

## First results of closed loop feedback control of NTMs at ASDEX Upgrade

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### Introduction

In high performance plasmas, Neoclassical Tearing Modes (NTMs) are regularly observed at reactor-grade  $\beta$ -values. They limit the maximal achievable normalized beta  $\beta_N$ , which is undesirable because fusion performance scales as  $P_{\text{fusion}} \sim \beta_N^2$ . ASDEX Upgrade has been developing a feedback system for NTM stabilization, which is based on mode detection and localization, ECCD deposition calculation and an optimized controller for moving the ECCD mirror. System details and description of recent improvements are found in another contribution to the conference [1].

### Experimental setup

In order to generate  $\beta$ -induced NTMs, a target plasma (compare figure 1) with  $I_p = 1$  MA,  $B_t = 2.5$  T and more than 13 MW of total external heating power supplied by NBI, ICRH and ECRH was chosen. The line averaged density is controlled at about  $7 \cdot 10^{19} \text{ m}^{-2}$  during the flattop phase. The plasma edge is cooled using nitrogen seeding, which also improves confinement [2] for reaching higher  $\beta_N$ .

The experiments always use similar timing. During the first two seconds, the plasma current is ramped to the flattop value and strong heating is applied to excite a mode with poloidal and toroidal mode numbers of either 2/1 or 3/2.

About 20 ms after the mode appears at  $\rho_{\text{NTM}}$ , localization of the island [2] typically succeeds and the ECCD deposition  $\rho_{\text{ECCD}}$  is adjusted by the controller such that it matches  $\rho_{\text{TARGET}}$ . Then, power is switched on and the stabilizing effect can be observed (cf. figure 2).

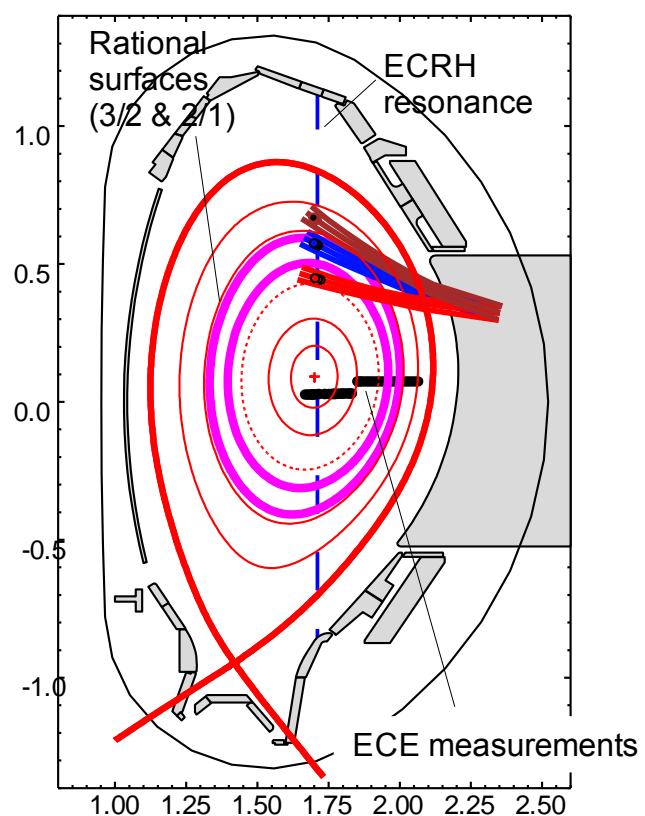


Figure 1: Cross-section of plasma showing used diagnostic configuration

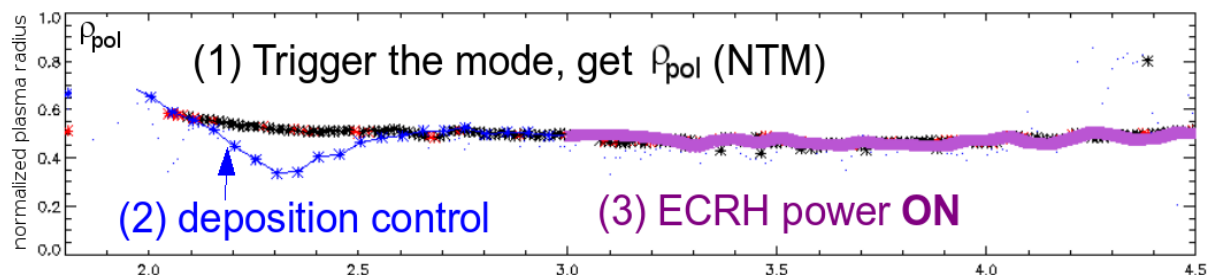


Figure 2: Illustration of time sequence as executed in all dedicated experiments

Since we rely on the equilibrium flux surfaces to map between mode location measurement (outer midplane) and ECCD deposition location (above plasma center), there is usually a small offset to take into account due to incomplete information about internal flux surfaces as they are calculated by a function parametrization (FP) approach using only magnetic data outside the plasma. Therefore, we attempt to measure the necessary shift by applying – in the same target plasma – different offsets between  $\rho_{\text{NTM}}$  and  $\rho_{\text{TARGET}}$ , which the MHD controller aims at when controlling  $\rho_{\text{ECCD}}$ . The first experiments thus deal with a systematic variation of the offset between  $\rho_{\text{NTM}}$  and  $\rho_{\text{ECCD}}$  and observation of the effect with regard to the stabilization.

So far, only a single gyrotron ( $P_{\text{ECCD}} \sim 800$  kW) was actively controlled for aligning current deposition with the target location. The time constant for initial alignment is about 100 ms, but once  $\rho_{\text{ECCD}}$  is located close to the island, the requirements relax. Deposition control can cope with the island movement which is slowed by current diffusion.

## Results

In order to find the actual (mis-)alignment between deposition above the plasma center and island position determined at the midplane in a given equilibrium, several discharges were performed in sequence using different, pre-programmed offsets  $\delta\rho = \rho_{\text{TARGET}} - \rho_{\text{NTM}}$ . We have meanwhile improved the system to allow dynamic changes of the offset  $\delta\rho$  during a discharge. The example shown in figure 3 (#28301) is such an experiment.

Multiple modes are triggered by the heating ramp at the beginning of the discharge, but a considerably large  $m=3, n=2$  island is triggered at 2.4 s, when the stored energy reaches about 1 MJ. It dominates the MHD activity for the rest of the discharge. Deposition control is activated at 2.9 s and ECCD power is switched on at 3.5 s. The mode amplitude immediately responds with a drop and a small, but noticeable rise in  $\beta$ . Different offsets between mode position and ECCD deposition result in different mode amplitude and thus different island size. The strongest stabilization effect seen in #28301 is achieved when deposition occurs at or just outside  $\rho_{\text{NTM}}$ . Due to the expected imperfections in the flux surface shape of the FP-

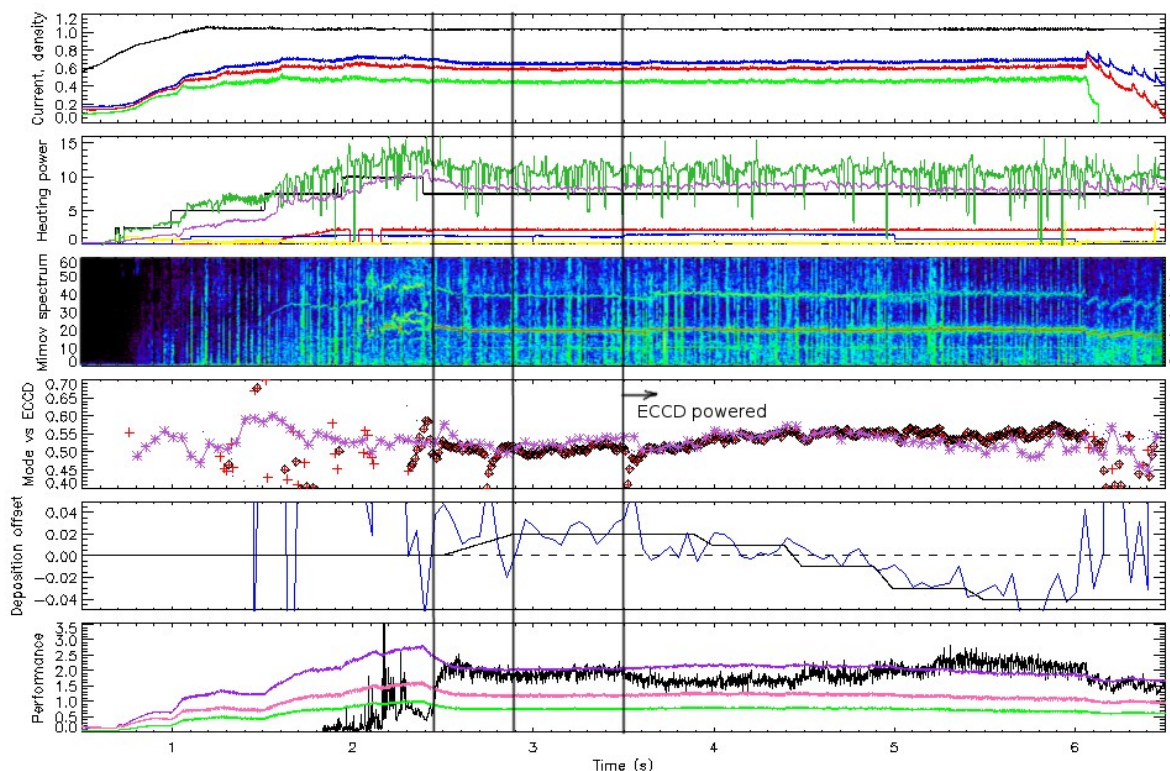


Figure 3: Time traces of offset scan experiment

- a) Plasma current [MA], line averaged density (edge, mid-radius, central chord)
- b) Heating power [MW] (NBI, ICRH, ECRH) and total power (incl.  $P_{OH}$ )
- c) Power spectrogram of Mirnov coil (dB/dt), y-axis in kHz
- d) Location of ECCD deposition, NTM position as evaluated from ECE, y-axis  $\rho_{pol}$
- e) Requested and actual offset in  $\rho_{pol}$
- f) Plasma pressure  $\beta_N$ ,  $\beta_{pol}$ , stored energy  $W_{MHD}$  [MJ] and mode amplitude [A.U.]

based equilibrium reconstruction and resulting differences between calculated and real flux surfaces, this is not in contradiction with theories suggesting maximal stabilizing effect just inside the rational surface.

In a different experiment (#27859-#27862), which uses a similar setup, the offset for  $\rho_{TARGET}$  was fixed in each discharge. When ECCD power is switched on in #27861, which used  $\delta\rho = -0.025$ , the strongest relative reduction of the island size (>70%) is seen. The other discharges produce different responses of the island amplitude between  $\delta\rho = -0.050$  (none),  $\delta\rho = 0.0$  (only after some time) and  $\delta\rho = -0.015$  (considerable, but less than  $\delta\rho = -0.025$ ).

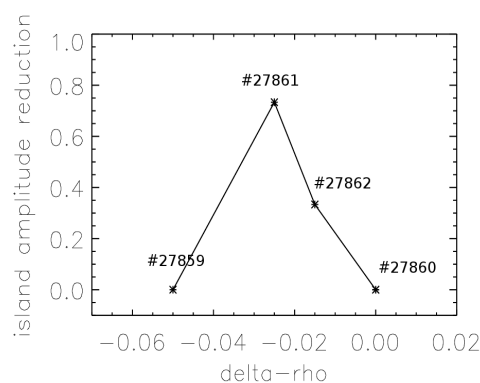


Figure 4: Dependence of 3/2 NTM amplitude reduction on alignment offset

## Summary

Fully closed loop operation (mode detection, deposition calculation and deposition control concurrently and in real-time) was demonstrated in multiple discharges, usually, but not exclusively, in the scenario described above. Cases with normal current ramp-up produce an  $m=3$ ,  $n=2$  island, but occasionally extraordinary events during the start-up phase may also lead to triggering of an  $m=2$ ,  $n=1$  island. For both cases, NTM localization and consequently ECCD deposition alignment using the controller work routinely and experiments exploring the operational space are ongoing.

We have proven that our approach using flux surface mapping is viable and the performed series of discharges with different fixed offsets shows that for the system to be capable of stabilizing NTMs, the power deposition location needs to be accurate within approximately 0.02 in  $\rho$ , which translates to about 1-2 cm in real space. By using a real-time equilibrium for mapping, an extra layer of complexity is added to a problem that can be solved differently, but the complex control scheme has the advantage of being generic enough to allow direct transfer of results to other experiments, in particular future experiments like ITER.

## Conclusion and outlook

ASDEX Upgrade has successfully commissioned a closed loop feedback control system for NTM stabilization based on electron cyclotron current drive (ECCD) using launchers with movable mirrors. Complete stabilization was not yet achieved for  $\beta$ -driven modes due to a lack of ECCD power with the single deposition-controlled gyrotron. Demonstration of complete stabilization using several gyrotrons is therefore the immediate next step.

In parallel, tests with the new Grad-Shafranov solver [3], which will provide a better equilibrium with the addition of internal magnetic measurements (MSE), are also ongoing. Experiments investigating the influence of current profile changes on mode stability and island size will commence, when the MSE diagnostic is fully integrated. We will be able to use the MSE diagnostic data directly in the real-time GS-equilibrium.

With realistic internal current profile information, the additional option to preemptively apply ECCD on rational surfaces for complete avoidance of islands will eventually lead to achievement of higher  $\beta_N$  plasmas than previously possible due to the NTM-onset  $\beta$ -limit.

## References

- [1] M. Reich et al., ECCD based NTM control at ASDEX Upgrade, EPS 2012
- [2] J. Schweinzer et al., Confinement of 'improved H-modes' ... with nitrogen seeding, NF 51, 11 (2011), 113003
- [3] M. Reich et al., NTM localization by correlation of Te and dB/dt, FST **61** (2012), 309
- [4] L. Giannone et al., Real-time magnetic equilibria for NTM stabilization experiments, EPS 2012