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The unintended influence of control systems on edge-plasma transport and stability in the Joint European Torus

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Plasma-Control System Interactions in Magnetically Confined Fusion Experiments

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** See annex of F. Romanelli et al, "Overview of JET Results", (24th IAEA Fusion Energy Conference, San Diego, USA (2012)).*

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ABSTRACT

The Joint European Torus (JET) [1] is the world's largest magnetically confined fusion (MCF) experiment. A unique sequence of 120 almost identical JET plasmas recently provided two orders of magnitude more statistically equivalent data than ever previously available. The purpose was to study movement of eroded plasma-facing material from JET's new Beryllium wall [2, 3], but it has allowed the statistical detection of otherwise unobservable phenomenon. This includes a sequence of resonant-like waiting times between edge-localised plasma instabilities (ELMs) [4, 5], instabilities that must be mitigated or avoided in large MCF devices such as ITER [6]. Here we investigate the causes of this phenomenon, finding a clear link between plasma confinement, ELM occurrence, vertical plasma oscillations, and an oscillation in a control coil current not usually associated with ELM occurrence. The results suggest a strong and unanticipated edge-plasma dependence on control system behaviour, suggesting that plasma confinement, stability, and control, should not be studied independently.

1. INTRODUCTION

The JET plasmas studied are 2T, 2MA, high confinement (H-mode) plasmas, with about 6 seconds of H-mode with type I ELMs, the final 2 seconds of which is exceptionally steady-state. Combining data from this final 2 seconds of H-mode, provides 240 seconds of plasma data with »10000 ELMs. The large quantities of data allows a finely resolved probability density function (pdf) for the waiting times between ELMs to be produced (figure 1). In contrast to expectations from previous work [7], the pdf has a sequence of maxima and minima separated by 8ms intervals, with the first maxima 12ms after the previous ELM [8]. This paper explores the causes of this phenomenon. Key to the analysis is the unprecedentedly large amount of data that is available, in principle each ELM is statistically equivalent. By synchronising data to the ELM times, and averaging it, detail can be observed that would not otherwise be visible. The ELMs are identified as in previous work [7], using the Beryllium II (527nm) radiation measured at the inner divertor in 0.1ms intervals. When synchronising the data to ELM times, we excluded data for which the previous ELM occurs within 40ms. This is to avoid large post-ELM responses from being included within ~30ms prior to an ELM, but reduces the dataset to ~3000 ELMs. The central limit theorem ensures that random errors are reduced by a factor of $1/\sqrt{3000} \simeq 0.02$, two orders of magnitude smaller than usual. The resulting plots (figures 2, 3, and 4) include the average and its standard deviation, plus values from a typical JET pulse in the set (83794). The Supplementary Material [9] lists the pulses that we consider, and further details of the analysis.

2. RESULTS

Figure 2 plots Langmuir probe measurements of deuterium ion fluxes to JET's inner divertor, and the rate of change of line-integrated plasma density measured along a chord through the plasma's mid-plane. Because the chord is through the mid-plane, the line-integral is insensitive to small vertical plasma displacements, and should solely measure changes in plasma density. Prior to an ELM, both plots show 8ms-period oscillations in the ion flux and rate of change of plasma density, with increased ion fluxes coinciding with decreasing density, and vice versa. Line-integrated edgedensity measurements are similar.

EFIT [10, 11] uses magnetic measurements from a large number of magnetic diagnostics that surround the plasma [12], to reconstruct the plasma's position and shape. It finds clear 8ms-period oscillations in the plasma's motion before an ELM, that appear to be confirmed by EMFs that are measured by flux loops above and below the plasma (figure 3). The measured EMFs are π out of phase with each other, consistent with a vertical plasma oscillation, and have a phase and amplitude that is consistent with the EFIT vertical velocity. It is well known that vertical plasma displacements can modify the edge-plasma's stability [13], and the oscillation's period is the same as for enhanced (or reduced) ELM occurrence and ion losses, so it is possible that they are triggered by the vertical oscillations. The maxima in ELM occurrence and ion fluxes are when the plasma is moving rapidly towards its furthest downwards displacement, and the minima in ELM occurrence and ion fluxes have the plasma near its uppermost position.

The correlation between EMFs, plasma motion, and ELMs, explains the phase relationship observed between ELM occurrence and measured loop voltages in JET's divertor [14]. Previous analysis [8] indicated that the oscillations observed in figures 2 and 3 must result from either a plasma phenomena or a real-time control system, but found no evidence for the vertical control system being responsible. JET also has a real-time shape control system that alters 9 coil circuits, including 4 divertor coils and circuits named: P1, P4, SHA, IMB, and PFX [15]. The divertor coils are used to control the plasma strike point positions, P1 controls the toroidal plasma current, P4 controls the outer gap (ROG), SHA controls the plasma's triangularity and elongation, IMB controls the top gap (TOG), and PFX can control the inner gap (RIG); although each circuit modifies the plasma's shape and position in a variety of ways [15]. The shape controller can modify these currents every 2ms, and they were recorded every 8ms, which is much less frequent than the data discussed so far and too infrequent for an 8ms-period oscillation to be observable in the time traces. Consequently the 240s of data and 3000 ELMs become essential. Figure 4 plots the measured currents after synchronising them to the ELM times and offsetting them by their value at the ELM (t=0), estimated by linear interpolation between adjacent data points. The result is surprisingly successful, with comparatively small error bars in many of the plots.

The divertor coil and SHA currents are comparatively unremarkable and are not shown here. As are the P4 currents, that show a gradual increase prior to ELMs but no oscillations. In contrast, P1, PFX, and IMB, show clear oscillations with an 8ms timescale prior to ELMs. These plots represent measured currents in the circuits (not voltages), with associated magnetic fields that modify the plasma's shape and position. For these plasmas the control system used P1 to keep the plasma current constant, PFX currents were requested to be kept a constant fraction of the plasma's current (that is approximately constant), and used IMB to control TOG. The IMB currents show clear oscillations with very small error bars, indicating that this 150A current oscillation has a very consistent 8ms period. The ELMs occur 4ms after a maximum in IMB, which is 12ms after the previous maximum. The maxima are at 12, 20, 28, 36, 44, and 52 ms before and after an ELM; identical to the timings of the maxima in figure 1. An increase in IMB current would be expected to pull the plasma down and outwards [15], a decrease in IMB to push the plasma up and inwards. Figure 5 is consistent with this, finding a downwards plasma acceleration when the IMB oscillation is +ve relative to its value at an ELM, and an upwards acceleration when it is -ve. The ELMs (and enhanced ion fluxes), occur as IMB pulls the plasma outward and downwards.

The size and coherence of the oscillations in IMB make a persuasive case for them being either the cause of the oscillatory phenomena discussed in this paper, or at least involved in sustaining it. As does their exact coincidence with enhanced (or reduced) ion fluxes and ELM occurrence, and the correlation between the sign of the IMB current's oscillation and the direction of plasma acceleration. How the oscillations arise is unclear, but it is known that oscillations can easily arise in a control system involving 9 independent circuits and the plasma [15]. The oscillations are not universally present in JET plasmas, and depend on plasma heating and fuelling for example 8. They could involve a coupling between various independent circuits, the plasma, and the plasma's motion, or a complex process or sequence of processes involving one or more of: plasma instabilities, turbulence, transport processes, material erosion and recycling, for example. A rigorous analysis is likely to require both a faster recording of control coil currents and an effective modelling of the plasma's response to them. We emphasise that because the currents in these circuits were only recorded every 8ms, it is impossible to observe the oscillations in the time series data - this was only possible by combining data from a large data set.

3. DISCUSSION

An unprecedented number of 120 identical JET plasmas has allowed the observation of a totally unexpected connection between a seemingly benign shape control system, ELM occurrence, and edge transport. There are numerous implications. Firstly, these and similar effects could be common but unobserved, due to insufficient data. This has clear implications for the analysis of experiments for ELM pacing in particular [13], there could be synergies favouring different ELM frequencies that need to be tested for. Second, it suggests that a control system or a plasma-control system interaction is causing vertical oscillations, and are either directly or indirectly modifying the plasma's edge-transport and stability, possibly through a sequence of processes or interations. More significantly, it suggests that plasma-control system interactions should not be ignored when modelling plasma transport and stability; and vice versa. This opens the possibility that entire classes of ELMs could involve synergistic control system interactions - this will be explored in greater detail elsewhere. Finally, the suggestion that IMB can modify edge transport rates leads us to ask, could it modify edge densities sufficiently to avoid ELMs entirely? We hope that these possibilities will be vigorously pursued in the near future.

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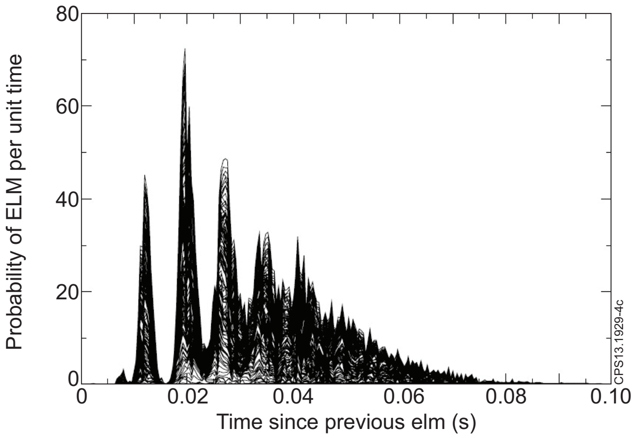

Figure 1: The ELM waiting-times from 120 almost identical JET plasmas are combined to form a single pdf for the waiting times between ELMs. Each line corresponds to data from a separate pulse, that are added to form the pdf. Reproduced from Webster et al. [8].

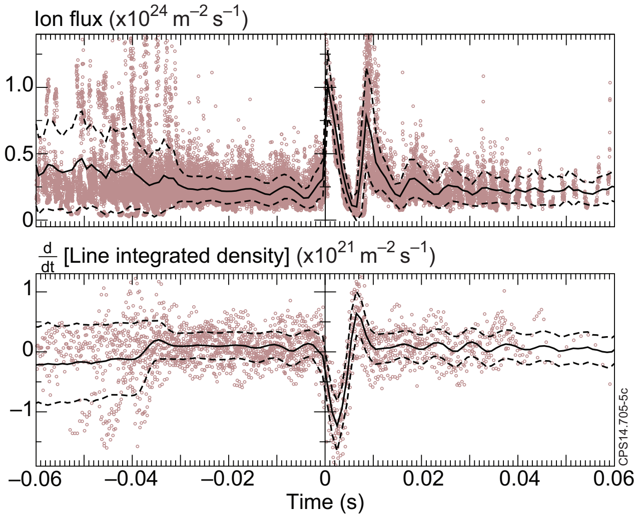

Figure 2: Top - Langmuir probe measurements of ion flux to the inner divertor ($\times 10^{24}$ $m^{-2}s^{-1}$) versus time (s), synchronised to the ELM times at t = 0. Bottom - the rate of change of lineintegrated density measured through the plasma's mid-plane (particles $m^{-2}s^{-1}$) versus time (s), synchronised to the ELM times at t = 0. Thick black lines are averages, dashed lines indicate standard deviations, and circles are typical measurements (Pulse No: 83794). Prior to ELMs there are 8ms-period oscillations, with increased (or reduced) ion fluxes that coincide with reducing (or increasing) plasma density, similar to 8ms-period plasma-position and control-current oscillations discussed later. The post-ELM signal is difficult to interpret due to large post-ELM plasma movements, strong control coil responses, and non-linear interactions such as impurity influxes.

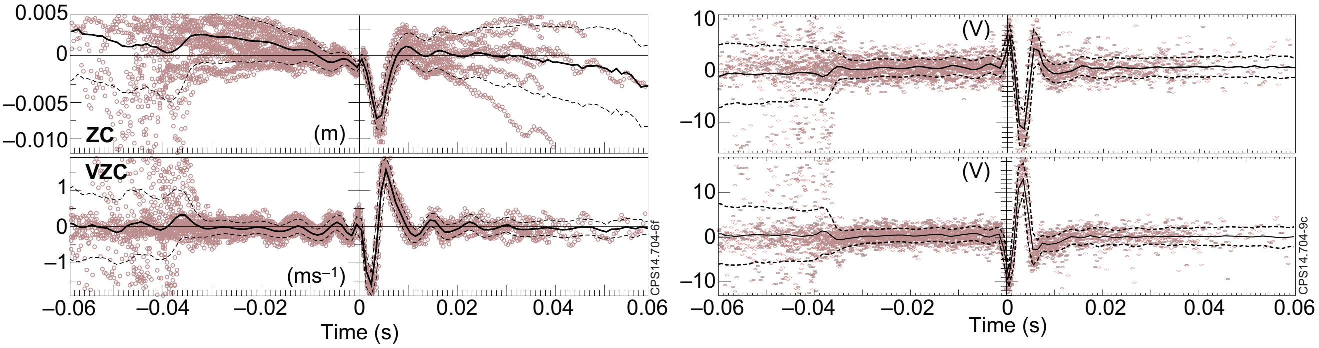

Figure 3: Top and bottom left are the vertical position (ZC) and velocity (VZC) of the plasma current's centroid, as calculated by EFIT [10, 11]. Top and bottom right are the EMFs measured by toroidal loops above and below the plasma respectively. The measured EMFs prior to ELMs are π out of phase, consistent with a vertical oscillation, and have a phase and amplitude consistent with the vertical oscillations calculated by EFIT.

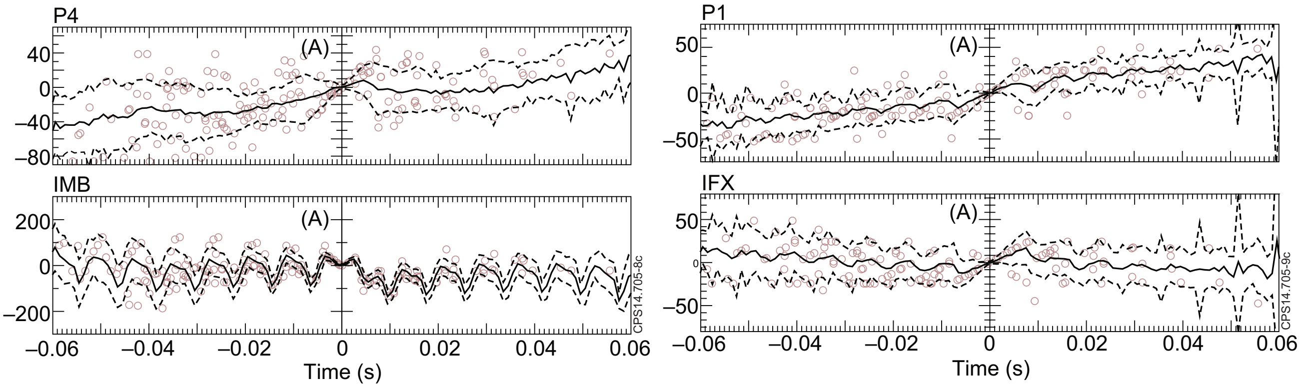

Figure 4: Changes in control system currents (Amps) versus time (s), relative to those at ELM time t = 0. Clockwise from top left, circuits: P4, P1, PFX, and IMB. Circles are a typical pulse (Pulse No: 83794), pulse-set averages and standard deviations are the solid and dashed lines respectively. The 8ms-period oscillations in IMB are very clear, and its standard deviation is comparatively very small. Note that these are oscillations in current (not voltage), that will magnetically perturb the plasma.

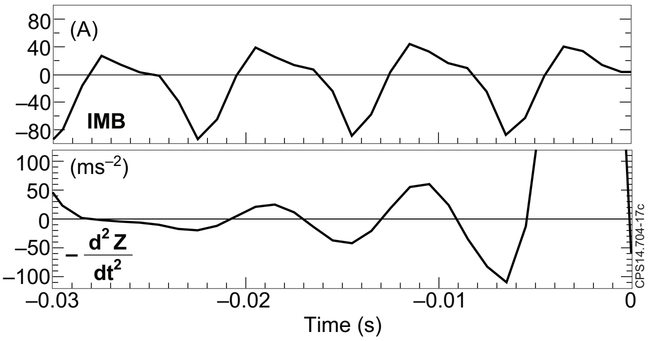

Figure 5: Top figure, the average IMB current prior to ELMs, offset to zero at the ELM time. Bottom figure, the average plasma acceleration downwards prior to ELMs, as measured by the acceleration at the plasma's X-point $(-d^2Z/dt^2)$. *When the IMB oscillation is positive then there is a positive acceleration downwards, when the oscillation is negative the plasma accelerates upwards.*