Transport in the Sawtooth Collapse

J. A. Wesson, B. Alper, A. W. Edwards, and R. D. Gill
JET Joint Undertaking, Abingdon, Oxfordshire, United Kingdom

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The rapid temperature collapse in tokamak sawtooth oscillations having incomplete magnetic reconnection is generally thought to occur through ergodization of the magnetic field. An experiment in JET using injected nickel indicates that this explanation is improbable. [S0031-9007(97)04484-0]

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The most important theoretical problem in plasma physics is the nature of the anomalous transport of particles and energy as observed, for example, in tokamaks [1]. A particular difficulty, which has become more apparent as diagnostic techniques have improved, is that of explaining the rapid transport in transient events such as disruptions, sawtooth collapses, and the edge localized modes. In the case of the sawtooth collapse in JET (Joint European Torus), a flattening of the electron temperature, out to almost half the plasma radius, can occur in less than 100 μs [2].

To put this time scale in context, it should be compared with a collisional electron thermal conduction time of more than a minute, and with a time of about a second for the actual level of anomalous transport typically observed in the center of the plasma.

It was once thought that the redistribution of plasma energy in the sawtooth collapse occurs through a reconnection of the magnetic flux, the helical magnetic flux inside the $q = 1$ surface being joined to an equal flux outside this surface [3]. In this model, the value of the safety factor q in the central region returned to a value close to one after the collapse. However, there have been several measurements of q during sawteeth in which it is found that the central value of q is well below one before the collapse, typically 0.7–0.8 [4,5], and in which it is hardly changed after the collapse [5,6]. This behavior is observed in JET discharges. In the simple model, this would mean that little reconnection takes place and the flux surfaces over most of the region inside the $q = 1$ surface remain nested. Clearly this behavior does not allow a fast redistribution of the temperature.

It is now widely thought that this problem can be resolved by invoking an ergodicity of the magnetic field [7,8]. It is envisaged that the sawtooth instability introduces toroidally nonsymmetric components to the magnetic field which, combined with the equilibrium field, lead to the destruction of the magnetic surfaces. The field lines wander in the poloidal plane as they go around the tokamak toroidally, and the center of the plasma becomes connected by these field lines to the plasma close to the $q = 1$ surface. The electrons can then carry their energy along the field lines at their very high thermal velocity. Experiments on JET in which the soft x-ray emission from a nickel impurity is studied during a sawtooth collapse make this explanation difficult to accept.

In these experiments a small amount of nickel is introduced by laser ablation [9]. The nickel diffuses inward with a radially hollow profile, the peak in this profile reaching a radius close to the $q = 1$ surface. At the next sawtooth collapse, the soft x-ray emission indicates that the nickel moves into the central core, and the nickel profile is flattened.

What makes this result interesting and significant is that the time scale for the nickel influx to the core is the same as that for the flattening of the electron temperature, around 50 μs. For ergodicity of the magnetic field to explain the electron temperature collapse, a thermal electron must travel along the ergodic field and cross the central region in this time. An 8 keV electron would travel 2 km and so this would be the required length along the field line. The much heavier nickel atoms have a thermal velocity 330 times smaller than the electrons and in the 50 μs they would travel only 6 m. Clearly they cannot reach the center of the plasma on this time scale by motion along the ergodic field.

This result implies that the impurity influx must be due to motion which is essentially in the poloidal plane. For a $q = 1$ radius of 0.5 m, a nickel influx taking 50 μs then requires a velocity of only 10^4 m s^{-1}, an order of magnitude less than the thermal velocity. If the impurity moves to the center in this way, it seems likely that the plasma electrons and ions do also.

The implications of this result will be discussed more fully after the experimental observations have been described.

The nickel experiment.—JET pulse number 21942 had a plasma current of 3 MA and a toroidal field of 2.8 T. The average electron density was 1.5×10^{19} m^{-3} and on the application of 6 MW of RF heating the central electron temperature rose to 8 keV. The discharge was subject to sawtooth collapses in which the central electron temperature fell to 6 keV. High time resolution temperature measurements show that the almost invariable behavior in the sawtooth collapse with discharges of this kind is that the $m = 1$ displacement occurs in typically

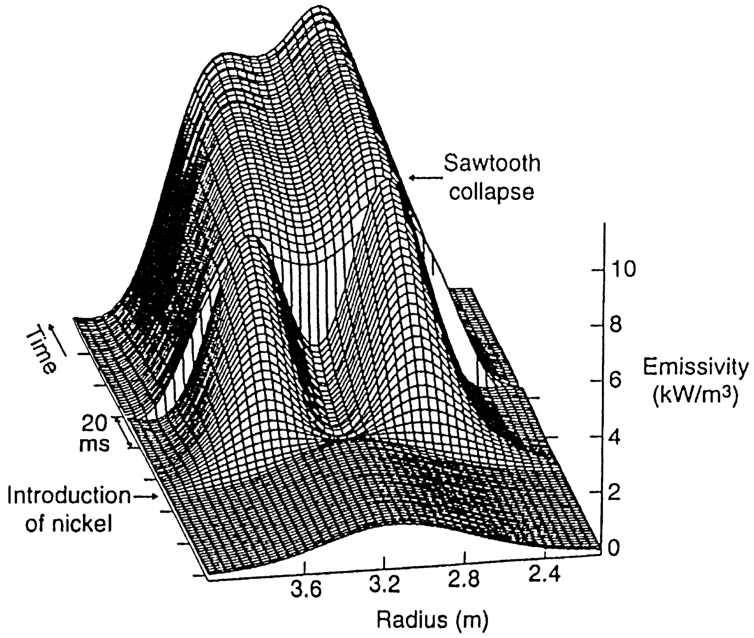

FIG. 1. Time dependence of soft x-ray emission profile showing the first sawtooth collapse after nickel injection.

50 μs, with a subsequent fall in the electron temperature on a similar time scale [10].

In this discharge a small amount of nickel is introduced into the plasma by evaporating a thin layer of nickel using a laser pulse. Although the nickel density is very low ($n_{\mathrm{Ni}} \sim 0.003 n_e$), the nickel contribution comes to dominate the soft x-ray emission. This nickel is transported inward from the plasma surface, but at the time of the first sawtooth collapse after the nickel injection, the soft x-ray profile is still hollow, the radiation peaking at around the inversion radius of earlier sawtooth collapses.

Figure 1 shows the time dependence of the soft x-ray emission profile, determined by tomographic reconstruction, during the first sawtooth collapse after the nickel injection. It is seen that the hollow profile is flattened across the core, while retaining a shallow minimum. The time scale is brought out more clearly in Fig. 2, which gives the time dependence of the central minimum of the soft x-ray emissivity. It is seen that the rise in emission is characterized by a time scale of ~50 μs.

Since the intensity observed by the x-ray detector would decrease with the fall in temperature, the only possible interpretation of this result is that nickel has penetrated to the axis on this time scale. To reinforce this point, Fig. 3 shows the time dependence of the maximum value of soft x-ray emissivity for the sawtooth collapse before nickel injection. It is seen that, consistent with our expectations from a temperature fall, the emissivity decreases on the same time scale that it rises with the nickel present.

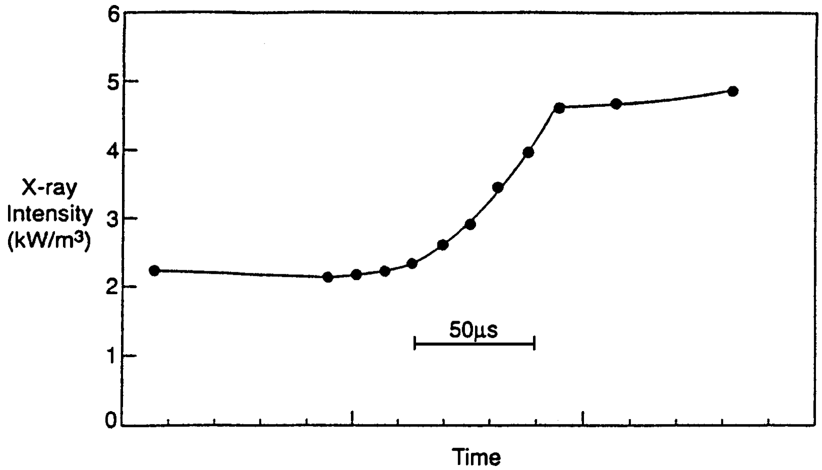

FIG. 2. Showing the rapid rise in central soft x-ray emissivity during the sawtooth collapse following nickel injection.

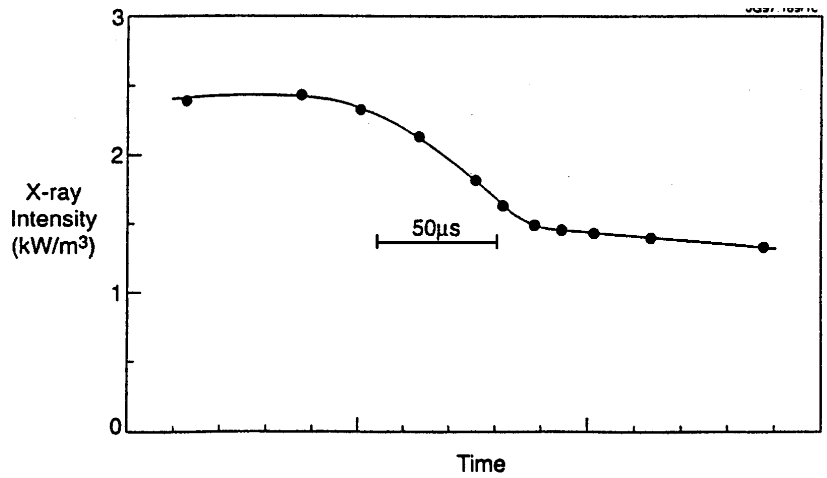

FIG. 3. Showing the fall in central soft x-ray emissivity during the sawtooth collapse before nickel injection, consistent with the temperature drop.

The question, therefore, is how does the nickel penetrate the core on a time scale of 50 μs?

Until now it has been easy to conjecture that ergodicity driven by the sawtooth instability would provide an explanation of the central temperature collapse when only a partial flux reconnection occurs. However, with this model the time scales of the electron temperature collapse and the nickel influx are predicted to be very different, whereas in the present experiment they are observed to be the same. If the electron temperature collapse were due to transport along an ergodized magnetic field line, the length along the field line would be determined by the distance traveled by a thermal electron during the collapse. For a thermal electron the observed collapse time dictates a length of around 2 km. In this time a nickel ion would only move a few meters along the field line, and the observed rapid nickel influx to the core could not be explained.

The result would seem to call for a direct motion of the nickel in the poloidal direction. The nickel ions would then have to move only 0.5 m to reach the core. However, this requires a nonideal motion perpendicular to the magnetic field, with its associated electric field. It is hard to see how an electric field could be generated to produce the required motion.

This conjecture of poloidal motion brings us into an area of discussion related to earlier sawtooth observations on JET. It was shown theoretically that if the central value of the safety factor q were close to one, the $m = 1$ instability would take the form of a poloidal convection in which the outer plasma is brought to the center [11]. It was found from the experimental results (i) that this quasi-interchange motion was indeed indicated by the soft x-ray measurements [10] and (ii) that the value of q was substantially lower than one, typically 0.8 [5]. These two results were, and remain, in conflict.

The present system of soft x-ray measurements [12] provides a much more accurate tomographic reconstruction of the soft x-ray emission during the sawtooth collapse. This shows a cold bubble formation indicating an interchange motion, in full agreement with the earlier results. Figure 4 gives a reconstruction for the sawtooth collapse shown in Fig. 3.

However, theoretically the quasi-interchange mode requires that the central value of q be close to one, and this is incompatible with the value calculated from magnetic measurements to be around 0.85 for this discharge.

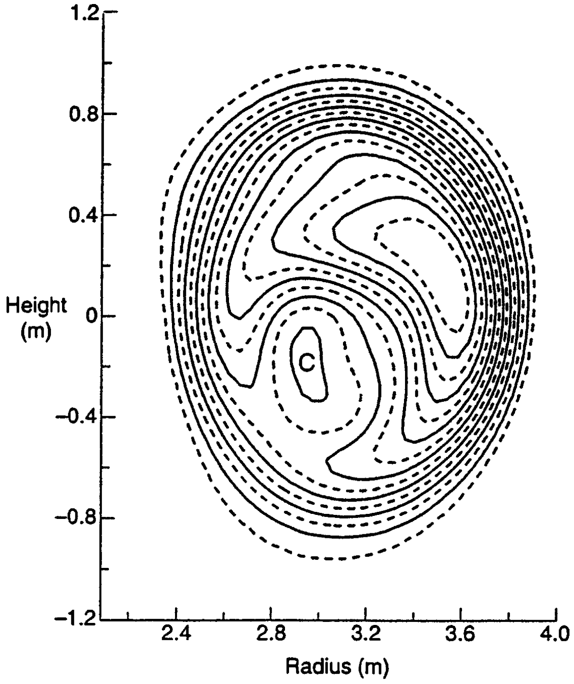

FIG. 4. Tomographic reconstruction of central soft x-ray emission contours during the sawtooth collapse showing a cold bubble, labeled C.

Summarizing, the principal result is that the observed behavior of the soft x-ray emission following nickel injection indicates that the sawtooth collapse does not occur through the onset of magnetic ergodicity. The time scale suggests a direct poloidal motion such as the convective motion implied by the soft x-ray tomography.

The observations call for a nonideal electric field which allows motion across the magnetic field. If the measured values of central q are incorrect, this motion could arise through a reconnecting quasi-interchange instability. Otherwise, we are looking for a new source of electric field.

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