Design of a feedback system to stabilise instabilities by ECRH using a combined ECW launcher and ECE receiver

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Abstract

At the TEXTOR tokamak a 140 GHz, 800 kW, 10 s gyrotron is employed for studies on ECW heating and ECCD. A key program is the suppression of tearing modes, which is aided by the unique facility at TEXTOR to program magnetic structures during a discharge (DED). A scheme is under development which aims to detect the perturbations on the electron cyclotron emission caused by these instabilities via the same line of sight as is used by the ECRH beam, and to use this information for feedback control of the instability. A brief overview of TEXTOR and relevant island parameters is given as well as a description of the upgraded ECRH system. This is followed by a description of the design of the transmission line coupler and receiver for island detection which constitutes the main topic of the paper. The final section sketches the feedback controller that processes the receiver signals, and controls the moveable launcher and the gyrotron power.

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1. Introduction

Neo classical tearing modes (NTMs) give rise to deterioration of plasma confinement and could lead to disruptions. A problem, in particular for larger machines like ITER, is that NTMs scale with the figure
of merit for confinement, the normalised $\beta_N$. Tearing modes, or magnetic islands, occur at rational flux surfaces and can be suppressed by heating and current drive using ECRH [1]. In order to obtain efficient suppression the ECRH needs to be deposited exactly in the centre of the island, and preferably at the correct phase with respect to the rotation of the island along the flux surfaces. A complication is that detection and localisation of the island(s) is normally done via a different optical path than that followed by the ECRH microwave beam, which complicates suppression because the absolute steering coordinates of the ECRH launcher that deposits the power must now be derived from a real-time plasma equilibrium reconstruction. An alternative scheme described here uses the ECRH microwave transmission line for detection of the island which, if the mode detected is centred around the gyrotron frequency, guarantees exact spatial overlap of the mode with the gyrotron deposition profile [2].

The immediate goal of the control system is to detect and suppress the $m=2$, $n=1$ tearing mode on the $q=2$ surface in TEXTOR.

TEXTOR is an ideal facility for developing such a scheme as a versatile ECRH installation is present, combined with the dynamic ergodic diverter (DED) [3] in the vacuum vessel which allows programming of reproducible magnetic islands.

2. TEXTOR dimensions and $m=2$, $n=1$ tearing mode

The TEXTOR dimensions are $R = 1.75$ m, $r = 0.46$ m, with typical plasma parameters $I_p = 350$ kA and $B_T = 2.25$ T. With the parameters mentioned above, the $q=2$ surface is located at about 30 cm from the plasma centre. Natural and driven $m=2$, $n=1$ tearing modes show a full island width typically between 3 and 12 cm, while the island can grow over this range within 50 ms [4,5]. The typical electron temperature in the vicinity of the island is 700 eV. Plasma rotation causes the islands to rotate at frequencies in the order of 1 kHz, the exact frequency depending on whether the mode is triggered by the DED, or occurs naturally in the plasma. The DED consists of a set of windings on the high field side inside the vessel, wound such that they follow approximately the field lines of the $q=3$ flux surface. If operated in the so called 3/1 mode a strong $m=2$, $n=1$ side band is present which can destabilise the $m=2$, $n=1$ tearing mode. This allows programming of the mode at known location during the discharge, which offers the possibility to study island suppression using ECRH with the moveable launcher preset at the correct position [1]. This possibility to induce islands will also be a valuable tool in experiments with the line of sight feedback receiver.

3. ECRH installation at TEXTOR

A comprehensive description of the ECRH installation at TEXTOR may be found in [6,7]. In this section the parameters relevant to the feedback system are discussed, and the recent upgrade of the front end optics is summarized.

The gyrotron power is 800 kW at a central frequency of 139.85 GHz and a maximum pulse length of 10 s. The maximum modulation frequency is 7 kHz, with a minimum power level below 150 kW. During modulation the maximum frequency deviation is 70 MHz.

Recently the upgrade of the front end components to 10 s pulse length has been completed by exchanging the old fused silica TEXTOR vacuum window with a CVD window (88 mm clear aperture), and by the installation of a new launcher.

The low loss and high thermal conductivity of CVD allow a 10 s gyrotron pulse with a duty cycle of 1:100. The thickness of the window is $2 \times \lambda_{CVD}$ which makes it resonant at the gyrotron frequency, however, in practice the optimum in transmission is very slightly shifted as shown in Fig. 1.

The loss tangent of the window was verified in the resonator facility at the Institute für Materialforschung in Karlsruhe, and determined to be 4.1E−5.

The moveable in-vessel launcher, actuators and corresponding controllers have been replaced. The steering range is $\pm 30^\circ$ in poloidal direction, and $\pm 40^\circ$ in toroidal direction. The spot size of the beam in the centre of the plasma is approximately 15 mm, and approximately 20 mm at the location of the 140 GHz resonance using the parameters mentioned in 2.1.

The launcher mirror is made of stainless steel in order to keep disruption forces down, but has a central copper insert to reduce surface heating, and an
Fig. 1. Plot of calculated transmission of the CVD window vs. frequency. The thickness of the window is 1.795 mm. The window is placed under a $1^\circ$ angle to reduce reflections back into the transmission line. (The effect of the $1^\circ$ angle on the resonance is negligible.)

overall copper coating to maximise the reflectivity at the surface. The mirror geometry and mass ($\sim$5 kg) is a compromise between thermal sink, mass inertia and maximum acceptable mechanical load on the support structure during plasma disruptions. The mirror is moved in the toroidal and poloidal direction using two actuators equipped with a set of servo controllers. The initial displacement of the launcher mirror is required to be $1^\circ$ within 10 ms, and the angular speed must be larger than $10^\circ$ per 50 ms. The launcher construction is such that rotation by $1^\circ$ translates to an actuator displacement of approximately 1 mm. The actuator spindles have a pitch of 10 mm. Taking into account additional masses and friction forces due to driving shafts and bellows, the spindle motors are purposely over dimensioned at 800 W with a torque of 2.5 Nm. The servo controllers were tuned to meet the requirements with little overshoot while still operating the motors below the maximum power. The controllers are freely programmable: several preset control parameters can be tuned and the controllers are capable of dealing with predefined set point trajectories, which can instantaneously be applied at the analogue inputs of the controllers, as will be required during operation of the feedback system.

Presently work is ongoing to develop a model of the dynamics of the overall launcher system, including a characterization of disturbances caused by the vacuum environment and the magnetic fields surrounding the launcher and actuators. In order to validate this model so-called frequency response measurements of the entire launcher are conducted. The model will provide useful insights in the operational limitations of the system, which is of particular importance for the development and optimisation of launcher control strategies in the line of sight feedback scheme described next.

4. Detection and localisation of islands using line of sight

In the line of sight scheme the islands are detected by monitoring the perturbation they cause on the electron temperature profile. The perturbation comes about since the island is a closed magnetic structure allowing fast heat transport over the surface of the island. As a result the electron temperature along the island is approximately constant, which will cause a flattening on the radial electron temperature profile of the plasma. This is illustrated in Fig. 2.

The rotation of the island in the plasma causes an alternating presence of the O-point and the X-point in front of the ECE antenna which in turn causes

![Fig. 2. The $m = 2, n = 1$ island sketched causes a “shoulder” on the radial electron temperature profile projected below it. The ECE frequencies are inversely proportional to the major radius $R$ (horizontal axis) by the $1/R$ dependence of the toroidal field.](image-url)
sinusoidal fluctuations on the ECE channels observing frequency bands on the trajectory of the island. In case the X-point of an island lies between two ECE channels, the fluctuations on these two channels will be 180° out of phase as periodically one of the channels will decrease in temperature, while the other will increase in temperature.

The line of sight feedback system described in this paper uses the ECRH launcher as an ECE antenna for detection of these fluctuations. Six channels are used, starting at 132.5 GHz and spaced at 3 GHz. The situation is sketched in Fig. 3. The moveable mirror is moved such that the three left hand side ECE channels are showing counter phase with respect to the three right hand side channels. By doing so it is ensured that the 140 GHz resonance intersects with the flux surface on which the island is centred.

Propagation of the ECE and ECRH beams in the plasma will be modified by diffraction. Ray tracing calculations, however, have shown that diffraction effects are minor [2].

5. Receiver and power budget

The radiometer channels are spaced around the gyrotron frequency, but crucially do not include the gyrotron frequency itself. This, combined with the fact that the bulk of the gyrotron power travels in the direction opposite that of the ECE power, enables the use of a frequency selective directive coupler in the ECRH transmission line to extract the ECE spectrum while suppressing the gyrotron component [8]. See the sketch in Fig. 4. The gyrotron frequency drift is in the order of 100 MHz only and sidebands or spurious modes have thus far not been observed with the TEXTOR ECE diagnostics.

The coupler is a dielectric plate (quartz) made resonant at the gyrotron frequency, but anti-resonant at the ECE frequencies. Resonances occur at multiples of $1/2\lambda$ and since the resonances are spaced closely, the plates are relatively thick (25.75 mm). The plate is placed in the ECRH transmission line at the location of a large waist to spread the flux density in the plate, and to ensure that the incident wave fronts are flat. This location is approximately 20 m away from the TEXTOR vacuum window, which is placed under an angle of 1° to minimise reflections off the window into the...
transmission line. These reflections are still expected to be a major cause of concern but installing the coupler and quasi-optics into the vessel is not possible due to the size of the components and the absence of a waist. A second dielectric plate, located outside the transmission line, is employed to reject the reflected power further.

The power in the ECE channels is found by using the approximation $kTB$ for the Planck equation for black body radiation ($k$ Boltzmann’s constant, $T$ electron temperature and $B$ the observed bandwidth). In order to still resolve fluctuations in the ECE around the $q=2$ surface the electron temperature that still needs to be detected is set to 100 eV. With an IF bandwidth of 500 MHz per channel this results in 10 nW per ECE channel per mode of radiation.

At the location of the first dielectric plate the power is estimated to be in the order of several nW, the most outward channels slightly more attenuated due to the reduced transmission of the CVD window. At the first dielectric plate the gyrotron component is expected to be in the order 100 W, mostly caused by reflection off the CVD window and scattering effects on the edges off the first dielectric plate. This difference in power of 110 dB must be reduced to a couple of dB at the mixer of the radiometer. For the total reduction by the two resonant plates a conservative figure of 30 dB is taken as clarified in the next section. The remaining 80 dB will need to be achieved by insertion of a notch filter at the front end of the radiometer.

The maxima in the reflection coefficients at the ECE frequencies in the dielectric plates are not unity but 0.4, which, combined with the other components shown in Fig. 4, is expected to reduce the power per ECE channel at the input of the mixer to approximately 100 pW. Taking a typical noise temperature for the radiometer of 10,000 K, and a video bandwidth of 20 kHz, the minimal detectable power is 10 pW, giving a signal to noise ratio of 10:1.

6. Critical aspects of the coupler

Achieving and maintaining a large suppression of the gyrotron component is complicated by the stringent requirements on alignment, and by absorption in the plate. The aspects believed to be the most critical will briefly be reviewed next.

A change in angle of incidence of 1° will give rise to a 250 MHz shift in resonance due to the change in optical path through the plate, which in turn will cause approximately 3% reflection. Expressed in decibels this is a reflected fraction of $-15$ dB below unity. A low loss dielectric material, Infrasil301 (Heraeus, Hanau, D), was chosen for the plates to minimise absorption, as this will degrade the quality of the resonance [9,10], and causes ohmic heating. At 90 GHz the loss tangent is specified as $2.9E-4$ [11], which will cause a reflected fraction of $-35$ dB towards the radiometer. In case a 3 s, 800 kW gyrotron pulse is applied the temperature of the plate will rise by 150 °C, which will cause a change in permittivity of quartz of about 0.5% [12]. This will shift the resonance by 250 MHz, which, as seen before, leads to deterioration of the reflected fraction to $-15$ dB.

The increase in temperature could potentially also lead to stresses, cracking, and deformations in the plate. These effects were investigated using a Finite Element code (ANSYS®). It was found that the axial deposition profile [10], i.e. in the direction of propagation of the microwave beam, did not cause a significant temperature gradient. The radial distribution in temperature, Gaussian with a maximum of $\sim 170$ °C in the centre and $\sim 30$ °C at the edge, causes a stress of 2.8 MPa, while the maximum allowed value is 50 MPa. The maximum deformation that occurs is $\sim 1.5 \mu m$, which causes a deviation off the resonance condition of less than 10 MHz.

In summary it is concluded that stresses and deformation are not expected to cause difficulties, but that losses in the plates, combined with long pulses and alignment issues will in practice limit the suppression of the gyrotron power to $\sim 30$ dB for the two plate arrangement. Laboratory experiments on samples are ongoing to verify this.

7. Feedback controller and outlook

The unit processing the radiometer signals, and controlling the launcher and gyrotron power, is referred to as the Feedback controller. The layout has not been decided yet, but it is likely to be a powerful digital signal processing card, or possibly a VME based system.

The video signals from the radiometer will be conditioned and next digitised by the feedback con-
controller. The data will in real time be subjected to programmed island detection algorithms [13]. A basic algorithm could be extracting the oscillations from the ECE channels and multiplying these in pairs. In case the oscillations are in counter phase, indicating an island, the result of the product has a negative sign, while in-phase oscillations will yield a positive sign.

The most elegant mode of operation of the feedback controller is sweeping the launcher gradually through the plasma, detecting an island, and applying ECRH. Note that this scenario does not require any other plasma signals, or knowledge on the absolute position of the launcher. In practice it will not be difficult to extend the control system to include plasma current, toroidal field, and absolute coordinates of the launcher, which will enable narrow scanning around the $q = 2$ surface.

Depending on how well the radiometer performs in the presence of ECRH, the island can be tracked during suppression, and the gyrotron power modulated to only heat during the O-point. On the other hand, if signal to noise appears to be bad, and the gyrotron component is still very large despite suppression, coherent addition might be required and a pin switch to isolate the receiver during heating.

If the scheme turns out to be successful, application of a similar scheme to ITER could be investigated. The line of sight principle would considerably simplify the system that needs to compute the correct launcher angles for suppression of NTMs. In a control loop such a simplification is very valuable. Extrapolation of the coupler based on the dielectric plates to ITER is not possible: both the increased ECRH power and pulse length would lead to over heating of the plate. Other coupling elements could be further explored though, based on e.g. refined reflected power measurements, gratings, or diplexers.

8. Summary

The TEXTOR tokamak, with ECRH installation and the DED, provides a very suitable environment for the development of a feedback system for the suppression of tearing modes. Such a system, aiming at a novel “line of sight” detection method of the perturbations in the ECE profile caused by the modes, is currently under construction. The reduction of the gyrotron component in the ECE receiver is a major challenge, a scheme is presented that could tackle the problem. The possible layout of the circuit that acquires the ECE signals, steers the launcher, and controls the gyrotron power is under development.

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