Progress on ECCD-based NTM rt-control at ASDEX Upgrade

M. Reich, A. Bock, K. Behler, L. Giannone, M. Maraschek, E. Poli,

J. Stober, W. Treutterer and ASDEX Upgrade team

Max-Planck-Institut für Plasmaphysik, EURATOM association, D-85748 Garching, Germany

In order to efficiently run high performance plasmas, Neoclassical Tearing Modes (NTMs), which are regularly observed at reactor-grade β-values, have to be controlled. Suppression of performance-limiting magnetic islands is the prime requisite, but controlled triggering of benign modes in order to avoid more deleterious ones is desirable as well. At ASDEX Upgrade, a steerable mirror is used to direct the ECRH (or ECCD) beam to the desired deposition location in the plasma. Since the deposition can thus be changed during plasma operation and in real-time, a feed-back control of magnetic islands is feasible.

The individual components of the full feedback loop for NTM control have been discussed previously [1]. Several sub-projects have since made considerable progress towards the fully integrated project. The ASDEX Upgrade real-time plasma equilibrium, which serves as the basis of many real-time diagnostic systems, and its progress are discussed separately [2]. The other two main ingredients, the TORBEAM real-time diagnostic and the mirror control application have recently reached production status and are the main topic of this paper.

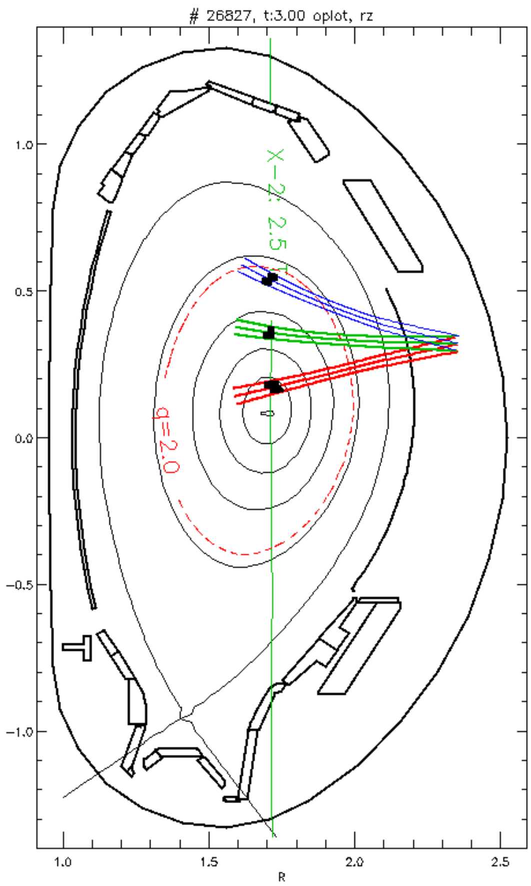

Figure 1: Accessible deposition locations

The plasma scenario chosen for demonstration has a plasma current of 1 MA and a toroidal field of 2.6 T on axis. This configuration allows to use ECRH at 140 GHz for both central heating (impurity control) and current drive across a range of minor radii with the beam directed as shown in figure 1. Safety margins for the movement of the mirror were chosen such that deposition is possible between $\rho_{pol} \sim 0.2$ and ~ 0.7, a range of radii known to contain the q=1.5 surface. Up to 5 sources (12.5 MW) of neutral beam injection (NBI) are necessary to push the plasma β above the threshold for NTM onset and typically excite an m=3, n=2 magnetic island, which is visible in the ECE radiation temperature profile (figure 2).

The core component of the NTM control project is the process which interfaces directly with the mirror. The desired mirror angle (α_{set}) is determined by extrapolating from the current deposition location (ρ_{tbeam}) and the expected change of the deposition ($\delta\rho$) with respect to a small change of the mirror angle ($\delta\alpha$) at the current setting of the launcher (α_{meas}). So the requested mirror angle change can be expressed as:

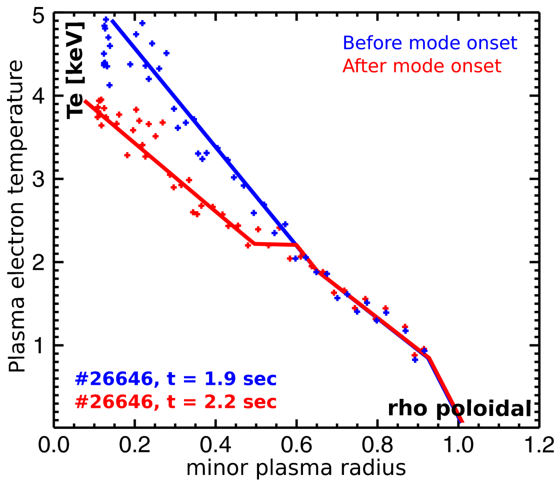

Figure 2: ECE temperature profile before (1.9s) and after (2.2s) NTM onset (2.0s)

$$\Delta\alpha = \alpha_{set} - \alpha_{meas} = \rho_{tbeam} \cdot \frac{\delta\alpha}{\delta\rho}(\alpha_{meas}) - \alpha_{meas}$$

The input to this process comes directly from the TORBEAM code, which is calculating ρ_{tbeam} and $\delta\rho / \delta\alpha(\alpha_{meas})$ using the numerical derivative at lowest order. The necessary inversion of the derivative is expected to be well-defined in the range of possible mirror angles. The implementation of this controller also takes into account the possibility of changes smaller than the accuracy of the mirror steering mechanism and doesn't forward such requests to the actual launcher, thus avoiding continuous stresses for the system's mechanics.

In order to deposit the ECCD beam at the location of the magnetic island (at the relevant rational surface), it is important to know the expected deposition location. The real-time capable TORBEAM code uses the magnetic equilibrium, the density profile and the mirror angle (which are measured by different real-time systems concurrently) to calculate this position by solving the ray tracing equations. It has been possible to optimize the code such that calculating one beam trace takes on average less than 50 ms on the designated 3.33 GHz x86 machine. In the chosen scenario (with a well behaved density profile and only mildly varying plasma equilibrium) the execution time averages at 35 ms with occasional peaks up to 40 ms. A major step forward was achieved by parallel execution of several such calculations using the MPI (message passing interface) protocol. It is now possible to calculate two beam traces simultaneously on one dual-core machine (already done in practice) and as many traces as needed on a suitable multi-core machine. The speed-up for up to 8 such nodes has been shown to scale nearly linear (i.e. each beam trace uses an extra CPU core and the increase of the total execution time is negligible). By using a fast interconnection network (e.g.

infiniband), alternate beam traces can also be run on a cluster of machines, which will become necessary as soon as more than one ECCD beam are to be controlled in the same discharge.

Before relying on the calculation of deposition location using the real-time TORBEAM, a thorough validation of the results was performed. Within a single plasma discharge, current, field, plasma shape and density were kept as constant as possible and the mirror was tilted in steps to provide several different deposition locations. By modulating the ECRH at 250 Hz, we determine the actual deposition location from the ECE spectral power at the ECRH modulation frequency (cf. figure 3) in each channel. When comparing this measurement to the calculated ECCD deposition using TORBEAM, the agreement is quite good. Occasional deviations of up to 0.08 in ρ_{pol} are thought to be caused by inaccuracies of the equilibrium and/or the resolution of the ECE system which is resolving only $\Delta\rho_{pol} \sim 0.04$. It is thus possible to use the calculated deposition for the experiments (no modulation for real-time deposition measurement necessary).

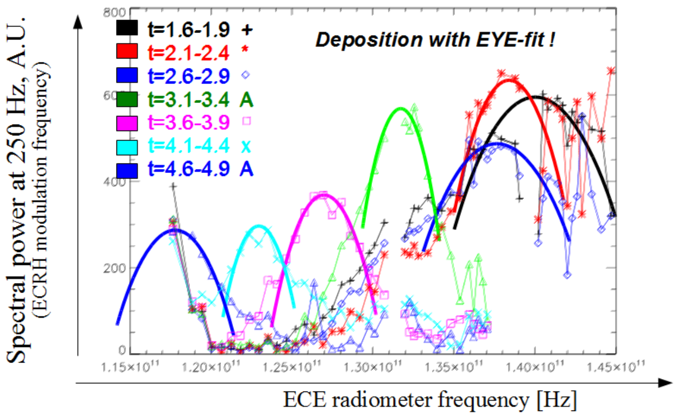

Figure 3: ECE spectral power of deposited ECRH

The most recent plasma experiment was aimed at triggering a magnetic island, measuring its amplitude and starting counter-measures as soon as the amplitude increases above a pre-set threshold value. The counter-measures consisted of sweeping the ECCD beam (in a pre-programmed motion) across the island position and observe the reaction of the mode-amplitude. We would have stopped the mirror and kept the beam depositing on the rational surface to prevent the island from reappearing, if the amplitude had shrunk to a second threshold. Mode creation and detection was successful, however, due to lack of ECCD power (and driven current) the island was not completely stabilized, the “mode stable”-threshold was not reached and the ECCD was moved further. Consequently, with the stabilizing term removed, the island increased in size again, triggering the mirror sweep a second time.

Using the fast (1 MHz) ECE measurements, which are acquired by a real-time capable system, we can attempt to localize the island with a correlation technique. By correlating the N=2 magnetic signal (also available on the same system) with each ECE channel, a correlation amplitude spectrogram can be plotted. While the maximum of the correlation amplitude in flux label coordinates (which each ECE channel is mapped to) apparently doesn't reflect the magnetic island's position, the phase between each ECE channel and the magnetic

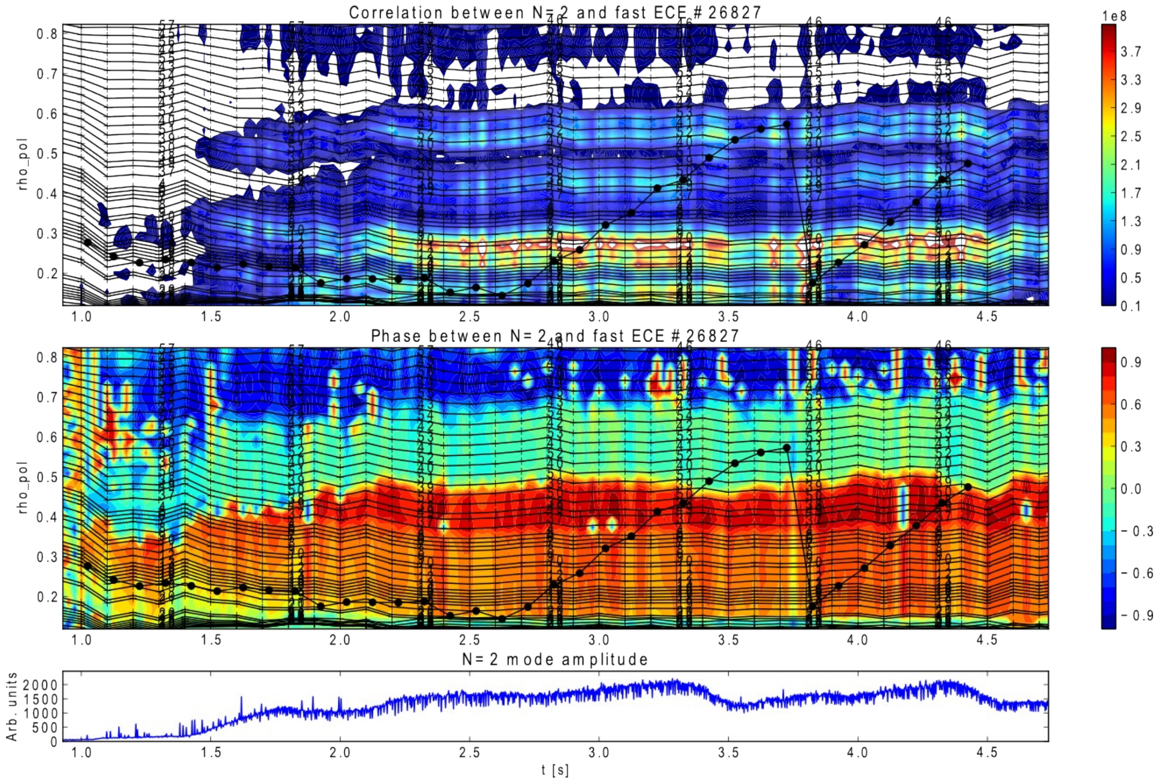

Figure 4: Magnetics & ECE temperature correlation (amplitude, phase and N=2 amplitude) ECCD deposition calculated by real-time TORBEAM is indicated in black circles

reference exhibits a jump of π which moves through a number of channels and can thus be unambiguously identified as the island's O-point. The smaller step in phase located around $\rho_{pol} \sim 0.35$ is due to a group of ECE channels located at slightly different height and thus seeing an explicit phase offset with respect to the island. One can now compare the calculated deposition location of the ECCD beam (as calculated by TORBEAM) with the measured ECE-magnetics correlation amplitude and phase as done in figure 4. The most stabilizing effect (mode amplitude shrinks) is achieved when the deposition crosses approx. $\rho_{pol} \sim 0.45$ (O-point location at t=3.4s). As soon as we have a robust algorithm for real-time detection of this phase jump of π (work already underway) we will close the NTM control loop.

We have established a plasma scenario in which β-driven NTMs are triggered and have shown that our real-time systems can detect and respond to the occurrence of such instabilities. The real-time TORBEAM code performs very well in its parallelized version and can provide useful deposition locations plus the numerical derivative for mirror movements for a number of beams every ~ 50 ms. The MHD controller has been commissioned and is ready for the proof-of-principle demonstration. Closing the full stabilization loop depends only on the available experiment time for this project in the ongoing campaign.

[1] M. Reich et al., **ECCD-based NTM control using the ASDEX Upgrade real-time system**, EPS 2010

[2] L. Giannone et al., **Real time magnetic equilibria for NTM stabilisation experiments** , EPS 2011