Persistent Density Perturbations at Rational-q Surfaces Following Pellet Injection in the Joint European Torus

A. Weller,[a] A. D. Cheetham, A. W. Edwards, R. D. Gill, A. Gondhalekar, R. S. Granetz,[b] J. Snipes, and J. A. Wesson

JET Joint Undertaking, Abingdon, Oxon OX14 3EA, United Kingdom

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In the Joint European Torus the ablation of injected pellets produces a striking resonance effect when the pellets reach surfaces with q values 1 and $\frac{3}{2}$. Subsequently, structures with mode numbers $m=1,n=1$ and $m=3,n=2$ are observed with the soft-x-ray cameras for up to 2 s as compact snakelike perturbations. These structures, which persist through several sawtooth collapses, give information on the radii of the $q=1$ and $q=\frac{3}{2}$ surfaces and the q-profile evolution. The observations can be explained by the formation of magnetic islands.

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The effects of injection of solid D_2 pellets into the discharges of the Joint European Torus (JET) have been studied[1] with use of the soft-x-ray imaging system. Immediately after pellet injection a very localized density and temperature perturbation has been found with $m=1,n=1$ topology. This perturbation exists for a very long time (>2 s), is clearly associated with the $q=1$ magnetic surface, and acts as a probe for this surface allowing, for example, the study of the position of the $q=1$ surface during a sawtooth cycle. Similar structures are seen with $m=3,n=2$ on the $q=\frac{3}{2}$ surface. The effects of ablation at rational q values have been seen previously[2,3] as irregularities of the H_α emission. The characteristics of these perturbations and possible explanations for their origin are presented.

Observation of the "snake" modulation.—Two soft-x-ray cameras[4,5] view the plasma with a spatial resolution of 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, injected radially in the equatorial plane into Ohmically heated JET plasmas ($B_\phi=2$–3 T, $I=3.0$–3.6 MA, elongation of 1.4, $a=1.2$ m, $R=3$ m) with velocities of $\simeq 1$ km s^{-1}, are detected with good temporal resolution (up to 100 kHz) by the vertically mounted soft-x-ray camera (Fig. 1). The discharges have regular sawteeth both before and after pellet injection. Immediately after pellet ablation, the density profile becomes very hollow and the temperature drops, leading to decreased x-ray emission. However, the most striking effect is the observation of a snakelike perturbation superimposed on a symmetric emission profile. The observations also show that the "snake" is due to the ro-

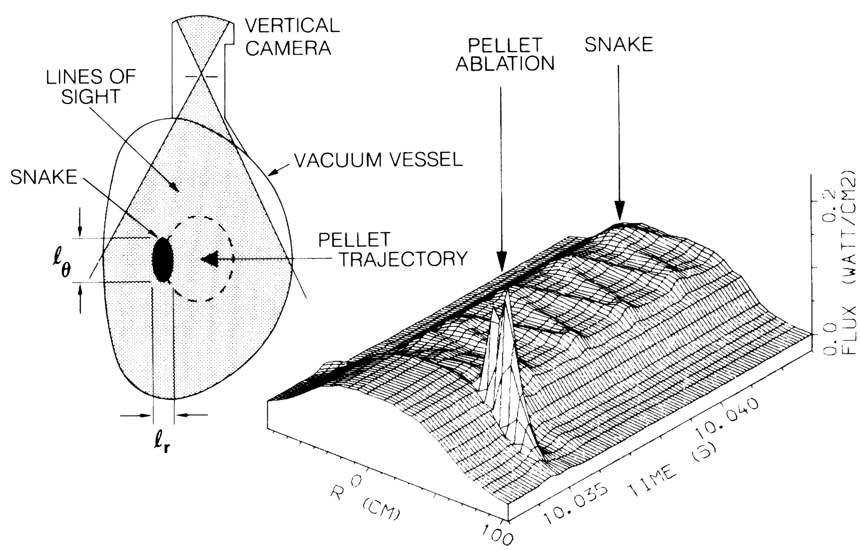

FIG. 1. Pellet ablation (10.035 s) and snake oscillation seen by the vertical soft-x-ray camera (50-μm Be filter). The x-ray flux is shown as a function of time and detector chord radius (R) measured from the plasma center.

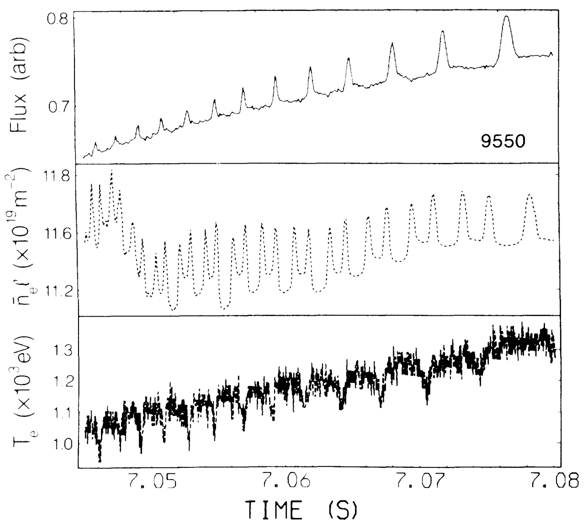

FIG. 2. Time correlation of x-ray flux, line density (from the 2-mm system), and T_e at the snake radius. (The soft-x-ray channel views close to the snake radius and therefore sees only one peak per turn.) The different phases of the signals are due to different measuring locations.

tation of a small region with enhanced x-ray emission.

The poloidal dimension (FWHM) of the snake (Fig. 1) is typically $l_\theta \approx 25$ cm and is calculated from the transit time across the field of view of either a central x-ray channel or the interferometer. The radial dimension, typically $l_r \approx 17$ cm, is calculated from the relative intensities of the snake viewed radially or poloidally.

In addition to the snake, a *transient* $m=1,n=1$ sinusoidal MHD oscillation is usually seen just after pellet injection. This effect has also been observed on other machines.[6]

Plasma parameters in the snake region.— The temperature and density in the snake region are determined with an electron-cyclotron-emission polychromator, a multichannel far-infrared interferometer, and a 2-mm microwave transmission interferometer (Fig. 2), with typical values given in Table I. The very large density perturbations are calculated from the line-integral measurements of density with use of the dimensions of the snake region determined by the x-ray and line-density measurements. The density within the snake can be up to twice that of the surrounding plasma although the total number of particles in the snake is only $\approx 1\%$ of the injected pellet particles. It is also observed that the snake can survive the substantial changes in density profiles, from hollow to peaked, which take place in the time (≈ 100 ms) immediately after pellet ablation. In the snake region, the temperature drop, ΔT_e, is always much smaller than the increase in density, implying locally increased plasma pressure. The ΔT_e gradually reduces after $\simeq 100$ ms to an undetectable level less than 100 eV, although the density increase, Δn_e, is unchanged. The topology of the snake is determined as $m=1,n=1$ from the soft-x-ray signals and the relative phase of the interferometer signal.

Relation to rational q values.— The observation that the snake has $m=1,n=1$ topology provides strong evidence that it is on the $q=1$ surface. This conclusion is reinforced by the fact that it is at the sawtooth inversion radius observed on the tomographically reconstructed soft-x-ray emission before pellet injection. Also in agreement with this interpretation are the following facts: (i) The formation of the snake depends sensitively on the location of maximum pellet penetration which must be inside the $q=1$ surface. (ii) There is a characteristic dip in the H_α light from the ablating pellet as it crosses the $q=1$ surface. The reduction in ablation occurs on this surface because only particles from a flux tube with $m=1,n=1$ are available, rather than the particles over the whole magnetic surface.

A similar effect is also seen associated with the $q=\frac{3}{2}$ surface. The x-ray signal patterns are more complicated, but an $m=3$ pattern with twice the frequency of the simultaneously observed $m=1$ modulation is clearly seen and is well correlated with the signals from the $n=2$ magnetic pickup coil combination. The radius of the $m=3$ perturbation coincides with the calculated $q=\frac{3}{2}$ radius.[7]

Lifetime of the snake and the position of the q=1 surface.— The snake is very long lived; it can survive sawtooth crashes, and can persist for longer than our ob-

TABLE I. Parameters of typical snakes. Shot 9550 was injected with a small pellet, the other shots with large ones.

Shot number	Time after pellet ablation (ms)	Δn_e (10^{19} m^{-3})	n_e (10^{19} m^{-3})	ΔT_e (eV)	T_e (eV)	l_θ (cm)	l_r (cm)	Duration of snake (s)
9550	13	3.4	4.9	135	1200	24	14	0.85[a]
9382	240	2.6	6.6	<100	1180	24	17	≥ 1.9[b]
9378	220	1.5	6.2	<100	1150	31	16.5	≥ 1.9[b]
9228	10	3.6	4.9	210	650	25	19.5	0.23[a]

[a]Terminated by a soft disruption.

[b]Still present at end of data acquisition.

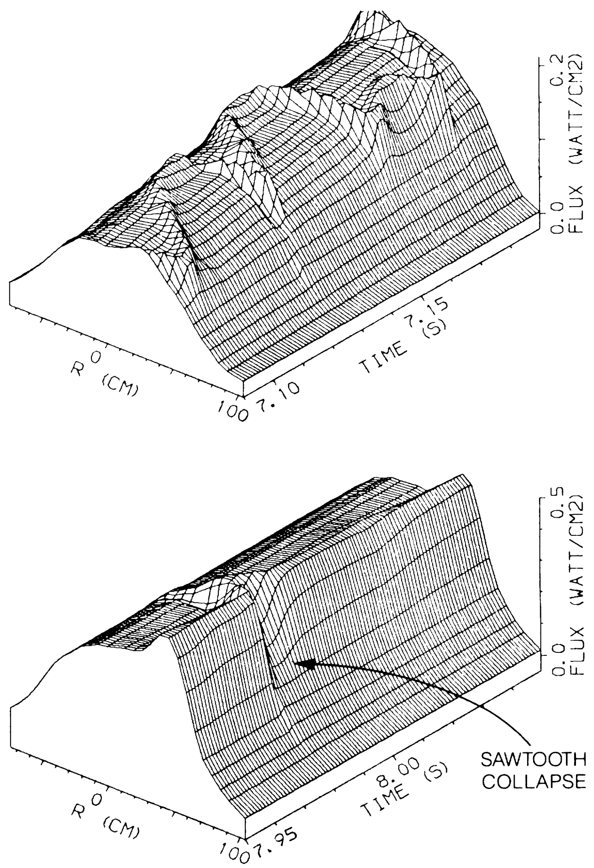

FIG. 3. X-ray signals from the vertical camera showing a long-lasting snake oscillation, which is locked in the lower figure. The relative amplitude of the snake is unchanged by the sawtooth collapse.

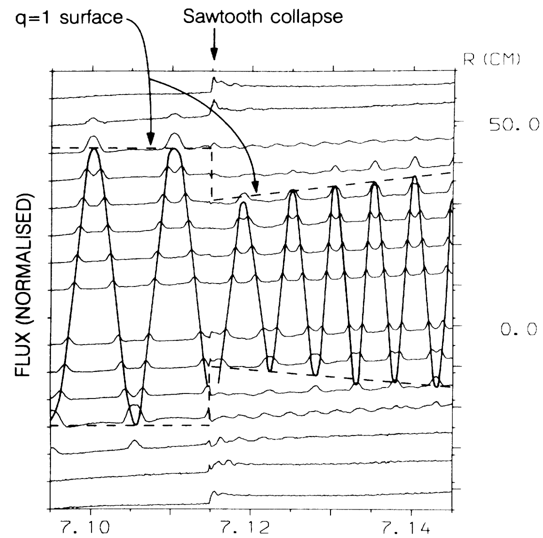

FIG. 4. X-ray–flux plot for the vertical-camera signals showing the inward shift of the snake during a sawtooth collapse. The solid line follows the point of maximum emission and the dashed line shows the inferred radius of the $q=1$ surface.

servation time (2 s). Its relative amplitude can have a decay time of >10 s or it can even increase. In Fig. 3 the x-ray emission profiles for two 100-ms time intervals show the persistence of the snake over 800 ms and the effect of a sawtooth collapse. The rotation observed in the upper part of the figure, unlike that of MHD oscillations in Ohmic plasmas, is in the plasma current direction; in the lower part there is no rotation although it restarts at later times. The snake is sometimes destroyed by a soft disruption or a very large sawtooth collapse.

The long lifetime of the snake allows the determination of the position of the $q=1$ surface (and $q=\frac{3}{2}$) during the sawtooth cycle. In Fig. 4 a substantial inward shift of the snake is seen after a sawtooth collapse with a 40% change in radius. This is followed by a slow outward movement of the snake and, therefore, also the $q=1$ surface.

Discussion.—The plasma behavior in the snake is unexpected and difficult to explain. If the equilibrium were to remain axisymmetric after injection of the pellet, the temperature and density perturbations would rapidly spread out along the magnetic field lines. Consequently, the perturbations would spread by collisional diffusion over the flux surfaces within tens of milliseconds, except for a very narrow region with $|1-q|<10^{-2}$. The persistence of the perturbation for $\gtrsim 2$ s therefore implies a changed magnetic topology. In fact, the temperature perturbation would be expected to produce such a change, as it would cause a (neoclassical) resistivity change $\tilde{\eta}$ producing a diffusive reduction in current density given by $\partial\tilde{j}/\partial t=(j_0/\mu_0)\nabla^2\tilde{\eta}$. The corresponding radial field perturbation then produces a magnetic island.[8] These calculations show that the observed $\Delta T_e/T_e$ is sufficient for the island to grow to the required size during the pellet deposition at $q\approx 1$. The question then arises as to how the perturbation persists.

If the persistence is assumed to be due to good confinement, a limit would be placed by Coulomb collisions. A simple random-walk model in the banana regime shows that the predicted confinement time, including the effects of both the electron and the ion pressure gradients, is ≈ 0.3 s. This is inconsistent with the observed decay rates of greater than several seconds. It is difficult, therefore, to understand the behavior in terms of an exceptionally good particle confinement. It may be that the observed state is a deformed stationary equilibrium to which the injection of the pellet has allowed access. There is then no need for individual particles to be confined as they may be continually exchanged with particles from the surrounding plasma.

Another question that arises is how the magnetic island itself is maintained. One possibility is that the observed depression of the electron temperature reduces the electrical conductivity along the field lines producing a local reduction in current density and a magnetic field perturbation which forms a magnetic island. Depending on the somewhat uncertain value of the shear at $q=1$, the observed island size can then be used to show that a $\Delta T_e/T_e$ value of 10^{-2} to 10^{-1} is required to maintain a steady structure. The observed value of $\Delta T_e/T_e$ is initially $\simeq 0.2$ but decays on the time scale of $\simeq 100$ ms to a value too small to be detected, $\lesssim 10^{-1}$. Thus although the required temperature depression is observed, no firm conclusion can be drawn. An alternative possibility is that the required decrease in the local resistivity is due to a small enhancement of the impurity concentration. This could be due to the electric potential which arises to confine the local deuteron pressure.

Experiments of this sort can clearly give useful information about the q profile by identifying rational surfaces. For example, an estimate of $q(0)$ can be obtained from the observed decrease in the snake radius, and therefore the $q=1$ radius (r_1), during a sawtooth crash for which typically $\Delta r_1/r_1 \approx -\frac{1}{3}$ (Fig. 4). Since the calculated change in the current profile due to sawteeth is quite small ($\Delta q \approx 0.02$) in JET,[9] a smooth q profile would have to be very flat in order to give the large shift in r_1 which the snake behavior reveals. For a parabolic q profile, $q(0) \approx 0.97$ before the sawtooth crash. This is important for the discussion of sawtooth models.

In summary, the snake structure is an unexpectedly persistent local perturbation of the plasma arising from pellet injection. It appears to be due to the generation of a magnetic island at the $q=1$ surface. It might involve a remarkably good level of particle confinement, but it is more likely that its long duration indicates a change to a new nonaxisymmetric equilibrium. These experiments also illustrate the use of pellet injection as a powerful method of probing the q profile.

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[a]Visitor from EURATOM-Institut für Plasmaphysik Association, Garching, West Germany.

[b]Visitor from Massachusetts Institute of Technology, Cambridge, MA 02139.

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