# ECCD-based NTM control using the ASDEX Upgrade real-time system

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## Introduction

Advanced scenarios of tokamak operation [1] are thought to be a key ingredient to achieving efficient fusion power. These scenarios aiming for high (and thus economical) beta values, are prone to the occurrence of magneto-hydrodynamic modes (due to pressure gradients, fast particle excitation, etc.). Neoclassical Tearing Modes (NTMs), which are common phenomena under these conditions, deteriorate the plasma confinement substantially. An avoidance of such modes or a controlled triggering of benign modes in order to avoid more deleterious ones is thus desirable. The method of choice for controlling and avoiding NTMs at ASDEX Upgrade is the deposition of ECCD inside the magnetic island for stabilization [2]. The deposition location is controlled by moving a mirror, which directs the ECRH beam.

## Methods

Important for efficient stabilization of NTMs at ASDEX Upgrade is putting ECCD current exactly onto the rational surface where the island forms or has formed. Thus, the initial problem to solve is finding the island position. In order to then apply ECCD using feed-back, one also needs to ascertain the deposition location of the ECRH. For both tasks, we envisage two methods each.

*Determination of island position*

Assuming an accurate equilibrium reconstruction, one can determine the location of rational surfaces and identify those likely to develop an instability (like m=2, n=1 or m=3, n=2) even before an island appears in the plasma. Alternatively, ECE measurements at high enough time resolution (in AUG typically >50 kHz) can make use of correlation analysis (Te fluctuations correlated with magnetic signals) to determine the mode location, as soon as an island rotates with the plasma. The ECE based method is usually more accurate, but may fail, if – due to plasma conditions – the SNR is not sufficient or ECE is no longer reliable (e.g. cutoff).

*Determination of ECCD deposition*

For determining the deposition location, which is well described by the TORBEAM code [3] as long as required input data (equilibrium, density and temperature profile, beam parameter) are available, the ECE again provides an alternative. By modulating the ECCD power at a predefined frequency (large enough to avoid mixing with ELM frequencies, which range up to 200 Hz at ASDEX Upgrade, but small enough to generate an electron temperature modulation, which is large enough to appear in the Fourier spectrum of ECE measurements), it becomes possible to not just calculate with TORBEAM, but also measure the actual deposition location of the ECCD beam and apply the necessary corrections to the mirror tilt to move the deposition towards the island, which eventually leads to stabilization.

*Real-time compatibility*

Both solutions are real-time compatible with algorithm latencies in the order of those required for achieving the necessary response times within the control loop. The relevant timescales are assumed to match growth times of NTMs, which are similar to current diffusion time-scales (~100ms). While the TORBEAM calculation currently is performing only marginally sufficiently fast (30-70 ms), but can likely be further sped up, the other sub-tasks (equilibrium: 3-6 ms, density profile: 1 ms, mode position by correlation: est. 10 ms, ECRH deposition correlation: est. 5 ms) are all within the envisaged control cycle period (10 ms).

## Real-time network

The concurrent execution of multiple codes which determine all necessary quantities like density profile, deposition location and island position in real-time is only possible by using distributed computing resources. The participating computers need to be interconnected by a suitable low latency real-time network and dimensioned appropriately for achieving their individual tasks in sufficiently short times. The upgraded ASDEX Upgrade real-time discharge control system (DCS) [4] provides support for data exchange between real-time diagnostics and the DCS itself over standard Ethernet connections (for low bandwidth and medium latency requirements) and a reflective memory architecture (for high bandwidth and/or low latency). Using this infrastructure, it is possible to divide the complex project of NTM stabilization into sub-projects which all interface with each other by well defined rules and standardized data paths.

A software framework has been built around the standard protocols to enable every physicist to quickly connect a diagnostic that is capable of real-time data processing to the real-time network and in turn enable every other connected node to profit from this data. A number of diagnostics have already started operation and provide and consume real-time signals using this framework [5].

The starting point of many data processing and raw data evaluation algorithms is the mapping of measured positions to the one-dimensional coordinate that originates from the equilibrium and is the normalized flux coordinate, usually $\rho_{tor}$ (if only the plasma core is important) but also $\rho_{pol}$ (if scrape-off layer coordinates are needed). Since at the time implementation of the fastest available equilibrium generation algorithm available as a real-time system was considered high priority and the implementation on a multi-core computer platform with LabViewRT as operating system [6] proved to be the quickest possible way, this implementation doesn't utilize the software framework. However, since it provides its output data (which mainly consists of the full flux matrix) in the default format on the real-time network, any real-time diagnostic can access the important mapping information. The incurred latencies (time until a full equilibrium is available to any real-time diagnostic) are less than 6 ms and expected to drop below 4 ms in the near future.

## TORBEAM

As an example for a standard real-time diagnostic (e.g. MSE, $n_e(\rho)$, $T_e(\rho)$), the implementation of TORBEAM into the real-time framework as a diagnostic is briefly described. The code TORBEAM calculates propagation and absorption of a Gaussian wave beam in the Electron Cyclotron frequency range in the plasma, for arbitrary launching conditions and experimentally prescribed magnetic equilibria, density and temperature profiles. A real-time version of that code, optimized for execution time, was compiled into a library callable from any software. The associated real-time diagnostic doing this uses the real-time framework to retrieve the required online data. Specifically, it collects the poloidal flux matrix, a real-time density profile, a plasma pressure estimate from magnetic measurements ($\beta_{pol}$) and the actual (measured) orientation of the moveable ECRH mirror that controls the angles of the ECCD beam and hence the deposition location. The combined results are used to calculate – using the library – the best estimate for the deposition location of the beam under the given conditions and results (the associated flux surface label) are sent back to the real-time network. By running several instances of TORBEAM in parallel on a multi-core machine with slightly different starting conditions (w.r.t. mirror angle $\alpha$), calculations predicting the (usually non-linear) relation between mirror tilt and deposition position can be achieved. Based on the knowledge of $d\rho/d\alpha$, a separate controller can effectively work on matching the otherwise determined flux label of the island position and the expected flux label for the deposition location before actually switching on power.

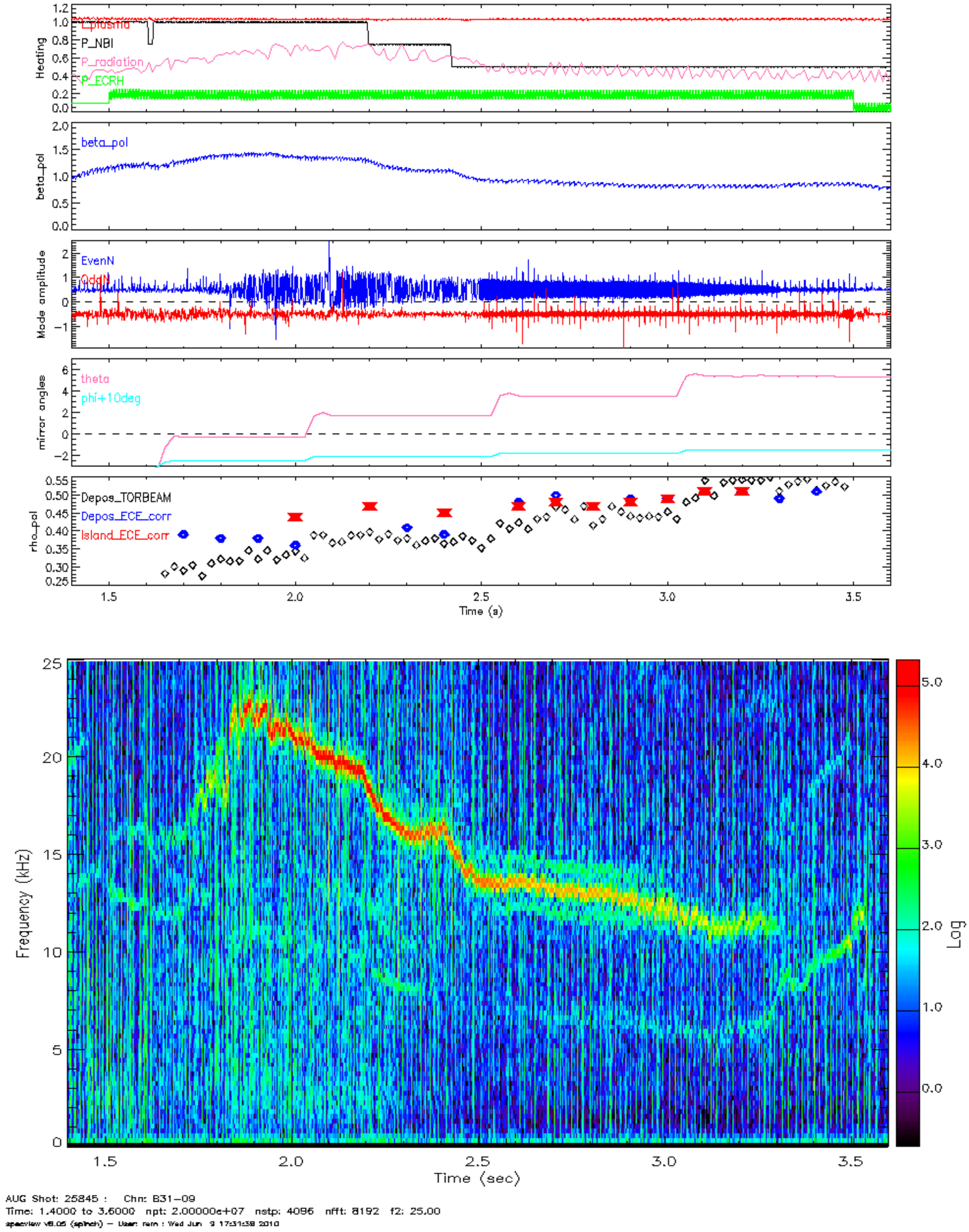


*Figure 2: Time traces of proof of principle discharge for mirror assisted NTM control using localized ECCD. First box: plasma current (red), NBI (black) and ECRH (green) heating, radiation (pink). Boxes 2-5: normalized beta, even and odd toroidal mode number signals, mirror angles (pol, tor.) of ECRH launcher. Box 6: TBM calculated (black), ECE determined (blue) ECCD deposition, NTM island position (red) Box 7: FFT frequency spectrum of magnetic pickup coil signal. All signals are plotted versus time.*

## Experiment

A proof of principle discharge with pre-programmed (feed-forward) mirror positions and sufficient heating to trigger a m=3, n=2 NTM was run successfully (see figure 1). It was designed to allow central ECRH heating for expulsion of impurities, requiring a toroidal field of 2.5 T. It had a plasma current of 1 MA, resulting in a q95 of ~4.6. Up to 4 sources of neutral beam injection (2.5 MW each) were used in combination with 1.5 MW of central ECRH) to trigger a magnetic island, which is relatively stationary after the heating power is reduced to 5 MW NBI + 1.5 MW ECRH. The deposition of additional off-axis co-current ECCD was shifted by stepping the launching mirror poloidally by a few degrees per step. For proper detection of the deposition, a modulation of the ECCD power at 250 Hz was applied.
The ECE diagnostic is the primary tool for analysis of the discharge. The poloidal sweep of the mirror also influences the toroidal angle by some amount. Plotted are poloidal angle (between -0.5 and +5.8 degrees) and toroidal angle +10 degrees (between -12.5 and -11 degrees). Plotted in black is the calculated deposition location using TORBEAM and a high resolution equilibrium and density profile (offline analysis). The blue points show the actual ECRH deposition by power spectrum analysis determined from 100 ms intervals of ECE data. Plotted is the position ($\rho_{pol}$) of the ECE channel with maximum amplitude in the frequency range 248 – 252 Hz. The red line depicts the mode island position, which is found by ECE frequency analysis at the mode rotation frequency. The actual position is determined by the electron temperature phase shift of $\pi$ between two neighboring channels. It can clearly be seen that right after the mode appears, the ECRH deposition – both calculated and measured – is inside the island's position (in minor radius). With the second change of the mirror position, the deposition moves very close to the island (power spectrum analysis at the ECRH modulation frequency would actually suggest that a match has been achieved), but does not yet lead to stabilization. The last step of the mirror, however, moves the deposition even further towards the plasma edge. Also, the island position shifts slightly. After this move of the mirror, the deposition coincides with the island and the result is that the mode amplitude starts to shrink and the island is completely stabilized at 3.3 seconds. At 3.5 seconds the experiment ends and from 3.7 seconds on, the plasma ramp-down commences.

## Conclusions

It was shown that an NTM could be stabilized by ECCD current drive. This is the first time at ASDEX Upgrade, that this was achieved by moving a poloidal mirror instead of slowly changing the magnetic field (or pre-setting the launcher) to achieve resonance within the magnetic island. Experiments closing the now possible control loop and thus demonstrate active control of NTMs by ECCD are planned for the end of 2010.
Since current diffusion times are expected to be much longer in reactor-grade experiments like ITER, transfer of this stabilization method to those devices is not problematic from the viewpoint of involved physical timescales. As computers are typically improving in performance, this control scheme is clearly viable in next step fusion devices.

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