

## **Control of tearing modes in a tokamak using a line-of-sight Electron Cyclotron Emission diagnostic**

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### **Introduction**

Real-time control of tearing modes (TMs) is required to achieve high performance tokamak discharges [1]. Localized Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD) is usually applied for suppression and stabilization of TMs, which will also be one of the main tasks of the ITER ECRH system [2]. Here, an experimental proof-of-principle of real-time, autonomous suppression and stabilization of TMs, by combining ECRH/ECCD and a 'line-of-sight' Electron Cyclotron Emission diagnostic [3,4] in a feedback loop is reported. For effective suppression both accurate deposition and power modulation of ECRH/ECCD are required [1].

### **Line-of-sight Electron Cyclotron Emission diagnostic**

A prototype 'line-of-sight' ECE diagnostic [3,4] was previously installed on the TEXTOR tokamak. The diagnostic is now applied as feedback sensor. The system uses a single transmission path for measurement of the ECE emitted by the plasma and transmission of ECRH/ECCD power into the plasma [3]. A steerable ECRH/ECCD launching antenna, steered both in toroidal and poloidal directions, collects ECE and transmits gyrotron power. The 'line-of-sight ECE concept' thus merges the observation of TM properties with the application of ECRH/ECCD. 'Line-of-sight' ECE avoids the error prone use of real-time equilibrium reconstruction and/or ray-tracing in the control loop and guarantees that localized ECRH/ECCD deposition is accurately aligned with a TM centre in the presence of perturbations. The technical implementation is difficult: EC emission at nW power levels must be separated from the high power ECRH/ECCD beam. The TEXTOR prototype uses a quasi-optical transmission line. A reso-

nant dielectric quartz plate, based on the Fabry-Perot interference principle separates the low-power ECE signal components at selected ECE frequencies from the high power ECRH/ECCD component. ECE is measured at six radial locations distributed equally in space around a fixed gyrotron frequency of 140 GHz. The radial spacing of the radiometer channels is 3 GHz  $\sim$  3 cm.

### Tearing mode control system

The TM controller executes the following steps: the six ECE signals are sampled at 100 kHz and fed into a TM recognition and localization algorithm. The radial TM location  $r_s$ , is inferred directly from the telltale electron temperature fluctuations caused by TM rotation. On opposite sides of  $r_s$  these fluctuations show a 180° phase reversal. A weighted averaged correlation of the ECE measurements provides an estimate of the  $m/n = 2/1$  radial mode location, with  $m$  and  $n$  the poloidal and toroidal mode number. This estimate is specified as an EC frequency  $f_{EC, \text{tearing mode}}(r_s)$  in GHz in the EC spectrum. The processing time of the algorithm is 16  $\mu$ s. In the second step, this frequency is compared to the reference 140 GHz ECRH/ECCD frequency. A feedback control error  $e = 140 - f_{EC, \text{tearing mode}}$  GHz is defined and a standard proportional integral (PI) controller is applied to minimize  $e$ . This controller corrects for alignment errors by changing the requested set-point angle that positions the launching mirror. A separate real-time position controller assures flexible, fast and accurate positioning of the ECRH/ECCD-beam. Its design is based on experimental analysis of the electro-mechanical ECRH/ECCD launcher dynamics. The poloidal injection angle can be swept from  $-30^\circ$  to  $+30^\circ$  within 100 ms with a maximum steady-state positioning error of  $0.6^\circ$ . Upon achieving alignment, i.e. when  $e \leq 0.5$  GHz, the ECRH/ECCD power is switched on. The position control loop ensures that ECRH/ECCD remains aligned with the mode. The control design is implemented on a field programmable gate array (FPGA). A parallel control loop modulates the ECRH/ECCD power synchronously in frequency and phase with the rotation of a TM, enhancing the suppression effectiveness. To this end, one ECE signal (typically channel 2 at 135.5 GHz) is fed into an analog phase locked loop (PLL) circuit. The output of the PLL is locked in phase and frequency to the first harmonic of the noisy ECE input, and is send as a block-wave pulse train to the input of the ECRH/ECCD power supply. The gyrotron power is controlled between a constant lower level of 70 kW and a peak level up to 850 kW by varying the electron beam voltage from 53.5 to 71 kV. The power modulation is controllable in a range from 300 Hz up to 5 kHz for the particular PLL implementation considered here.

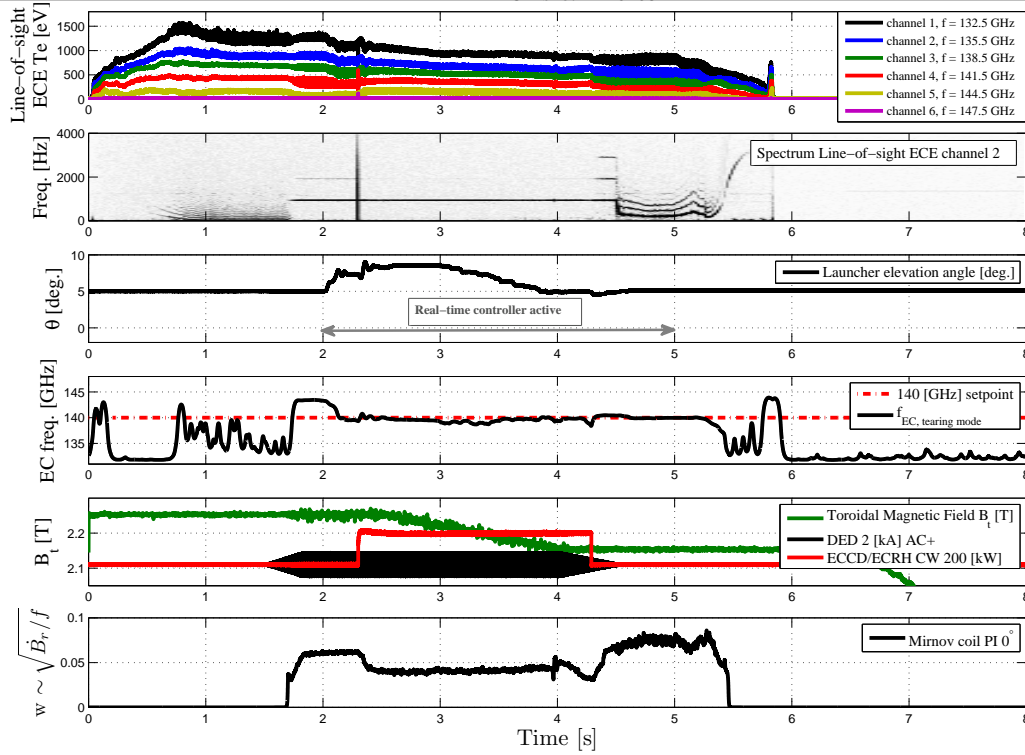


Figure 1: A 2/1 TM is induced by the DED at  $t = 1.7$  s. The real-time controller is switched on at  $t = 2$  s and the mirror is steered to align ECRH/ECCD with the mode as shown in the 3<sup>rd</sup> and 4<sup>th</sup> panel. When alignment is achieved (i.e.  $e \leq 0.5$  GHz), the controller switches on ECRH/ECCD. The mode is not suppressed completely as the DED remains active to drive the mode. From  $t = 2.5$  s a slow ramp down of the toroidal magnetic field  $B_t$  mimics a change in real space of the TM location  $r_s$ . The controller compensates for the perturbed alignment through steering of the poloidal injection angle (tracking). The mode remains suppressed till ECRH/ECCD switch-off, as reflected by the Mirnov signal in panel 6.

## Experimental results

Tearing mode control was studied in TEXTOR discharges with a toroidal field  $B_t = 2.25$  T and plasma current  $I_p = 300$  kA. The experiments focus on  $m/n = 2/1$  TM control. Co-tangential Neutral Beam Injection (NBI) is applied at 300 kW. In these plasmas, a locked 2/1 TM is created by ramping the current in the coils of the TEXTOR Dynamic Ergodic Divertor (DED) to 2 kA in AC+ mode. The mode rotates at 1 kHz as it is locked in frequency and phase to the resonant magnetic perturbation field of the DED. The toroidal ECRH/ECCD injection angle is fixed at  $4^\circ$ , effecting co-ECCD. The experiment in Figure 1 shows the capability of the controller to align 200 kW of ECRH/ECCD with a TM and suppress the mode in real-time. The discharge also demonstrates the tracking capabilities of the controller, which actively corrects a perturbed alignment between ECRH/ECCD and the TM. This alignment is perturbed by a slow ramp down of the toroidal magnetic field  $B_t$ , mimicking a change in real space of the mode location  $r_s$ . Figure 2 illustrates the capabilities of the PLL controller to follow rapid changes in the rotation frequency of a 2/1 mode and to modulate the ECRH/ECCD power in phase with the passage of the TM centre in front of the beam. A natural 2/1 TM is generated by early neu-

tral beam heating. After ECRH/ECCD switch-on the mode spins up in frequency as it is partly suppressed by ECRH/ECCD. In both the early low rotation frequency phase and the subsequent high rotation frequency phase, the PLL controlled ECRH/ECCD power pulse train accurately tracks the mode rotation frequency and phase. A detailed account of these experiments is given in Ref. [5].

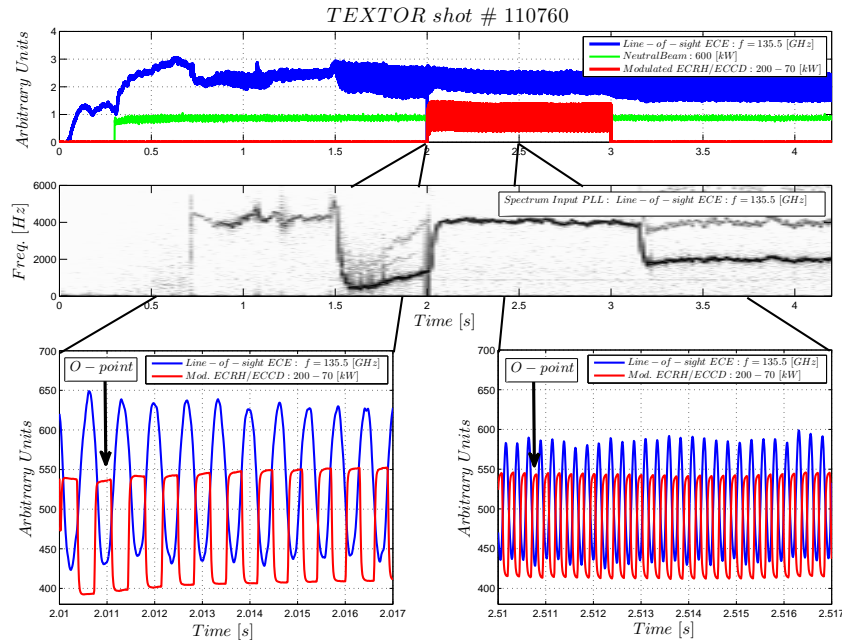


Figure 2: Real-time ECRH/ECCD power modulation synchronized to the rotation of a partially suppressed TM. Modulated ECRH/ECCD 200 kW - 70 kW is applied from  $t = 3 - 4$  s. Passages of the TM centre (indicated as O-point) coincide with minima in the 135.5 GHz ECE signal used as input for the PLL. The 2<sup>nd</sup> panel shows the frequency spectrum of the rotating 2/1 TM.

## Conclusion

The experimental results demonstrate the capabilities of the control system to track (externally perturbed) TMs in real-time. The results prove that relatively simple controllers are sufficient to meet the performance requirements demanded for effective TM control in terms of deposition accuracy and modulation of the ECRH/ECCD power synchronously with TM rotation.

## References

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