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Optimisation of Sawtooth Control using ECCD in ASDEX Upgrade

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Introduction

The sawtooth activity in a tokamak plasma plays a very important role in the determination of both plasma performance and profiles. The presence of sawteeth has the favourable effect of allowing the removal of impurities from the plasma core, particularly important in the presence of helium ash in a future reactor. On the other hand, sawtooth stabilisation produces centrally peaked temperature and density profiles, which are favourable for increasing the fusion yield. Long sawtooth periods (τ_{ST}) can lead to negative consequences, such as the creation of magnetic seed islands capable of triggering neoclassical tearing modes (NTMs) [1]. The presence of a significant central fast ion population can transiently stabilise the internal kink modes [2], leading, as a consequence, to very long τ_{ST}. Since plasma performance and fusion yield have opposite dependence on τ_{ST}, an optimised period length should be identified in order to maximise both. For these reasons, it is essential to develop methods for controlling τ_{ST}, and electron cyclotron resonance heating (ECRH) is particularly well suited for this purpose, because it is able to locally reach very high power densities and to drive current (ECCD).

Theoretical and experimental background

During recent years, several experiments have been performed to highlight the effects of ECRH and current drive (ECCD) on the sawtooth period, in particular in TCV. These experiments have motivated a set of related simulations, based on [2], with a sawtooth period model included in a transport code. The aim was to identify the separate effects of localised heating and ECCD in the stabilisation (i.e. τ_{ST} increases) and destabilisation (i.e. τ_{ST} decreases) of the sawteeth. The main results of this work [3] are very important for the interpretation of the results presented below. First, it has been shown that the most efficient locations for stabilisation and destabilisation with pure localised heating are outside and inside the $q = 1$ surface respectively. In particular, the simulations have shown that the heating location maximising τ_{ST} in radial scans of power deposition is closer to $q = 1$ for a narrow deposition width as compared to a wide one. Consistently with experimental observations, the model showed that co- and ctr-ECCD have opposite effects at same radial locations with respect to the $q = 1$ surface: inside $q = 1$ ctr-ECCD is stabilising, whereas co-ECCD is destabilising; outside $q = 1$ ctr-ECCD is destabilising, whereas co-ECCD is stabilising. Pure heating has the same effects as co-ECCD, therefore in the experiments the anti-symmetry breaks and the most efficient stabilisation and destabilisation are obtained with co-ECCD outside and inside $q = 1$ respectively [3]. In addition, the simulations showed that the magnetic shear at $q = 1$ is the driving parameter in determining τ_{ST} and, in particular, the modification of the speed at which it increases during the sawtooth ramp before reaching the critical shear and the crash is triggered.

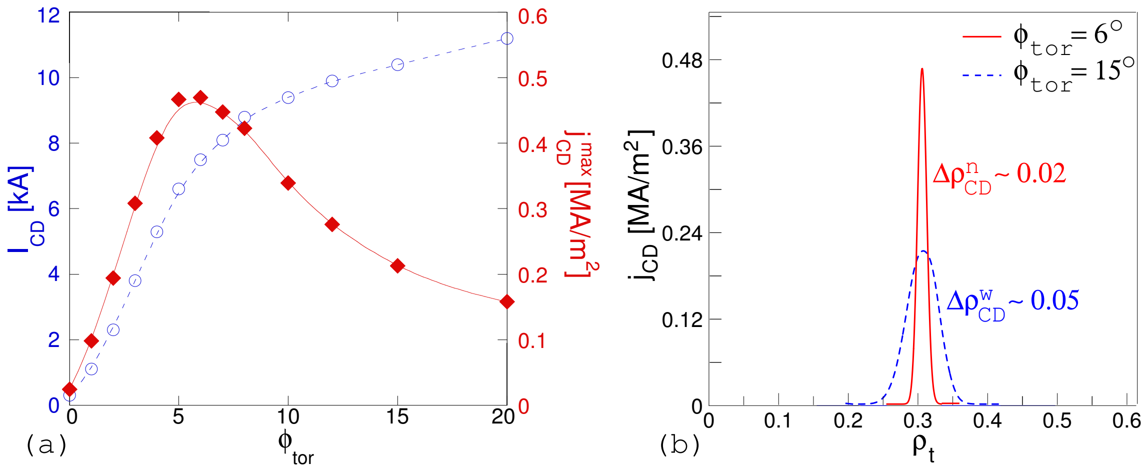

Figure 1: (a) Total driven current I_{CD} and maximum local driven current density j_{CD}^{max} as a function of the toroidal angle ϕ_{tor} with $P_{ECRH} = 700kW$. (b) Driven current density profiles calculated with TORBEAM for $\phi_{tor} = 6°, 15°$, i.e. narrow and wide deposition.

Sawtooth tailoring has been extensively investigated in ASDEX Upgrade H-modes heated by neutral beam injection (NBI) [4]. The results showed the possibility of both stabilisation or destabilisation with ECCD when the power is deposited at the right position close to $q = 1$. However, these experiments have been conducted at constant toroidal launching angles $\phi_{tor} = \pm 15°$ for ECCD, which basically maximise the total driven current I_{CD} and yield a broadening of the deposition widths, as shown in figure 1. As the magnetic shear at $q = 1$ is the key element for the sawtooth stability [2, 3], the local ECCD current density j_{CD} must play the key role, rather than I_{CD}, as shown in [5] for NTM stabilisation studies. The aim of this work is therefore to search for the optimum conditions for sawtooth tailoring by reducing the toroidal injection angle in order to maximise j_{CD} and, as a consequence, to minimise the power demand for an optimal control. We used a toroidal angle of 6° for which j_{CD} is maximised (see figure 1).

Experimental configuration and results

In order to investigate the dependence of τ_{ST} on the local driven current density j_{CD} and total driven current I_{CD}, a series of NBI-heated H-mode discharges similar to those described in [4] have been performed. The main parameters for these plasmas are: $I_P = 800kA$, $\overline{n}_e = 6.0 \cdot 10^{19} m^{-3}$, $q_{95} = 4.5$, $\kappa = 1.7$, $\delta = 0.16$, $P_{NBI} = 5MW$. The ECCD location, in both co- and ctr-ECCD, was moved across $q = 1$ by ramping the magnetic field, typically between $|B_T| = 2.1T$ and $2.3T$. All discharges have two B_T-ramps in opposite directions (for example: $2.1T \rightarrow 2.25T \rightarrow 2.1T$) and two different ECRH power levels ($P_{ECRH} = 700kW$ and $400kW$) have been compared as well. τ_{ST} is calculated from selected ECE channels laying always inside (normal sawteeth), respectively outside (inverted sawteeth) $q = 1$.

Figure 2 shows the comparison of the time evolution of τ_{ST} for the discharges performed with narrow ctr- and co-ECCD ($\phi_{tor} = \pm 6°$). Figure 2 (b) shows the evolution of τ_{ST} determined from the ECE channel shown in (a). Figure 2 (c) displays the evolution of of the ECCD deposition, ρ_{ECCD}, with respect to the sawtooth inversion radius ρ_{inv}.

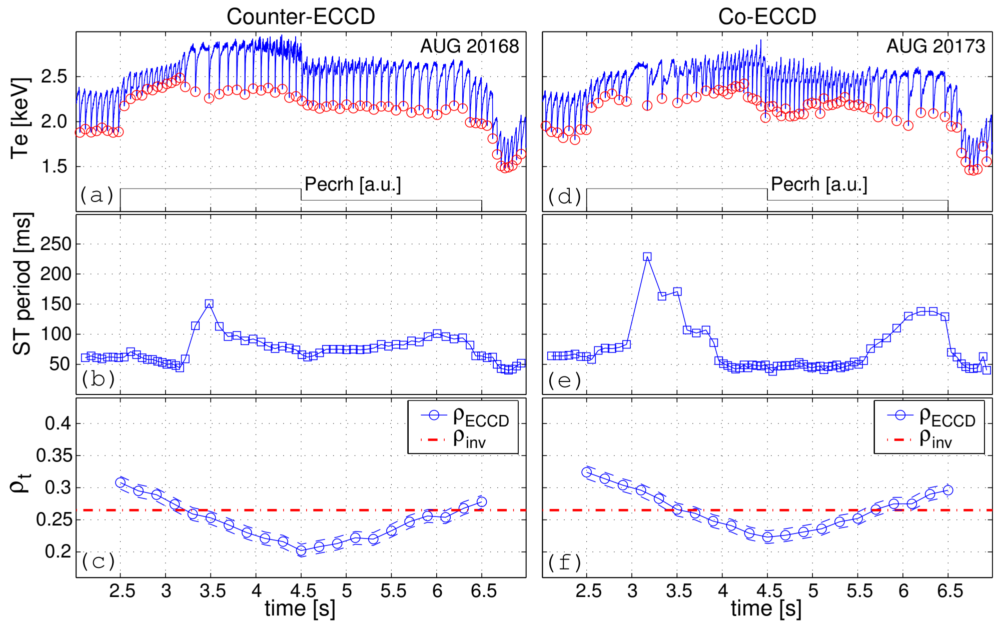

Figure 2: Comparison of the sawtooth period evolution during (b) ctr- and (e) co-ECCD radial sweep for the case of narrow deposition ($\phi_{tor} = \pm 6°$); (a,d) ECE electron temperature with ECRH power; (c,f) ECCD deposition sweep with respect to sawtooth inversion radius.

τ_{ST} evolves as expected from the ECCD deposition moving across the $q = 1$ surface. Ctr-ECCD induces destabilisation of the sawtooth period outside $q = 1$ and stabilisation inside. The modifications provoked by co-ECCD have the opposite trend: τ_{ST} is stabilised outside $q = 1$ and destabilised inside $q = 1$. By comparing the two figures, it is clear that ctr- and co-ECCD effects are not fully anti-symmetric in amplitude: co-ECCD is indeed more effective than ctr-ECCD. This is due to the contribution of pure heating, as reported above.

Because of this anti-symmetric property with respect to $q = 1$, it is convenient to plot τ_{ST} as a function of ρ_{ECCD}. This is shown in figure 3, where τ_{ST} during the ECCD scan, normalised to the sawtooth period during the NBI-only phase, is plotted as a function of ρ_{ECCD} for the wide (a,b) and narrow (c,d) ECCD depositions. The blue circles represent measurements during ctr-ECCD, the red diamonds during co-ECCD. For comparison, ρ_{inv} and $\rho_{q=1}^{MSE}$ ($q = 1$ location measured by MSE) are also shown. Both stabilising and destabilising effects of wide and narrow depositions are very similar. This indicates that the narrow deposition is likely to be more effective than the wide one and that the driving term for the sawtooth tailoring is not the total driven current I_{CD} but the local driven current density j_{CD}. The first indication is supported by considering the difference in ECCD width (factor of 2): the *effective time* during which the maximum effects on the sawteeth are induced is longer for the wide deposition by roughly 40%. This *effective time* is estimated from the "passing time" of one ECCD profile width, defined as the ratio between width and average speed at which ρ_{ECCD} is moving during the B_T-ramp. The second indication is supported by beam tracing calculations using TORBEAM [6], which show that I_{CD} in the wide deposition case is approximately 30% higher than in the narrow case (see figure 1). $q = 1$ is expected to be located at the crossing in sawtooth

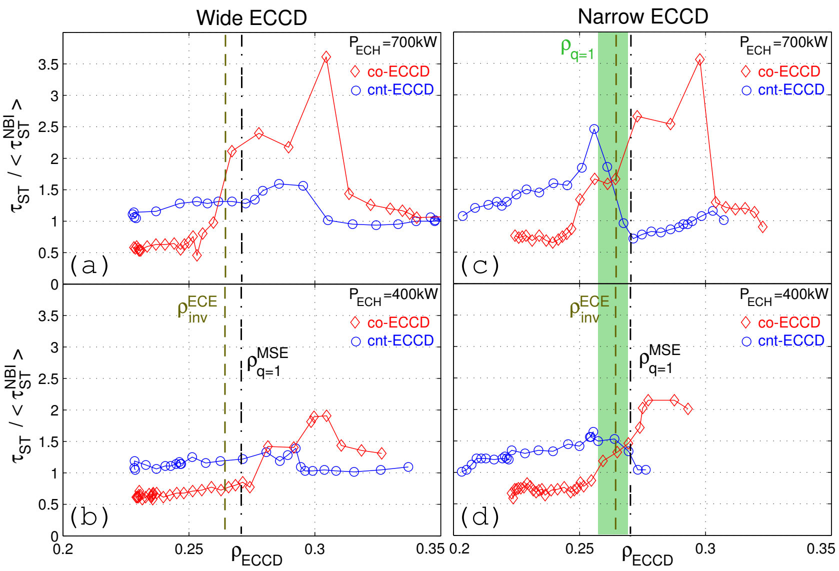

Figure 3: τ_{ST} evolution, normalised to the period during the NBI-only phase, during ctr- and co-ECCD versus ECCD deposition for (a,b) wide and (c,d) narrow depositions. The sawtooth inversion radius ρ_{inv}^{ECE} (from ECE) and the $q = 1$ radius $\rho_{q=1}^{MSE}$ (from MSE) are also plotted.

period between ctr- and co-ECCD, as indicated in the figures by the green regions. Indeed, the positions of ρ_{inv} and $\rho_{q=1}^{MSE}$ are consistent with the τ_{ST} response to the ECCD. The interpretation of the wider deposition cases is more difficult and modelling will be required.

Outlook

In order to estimate a sawtooth tailoring effectiveness, several analyses still have to be made. To consider are in particular the following: stabilising effects induced by fast ions produced by the NBI heating; quantification of the pure heating effects on τ_{ST}; effects of a possible displacement of $q = 1$; quantification of the sawtooth crash reduction during destabilisation. For future discharges, the experimental determination of $\rho_{q=1}$ will be very useful to limit the ρ_{ECCD} scan. This will especially facilitate the increase of the *effective time*, allowing the determination of the sawtooth period in more stationary conditions.

Acknowledgements

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