A GENERIC METHOD FOR CONTROLLED ECRH/ECCD LOCALISATION

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Introduction

Many applications of electron cyclotron resonant heating (ECRH) or electron cyclotron current drive (ECCD) require localisation of the deposited power or driven current at a specific position in the plasma. Examples include suppression of (neoclassical) tearing modes, control of sawteeth, and control of internal transport barriers associated to regions with low or reversed magnetic shear. To date, most experiments still rely on a feed forward approach to such applications of plasma control, which relies on prediction of the desired localisation and associated launch direction for the ECRH/ECCD injection. In general, a system for feedback control of the ECRH/ECCD localisation has the tasks (1) to detect the presence of the instability or transport barrier, (2) to localise its position, and (3) to set the steering angles of the ECRH/ECCD launcher to deposit at the desired position. In addition, tearing mode control may require the modulation of the ECRH/ECCD in phase with the mode rotation. In particular steps (2) and (3) may require detailed knowledge of the plasma equilibrium. In this paper we present a control method that performs all three tasks in a single step without the need for equilibrium reconstruction.

This control method is based on the principle that along a given line of sight, in thermal plasmas, the ECRH power deposition profile is identical to the effective electron cyclotron emission (ECE) profile at the same frequency. ECE at frequencies that are slightly shifted with respect to the frequency of ECRH, will come from areas adjacent to the region of ECRH power deposition. Thus, a control loop using ECE observations along the sightline of the ECRH beam only needs to steer the launcher such that the desired position of power deposition or current drive is identified to lie in between two ECE frequencies on opposite sides of the ECRH frequency. A sketch of the proposed control scheme is shown in Fig. 1. In the following sections some critical aspects of the control scheme are detailed as currently under design for implementation within the high power long pulse length TEXTOR ECRH system [1,2]. In addition some specific problems for implementation within the CW ITER ECRH system will be discussed.

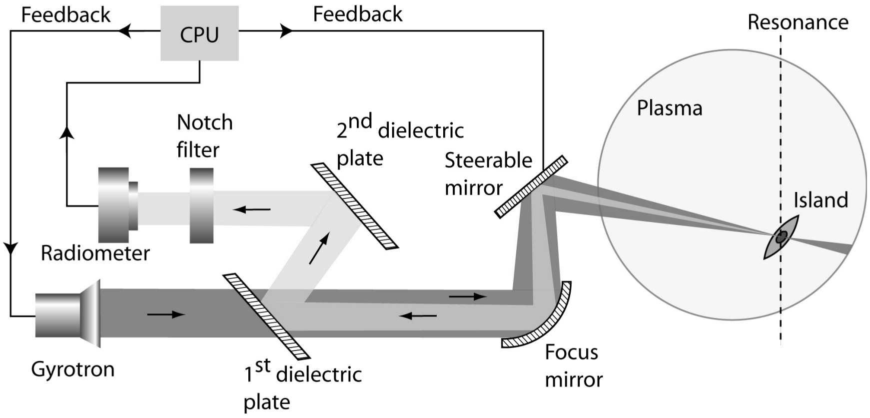

Figure 1 A sketch of the main components of the proposed scheme for controlled ECRH/ECCD deposition. The illustration shows an application for controlled power deposition inside a magnetic island.

ECE measurements in a high power ECRH transmission line

The main challenge towards the practical realisation of the proposed control scheme lies in the measurement of the low power (~ 0.1 µW) ECE that is propagating backward in the high power (~1 MW) ECRH beam line. In the system as sketched in Fig. 1 this is achieved by means of a resonant dielectric plate that is transparent for the high power ECRH frequency, but is reflective for the desired ECE frequencies. Figure 2 shows the transmission and reflection as a function of frequency for a 23.5 mm thick (water free) quartz plate, when placed at an angle of 9.5° oblique to the microwave beam. The angle and thickness are chosen such that a maximum in transmission (98%) is achieved for the 140 GHz frequency of the TEXTOR high power gyrotron, while the distance between adjacent resonant transmission/reflection frequencies is 3 GHz. Thus, the plate will be reflecting for the frequencies …, 132.5, 135.5, 138.5, 141.5, 144.5, 147.5 GHz, ..., which can subsequently be guided to an ECE radiometer for detection.

It is expected that about 2% of the high power microwaves will be absorbed in the resonant plate, giving rise to considerable heating of the plate. However, the quasi-optical transmission line at TEXTOR [1] allows to select a place where the diameter of the high power beam is relatively large, about 14 cm (1/e level of power). In this case, a full power 10 s pulse will result in an acceptable temperature rise of about 340 K. Water free quartz has been chosen not only for its low level of microwave absorption, but also for its extremely stable optical properties as a function of temperature and low thermal expansion: with the predicted temperature rise, a small rise in the resonant transmission frequency of less than 20 MHz is expected.

It will be unavoidable that a significant level of stray radiation coming from the high power microwave beam will be present. This stray radiation must be

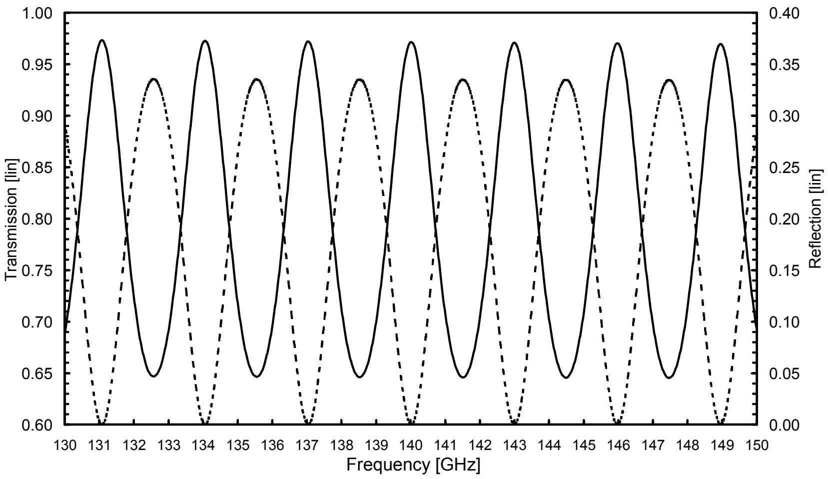

Figure 2. The theoretical transmission (full) and reflection (dashed) characteristics of a 23.5 mm thick quartz plate are shown, for the case the plate is placed at an angle of 80.5^{o} with respect to the microwave beam.

reduced to the level of the ECE radiation itself before entering the ECE radiometer or else could either damage the radiometer or perturb the ECE measurements. Possibly the largest source of stray radiation comes from the tokamak vacuum window in the transmission line: the current TEXTOR vacuum window reflection is relatively high at about 2% [2]. However, the latter is placed slightly oblique in the microwave beam, such that only a small fraction of the total power (less that 10^{-3}) is reflected backward along the transmission line. As can be seen from Fig. 2 less than 1% of this power will be reflected along with the backward propagating ECE towards the detection system. By using a second resonant plate (see Fig. 1), this level will be reduced even further, i.e. to less than 10^{-7} of the total power. The remaining difference of 10^{6} between stray radiation and ECE can be handled with a traditional notch filter.

A possible layout of a six channel radiometer for the frequencies of 132.5 to 147.5 GHz is given in Fig. 3. As a final safety precaution against the 140 GHz stray radiation, local oscillators are chosen such that the 140 GHz falls outside the bandwidth of the IF amplifiers. Assuming transmission losses of the order of 14 dB, using 200 MHz band pass filters and a video bandwidth of 10 kHz, a signal to noise ratio of better than 100 can be realised in case of a plasma temperature in the emission region of 500 eV.

Inputs for feedback control

The radial coverage of the six channel ECE radiometer is illustrated in Fig. 3 for a range of vertical launching angles of the ECRH and typical conditions of TEXTOR operation: a toroidal field of 2.25 T, central density 4.0 10^{19} m^{-3}, and central temperature 2 keV. The TEXTOR ECRH launcher can in addition be

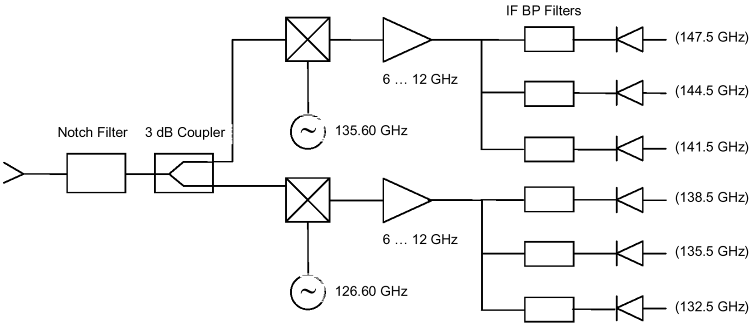

Figure 2. The design of a six channel ECE radiometer.

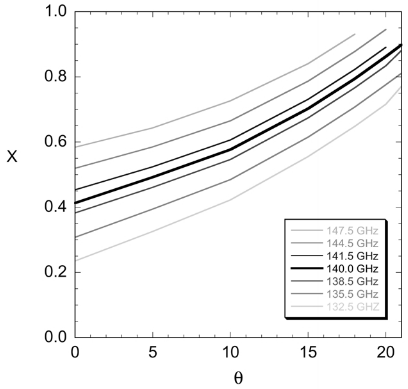

Figure 3. The normalised radial positions of the maximum of the absorption / emission profiles as a function of the vertical injection angle. The width of individual profiles is of the order of 1-2% of the minor radius. The figure shows the results for typical plasma conditions in TEXTOR: $B_T = 2.25$ T, $n_e(0) = 4.0\ 10^{19}\ m^{-3}$, $T_e(0) = 2$ keV. The ECRH injection is from the midplane on the low field side with a toroidal angle of 180^o, i.e. opposite to the major radial direction.

steered in the toroidal direction over a range from -40^o to $+40^o$ with respect to perpendicular injection to affect ECCD. The six channel ECE radiometer can cover about a third of the minor radius, which is sufficient to identify such features within this area as transport barriers and magnetic islands. For example, the largest step in measured temperature between adjacent channels exceeding a preset threshold value can indicate the presence and location of a transport barrier, while a phase jump of π between the temperature oscillations on neighbouring channels signals the location of a magnetic island. By steering the launcher – for example, by varying the vertical injection angle as in Fig. 3 – such that the desired feature is located in ECE frequencies adjacent to the gyrotron frequency, the ECRH power is assured to be localised at the desired position.

Implementation within the ITER ECRH system

One of the main tasks of the ITER ECRH system, in particular of the upper port launcher, is the control of neoclassical tearing modes. Consequently, the proposed control scheme is especially interesting for implementation on ITER. However, the implementation within the ITER ECRH system is fraught with a number of additional problems. First of all, the length of the ITER pulses

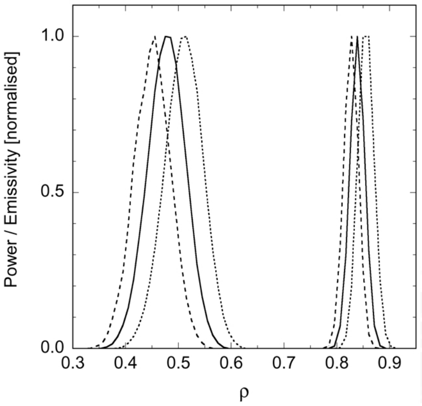

Figure 4. The normalised deposition / emission profiles for 168 (dotted), 170 (full), and 172 GHz (dashed) radiation obtained in case of the ITER upper port launcher at the two extremes (right -12°, and left +12°) of the remote steering range. The profiles are given as a function of the square root of the normalised toroidal flux ρ.

requires the effective CW operation of the ECRH system, which makes the use of a resonant plate to separate the ECE from the high power beam virtually impossible. Also, the current design of the ITER transmission lines does not contain quasi-optical sections in which the beams would have low enough power density as required for the use of resonant plates. Instead, one can employ the shallow mirror gratings that are already present in the MTP (meter for transmitted power). These are used for the deflection and subsequent measurement of a small fraction (typically 1%) of both the forward and reflected gyrotron power [3], but equally well deflect part of the backward propagating ECE. The second resonant plate could still be used as a first filter of stray radiation.

A second complication arises from the use of the remote steering principle in the current design of the ITER upper port launcher. Such a remote steering launcher can be applied only over a narrow bandwidth. Waves at slightly different frequencies than the design value (i.e. the gyrotron frequency) and injected identically to the gyrotron beam, will still exit the launcher in the same direction as the gyrotron beam but from a position which is slightly shifted in the steering plane. In case of the ITER remote steering launcher, at a steering angle of ±10°, and for a frequency difference of 2 GHz relative to the design frequency of 170 GHz, this shift is 0.94 cm. As the shift increases with the frequency difference, this precludes the usage of ECE frequencies shifted by more than about 2 GHz.

The current ITER design [4] foresees in a final fixed mirror, which is slightly focussing in order to minimize the beam size in the plasma. This has the additional benefit that also the shifted 168 and 172 GHz beams are almost refocused in the position of power absorption and emission. Figure 4 shows the deposition / emission profiles as expected for the ITER upper port launcher at the extremal steering angles of ±12°. Although the profiles are relatively broad, the resolution of the ECE at 168 and 172 GHz should be sufficient to detect magnetic islands with a width of about 5-10% of the normalised minor radius depending on the location of the magnetic island.

Conclusions and Outlook

Measurement of ECE emission along a line of sight overlapping with the high power microwave beam used for ECRH/ECCD appears technically feasible: in case of a quasi-optical transmission line and a pulse length up to several seconds, a resonant dielectric plate can be used to deflect the low power backward propagating ECE emission at selected frequencies out of the high power microwave beam line. This ECE emission can then be used in a novel scheme of controlled ECRH/ECCD deposition. Steering the ECRH launcher to centre a given feature in the ECE spectrum – indicating the presence of, for example, a magnetic island or a transport barrier – at the gyrotron frequency will automatically localise the ECRH/ECCD deposition at exactly this feature in the plasma. The proposed method is particularly suitable for control of such instabilities as (neoclassical) tearing modes, which is one of the main applications for the ITER ECRH system.

A project has been started to implement the proposed control scheme in the TEXTOR ECRH system. The proposed six channel ECE radiometer will measure a frequency range of 15 GHz centred around the gyrotron frequency of 140 GHz. This gives a coverage of about a third of the minor radius. Planned applications include the suppression of tearing modes, sawtooth control, and the control of transport barriers.

Acknowledgements

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