DENSITY PERTURBATIONS AT RATIONAL q–SURFACES FOLLOWING PELLET INJECTION IN JET

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Introduction – The ablation of pellets injected in JET [1] produces a pronounced resonance effect at rational q – values of 1 and 3/2. After ablation, $m = 1, n = 1$ and $m = 3, n = 2$ structures are observed as compact snake-like perturbations [2] by the soft x-ray cameras. The "snake" oscillation is caused by a rotating localised region of higher density, which can persist for $\geqslant 2\ s$. The observed effect can be used to measure the dynamic behaviour of the $q = 1$ and $q = 3/2$ surfaces. In particular, new information on the evolution of the q – profile during sawtooth collapses is obtained. The characteristics of these perturbations, their relationship to rational q – surfaces, and possible explanations for the existence of the "snake" are presented.

Observation of the snake oscillation – Two soft x-ray cameras[3,4] containing 100 detectors view the plasma with a spatial resolution of $\approx 7\ cm$ in orthogonal directions at the same toroidal position as the D_2 pellet injector. Pellets of 2.2×10^{21} or 4.5×10^{21} atoms are injected in the horizontal plane into ohmically heated JET plasmas $(2 \leqslant B_T(T) \leqslant 3,\ 3 \leqslant I_p(MA) \leqslant 3.6)$ with velocities of $\sim 1\ km/s$. Their penetration and ablation is deduced by observing the intense bremsstrahlung emission from interactions of plasma electrons with pellet particles, using the vertically mounted soft x-ray camera (fig. 1).

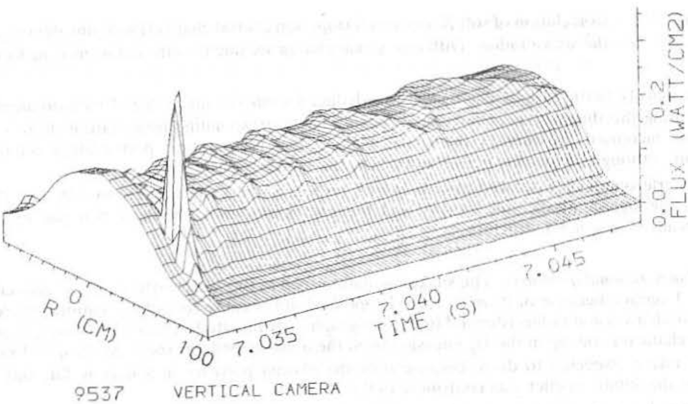

Fig. 1 : Soft X–ray flux (vertical camera, 140 μm Be – filter) around the time of pellet injection showing the initial peak from ablation and the subsequent "snake" oscillation.

Immediately after pellet ablation, the x-ray emission decreases due to the cooling of the plasma. The most striking remaining effect is the observation of a snake-like modulation superimposed on a symmetric emission profile. The snake is caused by the rotation of a small region of plasma with usually enhanced x-ray emission. The dimensions of this region and its position in the plasma can be accurately determined both directly from the experimental data, and also by tomographic reconstruction techniques. A typical snake has dimensions of of ~ 15 *cm* (FWHM) in radial and of ~ 25 *cm* in poloidal direction.

Plasma parameters in the snake region – The temperature and density in the snake region are determined from an ECE polychrometer and a 2 *mm* microwave transmission interferometer (fig. 2).

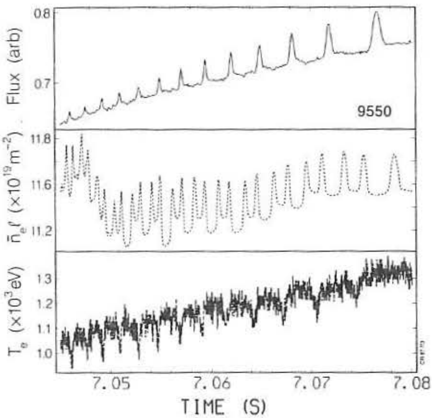

Fig. 2 : Correlation of soft X–ray signal (top, non central channel) with line density and T_e at the snake radius. Different signal phases are due to different measuring locations.

Large density perturbations $\delta n_e/n_e \leq 1$ are deduced from the line integral measurements of the density using the dimensions of the snake region. The corresponding temperature drop is smaller, indicating increased pressure in the snake region. The temperature perturbation reduces after ~ 100 *ms*, although the density perturbation remains unchanged.

The interferometer is displaced toroidally with respect to the x-ray cameras by 135° and the phase between the signals of the line density and the soft X–ray emission show that the snake has a topologically $m = 1, n = 1$ structure.

Relation to rational q–values – The snake oscillation seen in fig. 1 is clearly an effect associated with the $q = 1$ surface because of its $m = 1, n = 1$ topology and because its radial location coincides with the sawtooth inversion radius (derived from tomographically inverted signals). Moreover, at this same radius a characteristic dip in the D_α emission from the ablating pellet is seen. At the $q = 1$ radius the ablation rate is expected to drop, because only the plasma particles in a narrow flux tube, which intersects the ablating pellet, can contribute to the ablation.

Another observation is that the snake oscillation is more frequently seen, when the pellet is injected just before a sawtooth collapse. At this time the $q = 1$ radius has probably grown to its maximum value and the $q = 1$ surface is more easily accessible to the injected pellet, as shown later.

Occasionally, in addition to the snake at $q = 1$, a perturbation of higher symmetry is also seen. Analysis of the complicated soft X–ray signal patterns reveal a $m = 3, n = 2$ structure. A clear correlation with $m = 3, n = 2$ magnetic signals is also found, and the location of the perturbation coincides with the calculated position of $q = 3/2$.

Lifetime of the snake – The local density enhancement at $q = 1$ can persist for $\geqslant 2\ s$ without a significant decay or spreading during that time. This is even seen after several sawteeth which leave the structure unaffected. Fig. 3 shows the snake modulation during two 100 *ms* time intervals of the same discharge. Generally, the rotation slows down after some 100 *ms* and the snake is locked between sawtooth collapes (fig. 3 b, ~ 0.9 *s* after pellet ablation). During the sawtooth collapse a rotation is initiated for a short time.

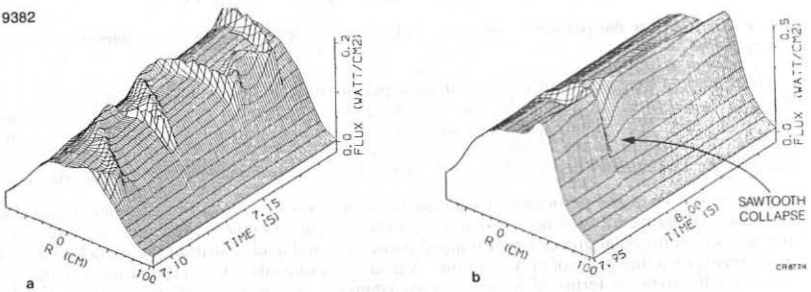

Fig. 3 : X – ray emission (vertical camera) showing a long lasting snake. In the later phase (b) the oscillation has locked. The sawtooth does not change the snake.

The long lifetime of the snake can be used to make a continuous determination of the position of $q = 1$. In particular, a large rapid inward shift of the $q = 1$ radius is seen during the sawtooth collapse phase followed by a slow expansion of the $q = 1$ surface after the collapse (fig. 4).

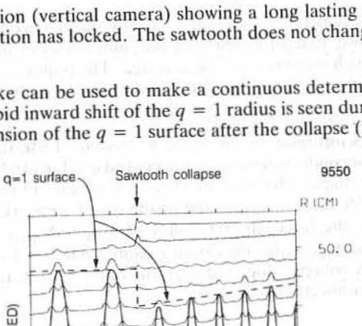

Fig. 4 : X – ray signals during a sawtooth crash, which shows the inward shift of $q = 1$ derived from the snake oscillation.

Discussion – In the case of an axisymmetric equilibrium, perturbations of temperature δT and density δn are expected to spread out poloidally by collisional diffusion along the magnetic field lines. Around $q = 1$, the spreading times scale like :

$$t_{spread} \sim \frac{1}{(1-q)^2}$$

Given the plasma parameters in the "snake" region, these values are found to be

$$t_{spread} \sim 100\ \mu s \text{ for } \delta T \quad \text{and} \quad t_{spread} \sim 10\ ms \text{ for } \delta n$$

These are times for the perturbations to fall below a 10 % level outside a very narrow region with $|1-q| < 10^{-2}$.

The observed long persistence of the density perturbation therefore implies the *formation of a magnetic island* at $q = 1$ due to the local cooling and the associated current perturbation along a helical flux tube. We estimate that a magnetic island of several centimeters width would grow within a time of $\sim 100\ \mu s$ due to the initial temperature perturbation $\delta T/T \geq 0.2$. During this time ablated particles are continuously deposited at $q = 1$, which later are confined effectively in the island.

The *persistence* of the particles in the magnetic island, however, is difficult to understand. First, neoclassical (banana diffusion regime) particle confinement times in the snake region are only $\sim 0.3\ s$; and second, the toroidal precession of trapped particles would lead to drift of the particles out of the snake region on a time scale of only $\sim 15\ ms$. A plausible explanation for the persistence of the snake may then be given in terms of a new non-axisymmetric stationary equilibrium, which has been accessed by the pellet injection. The higher density in the snake region could be maintained by inward convection, in a similar but not understood manner to the inward convection of particles in the bulk of the tokamak plasma.

Another observation is that the temperature perturbations become very small after $\sim 100\ ms$. However, calculations show, that an *island* with the dimensions of the snake can be *maintained* by $\delta T/T \approx 10^{-2} - 10^{-1}$, which is too small to be detected. The required current perturbation could also be produced by a local change of Z_{eff} due to the electric potential associated with the locally enhanced deuteron pressure.

The observed effect gives information about the $q-$*profile* : First, the radial position of $q = 1$ (and $q = 3/2$) are derived, and secondly estimates of the central q value can be made from the radial shift of $q = 1$ during a sawtooth collapse. Because the change in q caused by sawteeth in JET is $\Delta q \sim 0.02$ only[5], a smooth q – profile has to be very flat inside $q = 1$ with $q(0) \sim 0.97$ before the sawtooth crash in order to produce the large observed shift of $r_{q=1}$ ($\Delta r_{q=1}/r_{q=1} = -1/3$, fig. 4). For the discussion of sawtooth models it is also important to note, that $q = 1$ exists throughout the sawtooth cycle, and that a sawtooth collapse does not seem to cause a large rearrangement of the magnetic topology (eg. complete reconnection at $q = 1$).

References

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