

Controllers for high-performance nuclear fusion plasmas

Citation for published version (APA):

Baar, de, M. R. (2012). *Controllers for high-performance nuclear fusion plasmas*. Technische Universiteit Eindhoven.

Document status and date:

Published: 01/01/2012

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Inaugural lecture
Prof. Marco de Baar
February 3, 2012

A close-up portrait of Prof. Marco de Baar, a middle-aged man with short dark hair, smiling warmly. He is wearing a light-colored, possibly beige or olive green, button-down shirt. The background is a solid, bright blue. A thin white diagonal line runs from the top left towards the bottom right, passing behind the portrait.

Department of Mechanical Engineering

TU / **e**

Technische Universiteit
Eindhoven
University of Technology

Controllers for high-performance nuclear fusion plasmas

Where innovation starts

Inaugural lecture prof. Marco de Baar

Controllers for high-performance nuclear fusion plasmas

Presented on February 3, 2012
Eindhoven University of Technology

Introduction

In experimental tokamak research, the aim is to set up and sustain the conditions for the nuclear fusion reaction between the hydrogen isotopes Deuterium (D) and Tritium (T) in which the reaction products Helium (He) and neutrons (n) are released in addition to a significant amount of energy. The helium particle carries 3.5 MeV, and the neutron carries 14.1 MeV. Deuterium is readily available. Tritium can be produced in a reactor using the released neutron in the reaction with Lithium $n + \text{Li} \rightarrow \text{T} + \text{He}$ in which 4.8 MeV is released. Nuclear fusion could, therefore, be a very attractive power source, but its development represents a significant scientific and technological development.

The DT nuclear fusion reaction is most accessible at a temperature of approximately 200 million degrees Kelvin. At such high temperatures all materials are fully ionized. A successful reactor will confine an ionized DT mixture, or a DT plasma, at high pressures with low thermal losses. Nuclear fusion conditions can be achieved in various configurations, but the tokamak concept holds the triple product record.

The tokamak [1] is a toroidal vacuum vessel, in which the plasma is confined by magnetic fields. Typically, three sets of active magnetic field coils are used in tokamaks. First, the toroidal field coils produce a magnetic field in the toroidal direction. The primary poloidal field coils drive an inductive toroidal current in the plasma, where a poloidal magnetic field is produced. Additional poloidal components to the magnetic field for the vertical and horizontal positioning of the plasma and the shaping of the plasma are added by other coils. Finally, a set of dedicated divertor coils is used for setting up the diverted magnetic field configuration for the exhaust of heat and particles. This configuration is characterized by the location of the X-point, and the location of the strike points.

The coils for the poloidal field are typically operated in a closed-loop configuration, with the current and the plasma boundary for the control of the shape and location of the plasma normally determined using magnetic measurements that stem from a variety of coils. Although coils have been producing excellent data for feedback over the past decades, several factors make

them less suitable for reactor operation: reactor relevant plasma boundary sensing as well as the sensing of the magnetic configuration and the exhaust of heat and particles to the tiles in the divertor region.

Plasma heating in the early phases of the discharge is effectively obtained by the Ohmic dissipation of the plasma current. This process is efficient at high resistivity, and hence at low plasma temperatures. However, as the temperature increases, the efficiency is reduced. Therefore, various technologies (additional heating systems) have been developed to couple power into the plasma. As we will see below, in this lecture waves with frequencies in electron cyclotron range (~ 100 GHz) are relevant, but other schemes exist.

In a reactor the energetic helium particle that is produced by the fusion reactions is envisaged as the prime power source for plasma heating. The Helium particle should transfer its energy via collisions to the bulk plasma. The energetic Helium particle is often referred to as the alpha particle and the concept of plasma heating by energetic helium is called alpha heating. After the Helium has transferred its energy to the plasma, it should be exhausted. The thermalized helium is often referred to as ash.

As suggested in the previous paragraph, in addition to the inductive current, other, non-inductive currents can be driven in the plasma by the additional heating systems. The plasma can also self-generate a non-inductive current, the bootstrap current, which is most pronounced at locations where a significant pressure gradient develops.

The core of the plasma features high temperatures and densities, while the plasma periphery has relatively low temperatures and densities. The concomitant pressure gradient is compensated by the Lorentz force. As a consequence of the force balance, a set of nested toroidal surfaces of constant pressure forms in the plasma. The magnetic field lines and current flow lines are embedded in these surfaces where both the toroidal and poloidal magnetic flux is constant. The surfaces are therefore often referred to as flux surfaces. The magnetic field lines are helical. The magnetic winding number q is the number of toroidal orbits a field line must perform in order to fulfill one poloidal orbit. The flux surfaces and the thermodynamic quantities on them are functions of the normalized radial coordinate ρ . The spatial distributions of quantities as a function of the normalized radial coordinate ρ are called profiles. Figure 1b presents a cartoon of the nested flux surfaces.

The magnetic field in plasmas can evolve due to both convection and resistive diffusion. In most locations in the plasma, the convection dominates and the magnetic flux is conserved. At surfaces with rational q -values, however, it can be demonstrated that the convective redistribution vanishes, and the temporal variation of the magnetic field is due to resistive diffusion only. On these surfaces the flux is not conserved. This is particularly relevant on simple rational q surfaces such as $q = 1/1, 3/2, 2/1$ and $3/1$ where macroscopic resistive magneto-hydrodynamic (MHD) instabilities can develop. These modes break the toroidal flux-surface symmetry, and give rise to the formation of structures. These structures tend to show dynamics such as growth and saturation or a limit cycle type of behavior. The location of the rational q surfaces depends on details of the current distribution in the plasma, and is a priori unknown. The cartoon presented in figure 1c shows how the ideal toroidal symmetry can be broken.

For this lecture, two MHD modes are relevant: the sawtooth [1] and the tearing mode [1]. The sawtooth is a limit cycle of the current density profile. Sawtooth instability occurs at the $q = 1/1$ surface, and results in a crash-like reorganization of the plasma core. After the crash, the q -profile is flat in the core of the plasma, and $q > 1$ everywhere. Due to resistive diffusion, the current density profile peaks, and q will develop below unity in the center. When the radial derivative of q exceeds a critical value, a sawtooth becomes unstable. The current density profile peaks on a slow timescale and flattens on a fast timescale. The crash-like reorganization of the core is also observed for other quantities such as the temperature and density of the electrons. The flattening is associated with the quick radial transport of heat and particles. The typical sawtooth fingerprint is therefore a slowly increasing temperature inside and slowly decreasing temperature outside the mixing radius. The sequence is periodically reset by the crash.

Magnetic islands lead to a distortion of the flux surfaces and increase the transport in the direction perpendicular to the surfaces. They are helical, isolated structures in the plasma, with an additional axis of symmetry the O-point and a location where flux surfaces are thermally shorted (X-points). The O-point is a helical deficiency in the current density. In some cases the islands can destabilize the whole plasma column and lead to a sudden termination of the plasma.

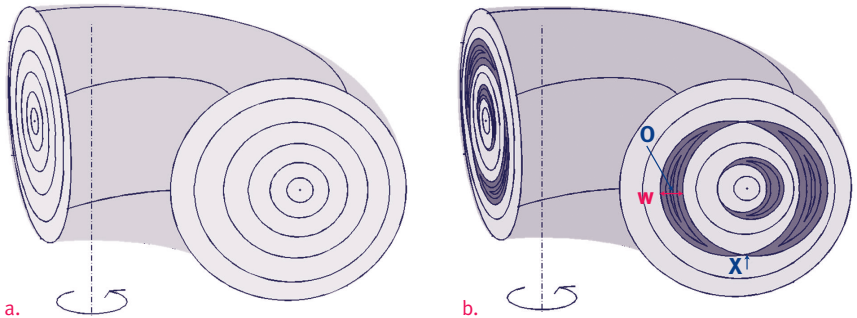


Figure 1 a.

Flux surfaces

a. Cartoon of nested flux surfaces.

b. Resistive MHD modes can break the toroidal symmetry.

Of special relevance for nuclear fusion reactors is the neo-classical tearing mode [2-6]. Long sawtooth periods therefore yield large perturbations in close proximity to other surfaces with rational q values such as $3/2$, and $2/1$. The transient magnetic perturbations from the sawteeth can create small islands, referred to as 'seeds'. These reduce the pressure gradient over the island, and reduce the bootstrap current. An inductive current density will develop to compensate for the lost bootstrap current. The dynamic evolution of the island is, first and foremost, the consequence of the competition between these effects. A critical seed island width can be defined. If the seed islands exceed this width, the loss of bootstrap current will be dominant, and the island will grow further until saturation mechanisms set in. If the seed island is smaller than the critical width, it will 'self-heal'.

For a given tokamak, the size of the critical island width depends on the plasma parameters. At normalized pressure the critical island size reduces while the saturated island size increases. Reactor relevant plasmas will be operated with a significant fraction of the current driven with the bootstrap-effect and will consequently be prone to NTMs. This raises the issues of sawtooth period control and NTM control. The actuator and sensor principles for a resistive MHD mode control system are well known. They are based on electron cyclotron emission (ECE) and electron cyclotron current drive (ECCD). ECE and ECCD are resonant processes that are the consequence of gyrating electrons in the toroidal magnetic field. The gyration frequency depends on the local toroidal field that is high near the inboard side of the tokamak (the high field side) and falls off to the outboard side (or low field side). Consequently, a correspondence exists between the gyration frequency and the location of the gyrating electron.

While gyrating, the electrons emit radiation at the gyration frequency and its multiples. This radiation, ECE, can be measured with a radiometer. ECE contains information on the local temperature and its variations. The electrons can also be actuated by coupling high-power electron cyclotron waves into the plasma. Although hardware settings and plasma conditions determine whether the wave will result in pure heating or the combination of heating and current drive, we will refer to ECCD throughout the text. Since the high localization of the ECCD results in a large effect on the local current density, ECCD is the perfect actuator for resistive MHD modes. High-power EC waves are generated by gyrotrons, transmitted to the tokamak via a transmission line, and directionally coupled into the plasma by a launcher that contains a movable mirror.

A rotating magnetic island will result in a quasi-periodic oscillation in the ECE signal. Also the sawtooth mixing radius is easily identified as the border between normal and inverted sawtooth oscillations. High-power ECCD has been successfully applied for tearing mode suppression and sawtooth period actuation. Optimal performance is achieved if the ECCD is deposited in the O-point. In the experimental test reactor ITER (presently being built in France), the ECCD will be coupled into the plasma via a number of launchers with steerable mirrors.

The present FOM program on nuclear fusion (FP120) 'Control of magnetohydrodynamic modes in burning plasmas' is on the interaction between the fusion-born energetic Helium particles and MHD modes in the plasma. The MHD modes can drive enhanced or premature losses of the energetic helium thereby affecting the efficiency of the alpha heating scheme mentioned above. On the other hand, the alpha-particles can affect the stability of the MHD modes. The energetic particles, for example, tend to stabilize the sawtooth cycle, and this may affect the exhaust of helium ash or the triggering of NTMs.

The interaction between the energetic particles and MHD is complex and multifaceted. Real progress can only be achieved by a combined effort of modeling and experimentation. FP120 therefore consists of three main thrusts: 1. development of diagnostics for MHD and fast particles, 2. modeling of MHD mode energetic particles and 3. the control of MHD modes. The work presented today is motivated by both an operational (MHD control is reactor relevant) and a scientific (MHD control will enable new meaningful physics experiments) element.

The work on control of MHD modes and plasma performance is carried out in the Control Systems Technology group in the Mechanical Engineering Department.

Five PhD students are financed by FP120 to work on the control engineering aspects of MHD. FOM, TNO, NRG and TU/e also collaborate within the framework of ITER-NL on the development of ITER relevant technology. Notably the work on the in-line ECE presented below could not have been carried without ITER-NL funding.

This lecture is organized as follows:

First we discuss the development of a set-up for tearing mode detection with an Electron Cyclotron Emission (ECE) sensor integrated in the beam line of an ECCD System. Implementations for quasi-optical transmission lines and for transmission lines with waveguides will be discussed. Tearing mode control in the German tokamak TEXTOR using in-line ECE will be presented. Then open loop and closed loop controllers for the sawtooth period will be discussed. I then will indicate how we will progress on the energetic particles-sawtooth interaction, and how we can extend our work to include plasma performance control.

Optimized sensor macroscopic MHD modes: in-line ECE

In order to actuate the tearing modes, we want to determine the radial location and the poloidal phase of the mode. Ideally, the high power ECCD then needs to be deposited near the O-point of the island. The requirements for this control strategy are rather stringent. In TEXTOR we should be able to deposit the ECCD within 1-2 cm of the rotating O-point.

Unfortunately, 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 ECRH/CD power absorption occurs. This is due to the uncertainty in the plasma equilibrium, the exact location of the plasma, and the relative calibration of the sensors and the ECCD beam.

An elegant solution to this problem would be offered by a method in which ECE is measured along the same sight-line as the incident ECCD beam (in opposite direction). The merit of the in-line ECE method is that the sensor and the actuator are in the same metric frame, and hence no equilibrium reconstruction and ray-tracing are required to calculate the optimal launcher angle. 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. Nearly all systematic error sources are avoided, including loss of calibration.

As discussed above, the islands will show up as oscillations in the ECE measurements. Optimal localization is obtained when the ECE frequency representing the island O-point coincides with the ECCD frequency. Any deviation between these two frequencies can be corrected by adjusting the deposition of the ECCD beam, normally by steering the mirror angle of the launcher. The phase of the ECE fluctuations yields information on the phase of the O-point location and the required modulation of the ECCD power.

The main challenge in applying this method is to prevent interference of stray radiation generated by the ECCD beam (kilowatts, originating from the megawatt ECCD beam) with the ECE spectrum (~100 pico Watts). This implies that a

high-quality notch needs to be developed that is both deep for the suppression of the ECCD beam and narrow to allow for ECE measurements in the vicinity of the ECCD deposition; in other words at frequencies close to the gyrotron frequency.

The German tokamak TEXTOR was ideal to get started with the MHD control work. TEXTOR is a tokamak with major radius $R_0 = 1.75$ m and a circular cross section with a minor radius of $a = 0.46$ m. During our experiments toroidal magnetic field on axis was $B_T = 2.25$ T, and plasma current was $I_p = 350$ kA. Importantly, TEXTOR has a set of helical coils called the dynamic ergodic divertor (DED), and it can be used to systematically trigger $2/1$ tearing modes. These modes can then be rotated in the plasma at a preset frequency (determined by the frequency of the alternating currents in the DED), or the DED currents can be ramped down to allow for the mode to rotate freely. The normal electron temperature on the $q = 2$ surface is in the range between 0.5 and 1 keV (~ 5 to 10 MK) while the rotation frequency of an $m = 2$, $n = 1$ island is several kilohertz. The ECCD system for MHD suppression features a gyrotron of 140 GHz, coupling a maximum of 800 kW for 10 s. During a pulse the gyrotron frequency is stable within 100 MHz. Transmission of the high-power gyrotron radiation to the tokamak is through a fully quasi-optical transmission line. Waves are injected from the low field side using a fast steerable mirror with two degrees of freedom. The horizontal injection angle can be changed for co- or counter-ECCD, while the vertical injection angle can be varied from to cover effectively the entire poloidal cross section. Waves are injected such that almost full absorption over a wide range of parameters is obtained. For the parameters mentioned above, the ECCD is on the high field side, and the EC deposition can be changed from the $q = 1.5$ to $q = 3$ surfaces by variation of the vertical injection angle. At higher magnetic fields the $q = 1$ surface can be accessed as well.

Based on these parameters, Oosterbeek designed a quasi-optical in-line ECE system for TEXTOR [7], and demonstrated the viability of the method. The notch attenuation was 130 dB around 140 GHz. The width of the notch was approximately 1 GHz. The first 50 dB attenuation was achieved using two dielectrical plates that each act as a Fabry-Perot system. A low-power compatible mm-wave notch filter is used for an additional 80 dB suppression. ECE measurements were done using a six channel radiometer. Oosterbeek showed that the system detects macroscopic MHD modes such as islands and sawteeth. These modes can be localized in the ECE spectrum in the presence of 400 kW of ECCD power. The minimum electron temperature fluctuations that can be detected are in the order of 10 eV.

As one of the plates in the TEXTOR set-up is mounted in the beam line, the applied in-line ECE solution for TEXTOR is not suitable for continuous wave (CW) operation. Dissipation in the dielectric plate in the beam line can lead to deformation of the plate and detuning of the notch frequency. Estimates for the TEXTOR system suggested a maximum operational time of 3 seconds. Moreover, the system is not suited for operation in waveguides. Figure 2 shows the TEXTOR in-line ECE set-up.

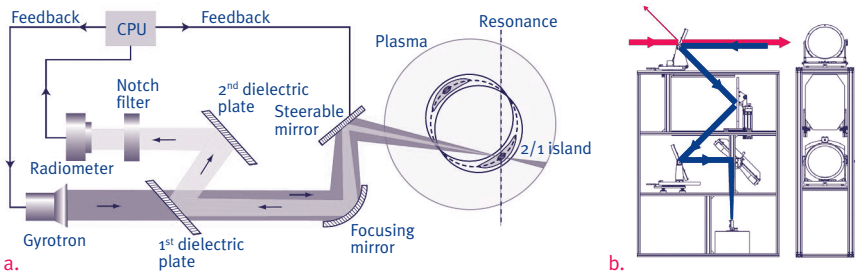


Figure 2 a.

b.

In-line ECE

- a. In-line ECE concept. ECE is measured along the same line of sight as the ECRH system.
- b. In-line ECE implementation for TEXTOR. Dielectric plates were mounted in the EC beam line and yielded the first 50 dB suppression. A low-power notch filter yielded an additional 80 dB.

Tearing mode suppression in TEXTOR

An integrated real-time control approach for suppression and stabilization of tearing modes was demonstrated on TEXTOR by Hennen et al [8]. The results were obtained by optimal sensing using the line-of-sight concept in combination with active launcher steering. Reliable and accurate detection of tearing modes and retrieval of their radial location was demonstrated experimentally using a real-time algorithm based on the detection of a phase jump in the ECE signals. The dynamics of the mechanical ECCD launcher were analyzed and optimized through the design of a dedicated feedback and feed-forward controller. The ECCD deposition has been aligned with respect to the center of the mode by matching the fixed actuator frequency of the gyrotron with the mode location in the ECE sensor spectrum. The alignment was achieved accurately and quickly by the controller.

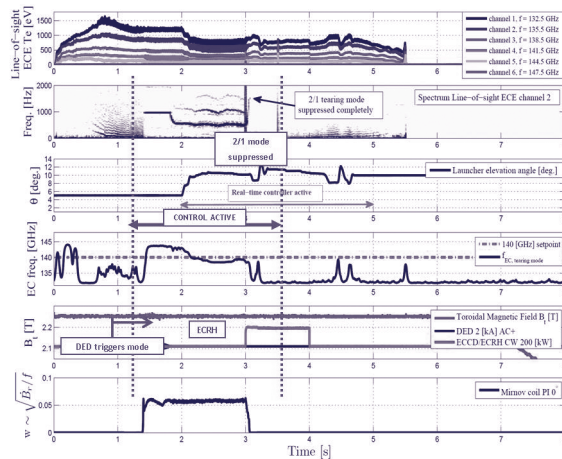


Figure 3

Tearing mode control in TEXTOR using in-line ECE.

In figure 3 we present one example of a successful tearing mode suppression experiment. The top box shows the ECE signals from the in-line system. The bottom box shows the toroidal magnetic field, the ECCD power and the alternating currents in the DED coils that are ramped up from 1.8 s. The oscillation in the ECE

channels discerns that a mode is triggered in the plasma. The island location system identifies the phase jump in the ECE signals at 144 GHz. From $t = 2$ s, the controller is enabled. Launcher alignment is achieved at $t = 2.15$ s when the phase jump occurs at 140 GHz, and ECCD power is now coupled to the correct radial location. The toroidal magnetic field is ramped up from 2.5 to 4 seconds. This scrambles the q -profile and the location of the ECE and ECCD deposition. In spite of this, the launcher remains locked on the island. The launcher steering compensates for the variation of the location of the tearing mode and maintains the alignment of the ECRH/ECCD deposition with respect to the mode.

Not shown here, but also relevant, is that our success in having the power modulation of the ECCD in phase with the O-point of freely rotating tearing modes. This result was obtained using an analogue type 2 phase locked loop in the frequency range 300 Hz - 5 kHz. The PLL extracts the mode's frequency and phase from ECE data. Experimental results proved that a PLL enables synchronization of the ECCD modulation with the O-point of the mode for a broad range of rotation frequencies.

Due to planning constraints, the TEXTOR results were obtained without modeling and system identification. Nevertheless, the results demonstrated effective tearing mode suppression and showed good performance in terms of settling time and steady-state error reduction. Control-oriented simulations however were carried out a posteriori.

A framework with sufficient detail for tearing mode control experiments was set up by combining the Rutherford equation (RE) for the tearing mode dynamics with a model of the electro-mechanical ECCD launcher, an equilibrium description of the $q = m/n = 2/1$ rational surface and models for the gyrotron timing [9]. For TEXTOR, the Rutherford equation is extended to incorporate the destabilizing effect of the DED perturbation field, while the bootstrap current and the effect of ion polarization are discarded. Assuming a symmetric tearing mode topology, the effect of both heating and current drive via ECCD on the tearing mode width can be included in the Rutherford equation. The resultant equation calculates the tearing mode growth-rate at the mode location given the stabilizing and destabilizing terms due to the plasma conditions and hardware.

The model was applied to analyze the dynamics and static equilibria of the system. The RE, constrained by the plasma equilibrium model and the ECRH launcher model, is linearized. The dynamics of the system are expressed in

frequency response functions (FRF) that estimate the linear dynamics of the system in specific operating points and can be used for the design and application of linear control techniques. Simulations are executed with the derived controllers in a simulation environment to assess the control response and to check the performance in terms of the response time, accuracy and robustness.

In figure 4, we present one result of the control oriented simulation. The DED initializes an $m/n = 2/1$ tearing mode at $t = 1.5$ s. The mode grows and saturates at a typical width of 0.07 m. From $t = 2.7$ s, ECCD is applied to stabilize the mode. A toroidal field ramp, a random noise source plus a sinusoidal excitation signal are applied. A properly tuned feedback controller, acting both on the launcher angle steering and gyrotron power, closes the feedback loop. The results demonstrate that the feedback controller is able to compensate the applied disturbances, preserve the alignment and stabilize the mode at a constant, fixed width within an error boundary of less than 0.01 m for the alignment error. The deviation in the suppressed tearing mode width is ± 0.2 cm. The feedback system effectively attenuates the perturbations on the system.

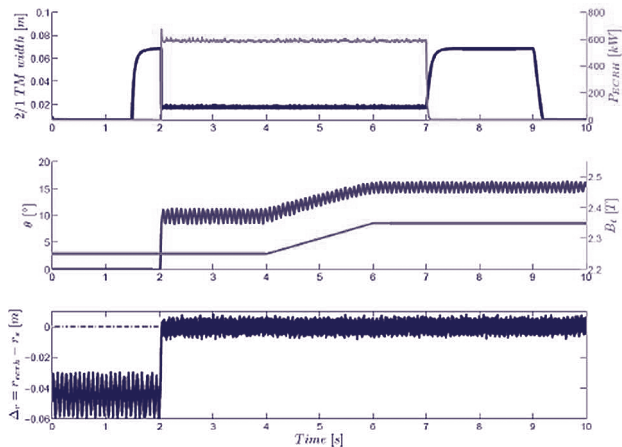


Figure 4

Closed-loop simulations of tearing mode suppression experiments in TEXTOR. A $2/1$ tearing mode is destabilized by the DED. The alignment between ECRH deposition and the tearing mode location is perturbed by a toroidal magnetic field ramp $B_t = 2.25$ - 2.35 T and a random noise plus a sinusoidal perturbation of the relative, radial misalignment, but the controller rejects these disturbances effectively.

One of the issues with island suppression on ITER is mode-locking. The island interacts with the wall, as a consequence of which the toroidal angular velocity reduces, and the mode growth rate increases. Van de Brandt et al [10] extended the Rutherford equation to take the effect of mode-locking into account for typical ITER conditions. If the mode appears at an a priori unknown location, the launcher has to track the mode. However, the launcher settling time exceeds the time required for locking. It is suggested that an alternative control strategy should be considered to avoid locking.

Hennen and Lauret et al [11] suggested such strategy. They used simulations to investigate the feasibility of feedback stabilization of small NTMs. The dynamics of the NTMs are described by the generalized Rutherford equation, including a term for the destabilizing bootstrap current. The stabilizing ion polarization effect is not taken into account in these simulations. These small islands would normally correspond to unstable, that is, self-healing islands. For typical ITER conditions, the equilibria of the GRE were calculated in different operating points at constant ECCD power. The GRE was linearized, and the system dynamics analyzed. Assuming the availability of real-time signals for the island width, three conceptual feedback controllers of varying complexity, performance, robustness,

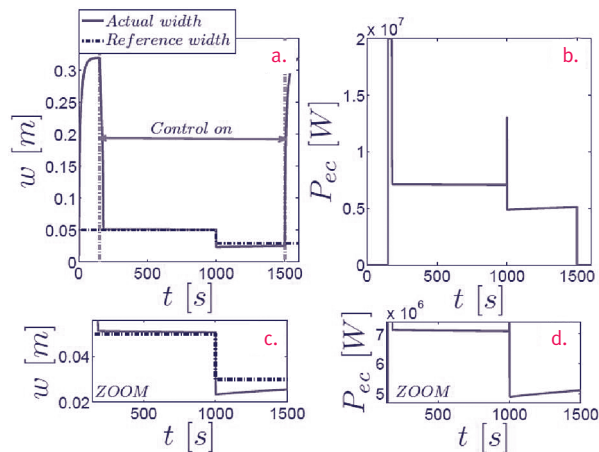


Figure 5

Simulation of a PI controller for small NTMs in ITER. Figure 5(a) NTM width versus time. 5(b) Applied ECRH/ECCD power P_{ec} versus time. Figures 5(c) and 5(d) Zooms of the island width and the ECCD power. The controller is enabled $t = 150$ s and disabled at $t = 1500$ s. Stabilization of the island width at 0.05 m with a small steady-state error is reached within 30 s. Next, the integrator action of the controller further reduces the steady-state error. When the reference is changed to 0.03 m, the island width remains stabilized, albeit with a larger steady-state error.

and required model knowledge are introduced. The simulations show the theoretical feasibility of small island stabilization at a specific reduced width.

In figure 5 one example is presented of the simulated small NTM control using a PI controller. Figure 5a depicts the reference and actual width of the NTM as a function of time. Figure 5b depicts the applied ECRH/ECCD power P_{ec} as a function of time. Figure 5c and 5d zoom in on the island width and ECRH/ECCD power, respectively. The control action is enabled at $t = 150$ s and disabled at $t = 1500$ s. The PI controller provides locally appropriate control with set-point dependent performance.

Closed-loop sawtooth period control

A systematic methodology for the structured design of feedback controllers for the sawtooth period was developed by Witvoet. For this, a combined Kadomtsev-Porcelli model of a sawtooth plasma actuated by an electron cyclotron current drive system has been set up. The model evolves the diffusion of the current density until the Porcelli stability condition is violated. This condition states that if the magnetic shear (radial derivative of the magnetic winding number) exceeds a pre-set critical value, the sawtooth will occur. For the sawtooth a simple Kadomtsev reconnection model that reorganises the flux within the mixing radius has been used for the sawtooth.

In [12] Witvoet derives the linearized single input - single output relations (transfer functions) from the varying deposition location of the electron cyclotron waves (ECW) to the sawtooth period. These transfer functions are derived around a large collection of operating points. Assessment of these control-relevant transfer functions shows that a sawtooth period controller requires an integral (I) action to guarantee closed-loop stability with zero steady-state error. Additional proportional-integral (PI) action can be applied to further improve the closed-loop performance. The parameters of both the I and PI controllers have been optimized in terms of stability, performance and robustness. The effect of the mechanical ECW launcher on the closed-loop performance was studied for realistic cases and has been shown to seriously affect the achievable closed-loop performance in present-day experiments.

High-performance sawtooth controllers were designed [13] and yielded accurate and fast convergent responses. Both degrees of freedom of the ECCD actuator (ECCD power, or driven current and the launcher angle) were explored and combined with advanced controller designs. By joining both control variables (launcher angle and driven current) in an overall controller design, high-performance control of the sawtooth period can be combined with control of the gyrotron power. Figure 6 shows time-domain simulations of the controller on the Kadomtsev-Porcelli sawtooth model comparing the performance of this high performance controller with the *siso* Integral controller. The actual sawtooth

period (red) almost overlays the reference (purple), and performs significantly better than the standard linear feedback on the deposition location (blue).

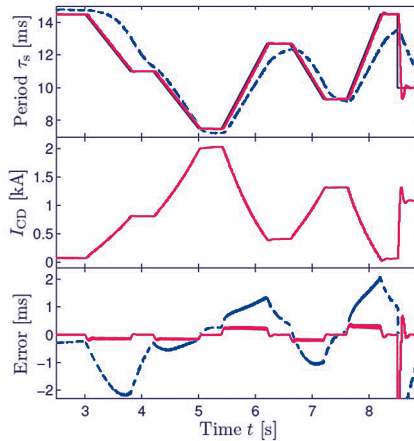


Figure 6

Simulink time domain simulations of the sawtooth controller performance. The actual sawtooth period of the high performance miso controller (red) almost overlays the reference (purple), and performs significantly better than the linear feedback controller on the deposition location (blue).

In [14] Bolder and Witvoet employ recent developments in extremum seeking control (ESC) to derive an optimized controller structure and apply practical tuning guidelines for its parameters. A cost function in terms of the desired sawtooth period is optimized online by changing the ECCD deposition location based on online estimations of the gradient of the cost function. This controller design does not require a detailed model of the sawtooth instability. Therefore the proposed ESC is widely applicable to any sawtoothing plasma or plasma simulation and is inherently robust against uncertainties or plasma variations. Moreover, it can handle a broad class of disturbances. This is demonstrated by time-domain simulations, which show successful tracking of time-varying sawtooth period references throughout the whole operating space, even in the presence of variations in plasma parameters, disturbances and slow mirror launcher dynamics. Due to its simplicity and robustness the proposed ESC is a valuable sawtooth control candidate for any experimental tokamak, and may even be applicable to other fusion-related control problems.

Open loop forcing of the sawtooth period

Lauret has suggested that an open-loop modulation of the ECCD power could lock the sawtooth period. Witvoet and Lauret used the control-oriented sawtooth model introduced above to study this phenomenon [15]. In the simulations, the deposition location is kept constant while the gyrotron power is modulated with a certain period and duty cycle. Extensive simulations show that when this modulation is properly chosen, the sawtooth period quickly synchronizes to the same period and remains locked at this value. It has been shown that the range of modulation periods and duty cycles over which sawtooth period locking occurs depends on the deposition location, but is particularly large for depositions near the $q = 1$ surface. These simulation results reveal a novel approach to controlling the sawtooth period in open loop, based on injection locking, which is a well-known technique to control limit cycles of non-linear dynamic oscillators. Injection locking appears to let the sawtooth period converge quickly to the modulation period. Moreover, the method has an intrinsic robustness against general uncertainties and disturbances.

Locking has been demonstrated experimentally on the TCV tokamak in Lausanne. Lauret et al [16] show the compelling evidence for this effect, in experiments in which the power, the duty cycle and the modulation frequency have been varied. An open-loop sawtooth period controller has been designed whereby the duty cycle and power modulation period were preprogrammed to change in time. The sawtooth period in figure 7 locks to the modulation period and follows the changing modulation period very well, even for the step-in modulation period. This shows that the sawtooth period remains locked when the modulation period changes continuously in time. Therefore precise, fast and robust sawtooth period control can be achieved by using the locking phenomenon. This control method has the added advantage that it does not need any real-time measurements of the sawtooth period, so faulty sawtooth detections have no influence on the control. Corroborating evidence for sawtooth period locking has been presented, in which the sawtooth period follows the modulation frequency of an externally applied high-power Electron Cyclotron wave source. High precision, fast and robust sawtooth period control has been demonstrated from 10 to 35 ms. This is almost the full range of achievable sawtooth periods with the gyrotrons used on TCV for

the chosen experimental conditions. This opens the possibility of open-loop control for physics studies and performance control.

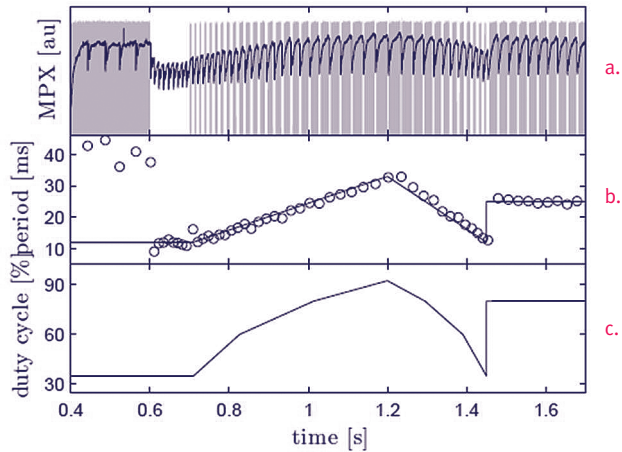


Figure 7

Open loop sawtooth control in TCV. a. Sawtooth cycle as measured with central soft-Xray and ECRH power. b. Measured sawtooth period (open circles) versus the reference (line). c. Power modulation period. At $t = 0.7$ s, the modulated gyrotron is enabled. During the modulation phase, the modulation period and duty cycle are preprogrammed to achieve locking.

Both the simulations and the experiment show that the locking effect is not associated with the crash. Rather, the modulated ECCD affects the evolution of the resistive current evolution of subsequent crashes differently and non-linearly until locking occurs.

Robust low latency sawtooth period determination

The real-time determination of the sawtooth-period is a requirement for sawtooth control. Some (ad hoc) approaches presented in the literature often work for a specific regime or device. Lennholm et al [17] proposed methods based on detection of the crashes of the sawtooth (ECE measurements) by simple difference filters. Although applicable in real time, this method lacks robustness, and fails in noisy signal environments. The noise sensitivity can be improved by applying a band-pass filter such that part of the noise is suppressed, but this reduces the accuracy and generally introduces significant signal delays. Furthermore, various types of time-frequency methods based on Fourier analysis have been used [18]. Although time-frequency methods work well for off-line analysis, they study the global frequency behavior of the limit cycles i.e. the repetition rate is generally inferred from a number of crashes. Consequently, in real time the estimate is delayed by a number of crashes, which can significantly reduce the performance of any control algorithm. In addition these methods are computational intensive. Closed-loop control requires a real-time detection algorithm.

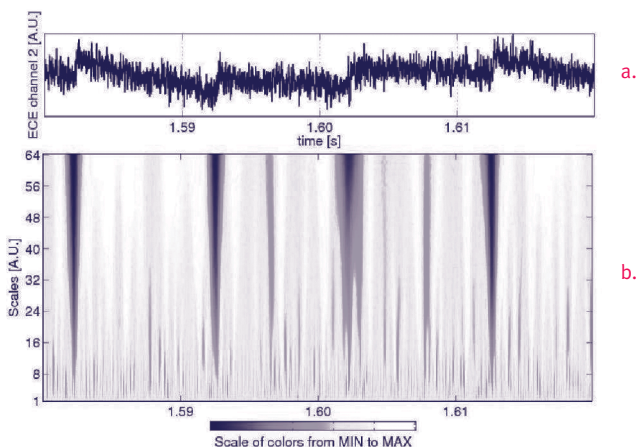


Figure 8

Robust, low latency detection of the sawtooth period. a. Data from the TEXTOR in-line ECE system showing the sawteeth. b. Multi-resolution detection with β -spline wavelets.

Van Berkel [19] derived an algorithm for optimized (low latency, robust and high fidelity) real-time sensing of the crashes. The algorithm is based on timescale wavelet theory and edge detection. With this method, the detection of crashes has considerably less delay than with the other methods. The realized accuracy of the detection algorithm is well below the uncertainty of the crash period for most crashes. The different sizes of the wavelets (scales) allow for multi-resolution analysis. This enables distinction between different sizes of sawtooth crashes. An accurate and robust algorithm was set up and tested on TEXTOR ECE sawteeth data, as presented in figure 8. Presently we are setting up this method for real-time application on TCV.

Although, strictly speaking, the crash detection method is demonstrated for sawteeth measured with ECE only, it can be applied to any periodic crash, measured with any temporally resolved data. A prime candidate for the analysis would be the Edge Localized Modes (ELMs), a family of instabilities that occurs in the plasma periphery of high-performance discharges. They are associated with excessive heat load to first wall components.

This presents the status of the MHD control elements in the FP120 program. We are exactly halfway through the program, and on track. As a next step we will finalize the installation of the in-line ECE system in AUG, and implement the controllers for the sawteeth that have been derived in the simulations. Once that is achieved, we will be in the position to broaden our scope.

First the availability of MHD controllers on AUG puts us in the position to carry out physics experiments. To give you a just a number of examples: Control over the sawtooth period enable systematic experimentation of the effect of the sawtooth on the formation of the seed island in the NTM dynamics. AUG is equipped with excellent diagnostics for such experiments. Stabilization of small islands by feedback control will allow the use of system identification to extend the model knowledge on the evolution of small islands, highly relevant for the further development of the NTM physics. Control of the sawtooth period also enables systematic experimentation of the effect of the sawtooth on losses of energetic particles or on impurities that accumulate in the plasma core. Also control of the island width allows for systematic experimentation of the effect of the island on losses of energetic particles. These are just a number of examples of relevant experiments that would come in reach. Many more examples will be conceived in which the control of processes in the plasma will facilitate systematic physics-oriented experimentation.

For the control engineers the next step would be to extend the functionality of the controllers to plasma regimes with dominant energetic particles. This is particularly relevant for the sawtooth cycle and poses a number of problems. First, diagnosing the energetic particle population in present-day tokamaks is difficult for off-line analysis, while real-time sensing of this population is simply out of reach. Also, the theory of the MHD fast particle interaction is complicated and the models that are presently available are not suitable for controller design.

We will therefore try to develop simpler, heuristic models of the sawtooth-fast particle interaction. Lauret noted that the class of predator-prey models could be suitable. In fact, he identified a number of very different problems for which predator-prey models could be relevant. The applicability of these models for controller definition and in observers will be assessed in the coming year.

The lack of accurate real-time sensing of the fast particle population is a special case of a much bigger problem. Donné, Costley and Morris [20] have shown that the majority of diagnostic techniques used in present-day tokamaks will not work in reactor grade plasmas such as projected for ITER's successor, DEMO. Possibly, observers could ameliorate this lack of suitable diagnostic techniques. We will develop and test an observer for the energetic particle-Toroidal Alfvén Eigenmode (TAE) interaction, to see if we can derive relevant information on the fast particle population.

In addition to the work on MHD control in burning plasmas, I am keen to open a line of investigation on plasma performance control. Therefore, the following lines of investigation are carried out: A method for the real-time determination of the local plasma transport is under development. A control oriented model for the current distribution in high performance plasmas has been set up. A fast, non-iterative, method for the assessment of the plasma surface lay-out has been developed.

Summary and conclusions

Novel elements of an ECCD feedback control system were presented employing a co-aligned ECE diagnostics system. Inherent accuracy in the positioning of the beam is achieved by measuring the ECE feedback signal and the injected ECCD beam travelling in opposite directions along the same optical path. The proof of principle of this approach was presented in TEXTOR, and a reactor relevant follow-up that has been constructed is currently being tested. This system is based on the diplexer FADIS MKIII. A two-beam interferometer absorptive filter is placed in tandem with FADIS MKIII for sufficient power reduction and optimal ECE signal transmission. A dedicated system for in-line ECE is presently being integrated. Real-time control of the cavity using a combination of power and phase measurements is envisaged to lock the notch on the varying gyrotron frequency within 5 ms.

Closed-loop radial tracking of the island and O-Point heating were demonstrated in TEXTOR. Controlled oriented modeling of the tearing evolution allowed for the design of controllers in which both the launcher angle and the gyrotron power are actuated. The modeling suggests the control of the island size can be controlled in real time. Control of the size of neo-classical tearing modes could present operational benefits and allow for dedicated experiments on small island physics.

A control oriented model for the sawtooth cycle has been formulated using the ECCD deposition location and driven current as inputs, and the sawtooth period as an output. The model has been used to derive and test a number of closed-loop controllers with varying robustness and performance. Robust low latency sawtooth period detection, a prerequisite for closed-loop sawtooth control, can be achieved using edge detection with dedicated wavelets.

The sawtooth model has also been used to analyze the concept of sawtooth period locking. Locking has been experimentally demonstrated on the TCV tokamak in Lausanne.

Future activities comprise the experimental implementation of the derived MHD controllers, the exploitation of these controllers in science-oriented experiments and the development of controllers for plasma performance.

It has been an honor and a pleasure for me to introduce this work. I want to stress that this work was done in close collaboration with a number of highly talented people, without whom this work would simply not have been possible. Some of these people are senior scientists with years of experience. I want to mention Maarten Steinbuch for giving me the support and trust to start this line of investigation. Egbert Westerhof is an eternal joy to work with due to his critical mind and sharp wit. Tony Donn e has supported me throughout the years in Rijnhuizen and at TEXTOR. Pieter Nuij has been paramount to the results on tearing mode stabilization in TEXTOR that will be discussed in a few minutes. More importantly, Pieter has proven to be an excellent engineer and teacher. Furthermore, Maarten de Bock, Roger Jasper, Niek Lopes Cardozo and Mark Scheffers of the Applied Physics Nuclear Fusion group are kindly acknowledged for our collaboration on sensing, spectroscopy and our concept for plasma equilibrium estimation.

I also want to stress the joy and inspiration from (former) Master and PhD students and post-doctoral students. What I have presented today is in essence their work, reflected in their papers. Matthijs van Berkel, Hugo van de Brandt, Jonathan Citrin, Snezana Djordjevic, Emrah Eminolglu, Bart Hennen, Gillis Hommen, Bert Maljaars, Menno Lauret, Hans Oosterbeek, Juan-Camilo Perez Munoz, Rob Voorhoeve, and Gert Witvoet are kindly acknowledged for their new ideas and insights, their quality, and the fun and energy they brought to the projects.

I thank my parents and brother for the support they have given me throughout the years.

But, first and foremost, I thank Nicole for her patience and understanding. I realize that it was very hard to accept the numerous lost holidays, the weekends of overtime, the outrageous travel in 2007 and 2008, and the papers that I had to write on Valentine's Day in Paris, and during our first night in Fiji.

Ik heb gezegd.

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Curriculum Vitae

Prof. Marco de Baar was appointed professor of Operation and Control of Nuclear Fusion Plasmas in the department of Mechanical Engineering at Eindhoven University of Technology (TU/e) on September 1, 2010.

Marco de Baar graduated in physics at Utrecht University in 1994. He obtained his PhD degree at Eindhoven University of Technology in 1999. From 1999 to 2002 he worked at the European tokamak JET (Culham, UK) as a full-time session leader. In 2003 and 2004, Marco carried out research on a number of international facilities such as ASDEX upgrade and TEXTOR (Germany), and DIII-D (USA). From 2004 to 2007, he was head of Operations for the Close Support Unit at JET. Presently, he is head of the Tokamak Physics Group at the FOM Institute for Plasma Physics Rijnhuizen (Nieuwegein, the Netherlands) and program leader for ITER-NL on the remote maintenance for ITER components and high-power mm-waves for plasma stabilization. Marco is a keen teacher, and has been actively involved in a number of outreach activities. He was a member of the jury in three subsequent European Union Contests for Young Scientists.

Colophon**Production**

Communicatie Expertise
Centrum TU/e

Cover photography

Rob Stork, Eindhoven

Design

Grefo Prepress,
Sint-Oedenrode

Print

Drukkerij Snep, Eindhoven

ISBN 978-90-386-3103-5
NUR 926

Digital version:
www.tue.nl/bib/

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