Real-time control of magnetic islands in a fusion plasma

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Introduction

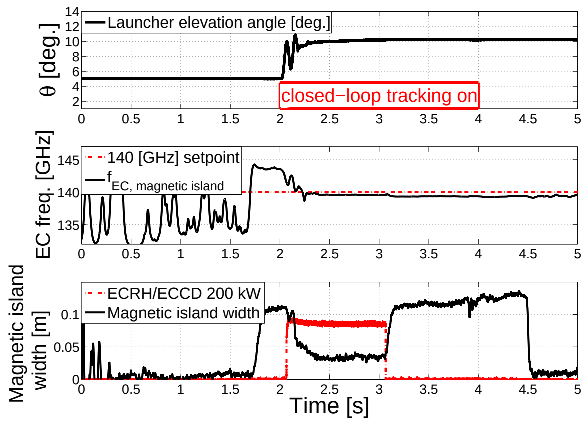
In nuclear fusion research, a hot, fully ionised plasma is confined by magnetic fields in a 'tokamak' reactor. A tokamak plasma is prone to instabilities such as magnetic islands, which harm the operational stability and performance. Real-time control of magnetic islands is in demand and has been demonstrated experimentally in the TEXTOR tokamak.

Real-time control of magnetic islands

The formation of magnetic islands is triggered by perturbation of the magnetic field and current distribution, which disturbs a plasma and its magnetic topology locally. Localized injection of high power microwaves or electron cyclotron waves (i.e. Electron Cyclotron Resonance Heating and Current Drive, ECRH/ECCD) via a steer-able mirror into the plasma induces a local heating and current drive mechanism, which suppresses the island width w. Magnetic islands cause a local flattening in the electron temperature profile of a plasma. A so-called Electron Cyclotron Emission (ECE) diagnostic measures the electron temperature and is applicable as a feedback sensor to monitor magnetic islands (typically a detection within 10 [ms] is required). For effective suppression, a magnetic island control system must direct the ECRH/ECCD beam precisely and fast at the center of the magnetic island. A maximum steady-state positioning error of 1-2 [cm] and a settling time of 100 [ms] are allowed. The settling time is limited by the dynamics of the steer-able mirror (launcher). In addition, feedback controlled on/off modulation of the ECRH/ECCD beam is required to synchronize the microwave injection with the rotation of the magnetic island. The islands pass the ECRH/ECCD beam with rotation frequencies up to 5 [kHz].

The real-time control system, used in the TEXTOR experiments, measures electron temperature fluctuations at a 100 [kHz] sampling rate at 6 radial coordinates. The ECE channels are distributed equally around the ECRH/ECCD deposition location (corresponding to an EC frequency f = 140 [GHz]). The radial mode location $f_{EC,\ magnetic\ island}$ is determined in real-time from the fluctuations and specified as a frequency in the ECE spectrum (in [GHz]). The magnetic island identification algorithm runs at a 16 [μs] clock rate on a Field Programmable Gate Array (FPGA).

A tracking loop minimizes the control error: $e = 140 - f_{EC,\ magnetic\ island}$, to align the 140 [GHz] ECRH/ECCD deposition and the island center. A standard feedback con-



troller $C_{magnetic\ island} = \frac{K_p}{s}$ is applied as tracking filter. A second feedback loop with additional feed-forward (BW: 12 [Hz], 5 [kHz] sampling rate) controls the angular position θ of the steer-able mirror. This controller is designed based on dynamical analysis of the steer-able mirror. Both feedback control loops are operated in cascade on the FPGA. Finally, an analog phase-locked loop is added to synchronize the ECRH/ECCD modulation with the island rotation (monitored by a single ECE channel). The figure shows an experimental result. A magnetic island appears in the time frame t = 1.7-4.5 [s]. The launcher is actively controlled in the time interval $t = 2-4$ [s] ($\theta_{initial} = 5°$) and alignment is achieved within 100 [ms] when $e = 140 - f_{EC,\ magnetic\ island} < 0.5$ [GHz] $\sim$ 1 [cm]. ECRH/ECCD (200 [kW]) is applied continuously from t = 2.1-3.1 [s] and the island is suppressed to a constant width.

Conclusion and outlook

The TEXTOR experiments demonstrate successful real-time controlled stabilisation of magnetic islands. A simulation model is currently developed to analyse the dynamics and to design more advanced controllers. The model includes magnetic island and plasma dynamics, models for the actuators, diagnostics, data-processing and control algorithms. Simulations will be performed for typical TEXTOR conditions and validated with experimental results.

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