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DETERMINATION OF THE SHEAR ON THE q=1 SURFACE OF THE JET TOKAMAK

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Abstract The large changes observed in visible light and X-ray emission when an injected pellet of solid D_2 crosses the q=1 surface of the JET tokamak are used to deduce the value of the magnetic shear on the q=1 surface. Very low values are found and the implications for theories of the sawtooth instability are discussed.

Introduction Knowledge of the shear and the safety factor (q) profiles in a tokamak are important in understanding mhd instabilities and, in particular, the behaviour of m=1 instabilities and the sawtooth are strongly influenced by the q-profile at the plasma centre. q(r) has been determined in JET from magnetic measurements[1] and more recently from Faraday rotation measurements[2]. In addition, the location of the q=1 surface has been inferred from measurements of the sawtooth inversion radius[3] and the radius of the 'snake'[4]. Despite this apparent wealth of information, the values of q on axis (q_0) and of dq/dr near the plasma centre are somewhat uncertain and apparent discrepancies exist between the measured value of q_0 and that deduced from the shift of the snake caused by a sawtooth crash.

It will be shown in this letter that important new information on dq/dr on the q=1 surface may be obtained from measurements of visible light (mainly H_α) and soft X-ray emission during pellet ablation. This method is new and quite different from the q(r) determinations made on TFR[5] by observing the orientation of the plasma tail originating from the pellet ablation region.

Experimental observations Pellets of solid D_2 with a radius of 1-2 mm were injected radially into JET on the mid-plane for refuelling studies. The experiments were carried out during the current flat-top of normal sawtoothing discharges with B = 2.1 to 3.1 T and I = 2.5 to 3 MA. The plasma density and temperature were in the ranges $\bar{n}_e = 1.3$ to 3×10^{19} m^{-3} and $T_e = 2.9$ to 4.2 keV. As the pellets crossed the q=1 surface, determined from the sawtooth inversion radius, a large drop in both the H_α and soft X-ray signals occurs as shown in figs.1 and 2. The soft X-rays are measured by the 38 detectors of the vertical soft X-ray camera and the H_α radiation is measured, after multiple reflection, by one of the very edge detectors which is not adequately shielded from visible plasma radiation but which receives no X-radiation.

Large resonance effects are not seen on other integer or rational q-surfaces (eq. q=2, $^3/_2$) and the small variations seen on the H_α signal when the pellet traverses the outer regions of the plasma are at different locations on successive shots and are not correlated with particular q-values. In the next section an explanation of these observations will be presented and values of dq/dr and q_0 will be found.

Ablation processes Pellet ablation mechanisms[6,7] are well understood with pellet ranges[8], H_α emission[9] and the absolute X-radiated power[10] in good agreement with calculations. During ablation, plasma electrons move along the magnetic field lines and lose energy in the ablation cloud which surrounds the pellet (of radius r_p) and protects it from direct electron heating (fig.3). The ablated material expands radially up to a critical radius[11] ($r_s \approx 2.5\ r_p$) and then flows along the field lines. The relative velocities are such that the plasma electrons can make many (~ 10) toroidal transits of the torus while the pellet ablation cloud crosses a flux surface. On a non-rational q-surface the electrons from many parts of the flux surface can interact with the pellet, but for integer or rational q (q_i and q_r) the flux tube closes on itself so that the reservoir of electrons which can heat the pellet is much reduced.

Although the ablated electrons will cool the plasma substantially, this takes place in JET on a longer timescale[7] than the time taken for the ablation cloud to cross a magnetic surface. Hence, although the pellet ablation process may eventually alter the magnetic field structure due to changed T_e (eg. to form a snake), it will not be modified during the time taken to measure the H_α emission and dq/dr.

On integer (and rational) q-surfaces the effects of shear on the ablation process needs also to be considered. On fig.4 a square region ABCD is mapped out after q_i toroidal transits to give A'B'C'D'. The distances a and b are related by

$$b = \frac{2\pi ra}{q_i}\frac{dq}{dr}$$

where r is the minor radius. In order to see a substantial reduction in ablation rate the two areas must have considerable overlap and b must be fairly small, ie.

$$b < 2a$$

or

$$\frac{dq}{dr} < \frac{q_i}{\pi r}$$

That is the shear must be small on the integer q-surface.

If q varies as $q = q_0(1+\alpha r^s)$ the condition becomes $(q_i-q_0)/q_i < 1/\pi s$. $1/\pi s \approx 0.16$ for a prabolic profile with s=2 and so this condition is only likely to be satisfied on the q=1 surface for normal sawtoothing tokamak discharges. This provides an explanation of the lack of observation of a dip in the visible light signal on integer q-surfaces other than q=1. A similar argument shows that large effects would not be expected on rational surfaces with $q_r = {}^3/_2, {}^5/_3, {}^5/_2$ etc., unless there were regions with locally reduced shear.

These considerations apply only to passing particles but towards the plasma centre the number of trapped particles becomes reduced making a pronounced resonance effect possible.

Determination of dq/dr Values of the shear on the q=1 surface may be found by considering the degree of overlap of the pellet ablation cloud with electrons which have made one toroidal transit of the machine (fig.5). Some overlap will occur, which will be taken to correspond to points P and P' of fig.1, when

$$\frac{dq}{dr} = \frac{r_{s_1}}{\pi r \Delta} \qquad (1)$$

where 2Δ = PP', and r_{s_1} is the radius of the pellet cloud when it reaches q=1 and is determined from the expression for r_p given by ref.6. A knowledge of the plasma temperature and density profiles before the injection of the pellet are also required. These vary as $n_e = k_1 y^{1/2}$ and $T_e = k_2 y$ where y is the distance from the plasma edge and k_1 and k_2 are determined from the experimental measurements. Integration of the expression for r_p then shows that

$$r_p = r_{p_0} \{1 - (y/y_R)^{2.81}\}^{3/5}$$

with y_R determined essentially by n_e and T_e. Although agreement with this expression is reasonable for the cases considered here, it is preferable to use the measured value of y_R to determine r_p on the q=1 surface. This produces a more accurate value of r_p (and hence r_s) towards the end of the pellet's range.

Putting in typical values into eq.1 gives $dq/dr = 5\times10^{-2}$ m^{-1} and, for a q-profile which varies as $q_0(1+\alpha r^2)$, $1-q_0 = 10^{-2}$ which gives q_0 extremely close to one. If, however, the q-profile had a local flattening in the region of q=1, the value of dq/dr would represent an average value in this region with width 2Δ and the extrapolation to determine q_0 could not be made.

These calculations have been carried out for a number of different shots. In the lower part of fig.6 the radius of the q=1 surface (r_1) determined from the minimum in the H_α signal is plotted normalised by B/I as a function of the normalised time (t/τ_s) during the sawtooth cycle. The normalised co-ordinates are used as shots with different B, I and sawtooth period (τ_s) are plotted together and it has been observed in studies of r_1 made from the sawtooth inversion radius that r_1 scales as I/B. It is seen that Br_1/I increases by ≈ 20% during the sawtooth cycle in reasonable agreement with the estimate[4] of 30% made from the shift of the snake during a sawtooth crash. The shear (upper fig.6) seems to be approximately constant throughout the sawtooth cycle.

Discussion Recently the theory of the sawtooth oscillation has changed considerably. The original observations on the sawtooth were explained by the Kadomtsev model which was based on the growth of a resistive island at q=1. In JET this model has been found to be inadequate to explain either the rapid collapse time[12] (100 μs) or the observed topological changes[13] observed during the crash. An ideal instability model was therefore proposed[14] which require extremely flat profiles at the plasma centre and this conjecture was supported by the deduction of q_0 from the snake observations and now from extrapolation of dq/dr.

However, more recent observations on JET from Faraday rotation[2] for both normal and monster sawteeth (with periods up to 3 s) gave $q_0 \approx 0.65-0.8$ (± 15%) and $q_0 = 0.7$ respectively. Although there are no dq/dr measurements for monsters, compatibility between these results and those of the present paper can be obtained only if q(r) has a complex radial dependence with local flattening at q=1 and a more rapid drop towards the centre.

What is then required of a theoretical model is an explanation of the stability of the observed q-profiles between sawtooth collapses and also of the fast collapse phase. Several models with apparently the correct q-profile have appeared. Bussac et al.[15] have discussed an ideal instability model with the required q-profile but they require the existence of a finite magnetic island on the q=1 surface for which there is no experimental evidence. Hastie et al.[16] have investigated the stability of ideal and resistive internal kink modes for a variety of q-profiles including those with $q_0 << 1$ and weak shear on q=1. The required stability between collapses was found for a tight aspect ratio torus but the fast observed collapse times could not be reproduced. The stability threshold of the m=1 kink has recently been investigated for JET[17] and showed stability for sufficiently low shear at q=1. However, this model required the shear to increase with time during the sawtooth cycle and this has not been observed experimentally. It would seem that the experimental observations are not yet adequately explained.

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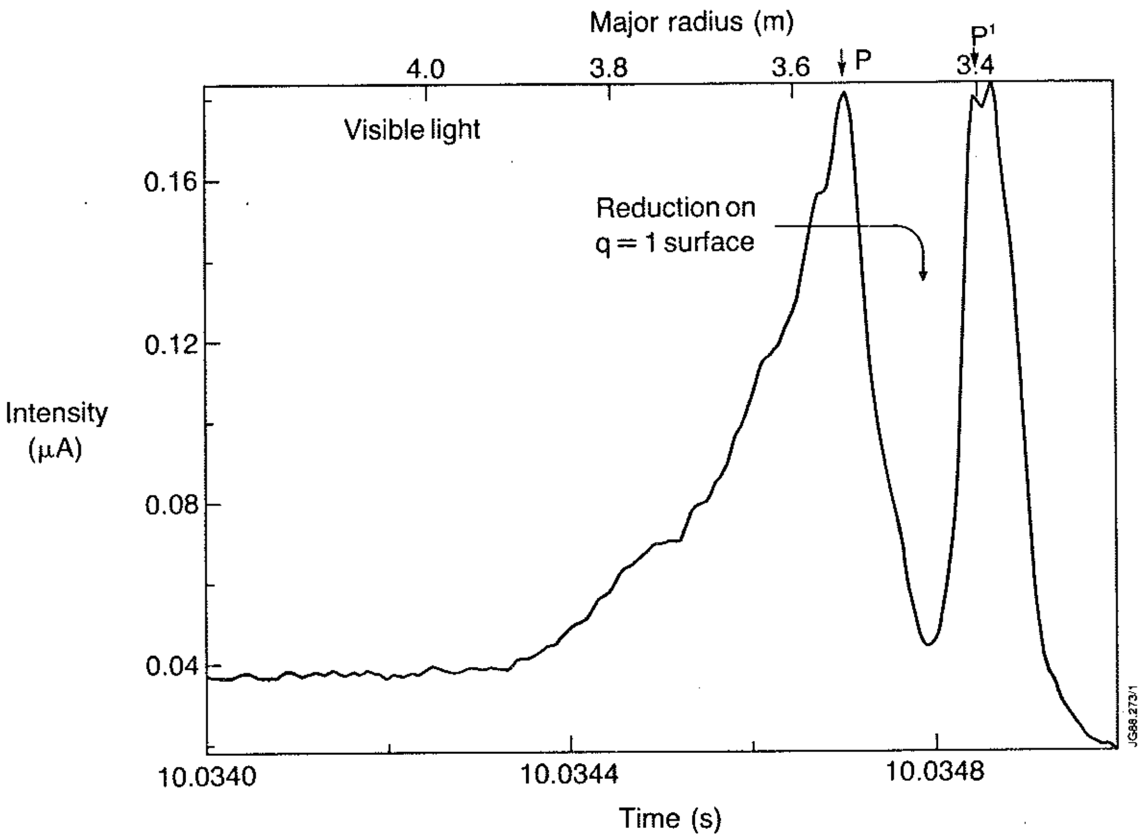

Fig. 1 H_α emission during pellet injection into JET. The pronounced reduction in emission as the pellet crosses $q=1$ is clearly visible.

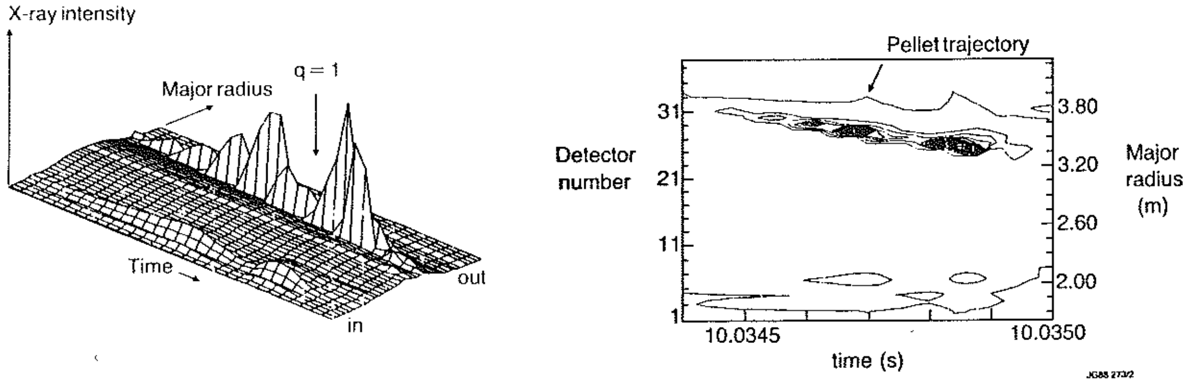

Fig. 2 3-D and contour plots of the soft X-ray intensity measured by the vertical camera as a function of time and major radius. The reduction at $q=1$ is again clearly visible.

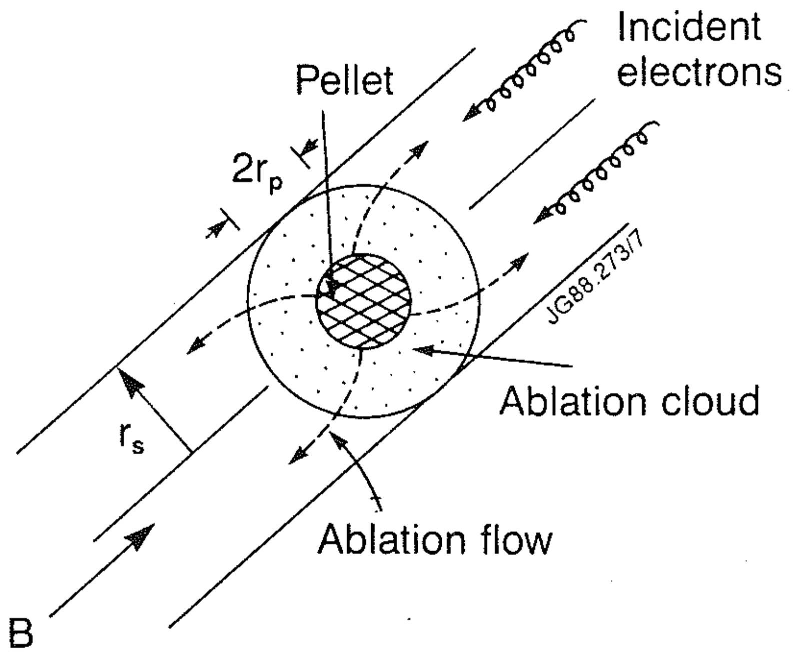

Fig. 3 Schematic showing the ablation of a solid D_2 pellet.

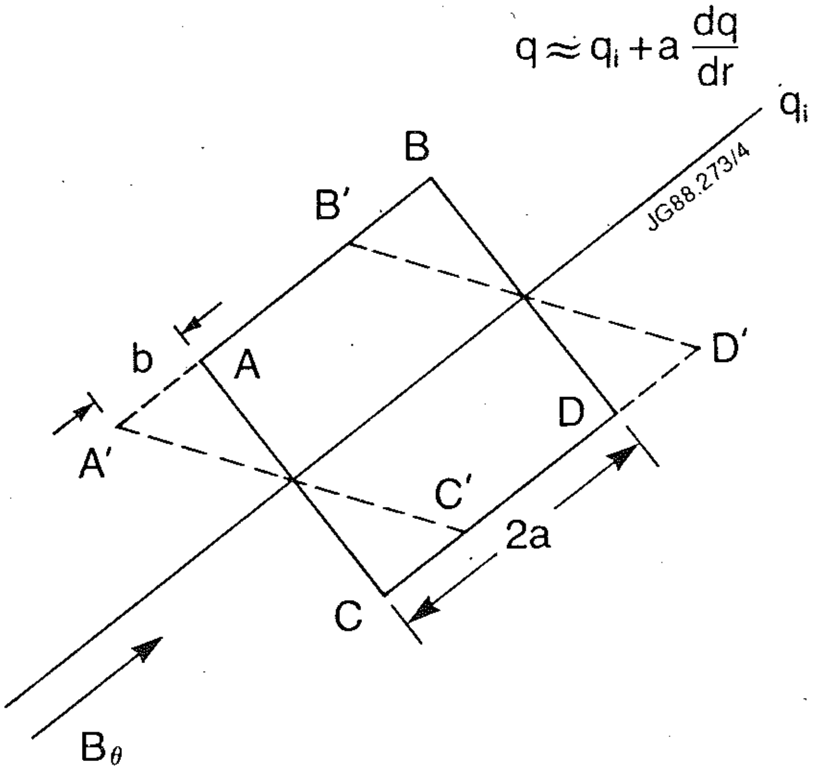

Fig. 4 Mapping of ABCD into A′ B′ C′ D′ after q_i toroidal transits of the torus.

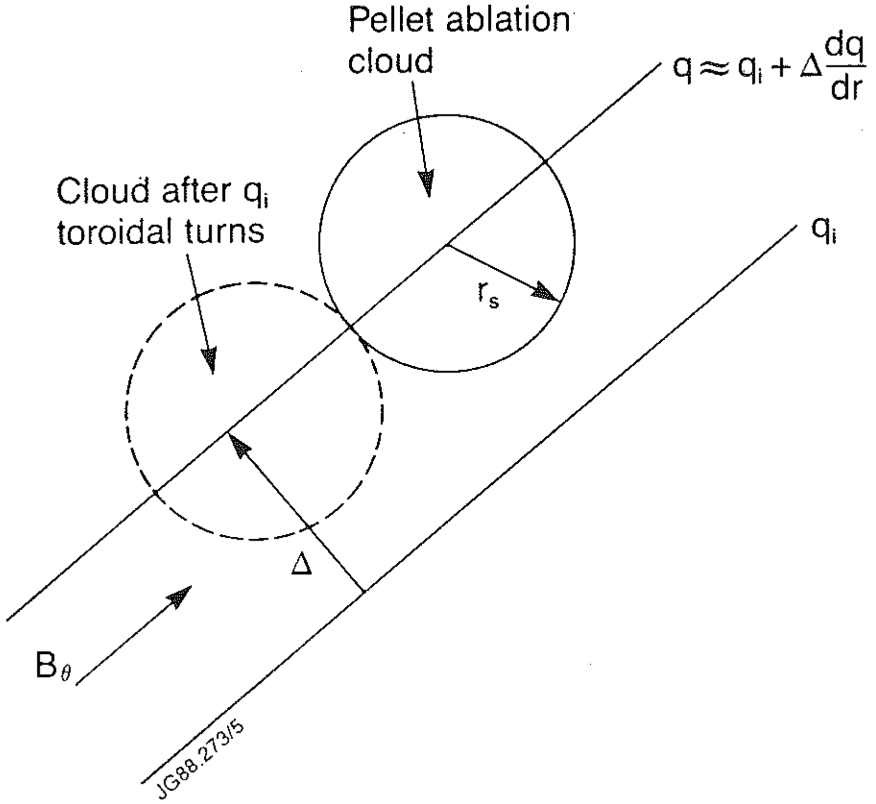

Fig. 5 Mapping of the pellet ablation cloud after q_i toroidal transits.

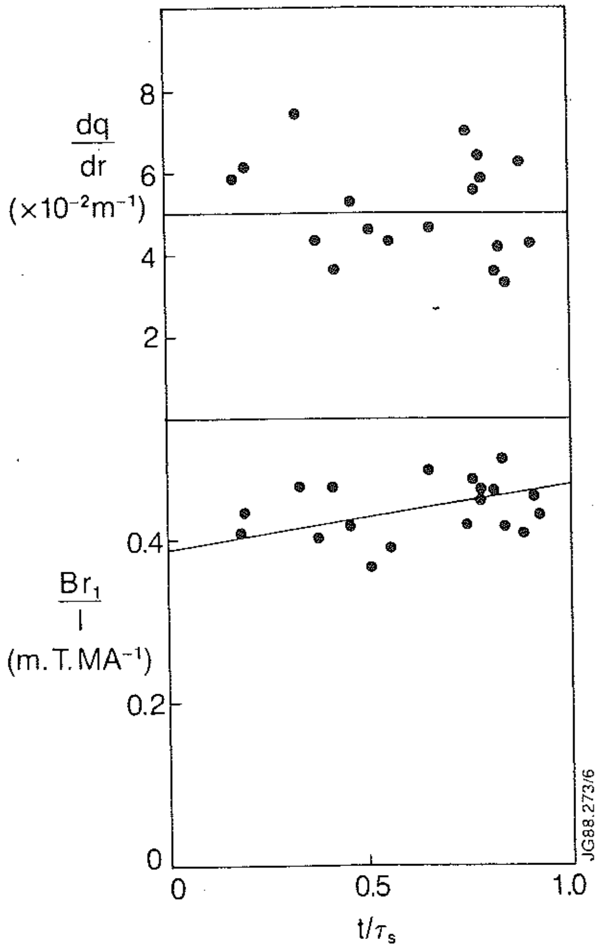

Fig. 6 Plot of the normalised radius of the $q=1$ surface (lower) and shear in $q=1$ (upper) as a function of the normalised time.