Control of MHD modes with a line-of-sight ECE diagnostic **EXW/P2-01**

M. de Baar,[1,4] W. Bongers,[1] R. van den Braber,[2] N. Doelman,[2] V.Erckmann,[3] B. Hennen,[1,4] W. Kasparek,[5] P. Nuij,[4] M. Steinbuch[4]

[1]*Fom institute for plasma physics Rijnhuizen, Association EURATOM-FOM, partner in the Trilateral Euregio Cluster and ITER-NL, P.O. Box 1207, 3430 BE, Nieuwegein, The Netherlands*
[2]*Dept. of Mech. Equipment, TNO Science and Industry, Delft, The Netherlands*
[3]*Max Planck Institut für Plasmaphysik, Association EURATOM-IPP, Greifswald,*
[4]*Eindhoven University of Technology, PO Box 513, Eindhoven, The Netherlands*
[5]*Institut für Plasmaforschung, Universität Stuttgart, Germany*

1. Abstract

A number of improvements are introduced for all elements of a closed loop system for MHD control. These improvements involve improved actuation, controller design, modelling and sensing. The sensing improvement is the further development of the in-line ECE concept, to make the concept compatible with a waveguide environment. On the actuator improvement comprises the design of a dedicated actuator to control the cavity of FADIS. FADIS could considerably simplify any large transmission line, as it allows for power combining, toggling and possibly in-line ECE. A control oriented model of the sawtooth is set-up, and used for controller design and optimisation. The modelling and controller design reported involve a linearization of the Rutherford equation, after which in simulink a extrumum seeking approach is implemented.

2. Introduction

Magnetohydrodanamic (MHD) modes, such as sawteeth and Neoclassical tearing modes (NTMs) affect the core properties of the plasma and the overall confinement. For optimal fusion reactor performance, the MHD modes therefore require to be controlled in Real Time. Any real time controller consists of an actuator, a sensor and a model. Controller optimisation implies the integrated optimisation of all of these components, and the demonstration of performance and robustness.

MHD modes in the plasma core and confinement region are most easily sensed with magnetic diagnostics, Soft X-ray, or Electron Cyclotron Emission (ECE). Actuation is foreseen with high power electron cyclotron waves, deposited in the plasma for local heating and current drive. Any tearing mode control scheme will aim to replenish the helical current deficiency, either via direct current drive, or heating (and hence modification of the resistivity) in the island. In order to obtain efficient suppression, the ECCD power needs to be deposited at the centre of an NTM magnetic island. To enhance efficiency, this power also needs to be synchronized in phase with the rotation of the island. The problem is that of real-time detection and precise localization of the island(s) in order to provide the feedback signal required to control the ECCD power deposition area with an accuracy of 1 to 2 cm. Sawteeth control schemes are implicitly or explicitly based on driving the internal kink-mode unstable at the desired moment. Electron cyclotron waves are applied to vary the magnetic shear at the q=1 surface. Details of the deposition of the EC waves with respect to the location of the q=1 determine the non-linear response of the plasma.

In this paper improvements of all elements of the MHD control loop are proposed. In section 2, the use of in-line ECE is proposed as an ideal sensor, and an in-waveguide implementation for In-line ECE is presented. In section 3, modifications are proposed to control the behaviour of the mm-wave system FADIS in real time, allowing for the use of the system for power combination, fast switching, and eventually as a first stage for the modelling for the control of tearing modes and sawteeth. In section 4, a new tearing mode control scheme is introduced, based on real-time optimum seeking.

2. Optimal sensing for tearing mode control

Inherent limitations exist in the interpretation of the mode location (radial positioning and poloidal phase) from instruments that sense the plasma at a different location than where the ECW power absorption occurs. An elegant solution to this problem is offered by a method in which Electron cyclotron waves are measured along the same sight line as that traced by the incident ECW beam but in opposite direction. Islands will show up as oscillations in the ECE spectrum. Optimal localization is obtained when the ECE frequency representing the island O-point coincides with the ECCD frequency. Any deviation between these two frequencies should be corrected for by adjusting the steering mirror angle of the launcher. The phase of the ECE fluctuations yields information on the modulation of the ECCD power needed to avoid X-point ECCD. In this way inherent positional and temporal accuracy of the feedback signal is assured because the incident beam and the ECE radiation travel along an identical optical path through the plasma and the launcher. This avoids nearly all systematic error sources troubling existing feedback methods, such as errors caused by mirror steering, beam refraction, rational q-surface positioning, and ECR positioning.

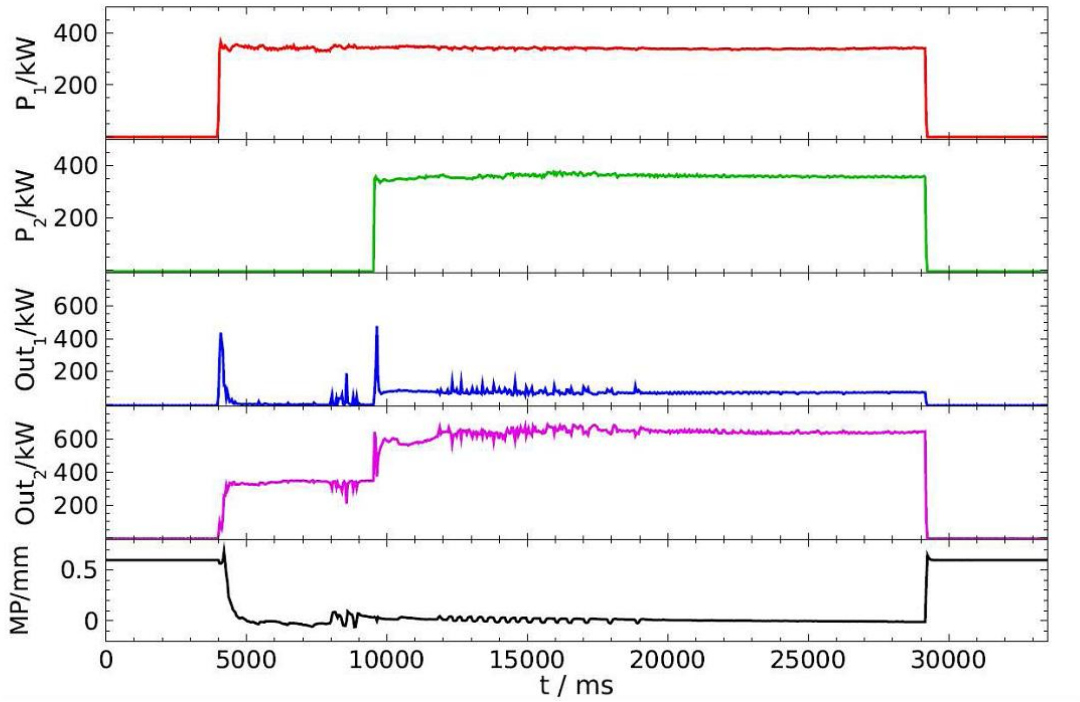
The main challenge in applying this method is to prevent interference of stray radiation generated by the ECCD beam (kilowatts) originating from the megawatt beam with the radiometer measuring the ECE spectrum (nanowatts). It was shown in TEXTOR that this problem can be overcome, but the technical solution for TEXTOR is not ITER relevant for two reasons. First, the method is not suited for CW operation, and secondly, it is not suited for operation in waveguide.

Therefore, a new concept has been developed, intended for implementation at AUG. ASDEX-Upgrade will be equipped with a novel ECCD system based on multi-frequency gyrotrons, tuneable in four steps over the range of 105 to 140 GHz. A special feature of the AUG ECCD system is the fast directional switch FADIS Mk II. The system's prime functions are to serve as power or Beam Combiner (BC), slow and FAst DIrectional Switches (FADIS) it can toggle the power from continuously operating gyrotrons between two launchers. FADIS is based on the quasi-optical interferometer principle: When in resonance, the diplexer transmits a narrow frequency band; when detuned, the beam is reflected by the diplexer. This selective characteristic implies that FADIS is in principle suited as a first step in decoupling the high-power

gyrotron source signal from the weak ECE signal. FADIS mode rejection however is limited to 30 dB, and this is for optimum tuning under ideal conditions.
A second, Mach-Zehner, interference filter in tandem with the FADIS is propose to deal with tray radiation from the gyrotron and cross talk between the two output ports operating at slightly different frequencies. The Mach-Zehnder design parameters are as follows: two equal beam splitters with the same parameters as the etalon filter and a phase lag length of 303 mm for a frequency difference of 989.38 MHz at a 141.34 MHz periodicity of the FADIS. The complete ECE based feedback control system for AUG comprises the Mach-Zehnder interferometer coupled in tandem to FADIS.

3. Real time control of the high power mm-wave component

A key parameter of the resonant diplexer is the interferometer or cavity path length. This path length should accurately match the frequency of the resonant beam. This condition not only should be met in the reference case but also should accommodate deviations. External factors like structural vibrations, mechanical creep, or thermal expansion may drive the path length away from its optimal value. Thermal effects also occur during switch-on of the gyrotron: A frequency droop of 300 MHz is observed as a result of thermal expansion of the gyrotron cavity. After 1 s, thermal stability is reached yielding frequency stability better than 5 MHz. A 300-MHz frequency change would drive the diplexer out of resonance, and hence, its power rejection capability would be lost.
To compensate for such change, an adjustment mechanism of the interferometer path length is needed, such that the frequency of the ECCD beam and the path length remain matched during switch-on. Specifications are driven by the dynamic range and accuracy of the path length required. A straightforward design solution is offered by a single mirror motion mechanism. The accuracy of this mirror movement should be better than 10 mm. Note that a relative path length error of 1 ppm has a similar effect on the performance of the diplexer as an equivalent error in the gyrotron frequency of 1 MHz. Thus, the path length adjustment mechanism should have a ratio of range and accuracy (motion ratio) of the order of 103. In order to meet these specifications, a single mirror motion mechanism based on an elastic guiding mechanism, featuring linear response behavior while avoiding potential complications due to friction, play, and hysteresis has been developed and constructed.
The compact, waveguide-compatible design features a feedback-controlled mirror drive for tracking of the resonator to the gyrotron frequency. High-power, long-pulse tests were performed with the 140 GHz ECRH system for the stellarator W7-X. Power was measured at the FADIS exits, and the mirror was jiggled to probe in real time the optimum condition. This real time extremum seeking control scenario is required as the power at the output is a non-monotonic function of the mirror position. Using this scheme, the requirements for power toggling and beam combing were met. In Figure 1, an example is given of the real-time combination of two beams.



The power that 'seeps through' during the mirror jiggling however is too much for the in-line ECE application. Therefore, a line of investigation has started, I which the movable mirror is controlled on both the power and the phase at the FADIS exits. This approach yields a monotonic relation between the FADIS outputs and the mirror position.

4. Simulation of feedback controlled tearing mode suppression

In addition to the advances in hardware for feedback control of tearing modes, discussed previously, control-oriented simulation models enabling benchmarking and testing of feedback control designs are desired. A control-oriented model was developed in MATLAB Simulink® for typical conditions in the TEXTOR tokamak (major radius R = 1.75 m, minor radius a = 0.46 m), taking into account the most essential dynamics of the tearing mode suppression problem. The modified Rutherford equation is generally used to describe a mode's time evolution [9]. In TEXTOR, tearing modes can be purposely excited by application of the perturbation field of the Dynamic Ergodic Divertor (DED). The usual representation of the Rutherford equation is therefore extended by an expression for the DED driving term: $r_s\Delta'_{DED}$ as given in Ref. [10]. Since most tearing mode experiments in TEXTOR are carried out at low β_p, the contributions of the bootstrap current and ion polarization are discarded [11]. Assuming a symmetric tearing mode topology, the effect of both heating and current drive via ECRH/ECCD on the tearing mode width can be included in the Rutherford equation in the term $r_s\Delta'_{CD,H}$. Here, expressions for the heating and current drive terms are used, which were derived in Ref. [12]. In simplified form the Rutherford equation then reads:

$$\frac{\tau_r}{r_s}\frac{dw}{dt} = r_s\Delta^{'} + r_s\Delta^{'}_{DED} - r_s\Delta^{'}_{CD,H} \quad (1)$$

Combining the modified Rutherford equation with: 1) a model of the electro-mechanical ECRH/ECCD launcher, 2) an equilibrium description of the q = m/n = 2/1 rational surface in radial coordinates subject to a given toroidal magnetic field and plasma current, and 3) models for the gyrotron timing and controllers yields a simulation framework, which encompasses sufficient detail to simulate tearing mode control experiments.

A simulation example with this model is plotted in figure 2. Both the open-loop and closed-loop simulation results are shown. The DED initializes a m/n = 2/1 tearing mode at t = 1.5 s. The mode grows and saturates at a typical width of 0.07 m. In the time frame t = 2-7 s. ECRH/ECCD is applied to stabilize the mode. The open-loop simulation fixes the launcher elevation angle at θ = 9.6° and P_{ecrh} = 600 kW. In addition a random noise source + sinusoidal excitation signal is added to perturb the alignment between ECRH deposition and the rational flux surface r_s , where the mode resides. As observed in the part of the discharge before t = 4 s, the launcher aligns the ECRH deposition sufficiently accurate with r_s. From t = 4 s onwards, an additional perturbation is added by ramping the toroidal magnetic field gradually from 2.25 T up to 2.35 T.

As a consequence, the alignment between ECRH and the mode is further disturbed and the mode width increases. A footprint of the perturbations is directly reflected in the suppressed tearing mode width. The same exercise is repeated in closed-loop, where a properly tuned feedback controller, acting both on the launcher angle steering and triggering + power level setting for the gyrotron, closes the feedback loop. The results demonstrate that the feedback system manages to keep both the alignment and the tearing mode width within an error bound of less than 0.01 m for the alignment error $\Delta_r = r_{ecrh} - r_s$, whereas the deviation in the suppressed tearing mode width is ± 0.2 cm. The feedback system effectively attenuates the perturbations on the alignment.

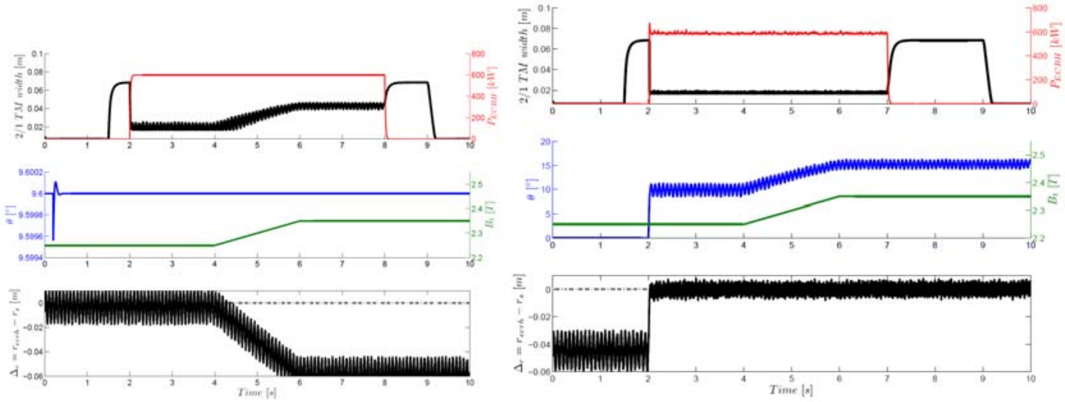


Figure 2: *Open-loop and closed-loop simulations of tearing mode suppression experiments. Typical TEXTOR conditions are used, where a 2/1 tearing mode is destabilized by the Dynamic Ergodic Divertor. In both simulations, the alignment between ECRH deposition and tearing mode location r_s is perturbed by a toroidal magnetic field ramp: B_t = 2.25-2.35 T and a random noise + sinusoidal perturbation of the relative, radial misalignment $\Delta_r = r_{ecrh} - r_s$. The open-loop experiment uses a fixed launcher elevation angle*

θ = 9.6°, with fixed ECRH power: P_{ecrh} = 600 kW. The open-loop result depicted on the left shows that the tearing mode is suppressed by the application of ECRH but it is impossible to stabilize the mode at a constant width in the presence of the applied disturbances. The closed-loop results demonstrate that a properly tuned feedback controller acting both on the launcher angle as well as the gyrotron power is able to compensate the applied disturbances, preserves the alignment and stabilizes the mode at a constant, fixed width.

5.Control Oriented Modelling of the sawtooth

To study the behavior of the sawtooth instability in a circular cross section tokamak, an infinite dimensional impulsive dynamical system has been set-up. The model describes the magnetic field evolution between crashes, and uses a combined Porcelli-Kadomtsev full reconnection description of the sawtooth crash. The crash condition is determined by a critical value for the magnetic shear at the q = 1 surface. The system's input is the ECCD mirror angle, and its output is the time between subsequent crashes (i.e. the sawtooth period). The sawtooth cycle is numerically implemented in and controlled by any arbitrary stabilizing controller C(z), which stabilizes on a specific critical shear. By applying small stepwise perturbations, the responses of the resulting deviations can be determined. Approximate can then be applied to estimate the closed loop transfer functions from the stepwise input. All low frequent (steady-state) gains match the DC-gains perfectly. Using linear models a number of specifications for the controller C(z) can now be determined: to guarantee closed loop stability, the gain of C(z) should be negative and should not be too large (due to the decrease in phase for increasing frequency); to obtain a good performance, C(z) should be integrative (to guarantee zero steady-state error) and its gain should be as large as possible.

Based on these specifications a Tustin integrative controller was then de signed using standard discrete time loop shaping techniques. The controller achieves bandwidths between 0.033 and 0.1 s, corresponding to settling times roughly between 10 and 30 sawtooth periods. Also, the analysis shows that robust closed loop stability is achieved for all Hi(z). The controller is connected with the original numerical sawtooth model in a Simulink feedback loop. The resulting closed loop is stable, and tracks the desired periods without any steady state error and with settling times in the order of 10 to 30 periods.

5. SUMMARY AND CONCLUSIONS

In this paper novel elements of an ECCD feedback control system are presented employing a co-aligned ECE diagnostics system. Inherent accuracy in the positioning of the beam is achieved by having the ECE feedback signal and the injected ECCD beam travelling along the same optical path, albeit in opposite direction. A FADIS, originally designed for switching the gyrotron power between different launchers through small variations of the gyrotron frequency, is used in this paper as a routing device for separating the low-power diagnostics ECE signal from the high-power ECCD beam. A two-beam interferometer absorptive filter is placed in tandem with the FADIS to obtain sufficient power reduction as well as optimize ECE signal transmission. The FADIS isolation Is 30 dB under optimum tuning conditions. In order to make the system robust against disturbances the cavity properties need to be controlled in real time. For this purpose, an actuator has been designed, and demonstrated in high power tests. In these tests, real-time power combination and beam-switching have successfully been demonstrated, using an real-time extremum seeking algorithm in which the power was sensed at the exits. The approach however is marginally applicable for in-line ECE. It is therefore presently investigated how phase information could be used to improve the control scheme. Discrete time approximations of a combined Porcelli-Kadomtsev sawtooth model were obtained, using step responses and approximate realization techniques. Standard discrete time methods were then used to design a controller for a specific operating region. This controller achieved perfect tracking with reasonable settling times in the whole region. Future research includes the extension to other operating regions, and the application of automated controller design methods.

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