

## Stabilisation of Neoclassical Tearing Modes in ASDEX Upgrade with ECRH

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**Introduction** In tokamak plasmas with low collisionalities  $\bar{\nu}_{ii}$ , neoclassical tearing modes (NTMs) are the most severe limitation to achieve high  $\beta$  values. This type of mode is excited by the lack of helical bootstrap current caused by the flattening of the pressure profile over an initial small seed island in a plasma otherwise stable against tearing modes. The local replacement of this lack of helical bootstrap current is experimentally realized by current drive with electron cyclotron heating (ECCD), which is known to allow a very localized current drive. Results of these experiments are compared with theoretical calculations.

**Current drive in the islands O-point** The most effective stabilisation can be expected by a local co-current drive (parallel to the plasma current) within the O-point of the island [1]. The current has to be localised with respect to the minor plasma radius  $r_{res}$  and to the relative phase of the rotating island. A radial scan has been done on a discharge by discharge based scan of the toroidal magnetic field  $B_t$ . The correct phase of the ECRH has been chosen by a feedback system between the ECRH and a combination of Mirnov signals giving the phase of the (3/2) mode. A partial reduction of the island size and a recovery of 20% of the mode induced loss in  $\beta_N$  could be achieved with  $P_{ECRH} \approx 0.8$  MW with 2 gyrotrons [2].

Theoretical calculation [3] as well as experimental results [2] suggest that DC current drive at or near the resonant surface is almost as efficient as phased ECCD. The further experiments were therefore done with a technically much easier DC ECCD scheme.

**Experimental setup for DC current drive** The usual plasma parameters for stabilisation experiments for phased ECCD as well as for DC ECCD were discharges with  $I_p = 0.8$  MA,  $B_t \approx 2$  T ( $q_{95} = 4$ ) and with  $P_{NI} = 10 - 12.5$  MW of neutral beam heating power. The density was typically of the order of  $\bar{n}_e \approx 5 \cdot 10^{19} \text{ m}^{-3}$ , and before the (3/2) NTM onset  $\beta_N = 2.2 - 2.8$  could be reached. The island is detected by a set of Mirnov coils and ECE measurements, which give the exact radial location and the width  $W$  of the island, as well as the location and width  $d$  of the ECRH deposition. Typical values for the island width are  $W = 8 - 10$  cm and for the deposition width  $d = 4 - 5$  cm.

The DC ECCD with 3 gyrotrons at 140 GHz, each depositing 0.4 MW RF power, has been applied to the plasma for 2 s after the mode has reached its stationary amplitude, leading to a loss of confinement. Typically 20% of  $\beta_N$  is lost compared to the value at the onset of the modes. The toroidal angle of the mirrors launching the RF wave have been set to  $\pm 15^\circ$  with respect to the magnetic field for counter- and co-current drive respectively. Additional to the current drive there is of course always a local heating effect at the resonant surface, leading to higher temperatures and hence reduced resistivity. On the one hand a subsequent increase of the current within the island stabilises the mode. On the other hand a modification of the local current gradient changes also  $\Delta'$  and hence the mode stability.

During the ECCD phase a slow magnetic field ramp (5 % of the nominal field in 1.5 s) of the toroidal magnetic field shifts the radial location of the ECCD resonance with respect to the island location. The ECRH is launched from the low field side of the torus, whereas the resonance is lying on the high field side. During the scan the position of the ECCD resonance moves over the island from a smaller to a larger minor radius. The ECCD resonance makes a shift in the order of 8 cm, whereas the shift of the minor radius of the mode is in the order of 2 cm [4]. The scan was necessary because from discharge to discharge there is jitter in the exact island position and should ensure that the island and the ECCD position match.

**Complete stabilisation by co ECCD at resonant surface** With the scheme described above, stabilisation of (3/2) NTMs could be reliably achieved. The ECRH power of 1.2 MW represents only 10% of the heating power of  $P_{NI} = 10$  MW from the neutral beam injection (see Fig. 1). After the mode has reached its saturated size the ECCD is switched on together with the preprogrammed magnetic field ramp. The launch angle of  $-15^\circ$  has been used for co current drive. After the mode has been completely stabilised the  $\beta$  recovers to the same value which could be reached in a discharge without mode, but with otherwise identical conditions.

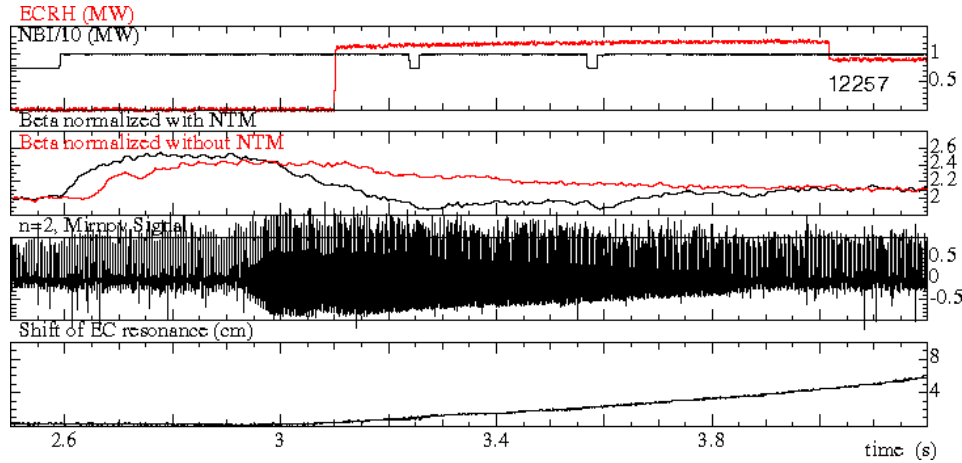


Figure 1: Complete stabilisation of a (3/2) NTM by co ECCD. Additionally to 10 MW of NI injection 1.2 MW co-ECCD is applied (first trace) together with a magnetic field ramp (last trace). During the scan the saturated NTM could be completely stabilised (third trace). The loss in  $\beta_N$  completely recovers compared to a case without an NTM but otherwise identical conditions.

During the ECCD phase an additional loss of confinement is observed. This is partly due to a loss in density which is then controlled by the gas feedback system increasing the gas puffing rate and leading to a loss of confinement [5]. The details of this density pump-out are not yet fully understood.

A further increase of the heating power from 10 MW to 12.5 MW leads to an increase of  $\beta_N$  which reexcites the mode at slightly higher values (see Fig. 2a). This may happen as the ECRH resonance has again moved out of the resonant surface. An attempt to increase  $\beta_N$  after the mode stabilisation to higher values compared to the onset value has been done. The field ramp has been stopped at the value of optimum stabilisation (maximal decay of mode amplitude). Steady state  $\beta_N = 2.5$  with 1.2 MW ECRH and a stabilised mode could be achieved in this optimized case (see Fig. 2b). This has to be compared to  $\beta_N \approx 2$  with an unstabilized mode. A 10% increase in heating power gives 25% increase in  $\beta_N$  and hence a 50% increase in fusion power ( $P_{fusion} \sim \beta^2$ ). After the ECCD is switched off, the mode instantaneously reappears in the plasma. This reexcitation has been only observed in this optimised case, where  $\beta_N$  recovers

to higher values and ECCD clearly suppresses the mode.

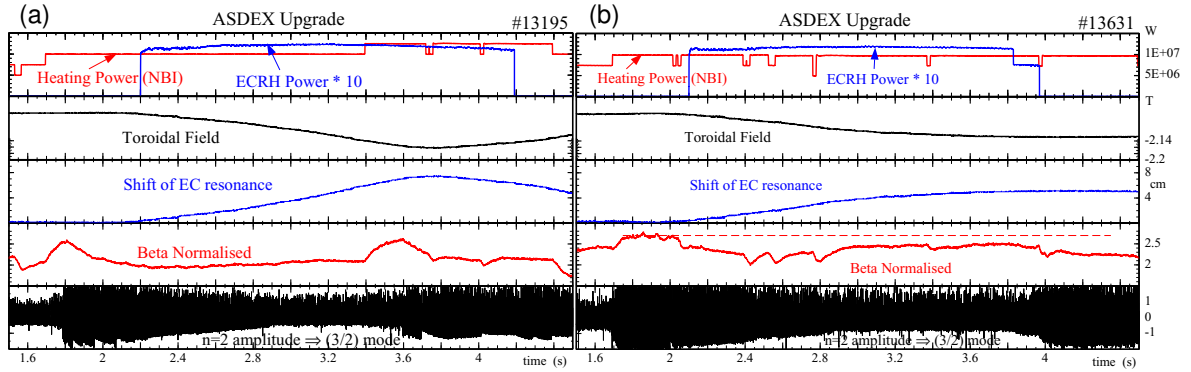


Figure 2: (a) A further increase of the NI power from 10 MW to 12.5 MW reexcites the mode at only slightly higher  $\beta_N$ . (b) A stop of the  $B_t$  ramp at the optimal value for stabilisation leads to higher  $\beta_N = 2.5$  values. At the end of the ECCD phase the mode gets excited again instantaneously pointing to a perfect resonance condition.

**Co versus counter ECCD at resonant surface** In order clarify whether the current drive or the heating is the main stabilising effect, a control experiment with counter-ECCD has been done. The launch angle of the ECRH has been changed to  $+15^\circ$ . In the case of counter-ECCD the local heating effect and the increased current within the island remains the same, but the externally driven current should have a destabilising effect, as it has the same direction as the missing bootstrap current.

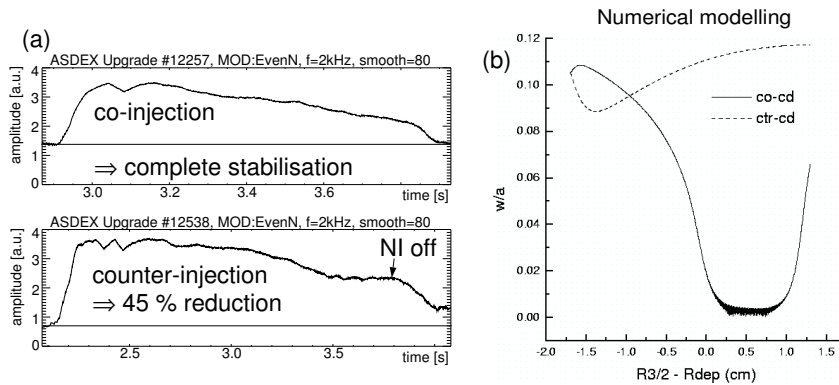


Figure 3: (a) Mode amplitude for co- and counter-ECCD determined from magnetic measurements during the field scan. In case of co-ECCD a complete stabilisation, in case of counter-ECCD a stabilisation to 55% of the initial amplitude could be achieved. (b) Mode amplitude during a shift of the ECCD resonance for co- and counter-ECCD from modelling. For co-ECCD a complete stabilisation, for counter-ECCD only a partial stabilisation is predicted in agreement with the experiment.

The experiments have shown that also in the counter-ECCD case there is a small overall stabilising effect. This reveals that the current drive effect and the heating effect are of the same order (see Fig. 3a for the mode amplitudes taken from magnetics). Instead of a complete stabilisation the mode amplitude could only be reduced to 55 % of its initial amplitude and  $\beta_N$  remains significantly lower.

**Island evolution and comparison with theory** The evolution of the island width taken from magnetic measurements for the co- and the counter-ECCD cases are shown in Fig. 3a. The island width has been determined from the magnetic perturbation field under the assumption  $W \sim \sqrt{B_{pert}}$ . The measured behaviour has been compared with theoretical modelling (see Fig. 3b).

The model takes self consistently the bootstrap current and the ECRH heating and current drive effect into account [3,6]. The island width is plotted as a function of the distance between the ECRH deposition layer and the location of the resonant surface of the mode. This scan has been performed in the experiment, besides the fact that the field can not be linearly translated to this resonance position. It can be clearly seen that the optimum position for co- and counter-ECCD is different in accordance with the experiment. Only for co-ECCD a complete stabilisation occurs, whereas in counter-ECCD case only a partial stabilisation is predicted.

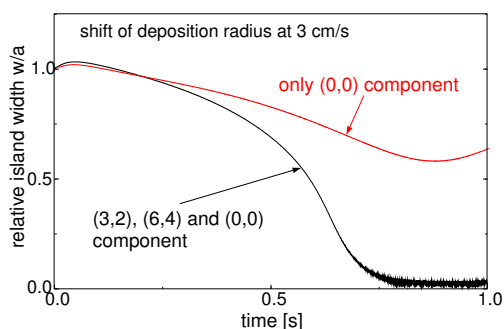


Figure 4: *Fourier analysis of the ECRH deposition for the stabilising effect of the different harmonics. Only the (0/0) component ( $\Rightarrow \Delta'$ ) and the higher (3/2) and (6/4) components together can stabilise the mode.*

An additional information about the stabilising effects can be taken out of a spatial Fourier analysis of the deposition of the ECRH. The (0/0) component contributing mainly through the change in the local current gradient and hence  $\Delta'$  alone can not stabilise the mode in the model. Only a reduction of 10-20% of the amplitude of the mode can be reached. It is required to use higher harmonics, especially the (3/2) and the (6/4) component to get a complete stabilisation (see Fig. 4). This shows clearly that the helical current in the island is required for the mode stabilisation.

**Summary** Reproducibly a complete stabilisation of (3/2) neoclassical tearing modes with ECRH current drive and heating could be achieved. The ECRH delivers only 10 % of the heating power and a local current of 1-2% of the plasma current is driven. For the future a more automatically working system for NTM stabilisation is planned to prove the practical use over a wider range of discharge conditions.

## References

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