EXPERIMENTS ON MHD MODE STABILISATION BY ECCD IN ASDEX UPGRADE

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1. Introduction

Neoclassical tearing modes have been shown to limit the maximum achievable $\beta_N = \beta[\%]/(I_p[\mathrm{MA}]/(a[\mathrm{m}]B[\mathrm{T}]))$, with $\beta = 2\mu_0\langle p\rangle/B^2$, in stationary tokamak discharges [1], [2], [3], [4]. This has led to a discussion of possible active stabilisation or reduction of the size of the magnetic islands associated with the instability. One promising candidate is localised current drive at the rational surface of interest, [5], [6], e.g. by Electron Cyclotron Resonance Heating (ECRH) or Current Drive (ECCD). Theory predicts that, with a driven current of the order of 1 % of I_p in the island O-point, noticeable reduction in island width should be possible, provided that the ECRH deposition width d is smaller than the island width W.

Several possible mechanisms for ECRH/ECCD stabilisation exist. With DC injection, the driven current due to the local change in resistivity and the driven current by ECCD both change the equilibrium current profile, thereby changing the stability index Δ'. In addition, due to the different CD efficiency between the island O- and X-point, a helical current should develop in the island and reduce the island size if driven in the co-direction for positive magnetic shear. The latter effect should be directly accessible by phased ('AC') injection into the island O-point. This paper reports on first experiments on these possibilities.

2. Experimental Setup

Experiments are performed in ASDEX Upgrade ITER like lower SN divertor discharges with $I_p = 0.8$ MA and $\bar{n_e} \approx 5 - 6 \times 10^{19}$ m^{-3}. To vary the localisation of the EC wave absorption, B_t is scanned in the region $1.96 - 2.2$ T, leading to a range of $3.9 \leq q_{95} \leq 4.4$. NBI heating power of typically 10 MW is used to trigger a neoclassical tearing mode at $\beta_N \approx 2.5 - 2.9$. We use 2 gyrotrons at 140 GHz, each of them delivering ≈ 400 kW of EC power to the plasma. The wave is injected in X-mode and absorbed at the second harmonic, i.e. at $B_0 = 2.5$ T for heating and somewhat lower field for CD. The localisation of absorption can also be varied by variation of poloidal and toroidal launch angle via a movable mirror.

The radial localisation of the EC wave deposition is modeled using the TORAY code and experimentally verified by modulating the ECRH power at 100 Hz in the low-β phase. We associate the maximum of δT_e at 100 Hz from the ECE diagnostic with r_{dep}, the centre of deposition. The wave deposition generally occurs on the HFS in these experiments. The ECE measurement comes from the LFS in order to avoid cross-talk between gyrotron and ECE antenna; the position is then mapped using the reconstructed equilibrium. ECRH corresponds to perpendicular injection, ECCD is achieved by varying the toroidal launch angle. An angle of 15^o from perpendicular was chosen to compromise bewteen the higher CD efficiency at larger angle and the concomitant broader deposition. For this choice, TORAY pedicts a driven current of 8-9 kA at 800 kW and a deposition width of d =4.5 cm. The radial localisation of the MHD mode r_{res} is inferred from the ECE diagnostic, where the island can be directly seen as a flattened region in the T_e-profile. Typical saturated island sizes of 8-10 cm on the HFS are inferred, ensuring that $W_{sat} > d$ holds. We scan B_t to match r_{dep} to r_{res}: we have $r_{dep} = R_0(1 - B_t/B_0)$, whereas r_{res} only varies on the scale of the minor radius and even weaker than linear when q_0 is fixed to 1 by sawteeth. In fact, from ECE measurements, we could not detect a significant change in the r_{res} for the scanning range given above.

For AC-experiments, it is necessary to inject into the island O-point only. The gyrotrons are triggered using a trigger unit generating square pulses from an $n = 2$ combination of Mirnov coils. At the moment, it is only possible to modulate both gyrotrons in phase. As the ports through which their beams are injected are spaced apart by 45^o in toroidal angle, it is necessary to compensate this difference by chosing different poloidal injection angles.

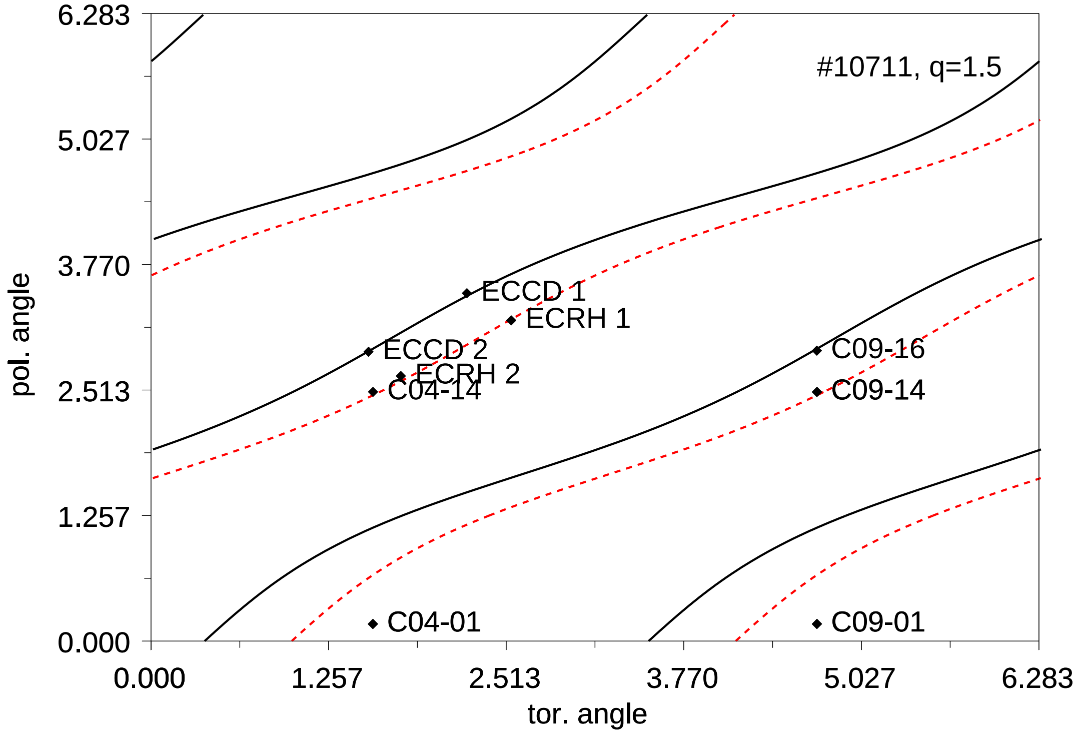

Fig. 1: Map of B-field lines on the q=1.5 surface of an ASDEX Upgrade high β equilibrium. The location of the EC wave absorption is shown for ECRH (dashed) and ECCD (solid) together with the location of various Mirnov probes.

For positive shear, the localisation of the O-point corresponds to a minimum of an integrated Mirnov coil signal. As the mode has constant phase along field lines, we can trace the position of the O-point along the field lines to the localisation of the EC wave deposition. Fig. 1 shows an example. For both ECRH and ECCD, the two gyrotrons deposit on one field line. The field line 180^o apart in toroidal angle, on which the $n = 2$ mode has the same phase, passes by the Mirnov coil C09-14 for ECRH and C09-16 for ECCD. Thus, the phase has to be adjusted relative to C09-14 for ECRH and relative to C09-16 for ECCD.

3. Experimental Observations

In ASDEX Upgrade, the resistive β-limit is often set by a (3,2) mode. However, at lower collisionality, also a (2,1) mode may occur. This mode usually locks, making phased injection difficult. We thus restrict our experiments to cases with a (3,2) mode at the moment. Fig. 2 shows an example of such a shot using AC ECCD: after the mode occurs at 2.75s, ECRH is switched on at 3.3 s for typically 100-150 ms (limited by the power handling capability of the modulator tetrode). The right side of Fig. 2 shows the accuracy of the phasing of the ECCD: although the phasing is not optimal, the phase is adjusted such that injection mainly occurs in the negative part of the integrated signal C09-16, i.e. in the island O-point. The modulation works even at the highest mode frequencies of more than 20 kHz.

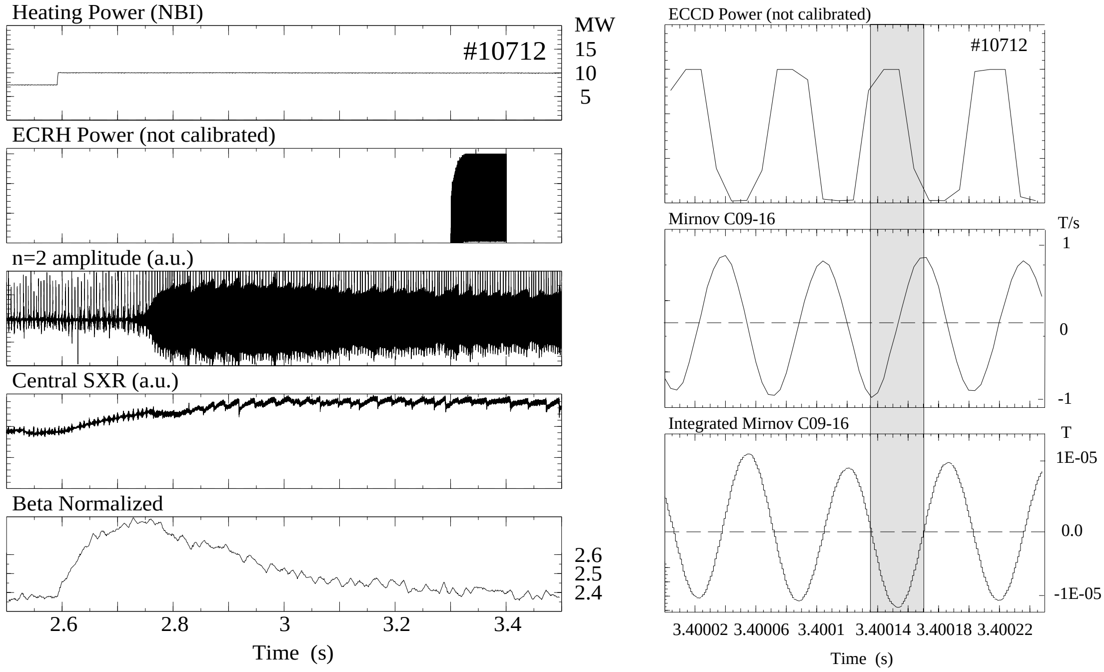

Fig.2: Overview of typical a shot used in the stabilisation experiments (left) and detail of the gyrotron phasing relative to the mode (right).

Experiments were carried out using pure ECRH. In a scan of B_t with DC injection, no effect on the mode was seen. This indicates that the injected power of 800 kW was not sufficient to change the equilibrium current profile via the local change in T_e. It is consistent with the fact that we could not observe a significant change in T_e due to ECRH on the ECE diagnostic in the phase with the highest NBI power, even for modulated ECRH at 100 Hz. One might expect that the change of T_e inside the island could be different, because the transport inside the island does not necessarily have to be the same as outside, but no clear change of T_e within the island was detectable. Only few experiments were done with AC ECRH so far, so that no further information is available.

Next, we tried AC ECCD with the parameters specified above. At 800 kW, modulated at a duty cycle of 0.5, the current driven in the island is estimated to be $\approx 4-5$ kA using the DC CD efficiency and neglecting any heating inside the island. This corresponds to 0.3 % of I_p. According to theory, this is not suffcient for complete stabilisation, but should give a noticeable effect. During a scan of B_t under these conditions, indeed first hints of an influence on the mode could be seen when r_{dep} approached r_{res}: Fig. 3 shows, on the left hand side, a shot in which ECCD was applied during the β-decay following the mode onset at $\beta_N = 2.4$. The mode amplitude visible on the Mirnov signal is modulated by the sawtooth crashes. After the first sawtooth during ECCD, the mode does not grow to the same amplitude as before. Also, the drop in β does not continue and a stationary value of $\beta_N = 2.4$ is maintained. As soon as ECCD is switched off, the mode grows to higher amplitude again and β continues to decay until a final stationary level of $\beta_N = 2.3$ is reached. However, the 'natural' fluctuations of β due to the sawtooth activity and the expected change in β due to the EC heating ($\sqrt{10.4/10}-1 = 2\%$) are of the same order as the effects ascribed to ECCD. Thus, the interpretation has to be taken with some care. Still, we could not detect a change in T_e inside the island, indicating that probably the radial positioning was not optimised.

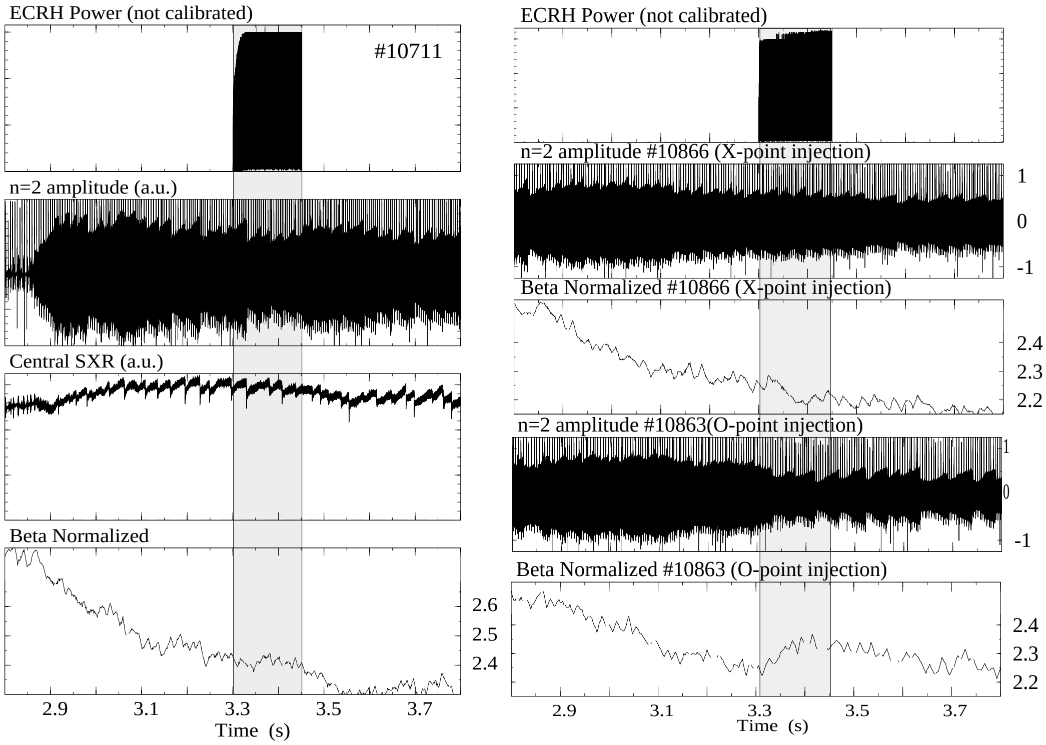

Fig. 3: Experimental examples: Maintaining a higher β with phased ECCD (left) and the effect of a 180^o phase shift between ECCD and the mode (right).

In order to verify the ECCD effect, we changed the phasing by 180^o and slightly adjusted B_t. The result is shown in the right hand side of Fig. 3 . Now, the increase in β in the ECCD phase of the shot with O-point injection is clearly higher than the natural fluctuation level. This is accompanied by a noticeable drop in the mode amplitude. In addition, with X-point injection, β drops, although the effect on the mode amplitude is less clear. This could be explained by the reduced CD efficiency in the X-point due to the reduced radial width of the island there.

4. Conclusions

From these first experiments, we conclude that there is a good potential for AC ECRH/ECCD to control neoclassical tearing mode activity. However, further experiments will be carried out to ascertain the results on DC injection and pure ECRH. More quantitative results will be obtained with the higher ECCD power available on ASDEX Upgrade after the delivery of two more gyrotrons in the near future.

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