ECCD based NTM control at ASDEX Upgrade

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Introduction

In high performance plasmas, Neoclassical Tearing Modes (NTMs) are regularly observed at reactor-grade β-values. They limit the maximal achievable normalized beta β_N, which is undesirable because fusion performance scales as $P_{fusion} \sim \beta_N^2$. ASDEX Upgrade has recently successfully commissioned closed loop feedback control for NTM stabilization based on electron cyclotron current drive (ECCD) using gyrotrons with movable mirrors. The feedback system allows systematic and detailed studies on how the stabilization effect by ECCD depends on the required power, the accuracy of alignment and the optimal tradeoff between total driven current and deposition profile. This paper, however, focuses on the description of the system and its components. First results of the system are being presented in a separate post-deadline contribution to this conference [1].

Method

For the closed feedback loop, the proper connection and coordination of several diagnostic systems with the discharge control system (DCS) is essential, hence a reliable framework has been designed, developed and tested [2]. The cooperating diagnostic systems are "Equilibrium", "ECE/Mirnov", "rt-TORBEAM" and "ECRH". The central coordination takes place inside the "DCS", which is controlling the whole plasma experiment.

The real-time equilibrium diagnostic [3] provides the coordinate system in terms of the normalized poloidal flux coordinate ρ_{pol}. It distributes the 39x69 element matrix containing the magnetic flux across a network based on reflective memory cards and reaches cycle times of less than 8 ms. In the near future we will operate a fast Grad-Shafranov solver that has the option to include MSE data as constraints. It will reduce cycle times to less than 5 ms and distribute the information as a compressed matrix. In this way the data rate achievable over UDP connections (instead of reflective memory) is sufficient to distribute the full equilibrium. The overhead incurred by the decompression is less than 100 μs and allows even more diagnostics to utilize real-time mapping functions. In addition to providing the flux matrix, the diagnostic precalculates pathlengths of 5 interferometer lines of sight to allow fast real-time density profiles (1 ms) and cold resonance positions in units of ρ_{pol} for the ECE diagnostic by mapping the intrinsic ECE coordinate frequency along the ECE antennae lines-of-sight.

The "ECE/Mirnov" subsystem is capable of localization of NTM induced magnetic islands. This is done by correlation of ECE radiation temperature with a Mirnov signal [4], spatially filtered for the mode number of interest. The spatial filtering comprises a projection of several toroidally distributed coils onto the Eigenstate of a rotating island with its canonical mode number ratio, typically 2/1 and 3/2. The localization algorithm achieves 5 ms cycle time and – using the equilibrium mapping – provides ρ_{NTM} to the DCS. The system can robustly localize low rational mode number NTMs for large enough perturbations extending over at least three channels of the ECE system. An example for an m=3 n=2 island is shown in figure 1.
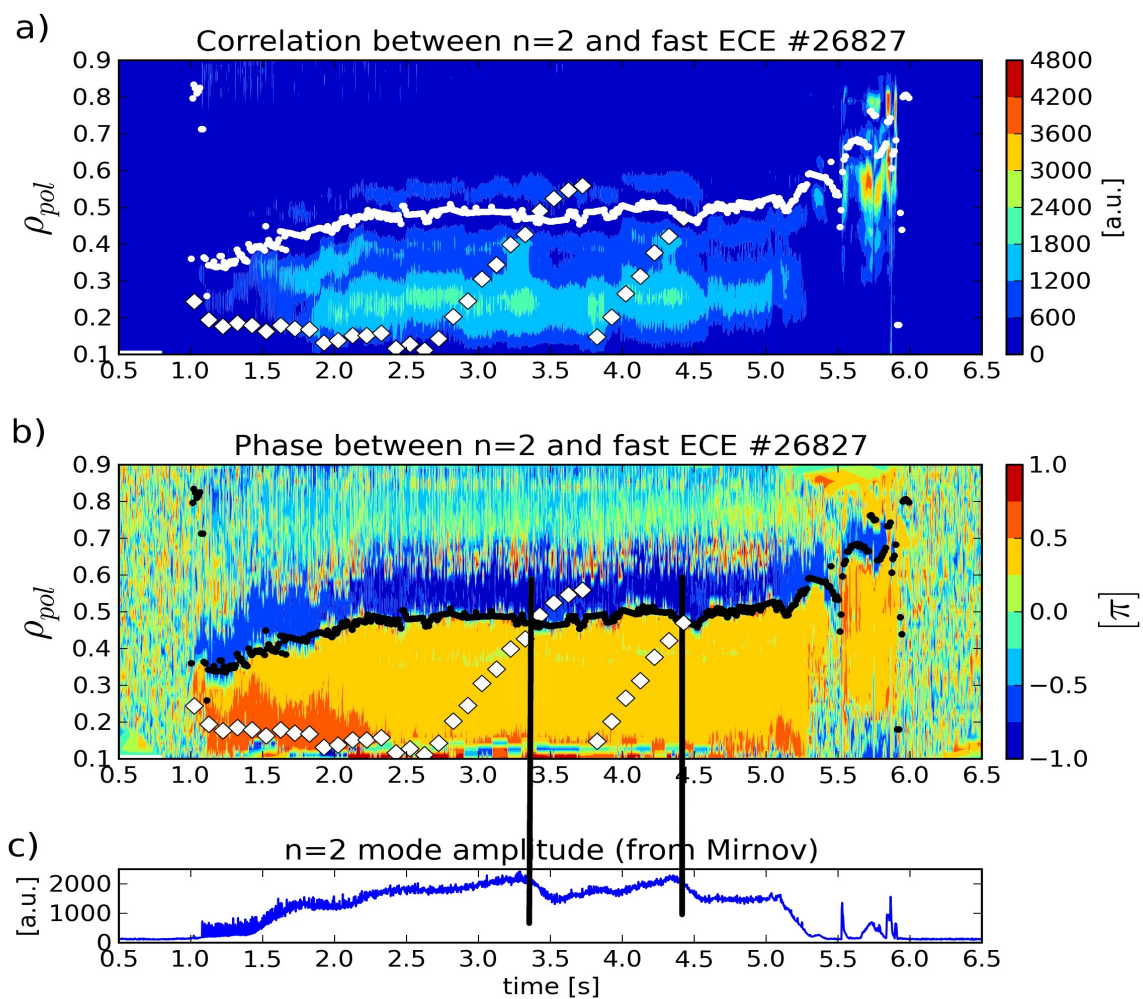

Figure 1: a+b) n=2 & ECE temperature correlation and ECCD deposition (white diamonds)
a) Amplitude between ECE and Mirnov (color) and NTM location (white dots)
b) Phase between ECE and Mirnov (color) and NTM location (black dots)
c) Island size estimate from envelope of n=2 signal (Mirnov)

The "rt-TORBEAM" subsystem is an accelerated version of TORBEAM [5] enhanced by interfaces to the DCS system. It reads the equilibrium, real-time density profile and further

plasma parameters (I_p, β_{pol}, …) to assemble a complete set of parameters necessary to calculate the deposition of the ECCD beam, which are: magnetic field components, fluxes, plasma densities and temperatures along the beam trajectory. A single run provides coordinates R, z and ρ of the peak power deposition, which is almost identical to the peak current deposition location, and takes about 15 ms for horizontally centered absorption. The calculation takes up to 25 ms for off-axis deposition, where the beam path is longer before full absorption at the resonance layer. For controlling the deposition location ρ_{ECCD}, the DCS system also requires a derivative $d\rho_{ECCD}/dx_{pol}$, where x_{pol} is the linear position related to the ECRH launcher mirror angle. It is the abslute position of the push rod used to control the ECRH launcher mirror angle. To get rate of change of ρ_{ECCD}, a second beam is calculated with a small change of x_{pol} to approximate the derivative, thus increasing the cycle time to ~45 ms. For a more accurate calculation, a polynomial approximation based on three beams is also possible, but not yet used for performance reasons. In order to control all 4 steerable gyrotrons simultaneously, up to 12 beams need to be calculated. This will soon be done in parallel using MPI [6] and take less than 30 ms per cycle (including an MPI overhead), while allowing us to know the deposition and the rate of change with x_{pol} of all 4 gyrotrons simultaneously.

The MHD controller is a subsystem of the DCS and computes an error in the linear position x_{pol} for the difference between ρ_{NTM} and ρ_{ECCD}, using the approximation:

$$x_{pol,error} = (\ 1\ /\ d\rho_{ECCD}/dx_{pol}\ ) \bullet (\rho_{NTM} - \rho_{ECCD})$$

Care is taken when the beam path is near perpendicular to a flux surface and $d\rho/dx$ may be extremely small. The calculated error is used as the input to a standard proportional integral (PI-)controller with anti-windup. The PI-controller produces a target value for the mirror actuator in every cycle ($T \approx 1.5ms$), which is further processed by a local PLC (programmable logic controller) of system "ECRH" with direct control over the mirror drive motor. An example of the real-time controlled mirror movement is shown in figure 2.
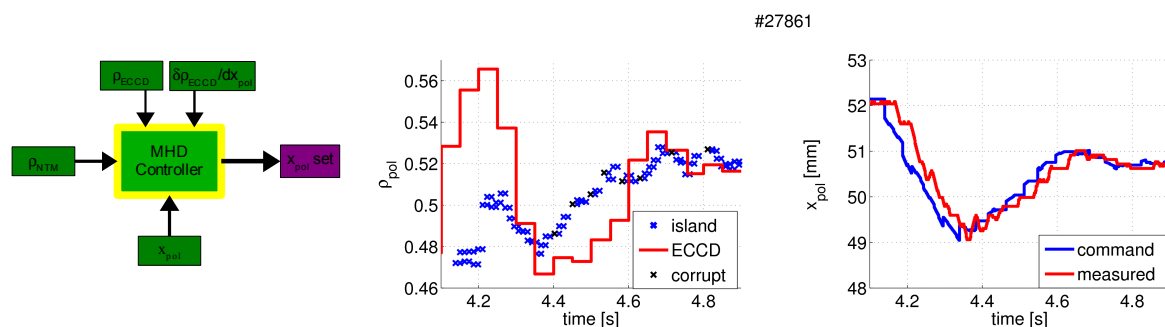

Figure 2:   *a) block diagram of MHD controller (NTM=island)*
           b) controller action in ρ-coordinates, corrupt data is ignored
           c) controller action in x_{pol}-coordinates

The gains of this controller have been optimized using a simulation of the complete control loop. Using the simulation, additional properties of the system could be learned. The time response of the system is restricted by the mirror actuator velocity (< 30 mm/s) and several sources of computational latency. Roughly, the equilibrium calculation has a cycle time of 8 ms, ray-tracing calculations take 40 ms, safety checks carried out by the PLC take 20 ms and the mirror requires a few ms to reach its maximum velocity. These latencies are in series, such that the total maximum dead time in the control loop is up to 70 ms. The dead time also prevents the use of higher controller gains, and hence a faster response, because the system would become unstable. As soon as the deposition has reached the island position, tracking is easier as the island moves only slowly with respect to ρ and $d\rho_{ECCD}/dx_{pol}$ is nearly constant.

The output of the deposition control can be both mirror angle and power switch. It directly connects with the "ECRH" system, which relays the mirror control signal to the push rod which is tilting the mirror and activates ECRH power on request. In the latest stage of development, the controller was enabled to activate power only when deposition reaches the vicinity of the detected island and when the island induced magnetic perturbation amplitude exceeds a preset threshold. In future experiments, power will stay switched off as long as the amplitude remains below the threshold or when deposition is too far away from the detected location. As soon as sufficient alignment for stabilization, which is empirically determined, is reached, power is switched on and the stabilizing current drive will reduce the magnetic perturbation amplitude until power is switched off at the "mode stabilized" threshold.

Conclusions

The system is operational and already used in routine operation. Fully integrated scenarios with impurity puffing together with ELM and NTM control are being conducted during the ongoing 2012 campaign. The MPI-based parallelization of rt-TORBEAM for the possibility of controlling multiple gyrotrons concurrently is the immediate next step which will complete the NTM stabilization system and allow to access higher β_N-regimes than currently possible due to limits imposed by beta-induced NTMs.

References

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