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ELMs and strike point jumps

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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 has been made at JET, showing that in all cases of Type I ELMs studied, strike point shifts were observed. In two cases studied in detail, the estimated equilibrium changes provoked by flux surface peeling agree qualitatively with the observed strike point shifts.
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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.

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A multi-diagnostic study of type I ELMs has recently been performed in an attempt to reproduce these observations and to investigate to what extent they might be consistent with the supposition that a layer of plasma is peeled off after an ELM. The fundamental basis for this expectation is a model in which 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 flux surfaces would open. Particles, energy and current would flow along these newly opened field lines and be quickly lost. Since the plasma pressure in the pedestal is high before the ELM, the edge toroidal current density must be large. The subsequent 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 cannot change on the ELM timescale). We expected the X point would move towards the plasma centre, upwards in JET vertical target plasmas.

2. Experimental observations of strike point movements in large type I ELMs

To maximize diagnostic sensitivity, plasmas were designed with infrequent ELMs and strike points positions optimised for good IR viewing and LP coverage. Discharges yielding the best data had plasma current $I_p = 2$ MA, toroidal field $B_T = 2T$, 15 MW of neutral beam injection heating and no gas-puff during the heating phase. They are characterised by 1 Hz compound ELMs [3] with a diamagnetic energy drop of order $\Delta W_{dia} = 500$ kJ in about 500 μs at each ELM. The same general behaviour of the strike points has been observed in a variety of other discharges.

Streak pictures (contours of surface temperature as a function of time and height, z, along the vertical target tiles) from the JET IR camera [4] are constructed by choosing pixels along target profiles at constant toroidal angle. Because of the acquisition procedure, time varies on each temperature profile. As shown in Fig. 1(a), $T_{surface}$ at the inner target has a clear maximum at -1.62 m, the pre-ELM strike point position. At the ELM, the temperature at -1.48 m suddenly increases, while the pre-ELM strike point position cools down. The hot spot appears and disappears in less than 65 μs. The presence of a thin, inhomogeneous surface layer leads to a prompt response of $T_{surface}$ to the heat flux arrival, but renders calculation of the heat flux density rather difficult [4]. Nevertheless, the combined decrease/increase in $T_{surface}$, observed at two different positions on the inner target, is a signature of a movement in peak heat flux density. This can be interpreted as a strike jump of up to 15 cm. The alternate interpretation of the image as heating of a flake is rejected, since that would not explain the simultaneous cooling of the pre-ELM strike position. At the outer divertor target, Fig. 1(b), the temperature does not respond as quickly to the heat flux arrival, but one can equally see that at the ELM a new hot stripe appears 2–3 cm above the pre-ELM strike position, which itself is cooling during the ELM.

Although cross-field diffusion of particles out of the divertor fan can lead to small errors, the location of the maximum in the target ion saturation current density profile (measured by the JET tile embedded Langmuir probe arrays [5]) can generally be taken as a good indicator of strike point position. Fig. 2 compiles various simultaneous measurements of the inner strike during a compound ELM: the D_α signal, IR $T_{surface}$ contours (3 ms time resolution, frame time), contours of ion saturation current (10 kHz sampling frequency) and the strike point height derived from both IR and LP measurements. The strike height is also shown for the outer target. Vertical shifts have been applied to the IR data to

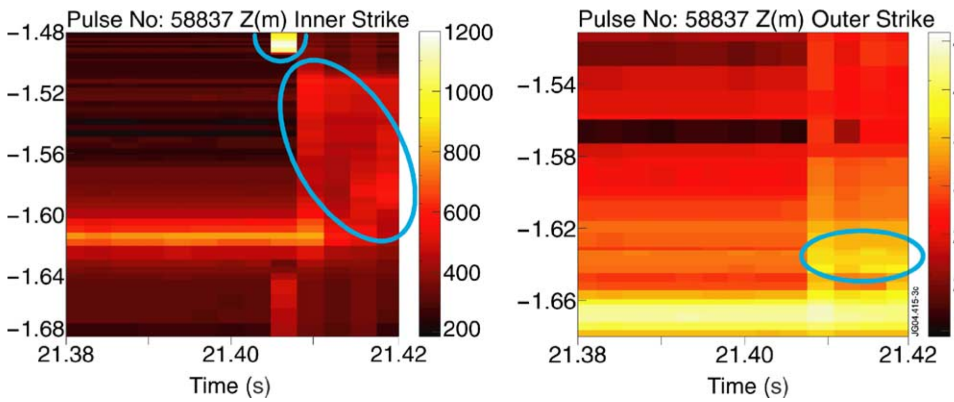

Fig. 1. (a) Contours of infrared measurement of tile surface temperature (Celsius) in the inner strike region of a vertical target plasma, as a function of time. (b) Tile surface temperature in the outer strike region. (For interpretation of colour in this figure the reader is referred to the web version of this article.)

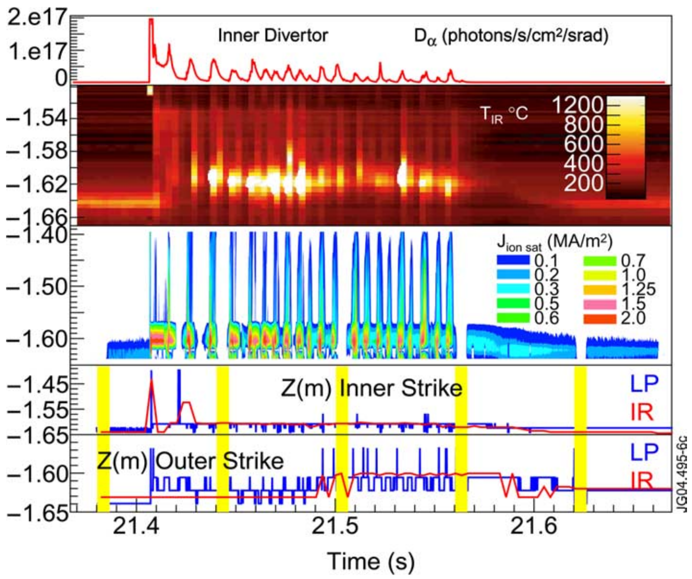

Fig. 2. ELM characteristics, in inner divertor leg: (a) D_α signal, (b) contours of tile temperature (Celsius) from IR, (c) contours of ion saturation current (A/m^2), from LPs, (d) strike positions, measured with Langmuir Probes (blue) and IR (red), (e) outer strike positions. Note: periodic voltage reversal is applied to LPs to avoid arcs. During this time, marked with yellow bars, strike positions are not well identified by LPs.

match the pre-ELM LP measurement (likely due to a camera misalignment). Due to the absence of a surface layer at the outer target, the position of maximum T_{surface} plotted in Fig. 2(e) varies more slowly. Fig. 2(c)–(e) show that the strike points jump upwards 10–20 cm inboard, and 7 cm outboard at the beginning of this compound ELM. Such a transient large jump is not observed at every ELM and occurs at only one time point. For other ELMs in the same discharge, it can be as large as 20 cm (inboard or outboard). About 100–500 μs later, the strikes settle at a position ~2–3 cm above the pre-ELM positions. Every subsequent small ELM in this compound ELM arrives at approximately the same post-ELM position, 2–3 cm above the pre-ELM strike position, as seen both in the T_{surface} and ion saturation current contours ((Fig. 2(b) and (c)) and in the position of their peak values (Fig. 2(d)). A few tens of milliseconds after the end of the ELM, the strikes slowly return to the pre-ELM position.

Are strike shifts associated with global plasma movements? No. The vertical position of the centre of SXR emission has a sudden (<100 μs) 7 mm downshift, followed by a return to the previous position in <100 μs, and a slow upward drift of 1 cm in 10 ms. This fast down-shift of the centre coincides in time with the large upward jump of the strikes (LPs), and so cannot be due to an upward plasma movement. Further evidence of plasma edge erosion, rather than plasma movement, comes from edge density measurements, obtained with a Li beam along a vertical line at the plasma top (100 ms time resolution). After each ELM, loss of density is observed from the top edge surfaces. The line integrated density is measured along 3 vertical lines located inboard and outboard of the magnetic axis, and at the outer edge (up to 1 ms resolution). A simultaneous sudden drop in all 3 line integrals indicates that the fast density loss observed by the Li beam is not due to an in-out movement of the plasma centre.

3. Modelling plasma peeling

Using Motional Stark Effect and Polarimetry (MSE + P) measurements, the pre-ELM plasma equilibrium has been reconstructed for the discharge discussed in Figs. 1 and 2, albeit with considerable error bars induced by large radial electric fields (not measured) and low time-resolution (20 ms). The reconstructed inner strike height agrees with LP measurements, but the outer is 3 cm higher. Such a discrepancy is not uncommon and does not affect the principal argument concerning relative changes in the equilibrium before and after the ELM. The reconstructed current density profile before the ELM is shown in Fig. 3. It is sensible, physically, since high edge pressure gradients imply high diamagnetism, which drives the toroidal current density below zero on the inboard side. This reduces the total plasma current loss due to shedding of flux surfaces since losses from inboard and outboard sides partly compensate each other.

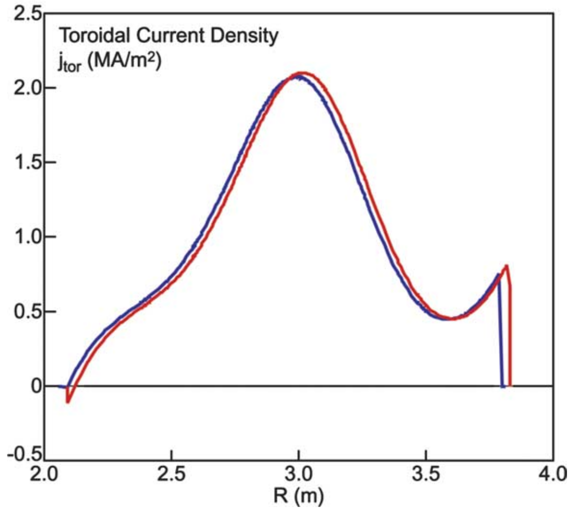

Fig. 3. Toroidal current density as a function of major radius at axis height, solid line before ELM, dashed line after ELM.

A linearized plasma response model of the plasma equilibrium [6] is used to compute a new equilibrium by peeling surfaces outside $\Psi_N = .95$ ($\Psi_N = 1$ at LCFS), accounting for induced currents in passive structures (large in sudden events in JET). The final current density profile is also shown in Fig. 3. This peeling results in loss of 90 kA of toroidal current, $\Delta W_{dia} \sim 1$ MJ, and upward strike jumps of 7 cm inboard, 5 cm outboard, all too large but in qualitative agreement with experimental observations. Clearly, a peeling of surfaces closer to the separatrix would give smaller strike point shifts and better quantitative agreement with measurements. Further modelling work to improve the pre-ELM equilibrium reconstruction is being performed before more detailed studies of the peeling are undertaken.

4. Transition between pre- and post-ELM states

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 cannot describe the temporal evolution of the system. The transition could, for example, be due to an X-point interchange stability, as proposed in [7], or to alternative separatrix instabilities.

What would be the characteristic times for flux surface peeling near the X-point? One estimate can be derived with the Kadomtsev sawtooth model [8]. Assuming a change in poloidal field at the post-ELM X-point, $\delta B_{pol} \sim 5 \times 10^{-2}$ T, an X-point displacement of $\delta r \sim 5$ cm due to peeling, local densities in the range $n_i \sim 1$–$5 \times 10^{19}\ \mathrm{m}^{-3}$ and temperatures $T_e \sim 50$–500 eV, the local Alfvén time would be, $\tau_A \sim = \delta r (m_0 n_{sion} m_{ion})^{1/2}/\delta B \sim 0.2$–$0.5\ \mu$s. The resistive time is $\tau_R = \mu_0 (\delta r)^2/\eta \sim 1$–$33$ ms, giving a Kadomtsev time $\tau_K = (\tau_A \tau_R)^{1/2} \sim 10$–$100\ \mu$s. Once edge current density loss has occurred and a 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. With a pedestal ion temperature of typically 1.5 keV, and a connection length in the private region of ~5 m (from 1 cm below the X-point to the target), and of ~20 m in the main SOL (from 1 cm outboard of the outboard midplane to the target), the time for ions to arrive at the target would be 12 and 50 μs, respectively. As most of these times are faster than our experimental resolution, we cannot describe the transition.

5. Conclusion

Measurement and modelling in JET both suggest that the post-ELM state, ~100–200 μs after the front of the ELM, can be described as a reduced plasma, that has shed current and previously closed flux surfaces, and has strike points closer to the plasma centre. Part of the after-ELM recovery would be associated with rebuilding of edge flux surfaces, not only of pressure gradients.

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