ECCD capabilities for NTM stabilization via the Upper Launcher from ramp-up to ramp-down phases in ITER

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The ITER Upper Launcher (UL) is designed to provide Electron-Cyclotron (EC) focussed beams delivering power to the plasma with the primary goal of reaching the $q = 2$ and $q = 3/2$ surfaces with the aim of stabilizing Neoclassical Tearing Modes (NTMs), and in addition the range around the $q = 1$ surface to control the sawtooth instability [1]. The UL comprises four ports, each housing eight beam lines, arrayed in an upper and lower row of four waveguides each. Each row is provided with independent steering mechanisms, referred to in the following as the Upper Steering Mirror (USM) and Lower Steering Mirror (LSM). A maximum power of 24 MW at a frequency of 170 GHz is foreseen for the first phase of operation, of which 20 MW (taking transmission losses into account) can be launched into the plasma. As a consequence, the maximum power that can be injected from the 16 beam lines of each row is 13.3 MW. In this paper, the performance of the launcher in relation to its capability of reaching the goal of NTM stabilization is studied. The derivation of the stabilization criteria used up to now as a guideline for the design of the launcher is reviewed. The power required for NTM suppression is evaluated for the whole evolution of a simulated ITER discharge.

Revision of the NTM stabilization criteria

Two stabilization criteria have been employed up to now to guide the design of the UL. The first criterion poses a requirement on the current density that should be driven by the launcher, namely that its peak value should exceed by a factor 1.2 the unperturbed bootstrap current density at the flux surface where the mode develops [2]:

$$\eta_{NTM} \equiv \frac{j_{\rm CD}}{j_{\rm bs}} > 1.2. \tag{1}$$

The second criterion is a condition on the total driven current, and can be expressed by the requirement that the driven current density multiplied by the full width of the deposition profile (proportional to the total driven current) and divided by the bootstrap current density should be larger than 5 cm [3]:

$$\eta_{NTM} w_{\rm CD} \gtrsim 5 \text{ cm}, \tag{2}$$

while the EC deposition width $w_{\rm CD}$ should stay below 5 cm. Both criteria can be derived from the modified Rutherford equation (MRE) [4] under different limiting assumptons, as shown below. The condition for a stable island size $\mathrm{d}w/\mathrm{d}t = 0$ (w is the full island width) can be written in the form

$$0 = -1 + \frac{w_{\rm sat}}{w} - 5\frac{w_{\rm CD} w_{\rm sat}}{w^2}\frac{j_{\rm CD}}{j_{\rm bs}}\eta_{CD}, \tag{3}$$

where $w_{\rm sat}$ is the saturated island width in the absence of ECCD, and the CD stabilization efficiency η_{CD} [5] weights the component of the driven current with the correct helicity. Eq.(3) is kept in its simplest form, neglecting among others any stabilizing effects at small island width. Requiring that no roots of Eq.(3) exist leads to the following criterion for NTM stabilization:

$$\frac{w_{\rm CD}}{w_{\rm sat}}\frac{j_{\rm CD}}{j_{\rm bs}}\eta_{CD} > \frac{1}{20}. \tag{4}$$

It is useful to distinguish between the case in which the ECCD profile is broader or narrower than the typical island width $w_{\rm marg}$ at which stabilization occurs. In the former limit, to express the stabilization condition it is more practical to exploit the fact that in ITER it can be assumed that $w_{\rm marg}$ is much smaller than $w_{\rm sat}$, so that the first term on the right-hand side of Eq.(3) can be dropped near marginal stability. Employing the limit [2] $\eta_{CD} \simeq 0.15w/w_{\rm CD}$ for modulated injection leads to the criterion $\eta_{NTM} > \frac{4}{3}$, corresponding to Eq.(1), which includes a reduction of the neoclassical drive due to geodesic-curvature effects. In the limit of large deposition profiles, modulation is essential for NTM suppression. In the opposite limit $w_{\rm CD} < w_{\rm marg}$, one finds $\eta_{CD} \simeq 1/3$ for both continuous injection and modulation. Eq.(4) then becomes $w_{\rm CD} j_{\rm CD}/j_{\rm bs} w_{\rm sat} > 3/20$. For a saturated island width of the order of 30 cm, as predicted for the $q = 2$ surface in ITER [3], this condition yields $\eta_{NTM} w_{\rm CD} \gtrsim 4.5$ cm, in good agreement with Eq. (2). A numerical evaluation of the right-hand side of the MRE covering both limits, i. e. using fits [3] for the function η_{CD} and including a transport threshold [6] on the neoclassical drive shows that the transition between Eq.(1) and Eq.(2) takes place for $w_{\rm CD}$ between 4 and 5 cm. In fact, the two criteria lead to the same stabilization power for $w_{\rm CD} = 5/1.2 \simeq 4.2$ cm. For smaller deposition widths, Eq.(2) should be employed and Eq.(1) in the opposite case. Since each criterion leads to the higher power requirements in its respective validity range, the stabilization power can be evaluated as the maximum of the requirements of both criteria. It is finally noted that a smaller saturated island width (around 25 cm) is predicted for the $q = 3/2$ surface in ITER [3], so that the stabilization criteria valid on the $q = 2$ surface hold *a fortiori* also there.

Performance analysis

The compliance of the UL with the task of NTM stabilization in ITER has been investigated using the beam tracing codes GRAY [7] and TORBEAM [8]. For each steering mirror, a single beam is computed (implying perfect superposition of the four beam of each row in the plasma), injected from $(R,Z) = (6.999, 4.414)$ m for the USM (with waist $w_0 = 2.9$ cm at a distance of 2.134 m in front of the mirror) and $(7.054, 4.178)$ m for the LSM ($w_0 = 2.1$ cm at 1.620 m from the mirror). The whole history, including ramp-up and ramp-down phases, of a simulated ITER discharge for the "standard" 15 MA, $Q = 10$ scenario [9] has been studied. The current flattop (coinciding with the H-mode phase) develops between $t = 80$ and 530 s. The plasma parameters near the end of the thermonuclear burn ($t = 520$ s) are quite close to those considered in previous analyses [10].

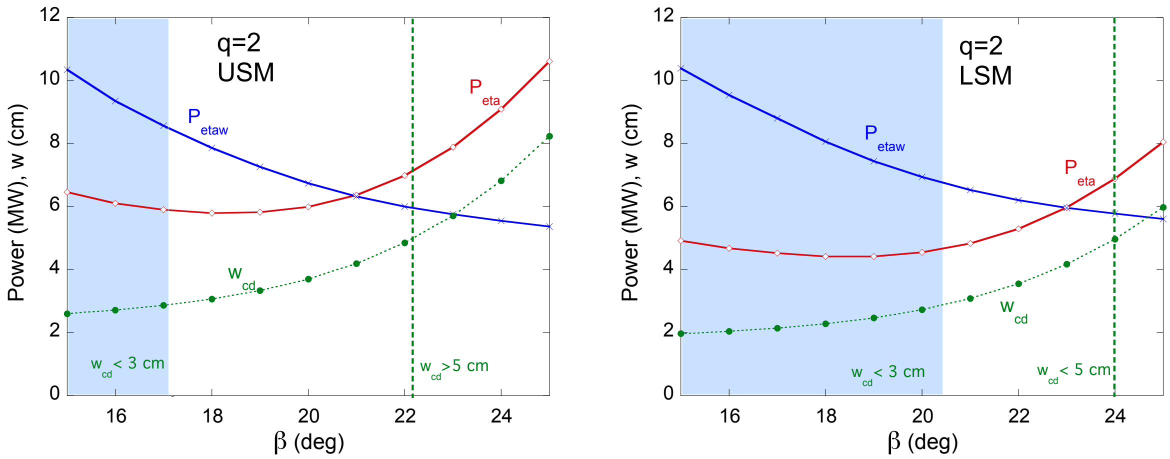

Fig. 1. *Power required for stabilization at the end of burn ($t = 520$ s) on the $q = 2$ surface, calculated according to Eq.(1) and Eq.(2) (curves labelled P_{eta} and P_{etaw}, respectively) as a function of the toroidal launch angle β for the USM (left) and the LSM (right). Also shown is the full width at $1/e$ level of the CD profile (GRAY results).*

Fig. 1 shows the power for NTM suppression, as computed from Eq.(1), labelled P_{eta}, and Eq.(2), labelled P_{etaw}, for different toroidal injection angles. The results refer to the $q = 2$ surface at the end of the burn phase. The curves corresponding to the two criteria cross as expected where $w_{CD} \simeq 4.2$ cm. This intersection point correspond to the minimum power requirement. For the USM, this condition is achieved for an injection angle slightly above 20°, which is the current design value. For the LSM, on the other hand, the higher focusing of the present beams implies that minimum stabilization power is reached at somewhat larger angles (around 23°), as already suggested [11]. According to the previous discussion, pushing the deposition width below w_{marg} does not increase the stabilization efficiency, so that any additional focussing should be exploited to drive more current, keeping w_{CD} around the optimum value.

The stabilization power computed for an entire simulated ITER discharge is reported in Fig. 2.

Two large peaks (the first at around $t = 80$ s, the second at $t = 530$ s) can be observed. The first one is due to the fact that in this simulated discharge the electron temperature drops before the L-H transition (while the density is increasing), with a negative impact on the CD efficiency. The second peak follows from the faster drop of the temperature with respect to density after the H-L transition, with a similar effect. The role of these transient phases is still to be assessed.

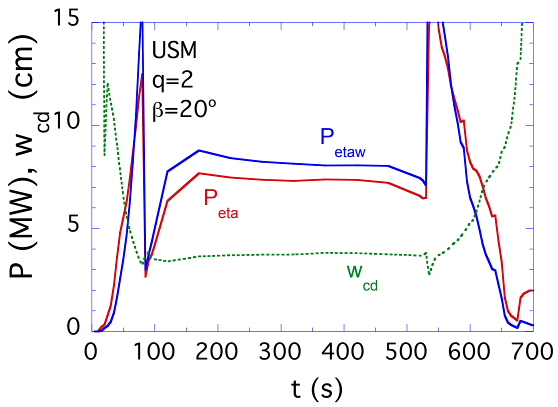

Fig. 2. *Time traces of the power required for stabilization for the* $q = 2$ *surfaces for injection from the USM at* $\beta = 20°$ *(left) and from the LSM at* $\beta = 22°$ *(right).*

In the flattop phase, NTM suppression is achieved for power levels around 7–8 MW, thus well within the capabilities of the system. For the toroidal injection angles considered in the figure, w_{CD} is close to its optimal value and both stabilization criteria yield similar predictions.

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