ECCD requirements and criteria for NTM stabilization in ITER scenarios

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Stabilization of Neoclassical Tearing Modes (NTMs) is of crucial importance in various ITER scenarios during different phases of the plasma discharge. The Electron Cyclotron Upper Launcher (UL) is being designed to comply with this primary goal [1], and an optimization work is in progress to establish the ECCD capabilities in different ITER conditions. EC current drive has been evaluated for various scenarios for the full temporal evolution of the discharge, focusing on the characterization of the performance at the $q = 3/2$ and $q = 2$ surfaces. The UL will operate at 170 GHz and deliver up to 20 MW (accounting for the transmission losses) to the plasma via four launchers [2]. Beam injection from each UL will occur via two mirrors, the Upper (USM) and the Lower Steering Mirror (LSM), varying the poloidal injection angle α keeping the toroidal injection angle β almost constant. The maximum power that can be injected from each set of steering mirrors is $P_{EC} \sim 13.3$ MW .

In order to have an overview of the expected performance of the EC system in a wide range of conditions, the whole time history of three scenarios [3] has been analyzed: the ITER baseline H-mode inductive scenario, 15 MA, 5.3 T, Q=10 (Case 1), and two variants, one with the longest possible current ramp-down (Case 2) and another variant with the shortest possible current ramp-up and ramp-down (Case 3), a half-field scenario, 7.5 MA, 2.65 T (Case 6), and a steady-state scenario, 10 MA, 5.3 T (Case 8).

The ECH&CD calculations presented here have been performed with the EC beam-tracing code GRAY [4]. A single circular Gaussian "virtual" beam has been used for each of the USM and of the LSM. The (R,z) launching coordinates are $(6.999, 4.414)$ m and $(7.054, 4.178)$ m, the beam waists 2.9 and 2.1 cm, and the focal distances 2.134 m and 1.62 m, for the USM and LSM respectively. Wave injection polarized as ordinary mode has been considered for all the cases at full field, while as extraordinary mode for the half-field case. An example of four beams aiming at the two rational surfaces $q = 2$ and $q = 3/2$ from both mirrors is shown in Fig. 1.

To characterize the ECCD performance for the UL, the EC driven current I_{CD}, the driven current density J_{CD} and its profile width w_{CD} have been calculated and compared to the bootstrap current density value J_{BS} at the rational surface in order to estimate the power required for NTM stabilization.

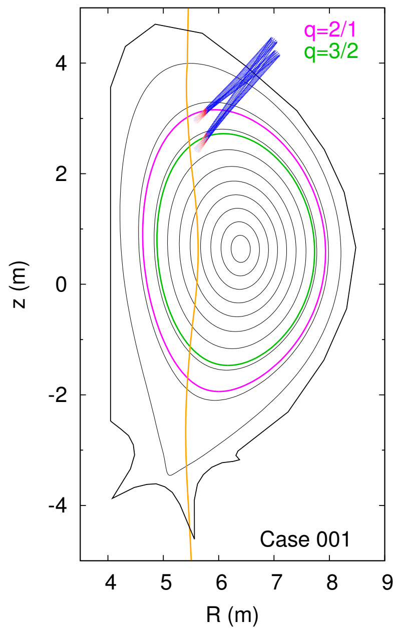

Figure 1: *Beam tracing from USM and LSM aiming at the $q=2$ (pink) and $3/2$ (green) surfaces for case 1 at $t=520$ s.*

ECCD has been evaluated at the end of the current flat-top phase varying the toroidal and poloidal injection angles in the range $25° \leq \alpha \leq 65°$, and $15° \leq \beta \leq 25°$, and for the full time history of the chosen scenarios for the nominal toroidal injection angle $\beta = 20°$. As expected, at fixed ρ the driven current I_{CD} and the current profile width w_{CD} increase with increasing toroidal injection angle, while the peak current density J_{CD} has a weak dependence on β with a broad maximum for both mirrors in the range $17° < \beta < 20°$ in the radial region of interest for NTMs. The LSM delivers larger J_{CD} and smaller w_{CD} than the USM for a given β, mainly due to the smaller size of the beam, while the total current I_{CD} is approximately the same.

The power required for NTM stabilization has been estimated making use of two stabilization criteria [5, 6], the first related to the driven current density $\eta_{NTM} = J_{CD}/J_{BS} > 1.2$, and the second to the total driven current, $\eta_{NTM} w_{CD} > 5$ cm, valid for $w_{CD} < 5$ cm. The power required for NTMs stabilization P_{stab} has been computed as the maximum between the power values required to satisfy the two above criteria. For this specific choice, the power required at a given rational surface is minimized for the β value for which $w_{CD} \sim 4.2$ cm. The behaviour of P_{stab} vs the toroidal injection angle is shown in Fig. 2 for both mirrors and cases 1, 6, and 8 at the end of the flat-top. For the half-field case, the minimum of P_{stab} at the $q=2$ surface is obtained for an angle $\beta \sim 20°$, with $P_{stab} = 3.2$ MW, the optimal angle being slightly smaller at the $q=3/2$ surface, with similar value of P_{stab}. Scenario 1 requires higher power levels, about 6.5 MW at the $q=2$ surface for the USM, mainly due to higher bootstrap current, and smaller T_e/n_e ratio. The even higher power ($\sim$ 8 MW) required in the steady-state scenario despite the high CD efficiency is explained with the large bootstrap current present in this scenario. Note that the minimum P_{stab} is reached at a smaller angle β due to the larger profile width w_{CD} obtained at a given β. The optimal toroidal injection angle minimizing P_{stab} is in the range $16° \leq \beta_{min} \leq 23°$,

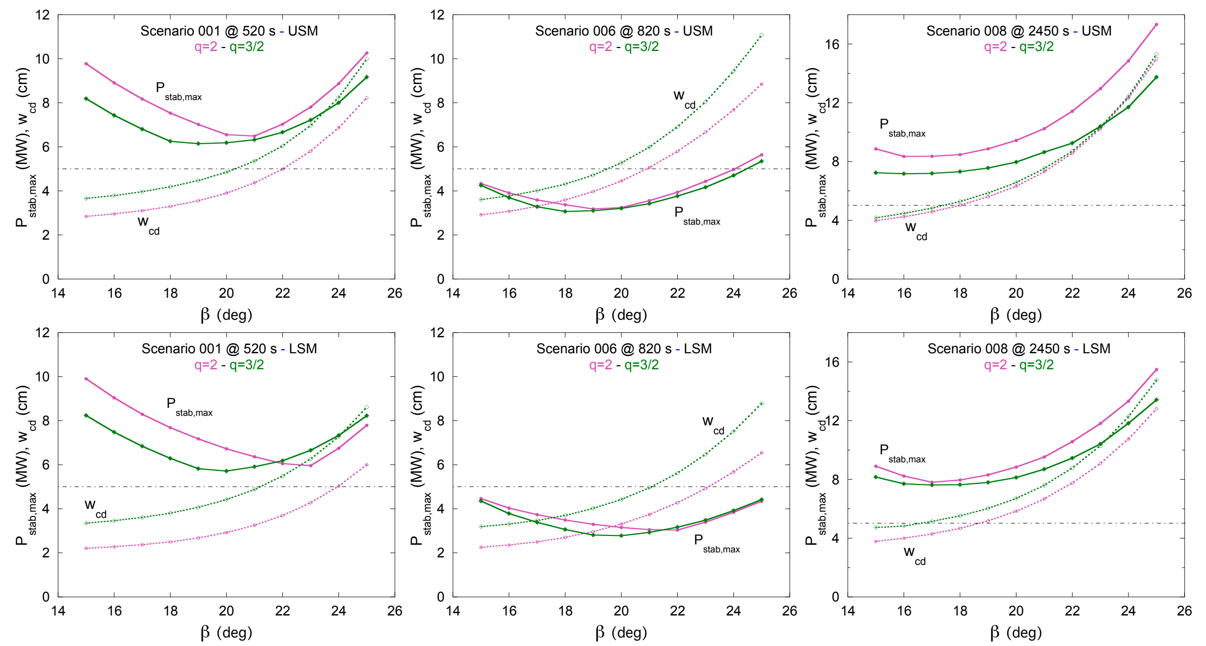

Figure 2: *Power (solid) required for NTM stabilization P_{stab} at $q = 2$ (pink) and $q = 3/2$ (green) surfaces, and EC current profile width w_{CD} (dashed), as a function of the toroidal launching angle β, for cases 1, 6, 8 and injection from USM and LSM at the end of the flat-top phase.*

depending on scenario, steering mirror and rational surface considered, with only marginally larger requirements at the nominal value $\beta = 20°$.

Stabilization power is almost constant during the current flat-top, while it shows large peaks at the L-H and H-L transitions for scenarios 1 and 6, where it exceeds the maximum nominal available power of 13.3 MW. This can be mitigated with different ramp-up and ramp-down phases like, e.g., for the late H-L transition of Case 2, and the lower T_e drop at the $q = 3/2$ surface that allow to remain within the limits of available power. However, further analysis is required for a more accurate evaluation of the power necessary in these phases.

Several effects can contribute to deterioration of the performance, leading to larger estimates of the required power. In particular, the impact of the current profile broadening on the NTMs stabilization efficiency due to finite beam width and wave-vector spectrum as well as density fluctuations has been investigated (see Fig.3).

The beam tracing code GRAY has been modified to allow for reconstruction of phasefront evolution of Gaussian beams and the computation of the associated **k** spectrum in plasma. Then, the power absorption is computed taking into account the finite $\Delta k_{||}$ in the wave-particle resonance condition for each "ray" of the beam, thus accounting for both the beam spot size and the finite $k_{||}$ spectrum. The obtained profiles are slightly shifted to higher ρ, wider and less peaked. The profile width increases on average by 10-15%, thus this a finite but relatively modest effect

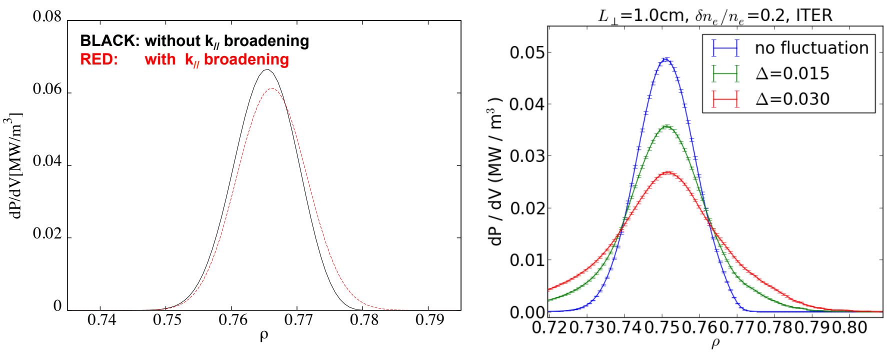

Figure 3: *Broadening of the power deposition profile broadening due to finite wave-vector spectrum width (left) and density fluctuations (right).*

on the profile at least in the considered ITER conditions.

The density fluctuations in the plasma boundary seem to have a larger impact. A new code WKBeam, based on the solution of the wave kinetic equation in the presence of fluctuations [7] retaining diffraction and full tokamak geometry, allows to quantify scattering-induced beam broadening. The turbulence is modeled as a layer of density fluctuations with $\delta n_e/n_e$ in the 10%-range (20% in Fig.3) located at the plasma periphery. The broadening effect due to density fluctuations is expected to lead to the most severe loss of localization of the EC deposition profiles for NTM stabilization in ITER. A broadening of the beam of a factor of two is to be considered realistic. Also here more detailed investigations are required.

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