Experimental observations of the X-point collapse and secondary islands with a resonant rotating perturbation field in TEXTOR

Y. Liang, H. R. Koslowski, A. Krämer-Flecken, O. Zimmermann, K. Löwenbrück, G. Bertschinger, R. C. Wolf and the TEXTOR-team

Institut für Plasmaphysik, Forschungszentrum Jülich, Association EURATOM-FZJ,Trilateral Euregio Cluster, Germany, www.fz-juelich.de/ipp

Abstract The influence of a rotating external perturbation field induced by the Dynamic Ergodic Divertor (DED) on the mode locking and unlocking processes has been studied on TEXTOR. Internal plasma minor disruptions at q=2 surface occurring during the process of locking of a m/n=2/1 tearing mode has been observed. The plasma confinement collapses at the X-points (X-point collapse) of the 2/1 islands chain without much effect on the width of the islands (O-points). With an external rotating perturbation field, the locked mode disruption can be avoided. The width of the 2/1 island was reduced when the locked 2/1 mode was spun up by the external rotating perturbation field. Secondary islands around a large 2/1 island (>8cm) have been observed by using ac DED on TEXTOR. The rotation frequency of the secondary islands is locked to the frequency of the external perturbation fields. The secondary island disappears when the 2/1 island becomes smaller (less than 6cm). The plasma confinement suddenly improved when the secondary islands vanished.

Introduction Experimental and theoretical studies of plasma disruptions caused by a locked mode have been investigated since the early stage of magnetically confined fusion plasma physics research, because the disruptions and related vertical displacement events induce many unacceptable problems (i.e. sudden thermal loading on the first wall, vessel halo currents and high energy runaway electrons) for future fusion reactors [1-3]. During the process of mode locking, internal plasma minor disruptions (where the plasma confinement is recovered after each collapse) at the q=2 surface, have been often observed before a major disruption in many devices [4]. Suppression of a tearing mode has been performed experimentally with different methods, i.e. ECRH localized heating and current driving (ECCD) [5]. Recently, the influence of the electromagnetic torque induced by an external static/rotating Resonant Magnetic Perturbation (RMP) on the tearing mode rotation has been studied experimentally and theoretically [6-10].

On TEXTOR (R_0=1.75 m, a=0.47 m, circular plasma cross section), the Dynamic Ergodic Divertor (DED) at the high field side produces either a static (dc) or a rotating (ac) helical RMP with frequencies of up to 10 kHz in either co- or counter-direction with respect to the plasma current.

Previous experiments have shown that the DED in m/n = 3/1 configuration (where m and n are the poloidal and toroidal mode numbers, respectively) is a good tool for the investigation of tearing mode related physics due to a large m/n = 2/1 sideband perturbation [9 10]. In this paper we report on experimental observations of (i) internal plasma minor disruptions at the q=2 surface occurring during the process of mode locking, (ii) secondary islands [11] generated around the large 2/1 island, and (iii) avoidance of plasma disruptions due to a locked 2/1 tearing mode by the application of a rotating RMP.

Experimental observations Internal minor disruptions often happen when the 2/1 island growths and finally locks on TEXTOR. Furthermore, a major plasma disruption can be initiated by the locked mode. The experimental results are based on both, measurements of the soft x-ray emission profiles and T_e profiles, which shows that sudden collapse events occurring at the q=2 flux surface without much influence on the 2/1 island, and there is strong evidence that these happen at the X-point of the island (X-point collapse). Figure 1 (a) and (b) show the time evolution and radial profiles of soft

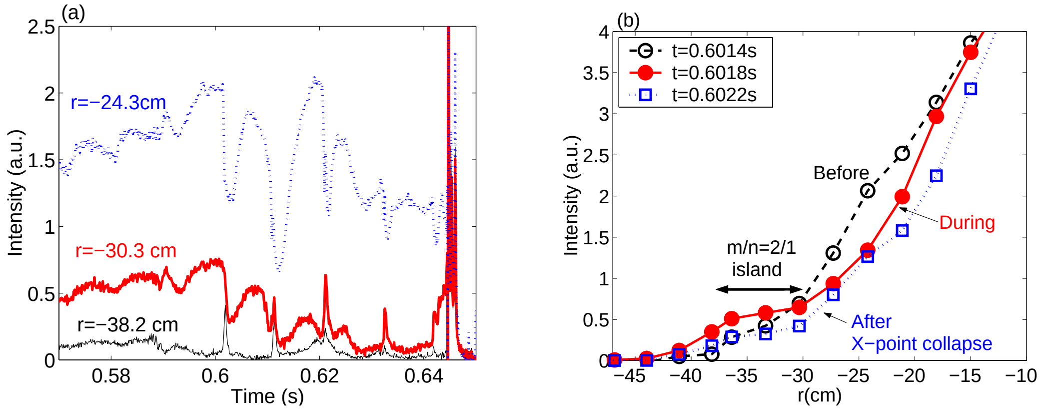

Figure 1 (a) Time evolution of line-integrated x-ray emission near the q=2 surface and (b) radial profiles of x-ray emission measured by a soft x-ray camera viewing the high field side of plasma.

x-ray emission near q=2 surface measured by a soft x-ray camera viewing the HFS in a discharge terminated after several internal minor disruptions due to a locked mode. The target plasma had a plasma current, I_p, of 400 kA and a magnetic field, B_t, of 1.9 T. A 2/1 island appears at t ~ 0.59 s, and it is located at a plasma radius of r = 0.32 m where a flattening in the x-ray emission profiles is observed. A non-linear growth of the island has been seen when the mode rotation frequency slows down to zero, and the sawtooth oscillation disappears. The x-ray emission profiles measured during one minor disruption clearly shows that the crash event happens at the q=2 surface where a large 2/1 island is formed. There is no significant influence of the minor disruptions on the width of the 2/1 island observed. The loss of central plasma confinement due to the crash is relatively smaller than that near q=2 surface.

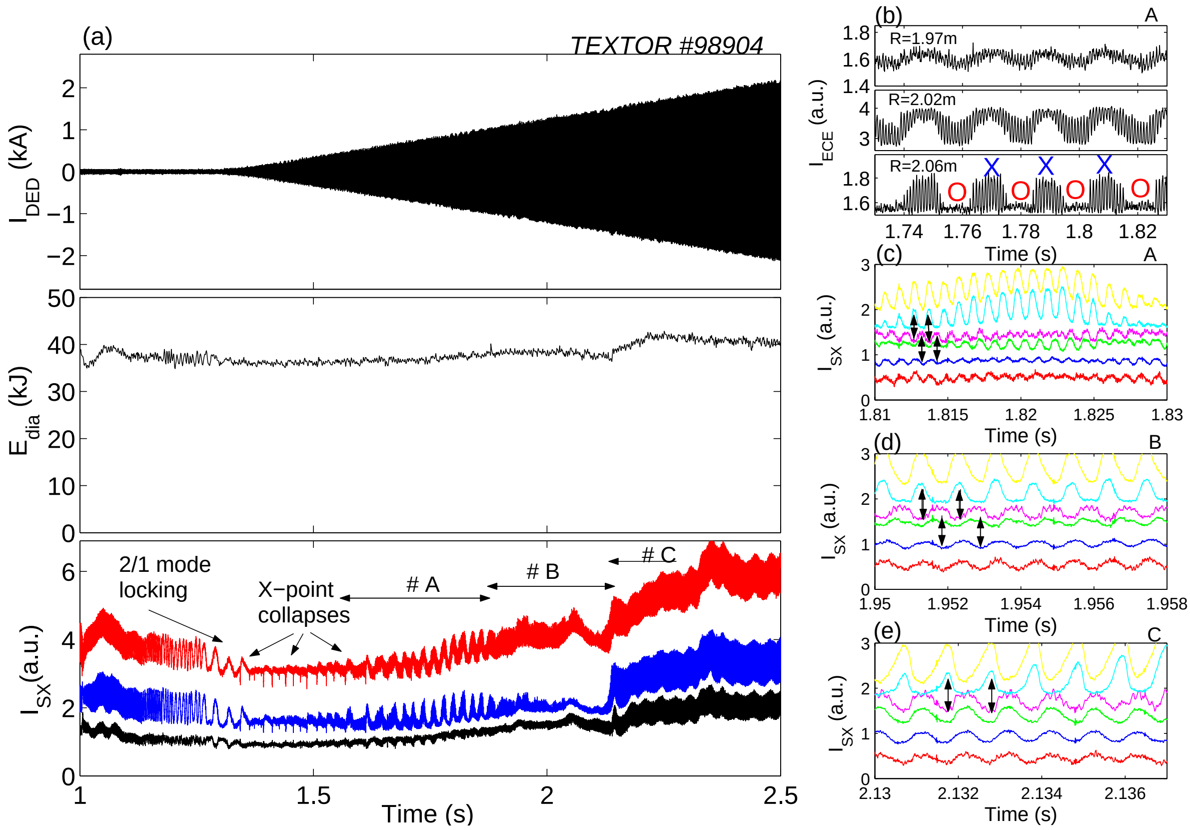

Figure 2 (a) Time evolution of DED coil current (I_{DED}), diamagnetic energy (E_{dia}) and line-integrated x-ray emission measured near the q=2 surface by a horizontal SX-camera, (b) ECE signals measured at different radii (R= 1.97m, 2.02m and 2.05m) during phase A, time extended plots of line-integrated x-ray emission measured near the q=2 surface (Z=-21.5cm; -24.5cm; -27.5cm; -30.5cm; -33.6cm and -36.6cm) during (c) phase A; (d) phase B and (e) phase C.

When a rotating RMP induced by the DED with a frequency of 1 kHz is applied to the plasma (I_p = 300 kA; B_t = 2.25 T; $\langle n_e \rangle = 2 \times 10^{19} m^{-3}$) with a large locked 2/1 island, three phases with different behaviors have been identified as shown in Figure 2 (a-e). In this discharge, the DED coil current, I_{DED}, is ramped-up slowly up to 3.75 kA within 2 s from the time when the rotation frequency of the 2/1 island is damped down to zero (t = 1.3 s). X-point collapses occur during the process of mode locking happened before the DED is applied. In phase A where I_{DED} is below 1 kA, the pre-seeded locked 2/1 island starts to rotate with a low frequency (~ 50 Hz) as seen in Figure 2 (a) and (b). In the same time, an oscillation around the 2/1 island at q=2 surface with a frequency of 1 kHz has been observed by both, SX-cameras and multi-channels ECE. The double phase reversals of the oscillating x-ray emission signals near the q=2 surface indicates that there is a small island structure rotating around the large 2/1 island, here it is called secondary islands. The X-point collapse events disappear when the rotating secondary islands are observed. In phase B, the rotation frequency of the 2/1 island spins up to the DED frequency of 1 kHz when I_{DED} is increased above 1 kA. The secondary island is still observed rotating around the 2/1 island as seen in Fig. 2 (d). A further increase of I_{DED} (> 1.5kA) results in a reduction of the 2/1 island width down to ~6 cm, and the secondary islands disappear as seen in Fig. 2 (e). A sudden increase in the plasma diamagnetic energy by ~13% has been observed at the time when the secondary islands vanish. No significant further change of the width of the 2/1 island is observed even when I_{DED} is increased up to 3.75 kA. The plasma is stable during the application of the rotating RMP, however, it disrupts later due to a non-linear growth of the locked 2/1 mode after switch-off of the DED.

Discussion and Conclusion

Spin-up of a locked 2/1 mode to the frequency of the external RMP induced by the DED is observed on TEXTOR. It is considered to be due to a toroidal momentum transfer through an electromagnetic torque $J_\varphi \times B_r$, where B_r is the radial component of the external RMP and J_φ is the toroidal component of plasma current flowing in the island region. Secondary islands rotating around the large locked 2/1 island have been observed when a low level of an external RMP is applied. The rotation frequency of the secondary island is locked to the frequency of the RMP, and it shows an evidence that a velocity shear could be generated near the resonant surface (q=2) by the electromagnetic torque induced by DED when the frequency of the 2/1 mode is far below the frequency of the RMP ($f_{2/1}<f_{DED}$). The reduction of island width during the process of mode unlocking with a rotating RMP has been observed, and it can be explained by a velocity shear near the resonant surface, which has a stabilizing effect on the island [7]. Secondary islands disappear when the width of the 2/1 island dropped down to ~6 cm, and a sudden recovery of plasma confinement occurs. A similar observation has been also found by changing the rotation direction of the RMP from co- to counter-current direction. The experimental results also show that the plasma major disruption due to a locked mode can be avoided by active control of the frequency of the tearing mode with a rotating external RMP. This mechanism is of importance for active MHD control in future machines, e.g. ITER.

References

[1] R. B. White, D. A. Monticello, and M. N.Rosenbluth, Phys. Rev. Lett. 39, 1618 (1977).

[2] J.A. Goetz, R. N. Dexter, and S. C. Prager, Phys. Rev. Lett. 66, 608 (1991).

[3] F. C. Schueller, Plasma Phys. Control. Fusion 37, A135-A162 (1995).

[4] H.Zohm, et al., Plasma Phys. Control. Fusion 37, A313-A324 (1995).

[5] E. Westerhof, et al., submitted to PRL (2006). [6] R. Fitzpatrick, Nuclear Fusion, 33, 1049 (1993).

[7] G. Kurita, et al., Nuclear Fusion, 32, 1899 (1992). [8] K. Oasa, et al., IAEA-CN-60/A3/A5-P14.

[9] H.R. Koslowski et al., accepted for publication in Nuclear Fusion (2006).

[10] Y. Liang et al., ECA 29 C (2005) P4.060.

[11] N. F. Loureiro, et al., Phys. Rev. Lett. 95, 235003 (2005).