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Stabilisation of Neoclassical Tearing Modes by ECRH in ASDEX Upgrade

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1. Introduction

The maximum achievable β in tokamak discharges is often limited by neoclassical tearing modes (see [1] and references therein). Therefore, a mechanism for their stabilisation is required for future reactor-scale experiments. It has been proposed to use ECRH to decrease or remove the magnetic islands associated with the instability [2]. Stabilisation can be achieved both by the change of equilibrium current profile and the generation of local currents in the O- or X-point of the island. Theory predicts that local currents in the island should be more efficient than the change of the equilibrium profile. Furthermore, co-current drive in the O-point should be more efficient than counter-current in the X-point because mainly the fraction of current deposited within the island separatrix will contribute to stabilisation.

Experiments on the stabilisation of the usual, current gradient driven tearing mode have demonstrated the control of the mode by ECRH (see [3] and references therein). It was found that generation of current in the O-point is an efficient tool, but, there is no pronounced difference between a phased injection into the O-point and DC injection, indicating that the destabilisation efficiency of X-point injection is small. First experiments on stabilisation of neoclassical tearing modes in ASDEX Upgrade demonstrated the reduction of the island size by an ECRH power small compared to the total heating power [4]. In these experiments, DC injection was also roughly as efficient as modulated injection. ECRH was injected under a finite toroidal angle, so that ECCD should play a role. The present paper reports on new experiments on this subject.

2. Experimental Technique

The experiments were carried out in lower single null ELMy H-modes with 10 MW of NBI heating that develop a (3,2) neoclassical tearing mode at $\beta_N \approx 2.2 - 2.5$. We concentrate on DC injection, which is technically easier. Now, 1.2 MW of ECRH power is routinely available in the plasma, generated by 3 gyrotrons at 140 GHz with pulse lengths up to 2 seconds. It was found before that the radial localisation of the magnetic island may vary from shot to shot by 1-3 cm. In order to reliably deposit the ECRH power on the resonant surface r_{res}, we slowly scan B_t in a range of 5 % to shift the EC resonance and therefore the deposition radius r_{dep} across the mode resonant surface. The EC resonance moves by 8 cm during the scan. From ECE measurements of the island structure, it was verified that the radial movement of r_{res} itself is smaller than 2 cm during the scan [5]. With this technique, it has been possible to match the deposition in every shot.

In these discharges, the density decreases during ECRH. The feedback-control reacts with an increased gas puff. This leads to a reduction of stored energy, even if no mode is present. Thus, the achieved values of stored energy are compared to a value derived from a confinement scaling taking into account the effect of gas puff [6], but not the mode. The mode amplitude is inferred from an n=2 combination of Mirnov coils. It was verified that the changes in mode frequency are small in the interesting time intervals, so that $\dot{B}$ can directly be used.

3. Experimental Results

3.1. Complete Stabilisation

In our previous experiments, a substantial reduction of mode amplitude had been observed, but complete stabilisation was not achieved with the available power of 800 kW. However, with the increased power of 1.2 MW we could reliably remove the mode during the B_t scan with DC ECCD. Fig. 1 shows an example.

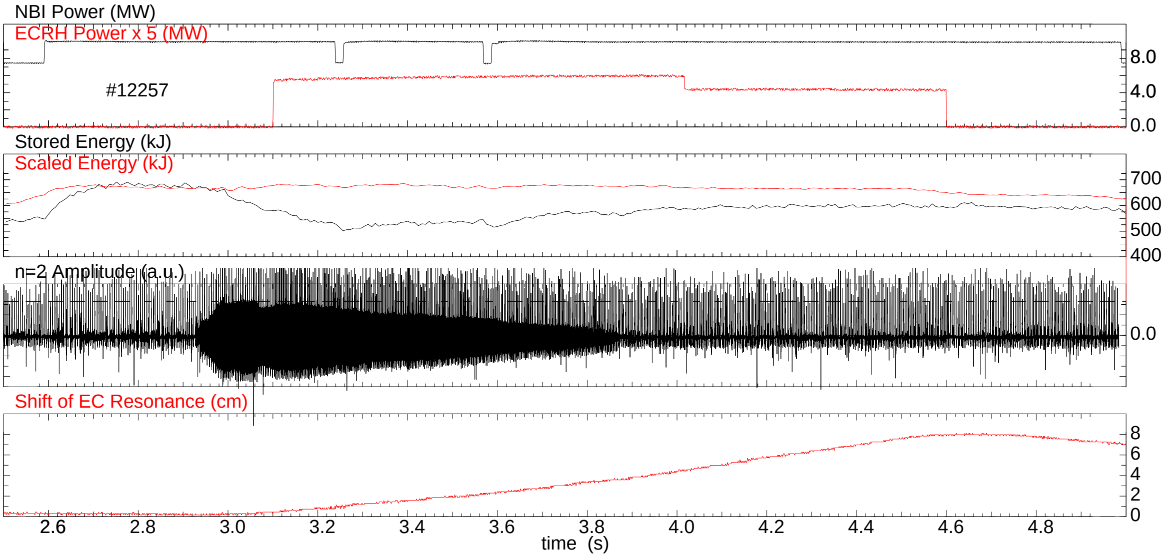

Figure 1: *Complete stabilisation of a (3,2) neoclassical tearing mode by 1.2 MW of ECCD.*

Applying the B_t scanning technique, the decrease of mode amplitude is much slower than the growth rate. This can be explained as follows: initially, we deposit the ECRH power outside the magnetic island. Then, as we move r_{dep}, we start to deposit some power in the island (deposition is on the HFS, so a positive shift of the resonance position means a shift towards the plasma centre). As r_{dep} approaches r_{res}, the maximum power is available for stabilisation. With the scanning rate used here, r_{dep} moves by an island half width ($\approx$ 3-4 cm) in 500 ms. In effect we perform a power scan on this timescale, which is slow compared to the growth time of the mode ($\approx$ 100 ms). Modeling the temporal behaviour using a Fokker-Planck solver to obtain $j_{ECCD}(r,t)$ and inserting this into the Rutherford equation as described in [4] yields good agreement in the temporal behaviour. Note that if the change of the equilibrium current profile was the dominant stabilisation effect, one would expect a switch from destabilisation to stabilisation when r_{dep} passes r_{res}. Such a behaviour has never been observed in our experiments. We thus conclude that local currents in the island play the main role.

The removal of the mode leads to an increase in stored energy. However, it can be seen that even after the mode has been completely removed, the stored energy does not recover completely. This can be partially explained by the confinement degradation due to the gas puff accompanying the ECRH injection as mentioned above. However, even if the stored energy is compared to the scaling taking into account the increased recycling (signal 'scaled energy' in Fig. 1), there is a small discrepancy left. Also, the mode does not come back after ECRH is switched off. This can be either due to a lack of seed islands, because the discharge changes its sawtooth behaviour, or to the reduced β that increases the stability against the mode. These unresolved effects will be subject to future studies.

3.2. *Co- versus Counter-CD*

The experiments referred to above were all done with co-current drive (i.e. injecting under an angle of -15^o with respect to perpendicular in the toroidal direction), where a current of the order of $\approx$ 10 kA should be generated by the ECCD effect. However, one also expects that the pure heating increases the temperature within the island, leading to an increased electrical conductivity and thus to a stabilising current. In order to assess the relative magnitude of the two effects, we reversed the injection angle to $+15^o$, leaving all other parameters unchanged with respect to the discharges discussed above. Now, we drive the ECCD current in the counter direction, which should have a destabilising effect. The current due to island heating is still in the co-direction. The result is shown in Fig. 2.

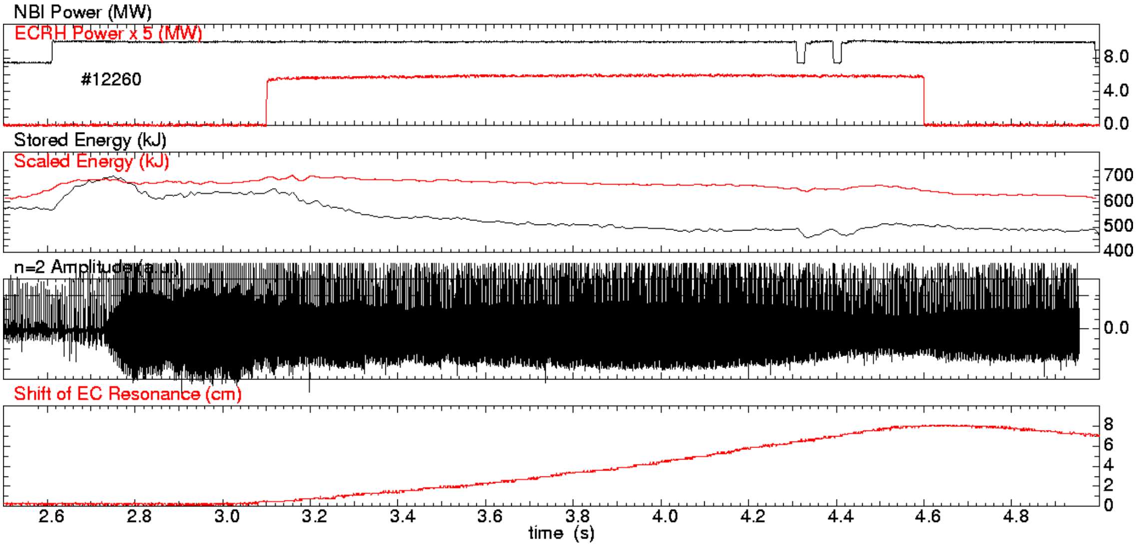

Figure 2: *With counter CD, the mode is not removed.*

It can be seen that there is little effect on the mode amplitude, although in this scenario, co-injection could reliably remove the mode. During the B_t-scan, there is first a slight increase in mode amplitude, followed by a small decrease with respect to the amplitude when ECCD is switched off. It is not clear in which phase the resonance matches the resonant surface, but the smallness of the (de)stabilising effect indicates that the two competing effects are of the same order of magnitude because their effects almost cancel. Thus, it is clear that the stabilisation observed in the co-case cannot be explained simply by the heating effect. It should also be noted that here, the presence of the mode leads to a significant reduction of the stored energy compared to the values expected from the confinement scaling.

3.3. *Localisation Requirements*

Finally, we analyse the requirements on localisation of the ECRH deposition. As explained above, the scan of B_t corresponds to a radial movement of the EC resonance across the magnetic island. Thus, one expects a stabilising effect as soon as r_{dep} enters the island, which comes to a maximum when r_{dep} is centerd on r_{res} and then decreases again as r_{dep} moves out of the island on the other side. However, this cannot be observed in the discharges with complete stabilisation, because obviously, the mode is already removed before r_{dep} moves out of the island. Thus, we use an experiment in which the ECRH power was only 400 kW of ECCD. This discharge is shown in Fig. 3.

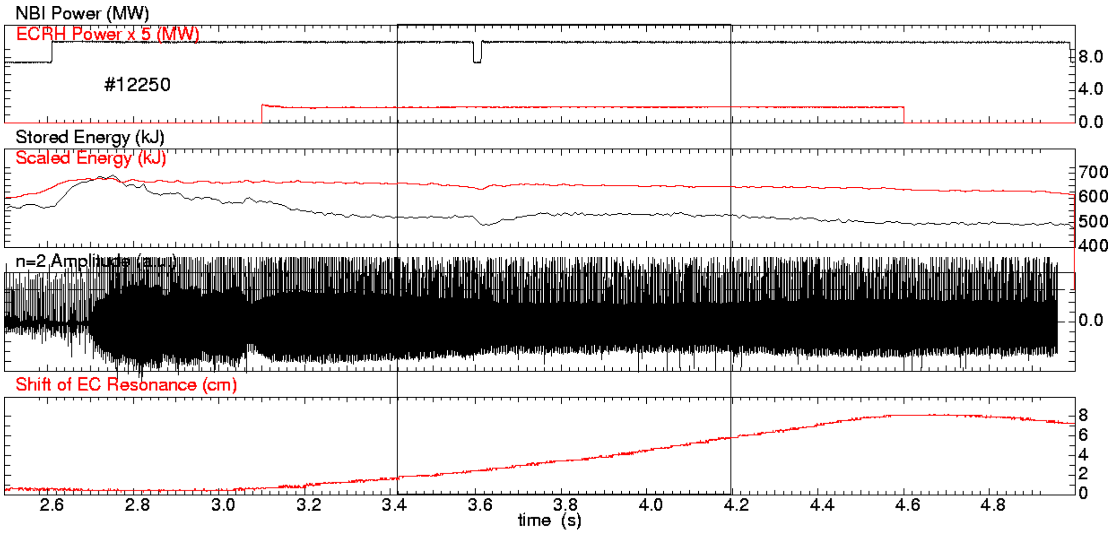

Figure 3: *Determination of the localisation requirement with reduced ECRH power.*

At this power level, it is difficult to see the effect of ECCD at all, because there also is a slow decrease of the mode amplitude due to the reduction of β (island width $W \propto \beta$). However, this effect always manifests as a decrease of mode amplitude with decreasing β. Therefore, we take as the onset of stabilisation the time where β does not drop any more, although the mode amplitude is further reduced, i.e. around 3.4 s. It follows a phase with constant β until around 4.2 s, where the decrease in β continues, accompanied by a slight increase of mode amplitude. We take this time point to be the time when stabilisation is no longer efficient. From this time interval, we can estimate the radial interval in which stabilisation is efficient to be $\approx$ 4 cm, assuming that r_{res} does not move by a comparable amount as justified by [5]. This number is close to the estimated island half width, but also to the deposition width of the ECRH, so that we cannot easily determine the physics behind it. However, it is clear that a precise positioning is required. On the other hand, it explains why a scan of r_{dep} by 8 cm ensures that correct deposition is always achieved within this interval.

3.4. Conclusions

We have demonstrated complete stabilisation of a neoclassical tearing mode by local currents in the island generated by DC ECCD of 10 % of the total heating power. Using a scan of B_t of about 5 %, we could reliably match r_{dep} to r_{res} within the scanning range. The effect of ECCD as opposed to the pure ECRH was verified by reversing the toroidal injection angle. From the difference between co- and counter-current drive we estimate the two effects to be of the same order of magnitude. From the scan, the localisation requirement was estimated to be of the order of both the island half width and the ECRH deposition width.

References

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