Optimal RF stabilization of NTMs in ITER and other large tokamaks

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Neoclassical tearing modes (NTMs) must be stabilised to avoid confinement degradation and disruptions. This is usually accomplished using radio-frequency waves to drive current at the O-point of the NTM island. Typically, NTMs rotate with the background plasma initially, before braking due to interaction with the resistive wall and finally locking to the tokamak's error field.

In present-day medium-sized devices, the islands lock at large widths due to the strong plasma rotation, such that the locking is quickly followed by a disruption. However, in larger future devices like ITER, the islands will lock at a small width, which makes rotating island stabilisation challenging and suggests one stabilise the locked mode instead. This can be accomplished by tuning the error field to lock the island in front of the rf-wave launcher, as done on DIII-D [1].

These small locked modes, e.g. $w_{\text{lock}} \sim 0.045a$ for the $2/1$ NTM in ITER [2], are far from the width at which a disruption is to be expected ($w \sim 0.3a$ [3]). Moreover, loss of H-mode due to braking of the background plasma rotation by the island only occurs approximately a momentum confinement time after locking [4], ~ 3 s in ITER. Loss of H-mode can therefore be avoided by stabilising the island quickly after locking, as shown on DIII-D [1, 5]. Furthermore, it is still unclear whether loss of H-mode would be a problem at these small locked island widths, as no confinement degradation is observed in ELM stabilisation experiments where small locked islands are induced at the pedestal top [6].

Locked modes can be stabilised more efficiently because most of the current is driven near the island O-point, allowing for lower power requirements for NTM stabilisation compared to rotating island stabilisation. Furthermore, the same geometric advantage translates to larger tolerances with respect to misalignment and broadening of the rf wave.

ITER's planned rotating island stabilisation of the $2/1$-NTM is challenged by two recent findings. First, the blanket modules reduce the time to locking to only 1.7 s [2] (for $Z_{\text{eff}} = 1.53$ [7]). Second, edge density fluctuations are predicted to broaden the electron cyclotron (EC) wave by a factor $2.5-3.5$ [8], strongly impacting the stabilisation efficiency.

As will be shown below, locked mode stabilisation is preferable to that of rotating islands in terms of peak power requirements, which would help free up EC power for other needs in ITER, e.g. for sawtooth control and core heating. Moreover, even the averaged power requirement for NTM stabilisation will be lower for locked mode stabilisation, because the power will need to be on at all times in rotating island stabilisation strategies. This holds true for continuous EC power if preemptive, and for modulated power because the detection threshold (~ 4 cm) is larger than the marginal stability width (~ 1.5 cm). In contrast, a locked mode can be fully stabilised, after which the EC power can be turned off until a new NTM is seeded and locks.

To determine the peak power requirements for NTM stabilisation, we temporally evolve the island width (1) and island rotation (2). The former is modeled by a Generalised Rutherford Equation including the effects of the classical Δ' [2, 9], the error field [10], the bootstrap and polarisation currents [11] and the rf current drive [12, 13]. The island rotation is set by the viscous [2], resistive wall [9] and error field [10] torques. This model represents an extension of previous work [14, 2] to include the effects of current drive and error field.

$$0.82\frac{\tau_r}{r_s}\frac{\mathrm{d}w}{\mathrm{d}t} = \underbrace{r_s\left(\Delta_0' + \Delta_{0,\mathrm{wall}}'\right)}_{\text{Classical}} + \underbrace{2m\left(\frac{w_{\mathrm{vac}}}{w}\right)^2\cos(\phi-\phi_{\mathrm{EF}})}_{\text{Error field / RMP}} + a_2\frac{j_{\mathrm{BS}}}{j_\parallel}L_q\left(\underbrace{\frac{2}{3w}-\frac{3w_{\mathrm{ib}}^2}{w^3}}_{\substack{\text{Bootstrap and}\\ \text{polarisation}}} - \underbrace{\frac{3\pi^{3/2}}{4w_{\mathrm{dep}}}\frac{w_{\mathrm{dep}}^2}{w^2}\eta_{\mathrm{NTM}}\eta_{\mathrm{aux}}}_{\text{Current drive}}\right) \tag{1}$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \underbrace{\frac{\omega_0(\tau_M/\tau_{M0})-\omega}{\tau_M}}_{\text{Viscous}} - \frac{1}{\tau_{A0}^2}\left(\frac{w}{a}\right)^3\left[\underbrace{\frac{C_1}{m}\frac{\omega\tau_w}{(\omega\tau_w)^2+1}}_{\text{Resistive wall}} + \underbrace{\frac{m^2}{256}\left(\frac{a}{L_q}\right)^2\left(\frac{w_{\mathrm{vac}}}{w}\right)^2\sin(\phi-\phi_{\mathrm{EF}})}_{\text{Error field / RMP}}\right] \tag{2}$$

An example evolution of the 2/1-NTM in ITER is shown in Fig. 1, where a broadening factor of 3 is assumed, the island is seeded at 2.1 cm, and 7.5 MW of EC power are used. This model can be used to compute the peak power requirements for stabilisation of the 2/1-NTM in ITER. Four scenarios are considered: a rotating island stabilisation scenario with continuous EC power turned on at all times (preemptive), a rotating island stabilisation scenario with 50% modulated power, with EC turned on only for $w > w_{\mathrm{detect}} = 4$ cm, and two locked mode stabilisation scenarios with varying times allowed for stabilisation after locking (2 and 10 s).

First, the broadening factor is varied in Fig. 2a, which quickly increases the power requirement for rotating island stabilisation while that for locked mode stabilisation remains modest, thanks to its higher stabilisation efficiency.

Second, the seed island width is varied in Fig. 2b, for a fixed broadening factor of 3. This shows how rotating island stabilisation cannot cope with large seeding events due to the now even faster locking, making locked mode stabilisation the more robust option.

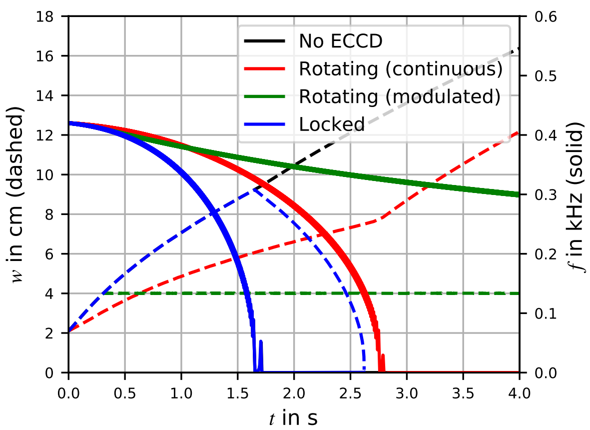
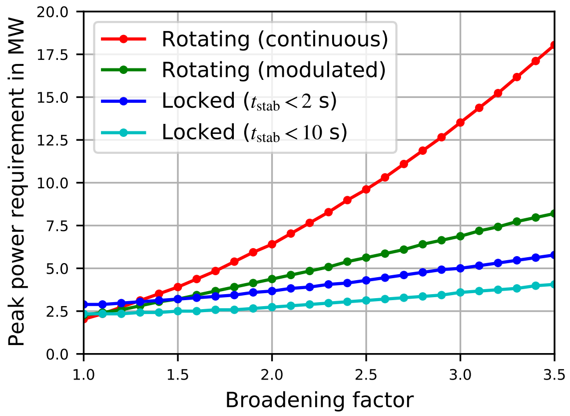
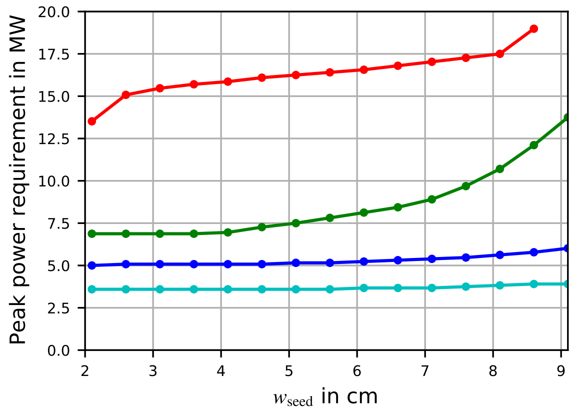


Figure 1: Example evolution of island width and rotation frequency for ITER's lower steering mirror (LSM), with a broadening factor of 3 and 7.5 MW of EC power.



(a) Power requirement for NTM stabilisation in ITER (LSM) with increased broadening of the deposition width, at a low $w_{seed} = 2.1$ cm.



(b) Power requirement for NTM stabilisation in ITER (LSM) with increased seed island width w_{seed}, at a broadening factor of 3.

Finally, the toroidal launching angle is varied in Fig. 3, using the values for the current drive efficiency and deposition width from [13]. The planned toroidal launching angle of 20° remains optimal for a locked mode stabilisation strategy, which could therefore be implemented in ITER without changes to its design.

We have shown that locked mode stabilisation is advantageous in large tokamaks, where the islands lock quickly and the stabilising rf wave is substantially broadened. This will already hold true in ITER, where a locked mode stabilisation strategy for the $2/1$-NTM in ITER would allow a reduction of the peak and averaged EC power as well as an increased robustness to large seeding events. A locked mode stabilisation strategy could thus prove crucial to help ITER accomplish its high fusion gain and low disruptivity targets. For more details, see [15].

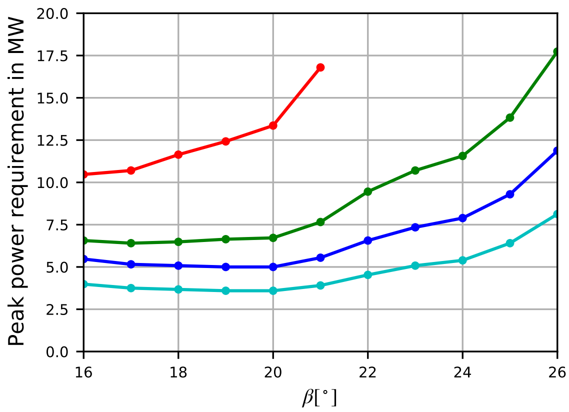


Figure 3: Power requirement for NTM stabilisation in ITER with varying toroidal launching angle β, at a broadening factor of 3 and a seed island width of $w_{\text{seed}} = 2.1$ cm. The corresponding legend is given in Fig. 2a.

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