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EC power management in ITER for NTM control: the path from the commissioning phase to demonstration discharges

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Abstract. Time dependent simulations that evolve consistently the magnetic equilibrium and plasma pressure profiles and the width and frequency rotation of magnetic islands under the effect of the Electron Cyclotron feedback system are used to assess whether the control of NTMs on ITER is compatible with other simulataneous functionalities of the EC system, like core heating and current profile tailoring, or sawtooth control. Results indicate that the power needs for control can be reduced if the EC power is reserved and if pre-emptive control is used as opposed to an active search for an already developed island.

1 Introduction

Covering nearly the entire plasma radius, the Electron Cyclotron system planned on ITER has high flexibility, potentially allowing for combined central heating, current profile tailoring and MHD stability control of sawteeth and Neoclassical Tearing Modes [1-3]. Every application has to be balanced with the other heating and current drive sources for optimization of capabilities and resources. A critical application of the EC system is for NTM control and stabilization, for which the Upper Launcher (UL) has been specifically designed. The Upper Launcher can accommodate the entire 20MW available, with up to two thirds delivered to either the upper or the lower steering mirror. Depending on how much power is needed for NTM control and stabilization in each phase of the discharge, other applications might be restricted. This work aims at finding conditions for optimal usage of the EC in all phases of the discharge, going from operation at half-field to full field.

Similarly to previous work dedicated to the assessment of NTM stability and control on ITER, this work also relies on the use of a Modifed Rutherford Equation that includes the effects of the EC current and heating. Differently from previous work, the assessment is done by evolving consistently the plasma equilibrium and the pressure profiles and the magnetic island width and frequency under the action of the EC feedback control. The simulations confirm some of previous offline calculations, for example that an alignment within half the EC deposition width is needed for NTM stabilization [4-6]. In addition, they identify a need for optimization of the ramp-up and ramp-down phase, in particular of entry and exit from H-mode. They also point to limitations in the choice of the control schemes due to the fast growth rate of the (2,1)-NTM compared to the mechanical response of the steering and of the power switch between launchers.

2 Approach to control simulation

In order to assess the EC control system requirements, it is important to simulate the evolution of the NTM island in combination with the plasma magnetic equilibrium and the kinetic profiles, as they evolve in response to the external heating and current drive sources. In order to provide a simulated response of the plasma, a MRE has been interfaced with TRANSP [7] and coupled to a feedback control algorithm for the tracking of rational surfaces and for the management of the input power in response to the NTM stability. The MRE used here is based on the approach by Fredrickson [8], which was validated against the (3,2)-NTM on TFTR. The original MRE has been extended to include the effect of the EC heating and current drive [5,9] and the rotation of the island. The electron cyclotron calculations are performed with the beam tracing code TORBEAM [10]. The effect of the alignment (or misalignment) of the EC with the rational surfaces is consistently taken into account in the calculation of the ECCD and ECH terms and in the tearing stability term through the magnetic equilibrium and plasma current profile calculated in TRANSP. Only cases with continuous EC injection have been considered since power modulation is expected to be effective only when the deposition width is comparable to or wider than the magnetic island [4], which is not the case for the ITER simulations considered here.

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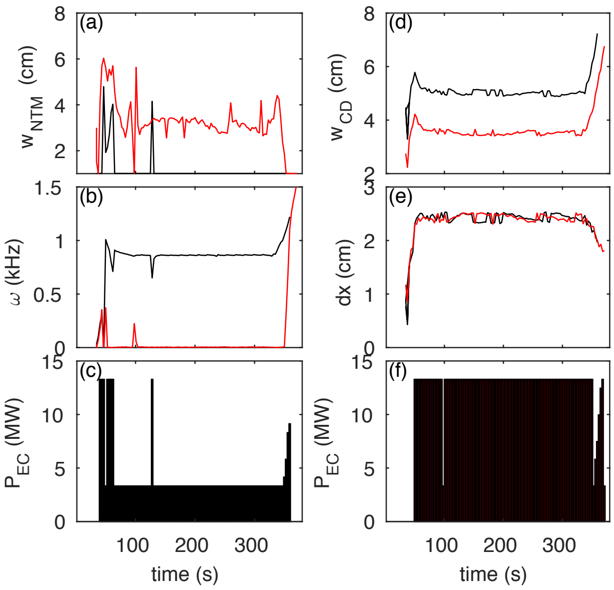

Fig. 1. EC feedback control calculations for a D-T discharge at 2.65T and 7.5MA. (a) width of the (2,1)-NTM (b) rotation frequency (d) EC deposition width (d) alignment between the EC and the q=2 surface (e) EC power for the case with broader w_{EC} (f) EC power for the case with broader w_{EC}.

3 Assessment of control requirements

Approaches to NTM control can be divided into two categories: control of modes that have grown above the detection threshold size and prevention of the triggering of instabilities. Figure 1 shows two simulations of a plasma discharge with D-T gas mix at 2.65T and 7.5MA. The time step in the simulations is 3s and corresponds to an upper limit on the constraints imposed from the hardware, namely the power switch between waeguides and the poloidal steering between the q=1 and the q=2 surface.

The Upper Steering Mirror (USM) is used to track the q=2 rational surface while the Lower Steering Mirror (LSM) is reserved for control of the (3,2)-NTM. A tolerance of 2.5-3.0 cm is assumed on the precision of the EC alignment, based on the requirements from the Plasma Control System [11]. It is also assumed that the feedback control reacts only when the magnetic island has grown to at least 4cm, which is consistent with projections of the ECE diagnostic resolution designed for ITER [12-14]. It is noticed that increasing the threshold size to 6cm does not increase the power requirements, while increasing the tolerance on the alignment does. In particular, if the EC deposition is misaligned by more than half the EC deposition width, stabilization might not be possible even with the entire available power of 20MW [15].

The time-dependent simulations (not shown here) indicate that the (3,2) does not lock in these plasmas while the (2,1) can lock in less than 5 seconds both in plasmas at half-field and full field. Thus the analysis is here focussing on the stabilization of the (2,1)-NTM with the USM. The two cases shown in the figure refer to different hypotheses on the beam width. Broadening of the beam width can be obtained by selecting the launching waveguides to spread the superposition of the beamlets. Additional broadening will be inevitable and caused by scattering of the waves due to turbulence fluctuations, in particular from the region around the separatrix [16]. These simulations can be interpreted as representative of a general case, where the wider the beam the lower the peak current density, for a constant total integrated current. The temperature and plasma current profiles are calculated consistently with the EC heating and current profiles and are therefore consistent as opposed to rescaling width and current for fixed temperature and bootstrap current profiles.

As shown in the figure, a broadening of the profile up to about 6cm is needed to fully suppress the (2,1)-NTM. After an initial investment of 13.4MW, which is the maximum available on either of the two mirrors of the UL, maintaining a constant level of about 3.32MW on the q=2 rational surface would be sufficient to prevent the NTM from growing back. The two phases with the highest power requirement are typically the end of the ramp-up phase, when the plasma enters H-mode, and the start of the ramp-down phase, at the H-mode back transition. Tracking the NTMs in this phase is challenged by current and density decay, with current profile peaking and inward shift of rational surfaces, as well as a natural broadening of the EC deposition width because the deposition becomes more tangential to the rational surfaces. Optimization of this phase is needed to reduce the risk of NTM mode locking and subsequent disruptions. The simulation with narrower deposition width indicates that the NTM cannot be suppressed even with 13.4MW power on the rational surface. Although the other mirror could be added to have the full available power available for stabilization on the q=2, here we are taking a safety margin approach to account for the limitations of the model used and assume that this mirror is reserved for stabilization of the (3,2)-NTM, if needed.

Simulations of the baseline scenario come to similar conclusions on the maximum tolerance on the alignment and on the minimum threshold size for detection. One difference is that the nominal Gaussian beam width in the O1-mode polarization at full field is about 75% wider than the width in X2-mode polarization at half-field. The constraints on the minimum deposition width needed for stabilization are therefore less stringent. Similarly to operation at half-field, also at full field the most critical phases are the entry to H-mode and the first third of the current ramp-down phase. Depending on the conditions of access to H-mode the (2,1)-NTM is predicted to lock between one and 15 seconds after exceeding the threshold width. Despite these differences, these cases all require an initial investment of up to 13.4MW on the mirror for suppression of the first NTM, then stability can be sustained with constant power on the q=2 surface. Similarly to the cases analysed at half-field, with a deposition width of at least 5 cm and with EC alignment maintained within half of the EC deposition width, stability can be maintained with up to 6 MW continuously tracking the q=2 surface. Because in the flattop phase the plasma is stationary, the requested poloidal angle is constant and a continuous tracking does not challenge the fatigue limit of the system.

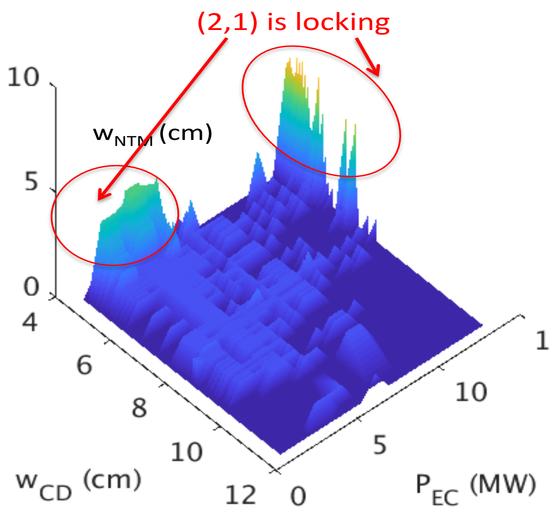

Fig. 2. Histogram of the (2,1)-NTM width as a function of the deposition width w_{CD} and of the injected power P_{EC}.

Figure 2 summarizes a number of simulations run under dfferent assumptions: removing the power from the q=2 surface after mode suppression is achieved and maintaining a constant power of 2 to 8 gyrotrons. For all these cases the deposition width w_{CD} has been varied between the nominal Gaussian width and 12cm. As shown in the figure, there is only one critical operational range at narrow deposition width. The two regions with the highest EC power correspond to simulations that drop the EC power to zero after suppression of the (2,1)-NTM. In those cases, the mode grows back soon after the power is removed from the rational surface. All cases with narrow w_{CD} lock, even with maximum power injected. Tipically, the island needs to be maintained below 6 cm to avoid locking. For deposition width broader than 5cm an upper limit on the power needed for stabilization can be set to about 5-7MW depending on the deposition width.

4 How NTM control affects plasma performance in the baseline scenario

The target of the baseline scenario is to demonstrate operation at fusion gain Q=10, the challenges include doing so while ensuring MHD stability, ELM control, disruption avoidance and low power heat load to the divertor. Since Q is calculated as the tatio of the alpha power to the external power, $Q=5P_\alpha/P_{ext}$, there is concern that NTM stabilization would reduce Q by increasing the EC power. Control schemes should therefore minimize the reduction in Q by minimizing the power needs and at the same time maximize the plasma performance by avoiding the reduction in confinement that is subsequent to the presence of NTM. This requires careful discharge planning, design and a robust control system that manages complex applications. Using the belt model [17] as a simple approximation for the expected reduction in confinement time, $\Delta\tau_E/\tau_E \sim 4\rho_s 3w_{sat}/a$, and assuming that the (2,1)-NTM can be maintained at a width of about 5-6 cm to avoid locking, the reduction in confinement would be only 5%. If this target is achieved with minimum EC power investment then Q can still be maintained around 9-10.

Figure 3 summarizes the variations of Q when active control is compared with pre-emptive control. For each time step in the flattop phase we have grouped all data as a function of the EC power on the q=2 surface and calculated the average Q and its standard deviation for a given value of P_{EC}. The coloured area represent the variation of Q among all cases analysed. The cases dubbed as active control are simulations where the EC power is turned-on only when the NTM is above the detection threshold size, whivh has been varied between 4cm and 6cm. The cases dubbed as pre-emptive are maintaining a constant power on the q=2 surface. For these cases a scan on the misalignment has been performed. The simulations that achieve the largest Q are those with pre-emptive control and with alignment maintained within half the EC deposition width.

Figure 4 shows a simulation of the ITER baseline scenario with EC feedback control. The current ramp-up phase is 80s long, with the plasma being diverted at about 12s and the radio-frequency heating and current drive being turned-on shortly after.

The electron density is built-up rapidly within the first 20s to provide a background plasma for good absorption of both Electron and Ion Cyclotron waves. In the flattop phase the EC power is reserved for NTM control; after the stabilization of the first (2,1)-NTM the power is dropped to a constant 5 MW and turned-on only

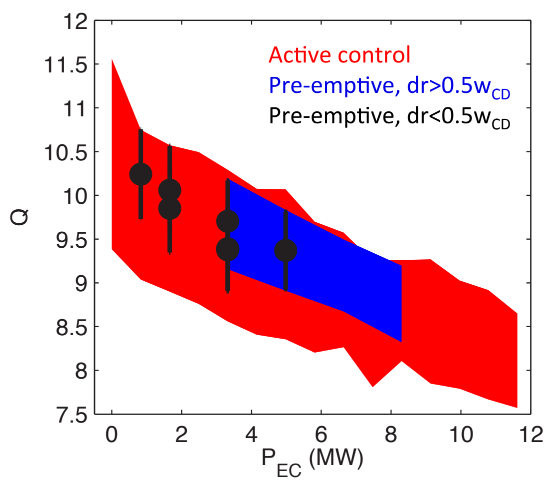

Fig. 3. Dependence of Q on the EC power on the q=2 surface for simulations with different control schemes and different assumptions on the EC alignment.

when needed. Since the power is reserved and does not need to be transferred from another application, the turn-on of the gyrotron is in practice instantaneous. The IC power is turned-off in the flattop under the assumption that it is reserved for other applications, for example sawtooth control. The apha power could be increased even further by turning-on the IC power, but this would also affect the sawtooth period and the fast ion stability. This simulation achieves Q=10 during the flattop phase. Since the (2,1)-NTM is maintained at a width below 5 cm, the reduction in the confinement is less than 5%. It is expected that turbulence effects would broaden the EC deposition profile. However, since it is assumed that the EC power is never completely removed from the q=2 surface, scattering effects are not expected to be an issue. In fact, while defocusing of the beam might be a problem when trying to stabilize an island that has already achieved a finite size that exceeds the EC deposition width, in the case of pre-emptive stabilization would instead play a favourable role by minimizing the negative effects of EC misalignment.

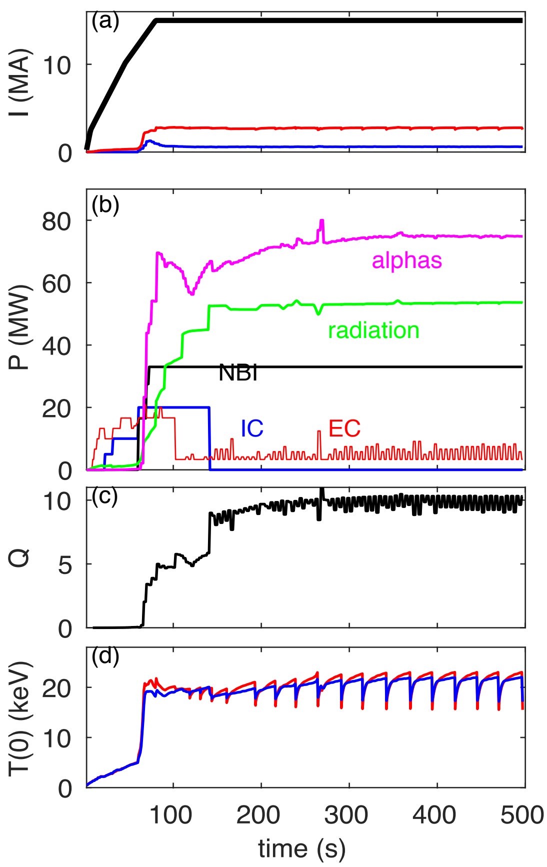

Fig. 4. TRANSP simulation of the ITER baseline scenario with EC feedback control for NTMs. (a) total current, bootstrap (red) and NBCD (blue) (b) external power, radiation and alpha power (c) fusion gain (d) central electron and ion temperature.

5. Conclusions

Controlling NTMs in ITER is critical for component protection, disruption avoidance and for optimization of the plasma performance and demonstration of fusion gain of Q. Time-dependent simulaitons that evolve consistently the plasma magnetic equilibrium and pressure profiles in response to EC feedback control of NTMs indicate that the EC power planned on ITER is sufficient to ensure control and that the main cosntraints come from the precision of the magnetic equilibrium reconstruction rather than on detection threshold of the magnetic island or time scales imposed by the hardware. While these results can inform on future steps to be taken on the design of a robust control on ITER, they depend on the assumptions in the simulations and on the limitations of the reduced models used for this assessment. In particular the NTM threshold and the effect of toroidal effects and mode coupling on the tearing stability term should be verified against nonlinear MHD codes. Validation of the MRE implemented in TRANSP is currently being undertaken against experiments on JET, ASDEX-U and DIII-D,both with and without EC feedback control.

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