EFFECTS OF ECRH AND ECCD ON THE MHD RELAXATION PHENOMENA IN TCV

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This paper describes studies of MHD relaxation oscillations in the TCV tokamak (R=0.89m, a=0.25m, I_p<1.2MA, B_ϕ=1,44T) during ECRH (> 1MW power) and ECCD [1]. Observation of the temporal evolution of the soft-X emissivity revealed various characteristic features apart from the standard "sawtooth" shaped relaxation oscillations. In many cases the appearance of particular shapes, like inverted sawteeth, humpbacks, and hills could be attributed to changes in the power deposition with respect to the inversion surface (or q=1 surface). These studies have taken advantage of the flexibility of TCV to move the plasma in vertical direction during a shot. The power deposition has also been varied by sweeping the launching angle of the ECW beam (using steerable mirrors) and by varying the toroidal field strength. Different types of relaxation oscillations as seen on the soft-X emissivity signals[2,3] are shown in Fig. 1.

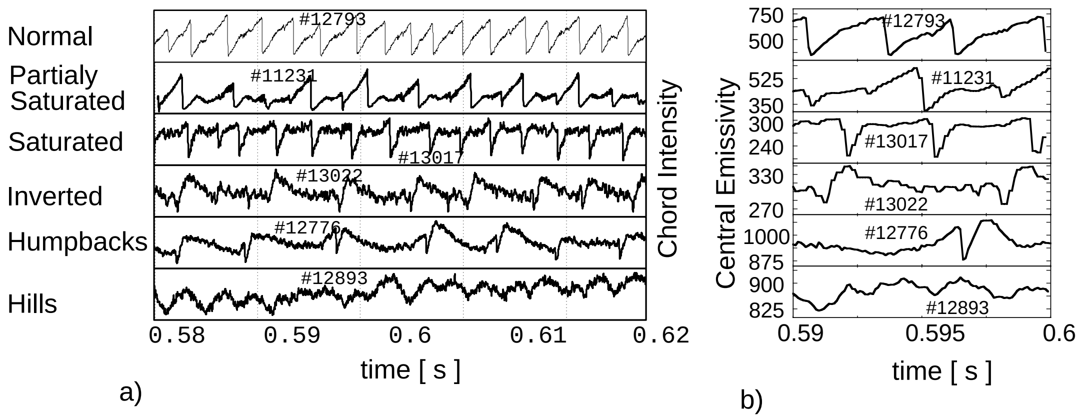

Figure 1. Different relaxation shapes observed during ECRH a) as seen by line integrated measurements, b) central (magnetic axis) emissivity from tomographic reconstruction show similar time dependencies.

In the case of ordinary sawteeth the variation of soft-X emissivity is usually interpreted as a variation in electron temperature. Our measurements indicate that this is no longer true for some of the other types of relaxation oscillations (such as humpbacks). Since the plasma emissivity in the soft-X range of wavelength is influenced not only by the electron temperature, but also, by the electron density and the effective ion charge, periodic variations of these parameters could, in principle, also influence the appearance of the relaxation oscillations. However, there are no other indications for rapid changes in electron density or Z_{eff}. Still, from a comparison between soft-X emissivity and temperature from Thomson scattering we find that in the case of the humpbacks the soft-X signal rises after a crash to a higher value than it would from the electron temperature alone. The evolution of central T_e (from Thomson scattering) and X-ray emissivity (at the same time steps) are shown in Fig. 2. In this figure the data taken from several humpbacks are represented on a normalized time scale (period fraction). Crashes occur at the normalized times "0" and "1".

Trying to generalize the temperature evolution during the cycle of a relaxation oscillation in the presence of ECRH, we find : $T_e(0)$ rises during the interval t1 after a crash, then saturates (interval t2), and finally rises again before the next crash (t3). Different shapes of sawteeth are just different combination of these times and the amount of non-thermal radiation: Normal "triangular" sawteeth do not have a saturation phase (t2=0); Saturated sawteeth have little or no temperature rise before a crash (t3≈0); Inverted sawteeth and humpbacks have a lot of non thermal radiation after crash; and hills are gentle fluctuations of a hot plasma (no instability, but SVD shows the inversion surface on large hills), representing the plasma behavior during fully stabilized sawtooth phase.

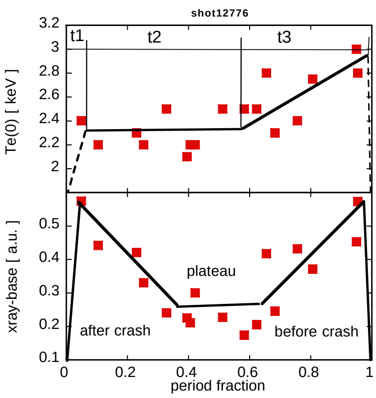

Figure 2. Central electron temperature as a function of the period fraction collected for many humpbacks of one shot, and central X-ray emissivity taken at the same time as temperature. Lines represent schematic behavior of both values.

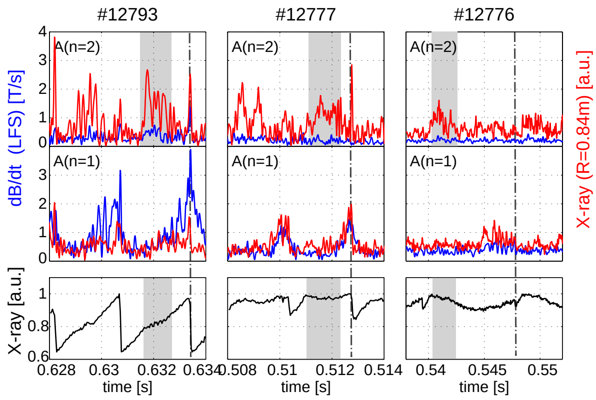

Figure 3. Toroidal mode activity during some of the sawtooth shapes. Vertical line indicate times of the crash in one of the sawtooth at each shot and gray lines indicates the strong n=2 mode activity. Modes activities seen by magnetic and X-rays are shown.

The saturation of temperature is caused by n=2 mode activity, present at the time of saturation, see figure 2. The mode (n=2) which creates saturation later decays and the temperature starts to rise again until the sawteeth crash. The mode n=1 is visible as a precursor to the crash and is growing during the second temperature increase. There is an apparent separation of modes, n=2 for temperature saturation and n=1 as a precursor to a crash.

The shape and the sawtooth period are not correlated. The sawtooth period is longest when heating near the inversion surface, and is the same in all positions on this surface. The sawtooth shape for the same shot, however, may be different when heating on different part of this surface, see Figure 3.

As expected, the sawtooth period is function of the current density profile, while the sawtooth shape is influenced by the n=2 mode which causes the temperature to saturate, and the amount of non-thermal radiation. This non thermal radiation seems to be correlated to a small amount of current drive which changes with the heating position on the flux surface. That is the current drive changes from the co to counter direction when heating below or above the midplane. The humpbacks and inverted sawteeth have been observed only with some amount of counter current drive on TCV.

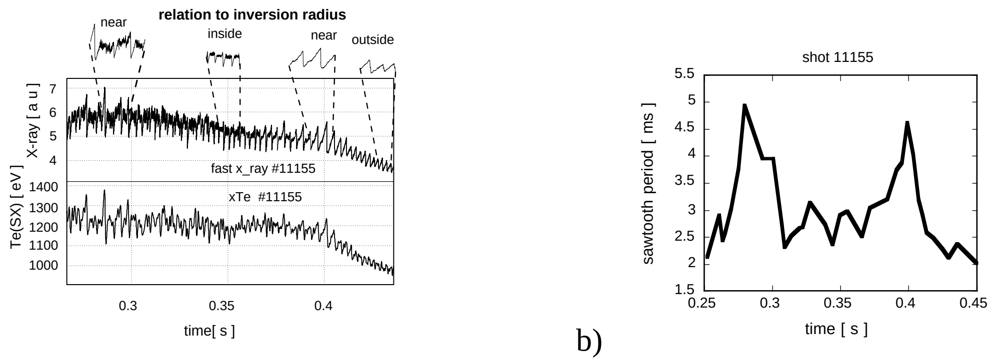

Figure 4. a) time dependence of X-ray radiation and soft X-ray temperature, beam crosses the inversion surface and 0.28 s "down" and 0.4 s "up". b) sawtooth period for the same shots.

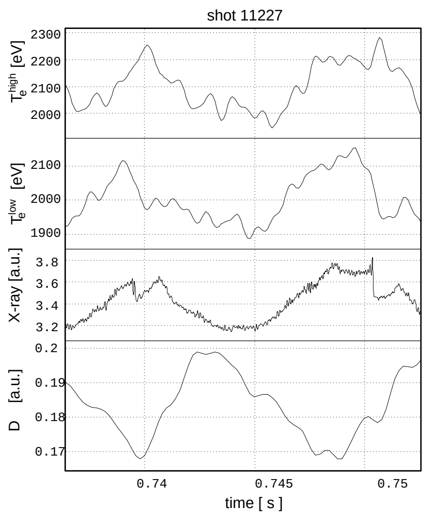

Figure 5. Time dependence of X-ray temperature, difference between high and low temperature and x-ray intensity for a shot with humpback sawteeth.

There are four wavelength channels of X-ray intensity for X-ray temperature measurements. As the X-ray temperature can be determined by only two spectral points, two "temperatures" may be calculated from measured signals and these two "temperatures" could be the same for a Maxwellian electron plasma. In Figure 5 two of these "temperatures" are plotted as a function of time for a shot with humpbacks relaxation. The "low" temperature refers to a combination of filters with lower pass cutoff energy than the "high" temperature combination. In this figure the D_α signal is also plotted.

One can see that just after the crash the difference in temperatures rises rapidly (the maximum value of the "high" temperature is after the crash in humpback) indicating an excess of the high energy photons at that time. This could indicate the presence of high energy electrons which produce radiation in excess of the Bremsstrahlung radiation of a single temperature of Maxwellian plasma. The "low" temperature corresponds closely to "Thomson" temperature, which is measured from the bulk electron distribution function. The high energy tail may exist before the crash, but is not effected by the crash and this is why the difference is larger after the crash; or, the crash may generates fast electrons which are enhanced by ECRH in certain heating conditions (small amount counter current drive).

The size (average radius) of the inversion surface during heating (ECRH) and co or counter current drive (ECCD) in the plasma center. The typical changes are visible in Figure 6. With ECRH the inversion surface expands when heating inside and has the largest radius when heating at inversion surface. It shrinks when the heating moves outside and it may even disappear, (q(0) is pushed above one).

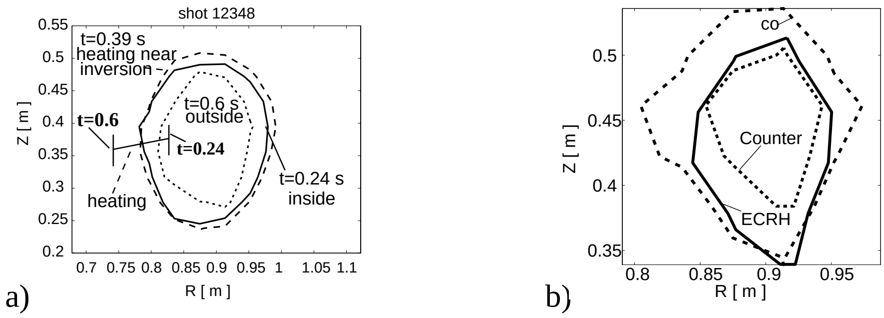

Figure 6. Inversion surfaces for a) shot with sweeping radial position of heating and b) for shots with ECRH Co and Counter CD.

Similarly for co ECCD the surface expands since a larger fraction of the total current is inside this surface and the surface shrinks with counter ECCD. The sawtooth shapes with co CD are either normal or saturate, while for the same target plasma counter CD produces full sawtooth stabilization (Hills) with the optimum wave elipticity, or humpbacks when most of the power is in the O-mode [4].

As mentioned befire during ECRH the maximum sawtooth period is obtained with the heating position at the inversion surface. With enough power the sawteeth may disappear completely, giving full sawteeth stabilization by modification of the shear near the q=1 surface. On the other hand we can drive q(0) above one by heating outside of the inversion surface and also obtain full sawteeth stabilization. Thus, two approaches to sawteeth stabilization are possible; by increasing sawtooth period to infinity, or by reducing it to zero.

In some situations humpbacks appear at two different normalized radii, when moving the power deposition location during a shot. The first one with power deposition near the inversion surface and the second series of humpbacks appears near the q=2 surface as calculated from magnetics. This second series may not be related to the q=2 surface but rather to the q=1 surface, since for a flat q-profile the inversion surface and the q=1 surface are largely separated and the q=1 surface calculated by the magnetics may be too small.

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