are much more detrimental to the confinement than the 3/2 modes since $(\rho_{q=2}/\rho_{q=3/2})^3 \sim (0.8/0.6)^3 \sim 2.4$. NTMs are metastable in typical scenarios with $\beta_N>1$ and in the region where $dq/d\rho>0$ [1]. 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.

The saturated island size of a NTM is the result of a complex balance between the main drive, the perturbed bootstrap current, and stabilizing terms. In addition, these contributions can have different dependence on the island size itself. Therefore the saturated island size is not necessarily proportional to the input ECCD power (electron cyclotron current drive). It has been shown that in some cases, a small increase in the current driven at the resonant surface results in a significant decrease of the island width, hence a significant confinement improvement. In this way one can obtain a maximum of the value of Q versus P_{ECCD}, at a value such that the mode is only partially stabilized [2]. Figure 1 illustrates well the strategy which is discussed here. It shows the fusion factor Q versus the delivered power driving localized current at the resonant surface. With $P_{ECCD}=0$, the modes reach their full saturated island width and are expected to lead to typical confinement degradation of 15% and 25% for the 3/2 (A) and 2/1 modes (B) in ITER. Therefore the points lie on the HH=0.85 (A) and HH=0.75 (B) curves. If P_{ECCD} is increased, even without confinement degradation, the value of Q decreases as $P_{NBI}/(P_{NBI}+P_{ECCD})$, this is why the solid lines decrease with increasing P_{ECCD}. Assuming that the mode can be fully stabilized with 20MW, the operating mode will be (C) on HH=1, resulting in a value of $Q\approx7$. As shown in Fig. 1(b), the right-hand side of the modified Rutherford equation, dw/dt, can be a complicated function of w, resulting in a nonlinear function of $w(P_{ECCD})$. Therefore, the operating points obtained with partial stabilization of the 3/2 and 2/1 modes can lead to a better Q factor than the value of 7 obtained with full stabilization, as sketched in Fig. 1(a).

In some cases, depending on the value of j_{cd} at the peak and the deposition width w_{cd}, the island width decreases rapidly with a relatively small input power. The final gain between full stabilization and a small saturated island can also be small when the value of w_{marg} is small.

The latter represents the island width below which the island self-stabilises. The value of w_{marg} is crucial to determine the best strategy for NTM control. If it is only of the order of 1% of the minor radius of a burning plasma, it has 2 consequences: 1) The difference in performance between a saturated island at $w \approx w_{marg}$ and full stabilization is small; 2) Small seed islands and thus small perturbations are sufficient to destabilize NTMs. In addition small islands require more accurate alignment of the ECCD beams. In these respects, another advantage of partial stabilization is that one controls at all time the desired size of the NTM and therefore alignment is known and controlled constantly.

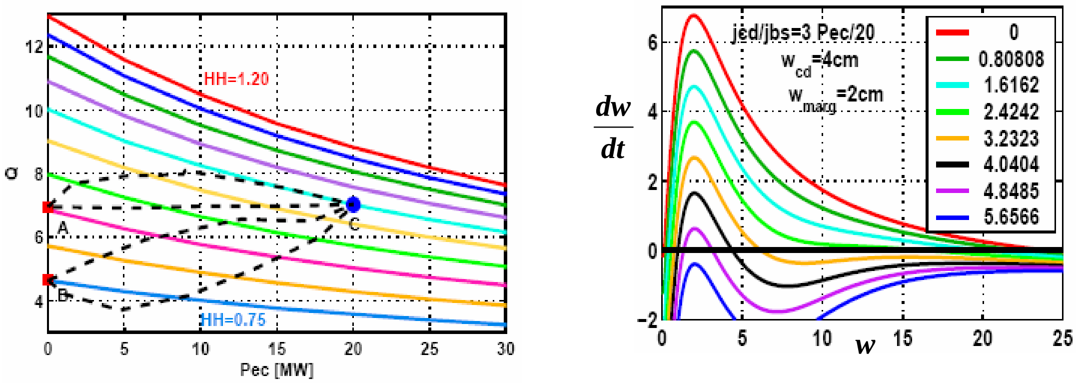

Fig. 1:(a) Sketches of $Q(P_{eccd})$ from stabilization in ITER of 3/2 (A) and 2/1 (B) NTMs. The lines are obtained with HH factor between 0.75 and 1.2, equally spaced. (b) dw/dt vs w for typical parameters and various P_{eccd} power between 0 and 5.65MW. The dependence on w can be even non-monotonic.

Other options can modify the best strategy for NTM control. An important possibility concerns the modulation of the ECCD power such as to drive current in the O-point of the island. It can increase the stabilizing efficiency, but it can also increase the cost of the ECCD system and decrease its reliability. These effects need to be discussed within the global assessment of the various strategies for NTM control. Another possibility is to prevent the formation of NTMs by applying ECCD before a seed island is triggered. This could be efficiently enforced if NTMs are triggered only at the sawtooth crashes, as expected from JET experiments [3]. In addition, if the sawtooth periods are relatively long, the duty cycle might be less than 50%, increasing further the effective Q factor. The possibility to control the sawtooth period with localized current drive can also be an efficient way to avoid NTMs or to lengthen the period between NTM triggers. In addition, the ECCD power is also heating the plasma near q=1, whereas the power is essentially lost when aiming at q=2 because of the local confinement.

The paper will discuss all these strategies and discuss the benefits and disadvantages within a self-consistent theoretical framework. It will be shown that the best choice is not unique and depends on the actuators specifications, like $j_{cd,peak}$ and w_{cd}, as well as on intrinsic plasma parameters like w_{marg}.

References

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