SAWTOOTH ACTIVITY DURING ADDITIONAL HEATING IN JET

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ABSTRACT Sawtooth oscillations have been studied with a wide variety of diagnostics in JET in additionally heated discharges. Multichordal measurements, combined with tomographical reconstructions, have allowed a detailed experimental study of the sawtooth collapse with high time resolution. It is shown that the initial part of the collapse has m=1 topology.

1. INTRODUCTION Sawtooth activity has been studied in JET during both ohmically and additionally heated discharges using a large number of diagnostics, including two X-ray diode array cameras, a 12 channel ECE grating polychromator, four channel Fabry-Perot and Michelson ECE systems, a microwave transmission interferometer, a microwave reflectometer, bolometry and a multi-chord far infrared interferometer. Sawteeth have also been observed by the neutron diagnostics and on the particle fluxes and ion temperatures determined by a set of four neutral particle analysers.

2. SAWTEETH DURING ADDITIONAL HEATING During both neutral injection and radio-frequency heating the sawtooth oscillation increases in amplitude and its period becomes longer (Figure 1). The observation of partial sawteeth is common and the sawteeth are accompanied by a wide range of mhd activity in the plasma central region, generally with m=1.
In particular, we often observe: (i) strong successor oscillations following the sawtooth collapse; (ii) strong mhd activity accompanying the partial sawteeth; (iii) a large saturated m=1 mode which is sometimes seen before the sawtooth collapse during RF heating and (iv) a large amplitude m=1 mode seen during beam heating. The main sawtooth collapse generally occurs without mhd precursors. During ohmic heating typical mhd frequencies of ~ 1 kHz are seen and with ICRH this decreases, sometimes to 250 Hz. With 4.5 MW of tangential beam heating the frequency increases to ~ 5 kHz, corresponding to plasma rotation with $v = 10^5\ ms^{-1}$. The radial location and poloidal mode number of the mhd activity in the central region has been studied with both the soft X-ray cameras and the ECE systems. For a particular discharge, the maximum amplitude of the mode occurs at approximately the same minor radius slightly inside the sawtooth inversion radius, regardless of its phase within the sawtooth

cycle. These modes are thought to occur on rational q surfaces and their relation to the q=1 surface is under investigation.

3. THE SAWTOOTH COLLAPSE A detailed study has been made on JET of the rapid (~ 100 µsec) part of the sawtooth collapse with the X-ray and the ECE systems. The two X-ray cameras view the plasma from vertical and horizontal ports at the same toroidal location with 38 and 62 detectors respectively. The detectors are shielded with 140 µm of Be to enhance their sensitivity to radiation from the central region of the plasma from which the emission is due mainly to He-like Nickel for RF heated discharges and recombination for beam heated discharges.

Further information on the sawtooth collapse comes from the ECE diagnostics. In particular the electron temperature at a fixed radius is measured with very high time (10 µsec) and temperature resolution (30 eV) using a Fabry-Perot instrument and the sawtooth development in both time and radius along a fixed chord is measured with a 12 channel polychromator system with similar resolution.

A typical sawtooth collapse, with successor oscillations, taken during an RF heated discharge, is shown in Figure 2. The letters A-F indicate the times used for Figure 4. A contour plot showing the X-ray signal intensities from the vertical camera as a function of detector number and time, taken at 200 kHz sampling frequency (Figure 3a), shows that the collapse occurs in ≈ 100 µs and in this case with a rapid outward movement of the hot central plasma core. A similar plot for a different sawtooth collapse taken with the ECE polychromator with a digitization frequency of 20 kHz (Figure 3b) shows that the plasma temperature behaves in a similar way to that of the X-ray emission but in this case with an inward movement. These measurements indicate that the initial part of the sawtooth collapse is due to bulk motion of the hot centre of the plasma off axis to r/a ≈ 0.3.

The detailed nature of the collapse and its successors have been studied by tomographic analysis 1) of the data from both X-ray cameras. By fitting the experimental data with radial Zernicke polynamials $\ell=8$ and angular harmonics m=2 (but excluding sin 2θ), the line integrated data observed by each X-ray detector is reduced to a two dimensional function of X-ray emissivity as a function of plasma major radius and height. The tomographic reconstructions were carried out at 5 µs intervals throughout the sawtooth collapse. Some of these reconstructions are shown in Figure 4 in the form of contour plots and illustrate the main features of the collapse. On each plot the relative times are shown and the maximum radiated power, P_m. Initially the hot central core moves rapidly away from the centre with a maximum velocity of $2\text{x}10^3$ ms^{-1} until it reaches r/a ~ 0.3 where the outward motion stops. The hot region then collapses on a time scale of 100 µs while at the same time the emissivity in the remainder of the central region increases. This implies a mixing of hot and cold plasma regions or rapid conduction of heat during this phase of the collapse. The final emissivity profile is not completely poloidally symmetric and it is the subsequent rotation of this distribution which is responsible for the observations of successor oscillations as can be seen from Figure 4. In other sawtooth collapses, without successor oscillations, the final state is completely poloidally symmetric.

The tomographic analysis clearly determines the m=1 character of the initial phase of the collapse and the strong n=1 mode seen by the magnetic coils at the plasma edge 2) to accompany the sawtooth collapse then determine the sawtooth collapse as an m=n=1 mode. The initial fast plasma motion occurs at different poloidal angles as expected for m = 1.

Our observations do not generally seem in good agreement with existing theoretical models and in particular are in disagreement with models which require growing or static magnetic islands before the sawtooth collapse

However, a very recent theoretical model3), in which the plasma motion occurs on a rapid time-scale due to an ideal m=1 mode would account for many of the features of our observations, particularly the observed initial plasma motion.

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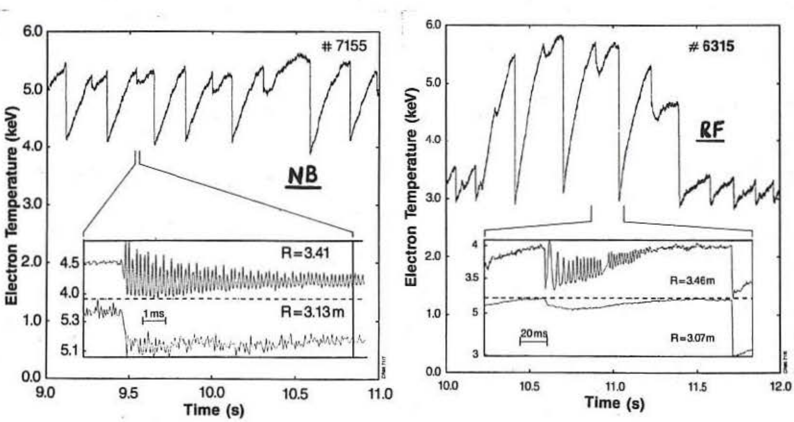

Figure 1 Sawteeth during additional heating. Note the much higher frequency mhd activity during the neutral beam heating.

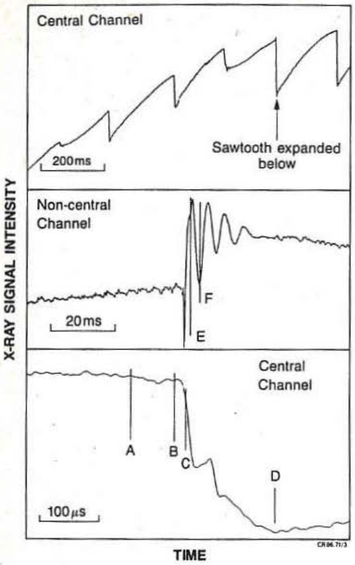

Fig. 2. X-ray signal on different timescales.

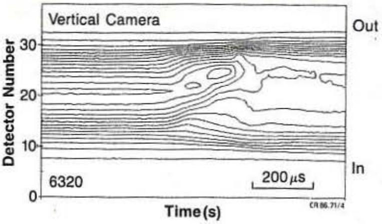

Fig. 3.(a). X-ray contour plot of line integrated intensity during sawtooth collapse

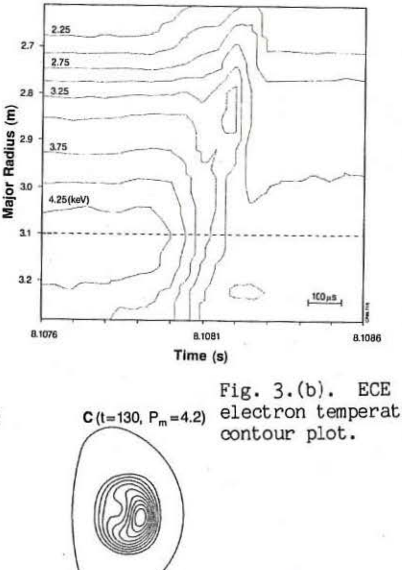

Fig. 3.(b). ECE electron temperature contour plot.

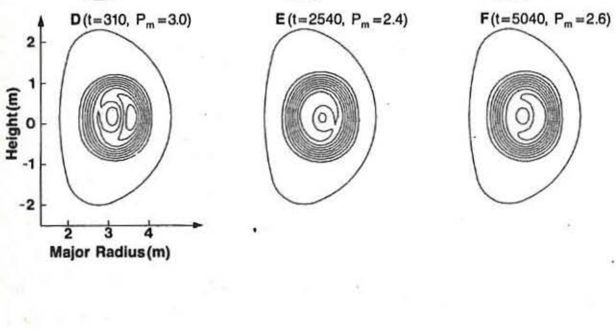

Fig. 4. Contour plots of X-ray intensity versus plasma height and major radius.