

OFF-AXIS SAWTOOTH-LIKE INSTABILITIES NEAR $q = 3/2, 2, \text{ AND } 3$ IN RTP

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1. The Phenomenon

In addition to the well-known central sawteeth, sawtooth-like instabilities (related to, e.g., double tearing modes, internal modes, interchange modes or transport catastrophes) have been observed in the outer regions of tokamaks [1,2] under specific conditions, most notably negative central magnetic shear. In the Rijnhuizen Tokamak (RTP, $R/a = 0.72/0.16$ m, $B \approx 2.2$ T, $I \approx 100$ kA, pulse < 600 ms), a family of off-axis sawtooth-like instabilities shows up in plasmas where stationary negative central shear and hollow temperature profiles are induced by off-axis electron cyclotron resonance heating (ECH) [2]. The temperature time "signature" of the instabilities is closely reminiscent of the central sawteeth, exhibiting a sharp ($< 10 \mu\text{s}$) collapse ('crash') of off-axis maxima in the electron temperature followed by a longer period (0.5-4 ms) of reheating. Reheat rates vary from 70-250 eV/ms. Radially dependent data show such other parallels as the existence of inversion and mixing radii as well as what appears to be diffusive outward heat pulse propagation outside of the mixing radius. This paper gives a phenomenological description of these off-axis "sawteeth" that are associated with low rational values of q ($3/2, 2, \text{ and } 3$).

2. The Experiment

RTP is an ideal tokamak for studying these phenomena as it is equipped with high-power ECH (110 GHz, 300 kW, about 5 times the Ohmic power), a high resolution, double pulse Thomson scattering system [3], and two ECE systems: a 20 channel heterodyne radiometer that probes a horizontal line of sight and a new ECE diagnostic [4] that images part of the (vertical) Thomson scattering chord. This makes a reliable T_e -calibration on Thomson data possible if the optical depths are in a safe range (i.e., above 3 or so). Discharges with line-averaged densities of about $3 \times 10^{19} \text{ m}^{-2}$ are used in all discussed cases so as to make sure that the optical depths are in this safe range. The imaging ECE diagnostic features 16 channels with a spacing of about 1.3 cm in the vertical plane. The spatial extent of the probed volume is about 7 mm in the horizontal plane. In all the following results, the ECE imaging local oscillator frequency was adjusted to make the observational chord coincide with the Thomson laser path as closely as possible, correcting for the relativistic frequency shift.

3. Typical Appearance

Figure 1 shows a typical result of an off-axis instability near the $q=2$ radius (the identification of the instabilities with certain simple rational values of q will be elaborated on below). In this case, 300 kW ECH power is deposited (during 150 ms) at the low field side (LFS) at the minor radius where the hot "ears" are observed. An averaging over 40 consecutive sawtooth crashes has been performed in order to reduce the noise and to make clear the overall temperature behaviour. The off-axis nature (leaving the center nearly unaffected) is clearly visible, as is the symmetry of the phenomenon along the vertical (or z) axis. The sawtoothing period is 1-2 ms for this $q=2$ case, about the same as for the central $q=1$ sawteeth observed in Ohmic discharges in RTP. A beautiful

example of Thomson scattering measurements on a sawtooth crash of this type is shown in Fig. 2. It shows the pronounced hot "ears" (before the collapse) - resulting in a strongly hollow temperature profile - and the very different situation 400 μs later (at the second Thomson pulse) right after the crash.

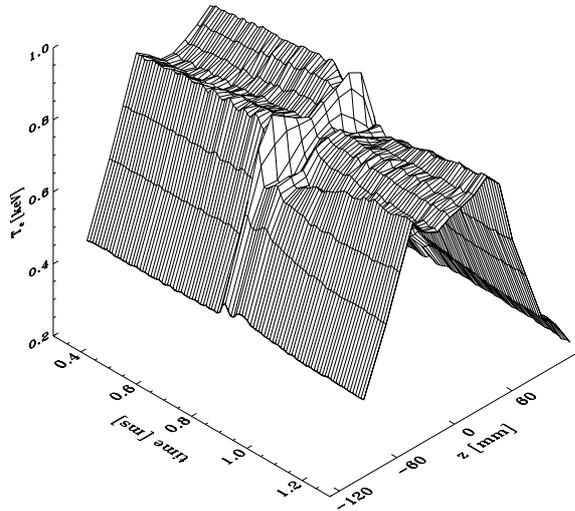


Figure 1. Example of a $q=2$ off-axis sawtooth event as measured by the imaging ECE system. About 40 successive crashes (shot no. r19980423.060, $I=65$ kA, $B=2.11$ T, 300 kW off-axis ECH) have been averaged to obtain the graph.

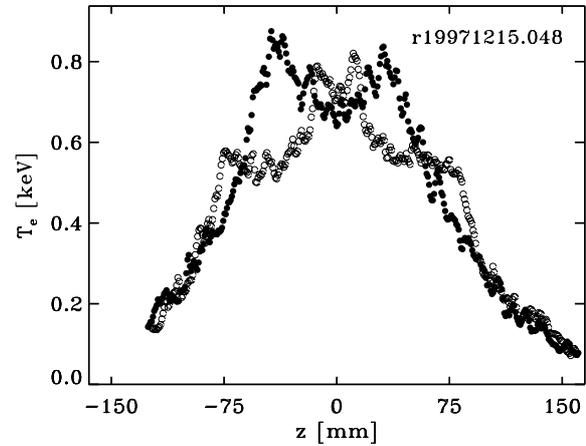


Figure 2. Thomson T_e profiles before (black dots) and after (open circles, 400 μs later) an off-axis sawtooth 'crash' at $q=2$. The central temperature changes only slightly.

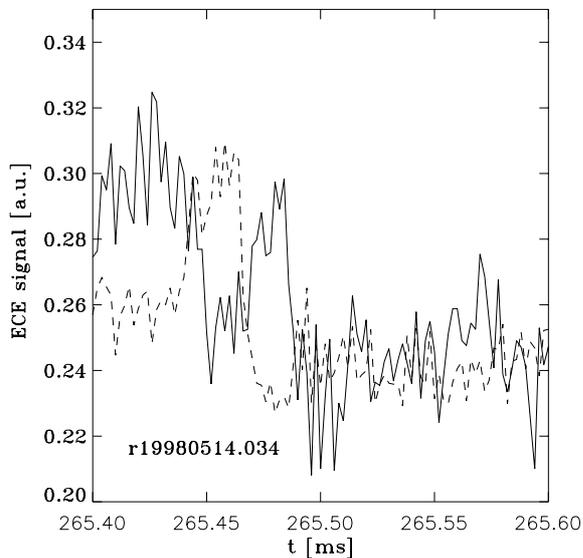


Figure 3. ECE signals at the temperature crash of a $q=2$ off-axis instability: vertical plane bottom (drawn) and horizontal plane, HFS (dashed), both at a minor radius of 30 mm. The vertical plane top channel (in phase with the bottom one), has been omitted for clarity.

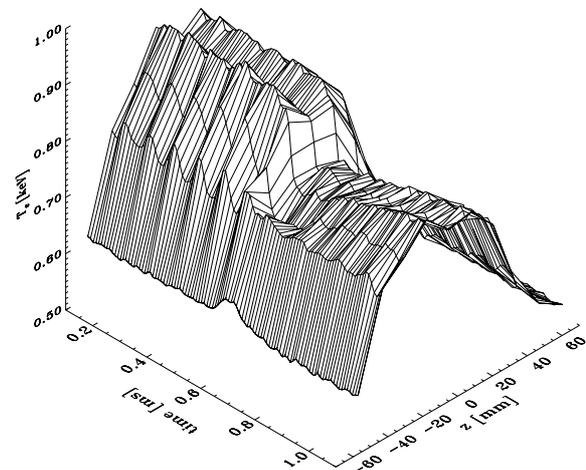


Figure 4. Example of a $q=3/2$ off-axis instability as measured by the ECE imaging system. About 20 crashes have been averaged (Shot no. r19980423.079, $I=65$ kA, $B=2.09$ T, 300 kW ECH).

At the crash time, a coherent mode can be observed, which sometimes (but not always) has the character of a growing precursor. To scrutinize the mode character of this dominant oscillation, signals from the "traditional" radiometer and ECE-imaging are plotted in Fig. 3. One can conclude from the graph that the collapse is not symmetric: one radiometer trace

(measured at the same minor radius but at the high field side (HFS)) clearly is out of phase with the ECE-imaging traces, which are in phase (only one is shown). The temperature drop is resolved and takes about 4-6 μ s on each of the ECE channels. The signals point to an $m=2$ type oscillation.

The family of sawtooth events can be extended by changing the deposition radius of the ECH power (by slightly changing the toroidal field): off-axis instabilities with a different character are then observed. Figure 4 gives a view of an instability which is associated with $q=3/2$. In this case, the center seems to be more affected, but this is due to the somewhat limited spatial resolution of about 1 cm: Thomson data on similar discharges [5] show a narrow range in the center to be nearly unaffected by the crash. The period of these oscillations is longer than in the $q=2$ case: 3-5 ms. Oscillations on both sides of the center can be seen: the ECE-imaging signals above and below the center are almost in phase and in antiphase with the signal of the radiometer at the corresponding horizontal location (compare Fig. 3): they point to an $m=2$ rotating mode. Oscillations of this type are frequently observed (and, in this case, must be somehow related to the crash position since they do not completely cancel out upon averaging) and help to pinpoint the location of the $q=2$ surface. In this specific case, the oscillations do not persist (in the averaged picture) after the crash, but there are also observations that do show this persistence.

When the ECH power is deposited further out, the $q=3$ variant of these instabilities is found (Fig 5). The odd parity mode character of the dominant oscillation at the crash time can be deduced from these averaged data. Again, the center is unaffected and the temperature profile is extremely hollow. The period of these $q=3$ events is about 0.7 ms.

4. q -Value Determination

The q -profiles of the discharges exhibiting central sawteeth (Ohmic discharge at 120 kA current) or off-axis instabilities have been calculated assuming neoclassical resistivity and a uniform Z_{eff} . The profiles indicate, that q is somewhat below 1 for the central sawteeth region, somewhat below $3/2$ for the instability region in Fig. 4, somewhat below 2 for sawteeth in Fig. 1, and below 3 for Fig. 5.

Confirmation of the identification of the instabilities with low rational values of q comes from the analysis of the crash (showing an $m=2$ character in Fig. 3 and an $m=3$ character in Fig. 5 and also -upon scrutiny- an odd parity for the crash in Fig. 4) and from the radial location of $m=2$ rotating modes that are frequently observed together with $q=3/2$ off-axis sawteeth: these appear just outside the main crash region for Fig. 4-type instabilities. The sawteeth in Figs. 1-3 show the clear even mode character that corroborates identification with $q=2$. Combination of this experimental evidence with the calculated q -profiles leads to the identification of the relevant q -values ($3/2$, 2, and 3) used to label the instabilities.

5. Reheat Rates

The reheat rates of the different sawteeth have been calculated using both averaged and raw data and appear to be approximately 70, 100, 200, and 250 eV/ms for the central, $q=3/2$, $q=2$, and $q=3$ events, respectively. The errors are considerable (at least 25 %) but the trend is significant. Assuming a no-gradient situation just after the crash, the theoretical temperature rise on the basis of the deposited ECH power (in the off-axis case) can be calculated to be around 2000 eV/ms. The difference with the measurements of a factor of about 10 and the trend for the central to $q=3$ sawteeth is under investigation.

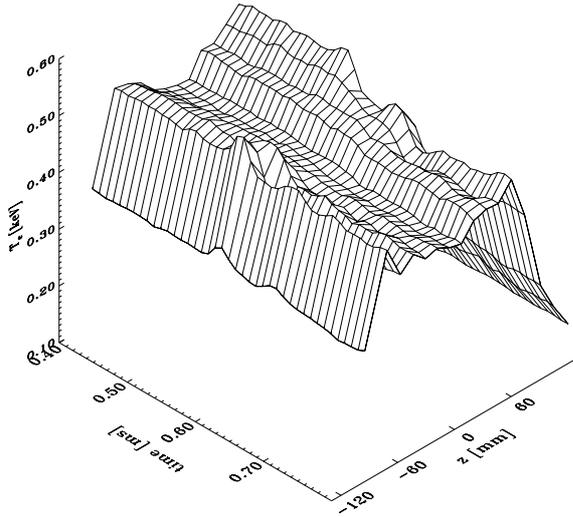


Figure 5. ECE profile of a $q=3$ off-axis instability (shot no. r19980423.067, $I=65$ kA, $B=2.18$ T).

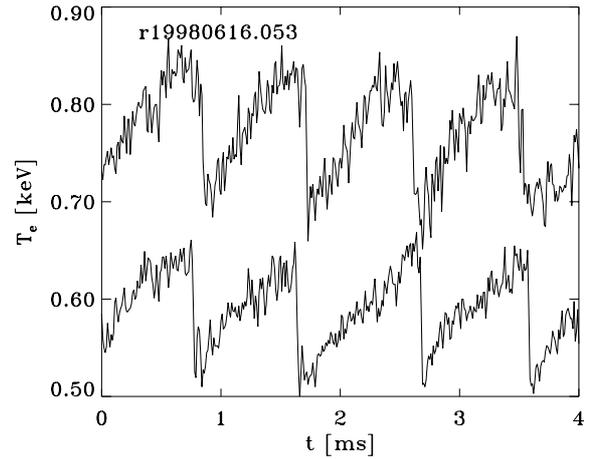


Figure 6. Typical off-axis $q=2$ sawteeth before (top) and after the decrease of the ECH power from 235 kW to 100 kW.

6. Parameter Study

In order to study the dependence of the off-axis instabilities on the deposited power, discharges showing the $q=2$ variant have been subjected to a sudden change in ECH power from 235 kW to 100 kW during the discharge. Normally, sawtoothing stops at the decrease of ECH power, only to resume about a current diffusion time (about 15 ms for RTP) later and lasting until the end of the ECH period. In one case the instabilities persist even during the power decrease. At the lower ECH power, the sawteeth show a somewhat smaller amplitude but an equal period and virtually the same reheat rate (typically 220 eV/ms at high power vs. 170 eV/ms at low power). This is illustrated in Fig. 6. The sawtoothing activity reacts to the large drop in ECH power by only a minor decrease in amplitude and reheat rate (20 %), while the period is unchanged.

The density has been varied during discharges with constant (high) ECH power, showing the onset of sawtoothing above line-integrated densities of about $2 \times 10^{19} \text{m}^{-2}$, but no significant changes in either period, reheat rate or amplitude have been observed.

7. Conclusions

We have observed a family of off-axis instabilities using Thomson scattering and two ECE-systems. These off-axis "sawteeth" occur in discharges with specific (off-axis) deposition of ECH power. The instabilities are found near simple rational values of q ($3/2$, 2, and 3) and show some clear parallels to the well-known central sawteeth. Only a slight influence of ECH power and density on the sawtoothing activity is observed. Other investigations, including the construction of a phenomenological model, are planned.

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