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ABSTRACT

If an ELM is a peeling of flux surfaces from the plasma, due to a broken separatrix, current density is lost as well as particles and energy. The fast loss of a current-carrying plasma layer modifies the plasma equilibrium, leading to sudden shifts in the strike points at each ELM, towards the plasma centre. An experimental study of this conjectured model of the ELM was made at JET, showing that in all cases studied (type I ELMs) strike point shifts were observed. In two cases studied in detail, the equilibrium changes agree qualitatively with the observed shifts.

1. INTRODUCTION

Strike point jumps in JET plasmas were first reported in 1995 [1]. The observation of a sudden inward shift of the inner strike and an outward shift of the outer one was made jointly with infrared (IR) cameras, soft X-ray arrays and Langmuir Probe (LP) arrays.

A multi-diagnostic study of type I ELMs in neutral beam heated plasmas attempted to reproduce these observations and contrast them with the supposition that a layer of plasma is peeled off after an ELM. The initial model in this study is that the ELM is due to local loss of solution of the Grad-Shafranov equation at a critical point [2], possibly due to a separatrix instability. A complete layer of previously closed field lines would open. Particles, energy and current would flow along these newly opened field lines and be quickly lost. Since before the ELM the plasma pedestal has large pressure, it must necessarily have large toroidal edge current density. The loss of a co-current carrying plasma layer from inside the separatrix results in the formation of a new, smaller separatrix, with displaced X and strike points (since the divertor coil currents do not change in that fast time scale). We expected the X point would move towards the plasma centre. For JET vertical target plasmas, the strikes would move upwards.

2. EXPERIMENTAL OBSERVATIONS OF STRIKE POINT MOVEMENTS IN LARGE TYPE I ELMS

To maximize diagnostic sensitivity, plasmas with infrequent ELMs (typically without gas-puff, and therefore with low density) were designed, and strike points were placed in positions with good IR viewing and LP coverage. The most studied discharges had 2MA, 2T, 15MW of neutral beam injection heating and no gas-puff during the heating phase, with 1 Hz compound ELMs, with a drop of diamagnetic energy of order ΔW_{dia} = 500kJ at each ELM, in about 500μs.

Streak pictures (temperature contours as a function of Z and time) from the JET IR camera [3] are constructed by choosing pixels along the vertical target profiles at constant toroidal angle. Because of the acquisition procedure, time varies on each temperature profile. As shown in fig.1(a), the surface temperature of the inner divertor target has a clear maximum at −1.62m, corresponding to the strike position. At the ELM the temperature at −1.48m suddenly increases, while the pre-ELM strike point position cools down. Here the presence of a thin inhomogeneous surface layer has a dual effect: the temperature response to the arrival of heat flux is very fast, but it is difficult to calculate the heat flux density [4]. Nevertheless, the combined decrease/increase of the surface temperature, observed at two different positions on the inner target, is a signature of a peak heat flux density movement, which can be interpreted as a strike jump of up to 15cm. The hot spot presented on Fig.1(a) appears and disappears on a very short time scale (fast acquisition line time is 65μs). In the outer divertor target, Fig.1(b), the temperature does not respond as quickly to heat flux arrival, but one can equally see that at the ELM a new hot stripe appears 2-3cm above the pre-ELM strike position, which is cooling.

The JET divertor Langmuir Probes (LP) [5], operating in ion saturation mode, provide another measurement of strike point position, as the location of the maximum ion saturation current. The sampling frequency in these experiments is 10kHz. The observed jumps are of the same approximate magnitude as the IR data indicates (3ms time resolution, frame time), as shown in Fig.2, where we plot position of highest ion saturation current and IR temperature. In the outer divertor the IR data was shifted upwards 3.5cm to match the LP measurement (a likely camera misalignment). As the thermal response of the outer tiles is slower (no deposited layers) the position of maximum IR temperature plotted in Fig.2 does not jump, even if the corresponding heat deposition shifted, as inferred from Fig.1(b).

As illustrated in Fig.2, there is a transient observation of a rather large shift, of order 10-20cm inboard, and 7cm outboard. This transient large jump is not observed in every ELM, it is only one time point, and it can be as large as 20cm (inboard or outboard) in other ELMs in the same discharge. Afterwards the strikes settle at a position that is about 2-3cm above the pre-ELM positions, until a few tens of milliseconds after the end of the ELM, when the strikes slowly return to the pre-ELM position, as shown in Figs.2 and 3. We believe that the sudden large jump is associated with the transition between pre-ELM and post-ELM equilibria (filaments? see discussion section), while the post-ELM new equilibrium (200-500μs after the ELM) has shifted strike points.

Before we proceed to discuss a shedding of flux surfaces as an explanation of the shifted strike points, we show that the shift is not due to a plasma centroid movement.

The position of the centre of SXR emission shows a sudden (<100μs) downshift of 7mm (not understood), followed by a return to the previous position in < 100μs, and a slow upward drift of 1 cm in 10ms. The fast down-shift of the centre coincides with the upward shift of the strikes (LPs), so the sudden upward shift of the strikes is not due to an upward plasma movement. The slow drifts are driven by the position control system. In the slow, 2-3ms time-scale, magnetic and SXR measurements of central position agree.

The plasma density is measured with a Li beam at the plasma top (100ms time resolution), along a vertical line, and as a line integral in 3 vertical lines at either side of the centre, and at the outer edge (up to 1ms resolution). After each ELM, erosion of the plasma top is observed, as shown in Fig. 4a. Since the plasma centre has not moved down, the erosion is due to a loss of density from the top edge surfaces. The sudden drop in all line integrals of density, shown in Fig. 4c, indicates fast loss of particles, not an in-out movement. The detailed multi-diagnostic study described above was only done for 2 discharges. The comparison between IR and LP measurements is available for many more discharges, and always show strike displacements at an ELM of some cm, with both diagnostics, occasionally showing the large sudden jumps. In a large variety of discharges the LP system shows that the post-ELM state strike positions shift upwards by some cm after each type I ELM in JET. The data is too sparse to allow a scaling study.

3. MODELLING PLASMA PEELING

Using Motional Stark Effect and Polarimetry (MSE+P) measurements, the pre-ELM plasma equilibrium has been reconstructed, albeit with large error bars induced by large radial electric fields (not measured), high density at the plasma core and low time-resolution (20ms). The inner strike point is as given by LPs, but the outer is 3cm higher. The reconstructed current density profile before the ELM is shown in Fig.5. It is sensible, physically, since high edge pressure gradients imply high diamagnetism, which drives the toroidal current density below zero in the inboard side. This reduces the total plasma current loss due to shedding of flux surfaces, as loss from inboard and outboard sides compensate each other.

A linearized plasma response model of the plasma equilibrium [6] is used to compute a new equilibrium by peeling surfaces outside Ψ =.95 (Ψ =1 at LCFS), taking into account induced currents in passive structures (large in sudden events in JET). The final current density profile is also shown in Fig.5. This peeling results in loss of 90kA of toroidal current, ΔW~1 MJ, and upward strike jumps of 7cm inboard, 5cm outboard, both too large but in qualitative agreement with experimental observations of a settling of the strikes 2-3cm above the pre-strike positions. The overall plasma boundary moved upwards and inwards, also in qualitative agreement with earlier observations [7]. Clearly, a peeling of surfaces closer to the separatrix would give a smaller shift of strikes and better quantitative agreement with measurements. Further modelling work to improve the pre-ELM equilibrium reconstruction is being carried out before more detailed studies of the peeling are undertaken.

DISCUSSION

Our conjecture of the ELM as a transition between two neighbouring equilibria is based on a study of criticality of the Grad-Shafranov equation [2], which can not describe the temporal evolution of the system. The transition could be due to an X-point interchange stability, as proposed in [8], although more realistic geometry and current density profiles may need to be included in the theoretical treatment to ascertain if this is the case. Characteristic times for the peeling transition at the X-point can be estimated with the Kadomtsev sawtooth model [9]. The local Alfvén time would be associated with the change in poloidal field at the X-point, δB_{pol}~ 5 10^{-2} T, the displacement of the X-point due to peeling, δr~5cm, the local density n_i~1-5.$\times 10^{19}$, and temperatures T_e~ 50-500 eV: $\tau_A = \delta r\ (m_0\ n_{ion}\ m_{ion})^{1/2} / \delta B$~ 0.2-0.5ms. The resistive time is $\tau_R = \mu_0\ (\delta r)^2/\eta$~ 1-33ms. The Kadomtsev time would be $\tau_K = (\tau_A \tau_R)^{1/2}$~ 10-100$\mu$s. Once edge current density loss has occurred and the post-ELM equilibrium is established, particles, energy and current would flow along the newly opened field lines, both in the main SOL and in the private flux region. The time for ions to arrive at the target would be $\tau_{ion}=L_{connection\ length}/v_{th\_ion}$. With a pedestal ion temperature of typically 1.5keV, and a connection length in the private region of ~5m (from 1 cm below X-point to target), and of ~20m in the main SOL (from 1cm outboard equator to target), these times are, respectively, 12 and 50μs. As all of these times are faster than our experimental resolution, we can not describe the transition state.

The transition between the pre-ELM and post-ELM "peeled" state could happen as a homogenous loss of the outer flux surfaces, as we originally envisaged. Recent observations in MAST [10] show that ELMs can release plasma filaments, with visible paths in the public SOL. The MAST ELMs may not correspond exactly to JET type I ELMs, but the possibility of flow along a loose filament to target and/or other in-vessel surfaces is interesting. Current loss could take place along these filaments, and be very localized. In JET radial loss speeds associated with ELMs have been measured with a reciprocating probe, they can be as large as 1km/s [11], so the particle, energy and current loss could take place in 50μs across the 5cm gap between outboard plasma boundary and outboard limiter, if a radial filament were to connect these points.

In fact, the sudden transient displacements observed at the beginning of some ELMs, described in Section 2, could reflect the detection of a stray filament, rather than a new strike point position. Only studies with faster time resolution can distinguish both situations.

Regardless of how the new equilibrium is arrived at, measurement and modelling both suggest that the post-ELM state can be described as a reduced plasma, that has shed previously closed field lines. Part of the after-ELM recovery phase would associated with rebuilding of edge flux surfaces, not only of pressure gradients.

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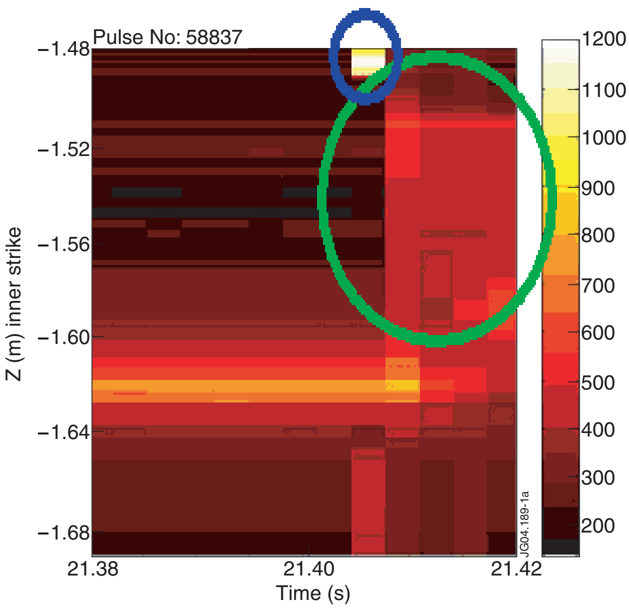


Figure 1(a): Contours of infrared measurement of tile surface temperature in the inner strike region of a vertical target plasma, as a function of time. Marked with the blue circle is the first observed high temperature point. Pre-ELM strike position cools down.

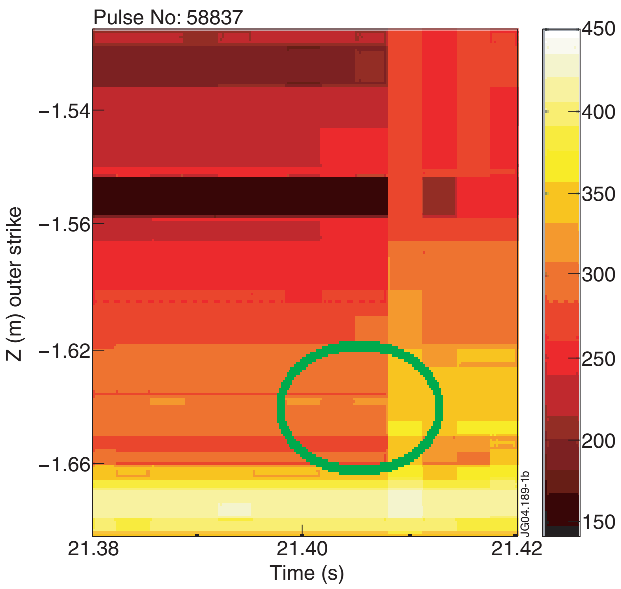
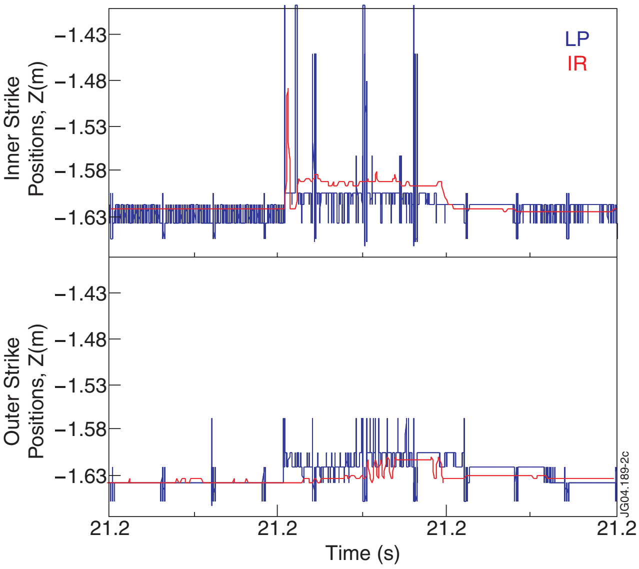


Figure 1(b): Tile surface temperature in the outer strike region.



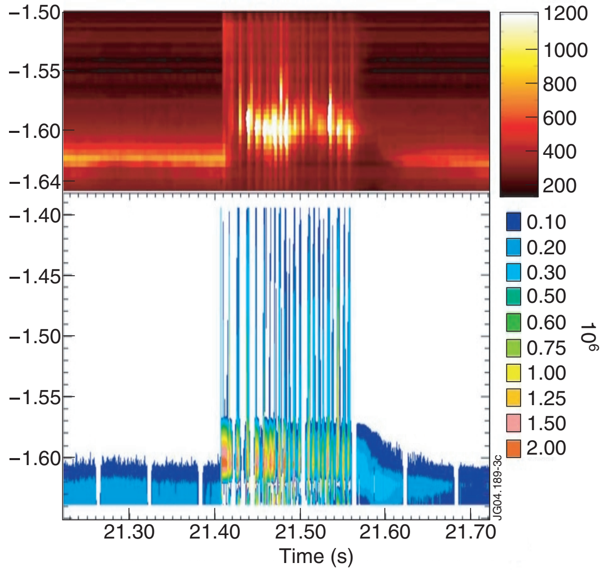
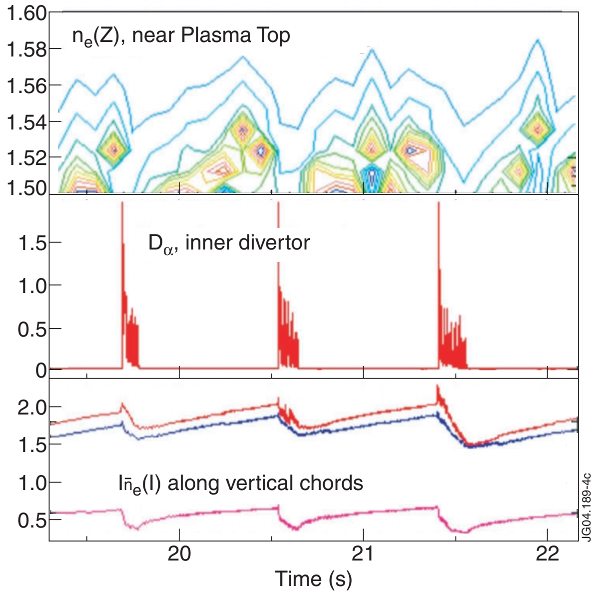


Figure 2: Strike positions, inner and outer, measured with Langmuir Probes (blue) and IR (red). The periodic down-spikes are transient sweeps to negative voltage, an artefact of the measurement technique of the LPs.

Figure 3: Contours of IR-measured temperature and LP-measured ion saturation current (A/m^2), in the inner divertor regions.



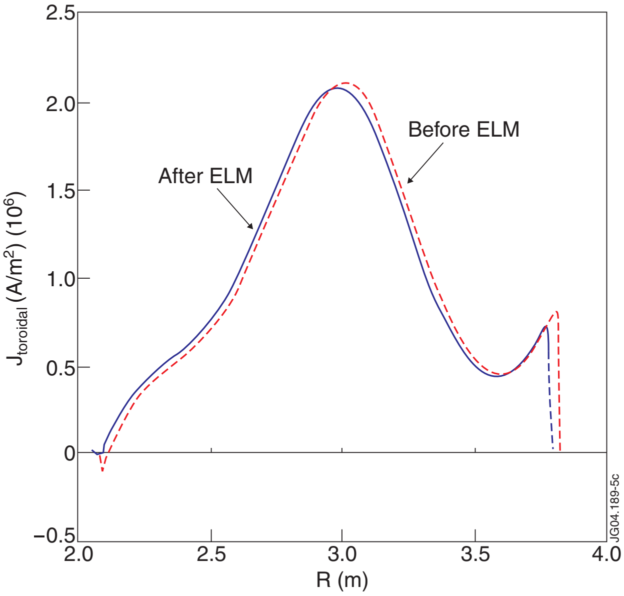


Figure 4: a) Density profile contours, measured with Li beam at plasma top: after each ELM, there is a reduction in the upper density, indicating either a downward displacement of plasma or a peeling of outer surfaces. b) D_α in inner divertor. c) Line density along central inner (red), outer (blue) and edge (pink) vertical lines.

Figure 5. Toroidal current density as a function of major radius at axis height, red before ELM, blue after ELM.