26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 613 - 616

Parameter study of off-axis sawtooth-like instabilities in RTP

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1. Introduction

A family of off-axis, or annular, instabilities have been found and studied in the Rijnhuizen Tokamak Project (RTP). In RTP ($R/a = 0.72/0.164$ m, $B_\phi < 2.5$ T, $I_p < 140$ kA, pulse duration < 600 ms) these phenomena are invoked in a controlled way in discharges with specific (off-axis) deposition of electron cyclotron heating (ECH) and persist during most of the heating period (many current diffusion times).

The instabilities are associated with resonant surfaces near simple rational values of q (3/2, 2, and 3). A parameter study shows an increase of reheat rate and a decrease of sawtooth period both with increasing ECH power (P_{ECH}) and increasing density (n_e).

The phenomena are studied using a high resolution, double pulse Thomson Scattering (TS) system [1, 2], two 16-channel soft X-ray (SXR) cameras, and two electron cyclotron emission (ECE) systems: a 20 channel heterodyne radiometer that probes a horizontal line of sight and a new ECE diagnostic [3]. The latter images part of the vertical TS chord (ECE-I), featuring 16 channels with a spacing of 13 mm in the vertical plane.

2. General Phenomenology

Three types of annular sawtooth-like instabilities are invoked in plasmas where stationary Negative Central Shear (NCS) and stationary hollow electron temperature (T_e) profiles are induced by off-axis ECH (110 GHz, $P_{\mathrm{ECH}} \leq 300$ kW, about 5 times the Ohmic power) [4]. With the means to manipulate the T_e profile and thus the q-profile it is possible to achieve controlled excitation of the off-axis sawteeth in RTP. By varying the exact radius of ECH deposition (ρ_{dep}) the sawteeth can be (1) invoked at a choice of rational surfaces (corresponding to q= 3/2, 2, or 3), can be (2) made to persist as a repetitive instability during many current diffusion times, and can be (3) switched on or off at will. The T_e time "signature" of the instabilities is closely reminiscent of the central sawteeth, exhibiting a sharp (20μs) collapse of (annular) maxima in T_e followed by a longer period (0.5-4 ms) of reheating. It should be noted that the phenomena exhibit strong sensitivity to ρ_{dep}: very small changes in B_ϕ (corresponding to changes in ρ_{dep} of about 1 mm) can cause the sawtoothing to stop or restart.

Figures 1 and 2 show the TS and ECE-I signatures of the different sawtooth types. The off-axis events in Fig.1b-d show the characteristic hollow T_e profiles (corresponding to NCS conditions) before an annular sawtooth collapse (the "hot ears" marking the ECH deposition region) and the smoothed-out situation just after the crash. The off-axis nature of these instabilities, leaving $T_e(0)$ virtually unaffected, comes out convincingly in these measurements, especially for the q=2 and q=3 cases. The sawteeth near q=3/2 only show a very narrow region where T_e is unaffected (Fig.1b). This is not completely resolved

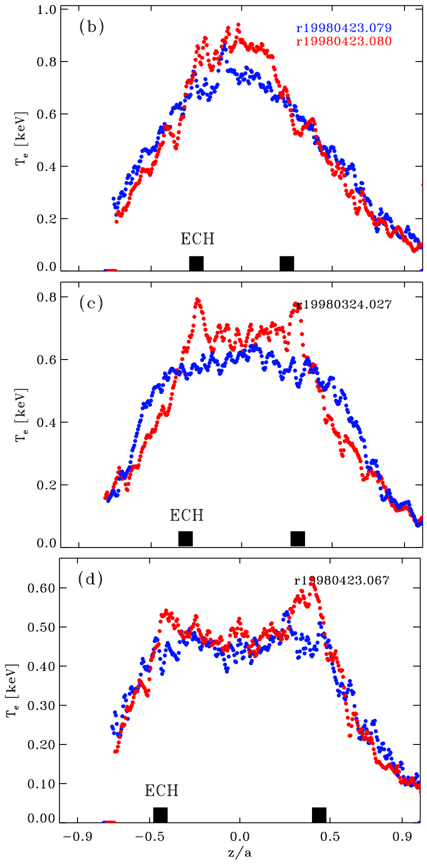

Figure 1: *TS T_e data for q=3/2 (b), q=2 (c), and q=3 (d) off-axis sawtooth instabilities, just before (red) and just after the crash (blue). q_a = 5.5-5.9, I_p = 65 kA, 300 kW ECH; ρ_{dep} is indicated by the black bars.*

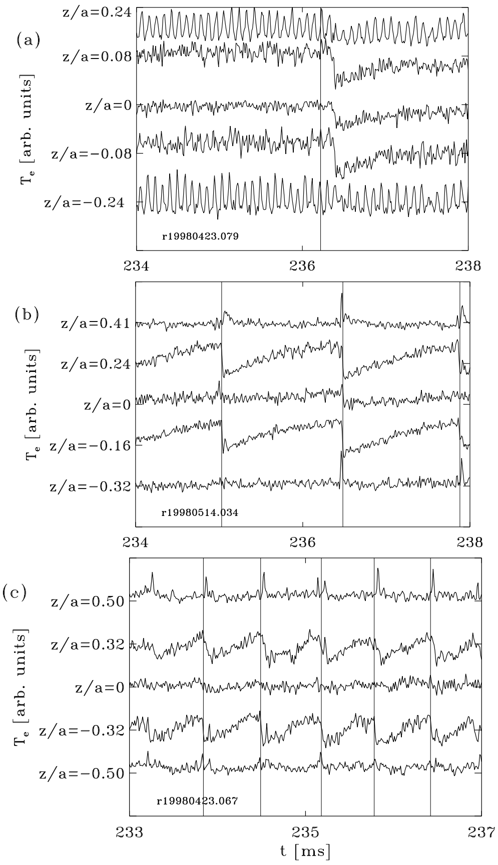

Figure 2: *ECE-I traces for different radii for the q=3/2 (a), q=2 (b), and q=3 (c) off-axis sawtooth instabilities, under the same conditions as Fig.1b-d.*

by the ECE-I system, which does show a T_e drop on the central channel in Fig.2a, much smaller, however, than on the neighbouring channels. Only the central q=1 sawtooth (not shown here) exhibits the typical crash associated with $m = 1$ sawtoothing, with a marked influence on $T_e(0)$. Note that all sawtoothing occurs at ρ_{dep}.

The off-axis sawteeth are reproducible and have been observed in many plasma discharges with comparable conditions. The sawtoothing periods in Figs 2a-c are characteristic and reproduce to within 30 %, both within a discharge and between discharges. A persistent m=2 rotating mode is often observed on ECE channels outside of the crash region for the $q = 3/2$ type (see Fig.2a, oscillations at $z/a = \pm 0.24$), giving extra information on the q-profile.

3. Mode Analysis

At the crash time of the off-axis sawteeth a coherent mode can be observed which sometimes has the character of a growing precursor or a trailer. The poloidal mode character of the dominant oscillation can be determined using signals from both ECE systems together; see [5] for details. For the discharges in Fig.1 q-profiles have been calculated assuming neoclassical resistivity (including the bootstrap current) and a uniform Z_{eff}, using the TS T_e and n_e profiles as input data. These calculations confirm the q values of 3/2, 2, and 3, for the three types of sawteeth.

4. Parameter Study

Reheat rates have been determined by performing a linear regression on the calibrated ECE-I signals over 300 μs immediately following a sawtooth crash. Just after a crash $\nabla T_e \simeq 0$ at the sawtooth location (see Fig.1), hence all absorbed ECH power should initially be detectable as T_e rise. The reheat rates found are $\sim$ 190, 170, and 210 eV/ms for the $q = 3/2, q = 2$, and q=3 events, respectively, corresponding to absorbed power densities of 1.5, 1.4, and 1.7 ($\pm$ 30%) MWm^{-3}. These values depend on n_e and $P_{\rm ECH}$ (see below). The values can be compared with the ECH deposited power densities in the case of 100% single pass power absorption (as indicated by ray tracing calculations). Assuming the ECH absorption volume to have the shape of an annular shell within the torus, of which the dimensions can be inferred form the measurements in Figs 1, 2, the deposited microwave power density for the q=3/2, q=2, and q=3 off-axis sawteeth amounts to 27, 11, and 8 MW/m^{-3}, respectively. The large discrepancy with the aforementioned values in both trend and absolute value is presently not understood.

$P_{\rm ECH}$ has been changed during a discharge, typically between 100 and 300 kW, in particular in discharges with q=2 off-axis sawtoothing. Both power step-up and step-down have been applied, all other machine parameters being kept fixed. Generally, the occurrence of off-axis sawteeth shows no clear relation with the level of $P_{\rm ECH}$. The characteristics of

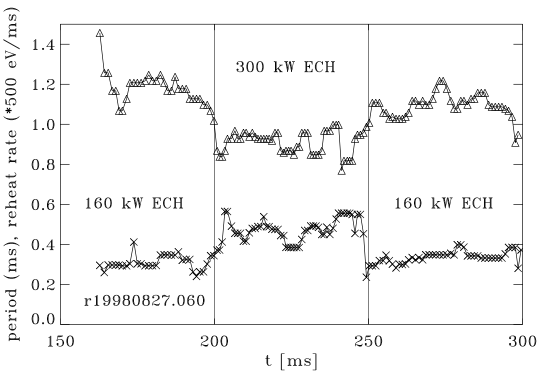

Figure 3: *The influence on sudden changes of $P_{\rm ECH}$ (from 160 to 300 kW and back at t=200 and 250 ms, respectively) on reheat rate (crosses) and period (triangles) of q=2 off-axis sawteeth in RTP. A median filter of width 5 has been employed for data smoothing.*

the sawteeth do show a dependence on $P_{\rm ECH}$. There is a marked change in both period and reheat rate as $P_{\rm ECH}$ steps up or down, see Fig.3. Taking data from a large series of discharges together, a considerable data scatter is found; nevertheless, a trend of decreasing period and increasing reheat rate with increasing $P_{\rm ECH}$ was detected.

During a number of discharges n_e has been ramped in q=2 sawtoothing discharges. Figure 4 shows the reheat rate and sawtooth period as functions of line-averaged electron density for two discharges with density ramps (otherwise conditions as in Fig.1). The value of n_e for a specific sawtooth event was computed by time averaging the line-integrated density data over the corresponding sawtooth period. In contrast to most observations on central sawteeth (e.g., [6]), the off-axis sawtooth period seems to decrease slightly with increasing density, whereas the reheat rate increases. This behavior may be related to the

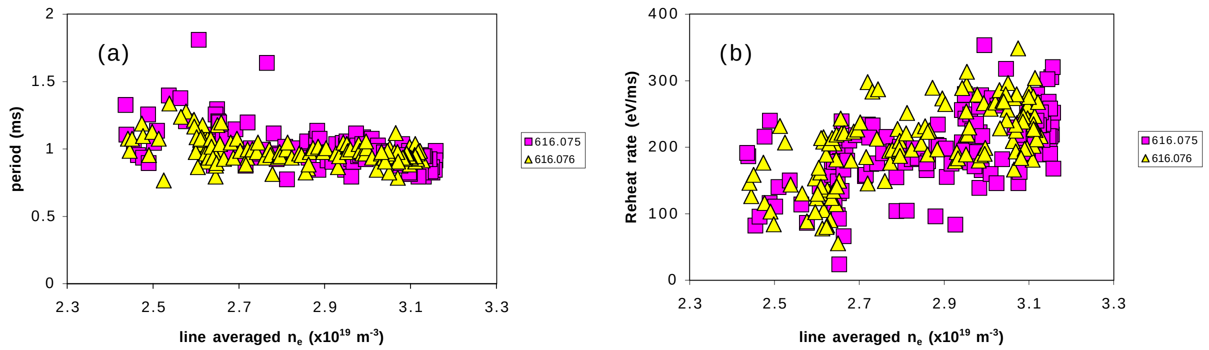

Figure 4: *Influence of density ramping on q=2 off-axis sawtoothing in RTP for two discharges (P_{ECH} = 300 kW), displaying annular q=2 sawtoothing. Shown are the sawtooth period (a) and sawtooth reheat rate (b) as functions of line-averaged electron density.*

discrepancy between calculated and experimental power densities.

5. Discussion and Summary

Annular relaxation phenomena in the outer regions have been reported on, e.g., TFTR and TEXTOR [7, 8]. FTU and Tore Supra have reported repeated off-axis sawtooth-like events when NCS was induced by lower hybrid current drive or ECH [9, 10]. These off-axis events are usually observed in transient phases and have been related to MHD activity or transport catastrophes near low rational values of q, mainly q=2.
The controlled steady state off-axis sawtoothing in RTP at several low rational values of q puts the central q=1 sawteeth in a broader perspective and may prompt the search for a more generic sawtooth mechanism. Off-axis sawteeth may be just as common in NCS discharges as q=1 sawteeth are in centrally heated plasmas, but the former can be manipulated by tailoring the q-profile. This opens up the possibiliy for pumping helium fusion "ash" by inducing off-axis sawteeth, even in reactor scenarios where the central q remains well above unity. Indeed, increased impurity outward transport has been observed during irregular annular crashes in TEXTOR [8].

Acknowledgements

This work was done under the Euratom-FOM association agreement with financial support from NWO and Euratom.

References

[1] C.J. Barth et al, Rev. Sci. Instrum. **68**, 3380 (1997)
[2] M.N.A. Beurskens et al, submitted to Plasma Phys. Contr. Fusion (1999)
[3] B.H. Deng et al, Proc. 25th EPS Conference on Con. Fus. Pl. Phys., Prague (1998)
[4] G.M.D. Hogeweij et al, Nucl. Fusion **38**, 1881 (1998);
M.R. de Baar et al, Phys. Rev. Lett. **78**, 4573 (1997)
[5] R.F.G. Meulenbroeks et al, submitted to Phys. Plasmas (1999)
[6] F. Bombarda et al, Nucl. Fusion **38**, 1861, and references therein
[7] Z. Chang et al, Phys. Rev. Lett. **77**, 3553 (1996)
[8] J. Rapp et al, Plasma Phys. Contr. Fusion **39**, 1615 (1997);
H.R. Koslowski et al, Plasma Phys. Contr. Fusion **39**, B325 (1997)
[9] P. Buratti et al, Plasma Phys. Contr. Fusion **39**, B383 (1997)
[10] S. Turlur et al, Proc. 22nd EPS Conf. on Con. Fus. Pl. Phys., Bournemouth, Vol. IV, 73 (1995)