32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.071 (2005)

Suppression of Tearing Modes by Electron Cyclotron Heating and Current Drive

E. Westerhof[1], A. Lazaros[1], I.G.J. Classen[1], E. Farshi[1,2], J.A. Hoekzema[2], H.R. Koslowski[2], A. Krämer-Flecken[2], A. Merkulov[1], J.W. Oosterbeek[2], J. Scholten[1], O. Zimmermann[2], and the TEXTOR-team

[1] *FOM-Institute for Plasma Physics Rijnhuizen*, Association EURATOM-FOM, PO Box 1207, 3430 BE Nieuwegein, The Netherlands, www.rijnh.nl*

[2] *Forschungszentrum Jülich GmbH, Institut für Plasmaphysik*, Association EURATOM-FZJ, 52425 Jülich, Germany*

** Partners in the Trilateral Euregio Cluster*

1. INTRODUCTION

The Dynamic Ergodic Divertor (DED) [1] installed at the TEXTOR tokamak (R = 1.75 m, a = 0.46 m) is a flexible tool for the manipulation of the magnetic topology. It consists of 16 coils plus two compensation coils with helicity q=3. It can be operated either in DC mode, or in AC mode at different frequencies up to 10 kHz. The individual coils can be powered in such a way as to produce a dominantly m/n=12/4, m/n=6/2, or m/n=3/1 magnetic perturbation. The perturbations, generated in the 3/1 mode of operation, penetrate particularly deep into the plasma, and can be used for the controlled generation of tearing modes. In particular, a large m=2, n=1 side band perturbation is present, which above a certain threshold in the currents in the individual DED coils triggers an m=2, n=1 tearing mode that is locked to the perturbation field [2]. In the experiments reported here, these well controlled, perturbation field induced tearing modes have formed the target for fundamental studies of tearing mode control by local heating and current drive as affected by ECRH and ECCD.

Localised heating or current drive can affect the magnetic island created by the tearing mode in different ways. Firstly, it has an effect on the island growth through heating or current drive inside the island: heating or co-current drive near the O-point of a magnetic island suppresses the island, whereas heating or co-current drive near the X-point has the opposite effect [3]. Secondly, it affects the island through changes in the equilibrium temperature and current density profile: these profile changes then lead to corresponding changes in the tearing mode stability parameter Δ' [4]. The first effect may benefit from modulated application of the ECRH in order to avoid power deposition near the X-point, while the second should be independent of the phase in which the power is applied.

2. EXPERIMENTAL CONDITIONS AND METHODS

All experiments have been carried out for fixed plasma conditions with a toroidal field of $B_T = 2.25$ T, plasma current $I_p = 300$ kA, and line averaged density $n_e = 2.0\ 10^{19}\ m^{-3}$. Through most of the discharge neutral beam injection (NBI) is applied at a power of 300 kW for diagnostic purposes. The DED is applied in its 3/1 mode at +1 kHz AC and the amplitude of the current in the individual coils is ramped up to 2.0 kA. Under these conditions the threshold for the triggering of the m=2, n=1 tearing mode is at a DED current amplitude of about 1.6 kA. During the plateau phase of the DED current an ECRH pulse (140 GHz, up to 800 kW) is applied and its effect on the 2/1 tearing mode is studied. By changing the vertical injection of the ECRH beam the radial location of the power deposition has been varied. Variation of the toroidal injection angle has allowed to vary between co- and counter-current drive as well as pure heating. Since the mode is locked to the DED perturbations, a DED coil current provides a conveniently stable reference signal for a phase locked modulation of the ECRH power. For these high frequencies, modulation is only possible through variation of the beam voltage, which implies a modulation between two power levels (high-low). Both duty cycle (the relative length of the high power phase) and phase (the start time of the high power phase relative to the DED current seen as a *sin*-wave) have been varied to study the effectiveness of modulated ECRH.

A relative measure of the size of 2/1 magnetic island is obtained from the 1 kHz oscillations observed on the electron cyclotron emission (ECE) at 141 GHz which originates from close to the $q = 2$ surface on the high field side of the tokamak. The ratio of the amplitude of these oscillations during the ECRH pulse over those during the foregoing DED plateau phase, $\tilde{T}_{ECRH} / \tilde{T}_{DED}$, forms a good measure of the suppression ratio of the 2/1 tearing mode by ECRH. These estimates for the suppression of the magnetic island could be confirmed by other diagnostics [5].

3. EXPERIMENTAL RESULTS

In Figure 1 we show the results from a typical discharge in which the ECRH power has been deposited very close to the $q = 2$ surface. The figure shows from top to bottom, the current in one of the DED coils, I_{DED}, the ECRH power, P_{ECRH}, the ECE intensity at 141 GHz, T_{141}, and the amplitude of the 1 kHz oscillations in the latter signal, $\tilde{T}_{141}$. The blue bars on $\tilde{T}_{141}$ indicate the timeframes over which the oscillation amplitudes before and during the ECRH pulse are averaged in order to obtain the suppression ratio of the 2/1 tearing mode. In this particular case, the magnetic island is almost complete suppressed and this method gives a suppression ratio of 0.10. Only after the DED is switched-off, is the island completely suppressed. The suppression ratio is found to depend very strongly on the precise location of the power deposition. In the experiments, this location has been varied by changing the vertical injection angle of the ECRH beam. Figure 2 shows the results of two such radial deposition scans for 800 kW of injected power: in one case a toroidal injection angle of -2^{o} has been used for co-ECCD, while in the other case a toroidal angle of $+2^{o}$ has been used resulting in counter-ECCD. Also indicated in the figure are the full width of the magnetic island before application of ECRH (w/a $\approx$ 0.13) and the width of the ECRH deposition region ($\Delta r_{dep}/a = 0.02$, FWHM). Clearly, the strongest suppression is obtained when the power is deposited at the centre of the magnetic island. Co-ECCD is seen to be only slightly more effective for mode stabilisation than counter-ECCD, which indicates that heating rather than current drive is the dominant effect. In order to verify this conclusion, we have performed a scan in toroidal injection angle ϕ thus varying the EC driven current and current density. This scan has been performed at an ECRH power of 200 kW. At this power, the mode is only partly suppressed, which should make any effect of the current drive on the suppression ratio better visible. Figure 3 shows the suppression ratios as a function of ϕ. Again the effect of the current drive is seen to be small, confirming that the dominant source for the suppression of the 2/1 magnetic island comes from heating. Calculations for these parameters predict a maximum driven current density of the order of $\pm 2\ 10^4$ A/m^2, which is achieved at an angle -6^o or $+4^o$ for co- or counter-drive, respectively. This is indeed relatively small compared to the current density at the $q = 2$ surface, which is estimated to be $6.5\ 10^5$ A/m^2.

Previously, we have shown through the application of modulated ECRH that power deposited near the O-point of the magnetic island is more efficient for stabilization than power deposited near the X-point: in a scan of the ECRH high power phase relative to the timing of the passage of the O-point of the magnetic island through the ECRH power deposition region, the strongest mode suppression has been observed when the power is deposited at the O-point [5]. These results were obtained with modulation between a high power of 780 kW and a low power of 170 kW at a duty cycle of 50%. To further study the benefits of power modulation, we have performed a scan in duty cycle while keeping the centre of the high power phase coincident with the passage of the O-point. In this case, the power has been modulated between 400 and 70 kW. The results are shown in Fig. 4, where the 0% and 100% duty cycle points indicate the suppression ratios obtained for the injection of 70 kW and 400 kW CW, respectively. A minimum is obtained at a duty cycle of 70%. The additional power that is added beyond this point does no longer help to stabilize the mode and even leads to a small increase in its amplitude again. The dashed curve in this figure corresponds to the suppression ratio that is obtained with 200 kW CW. This corresponds to the same averaged power level as the 40% duty cycle point.

4. SUMMARY AND CONCLUSIONS

The 2/1 tearing mode triggered by the DED at TEXTOR has been suppressed by properly localised ECRH. Because the mode suppression is observed to be relatively insensitive to the driven current or toroidal injection angle, heating must be responsible for the main effect. In addition, a clear benefit of power modulation is observed. This indicates that direct heating of the magnetic island and the consequent decrease of the resistivity at the O-point, rather than changes in the local temperature and current density profiles, is the dominant mechanism responsible for the suppression of the 2/1 magnetic island.

ACKNOWLEDGEMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/FOM, was carried out within the framework of the European Fusion Programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] K.H. Finken (Ed.), Special Issue: Dynamic Ergodic Divertor, Fusion Eng. Design **37** (1997) 335.
[2] H.R. Koslowski, et al., 31st EPS Conf. London (2004), ECA, Vol **28G**, P-1.124.
[3] Y. Yoshioka, et al., Nucl. Fus. **24** (1984) 565; H. Zohm, Phys. Plasmas **4** (1997) 3433.
[4] E. Westerhof, Nucl. Fus. **27** (1987) 1929, and **30** (1990) 1143.
[5] E. Farshi, et al. , 31st EPS Conf. London (2004), ECA, Vol **28G**, P-1.122.

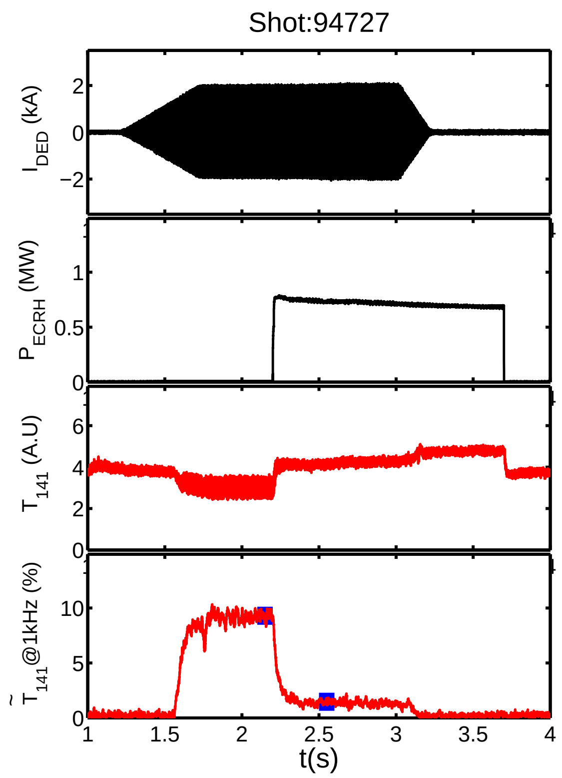

Figure 1.

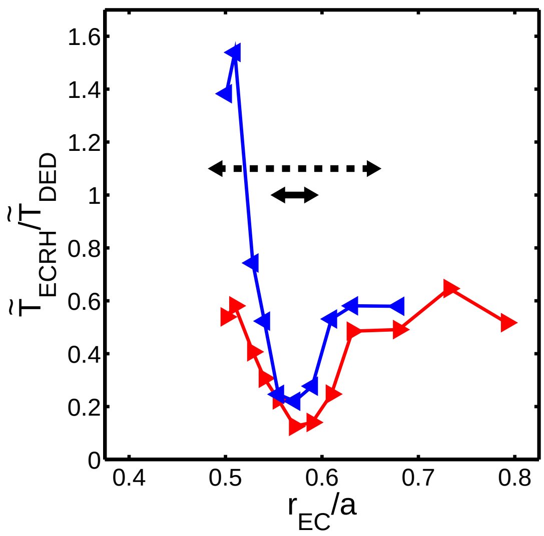

Figure 2.

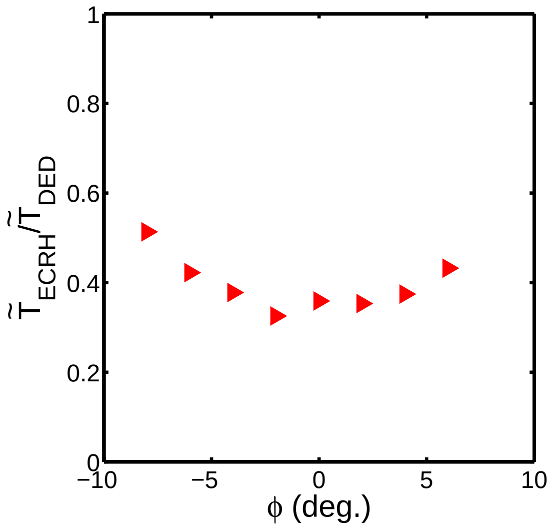

Figure 3.

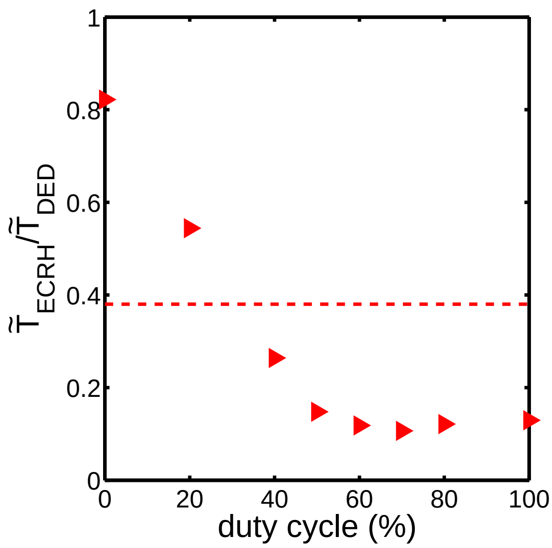

Figure 4.

FIGURE CAPTIONS

Figure 1. The discharge scenario is shown. First, the current (1 kHz AC) in the DED coils is ramped to 2 kA (top panel). Next, ECRH is applied (second panel). The third panel shows the 141 GHz EC emission, and the final panel the amplitude of its 1 kHz oscillations. These are a measure for the size of the 2/1 magnetic island. The 2/1 tearing mode is triggered at 1.6 s, and it is clearly suppressed when ECRH is applied. The ratio of the oscillation amplitudes during the blue time intervals defines the suppression ratio $\tilde{T}_{ECRH} / \tilde{T}_{DED}$.

Figure 2. The suppression ratio is shown as a function of the 800 kW ECRH deposition radius. The red curve corresponds to co-ECCD (toroidal angle -2^{o}), the blue to counter-ECCD ($+2^{o}$). The dashed black line indicates the full island size, and the full one the width (FWHM) of the ECRH deposition profile.

Figure 3. The suppression ratio is shown as a function of the toroidal injection angle ϕ. The ECRH power in this case is 200 kW.

Figure 4. The figure shows the suppression ratio as a function of the duty cycle. The duty cycle gives the length of the 400 kW high power phase which is centred at the O-point of the magnetic island. The dashed line indicates the suppression ratio for a 200 kW CW pulse.