

Global control system and synchronous natural ELMing in the ASDEX Upgrade tokamak

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1. Introduction

H-mode plasmas are typically unstable to edge localised modes (ELMs), in which plasma escapes and strikes the vessel wall. ELMing can be modified by externally triggering smaller, more frequent ELMs by injecting pellets[1] of frozen deuterium that modify the plasma edge or by using external field coils to apply magnetic perturbations[2-4]. Maintaining a steady state tokamak plasma requires active vertical position control[5]. The ASDEX Upgrade control system achieves this using currents in the poloidal field coils. Here we study natural ELMing during intervals in which the control system current in these field coils continually oscillates, and can become synchronized with oscillations in the plasma outboard edge position (R_{out}) and total MHD energy (W_{MHD}). In these synchronous states, ELMs all occur when the control system coil current is around a specific phase, irrespective of its amplitude. This supports our new paradigm, for which there is evidence on JET[6-9], that the global plasma dynamics emerging from nonlinear feedback between plasma and control system is part of natural ELMing. Knowledge of the control system signal phase indicates future times when ELM occurrence is more likely, which may assist ELM mitigation in real time.

2. Current in the control system field coils: analytic phase and synchronous dynamics

We present detailed analysis of ASDEX Upgrade plasma 30792 ($I_p=0.8\text{MA}$, $B_T=2.5\text{T}$) during the early part of its H-mode where there is natural ELMing. ELM occurrence times (see Fig.1 caption) are inferred from the thermionic current in a tile in the divertor region. The control system dynamics is inferred from the instantaneous analytic phase of the current in the upper toroidal field coils (I_C^u) that provide active vertical control of the plasma. We infer the global plasma state from the values of W_{MHD} and R_{out} . These signals are sampled at $50\mu\text{s}$ time resolution, and the time dependent amplitude and phase of the I_C^u signal are obtained as follows. We first subtract a 1000 point running mean to remove the time-varying baseline of the I_C^u signal, then obtain its analytic amplitude and phase by Hilbert transform: a real valued signal $S(t)$ and its Hilbert transform, $H(t)$ together define the analytic signal $S(t) + iH(t) = A(t)\exp[i\phi(t)]$ with instantaneous amplitude $A(t)$ and phase $\phi(t)$. The instantaneous phase is defined relative to a single reference value, here, its average at the

times of each ELM. In the left panels of Figs.1 and 2, the ELM crash is seen as a sharp drop in W_{MHD} with inward movement of R_{out} ; we define the time t_B to be when W_{MHD} and R_{out} are around their peak values, shortly before the ELM crash. Fig.2 identifies an interval where the current in the control system field coils is roughly oscillatory, and we find that in this ASDEX Upgrade plasma, the ELMs tend to occur when this current is at a particular phase of its oscillation.

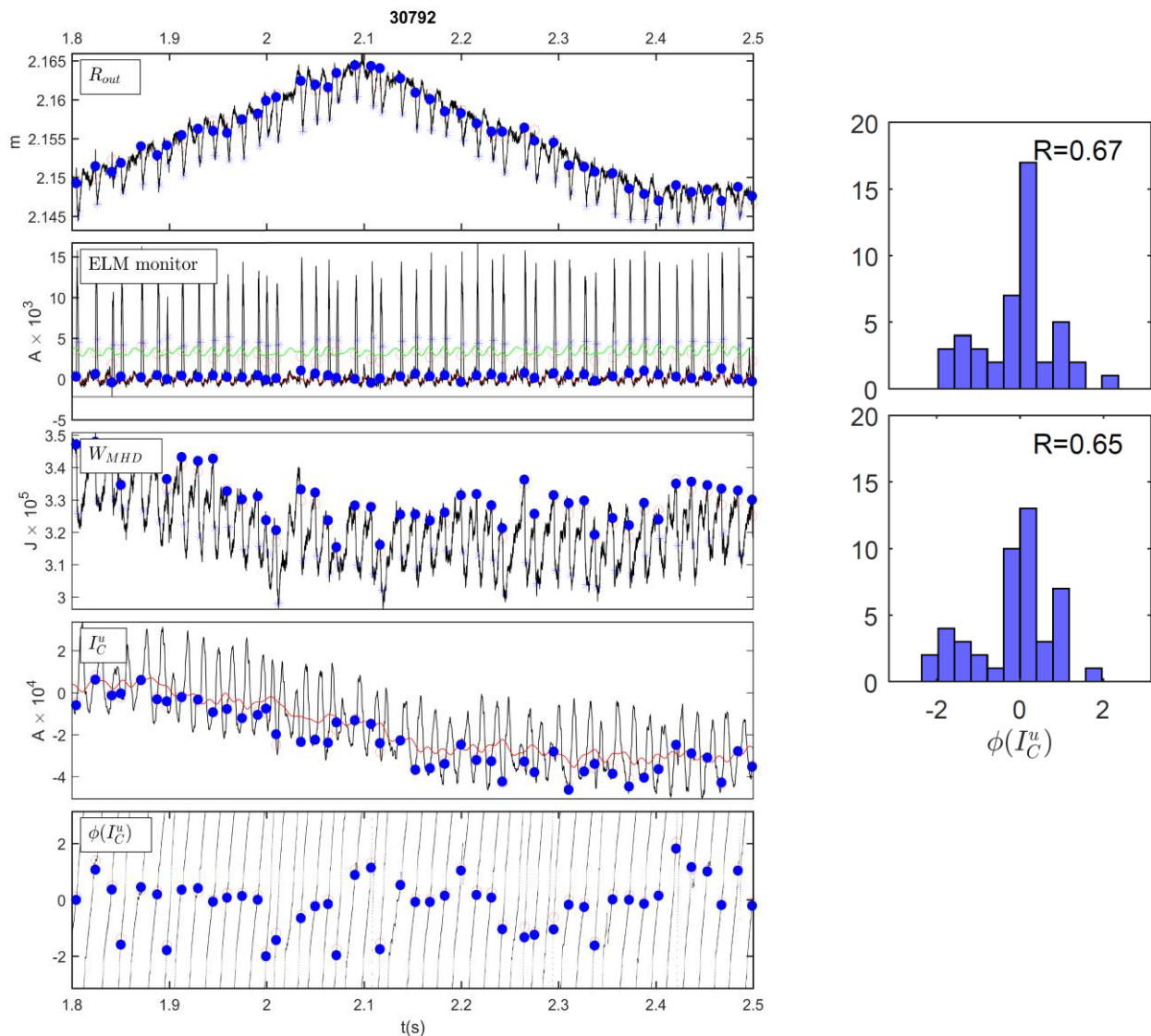


Fig.1 (left): Time traces plotted for time window $t = 1.8\text{s}$ to 2.5s in plasma 30792, which exhibits intervals of synchronous dynamics. From top to bottom we plot with black traces: the edge position (R_{out}); the current in a tile in the divertor region (ELM monitor); the total MHD energy in the plasma (W_{MHD}); the current in the upper vertical control system coil (I_C^u); and its analytic phase $\phi(I_C^u)$. ELM occurrence times are determined from the ELM monitor signal, see also Fig.2. For each ELM, the onset time t_R (open red circle in Fig.2) and end time t_F (blue star in Fig.2) are at the data points just before the ELM monitor signal upcrossing and downcrossing, respectively, of a threshold (green line) which is one standard deviation away from the running baseline of the signal (red line). The filled blue circles are at a time just before the start of the ELM crash, $t_B = t_R - dt$, here $dt = 350\mu\text{s}$. Fig.1 (right): Histograms of instantaneous phase of the I_C^u signal plotted at the ELM onset time t_R (upper panel), and just before it at t_B (lower panel). The Rayleigh R statistic is given for each; if at a given time

before the ELM, the signal was always at exactly the same phase, then one would obtain $R(t) = 1$. The null hypothesis of uniformly distributed phases can be rejected with 95% confidence for $p < 0.05$, and here $p < 10^{-10}$.

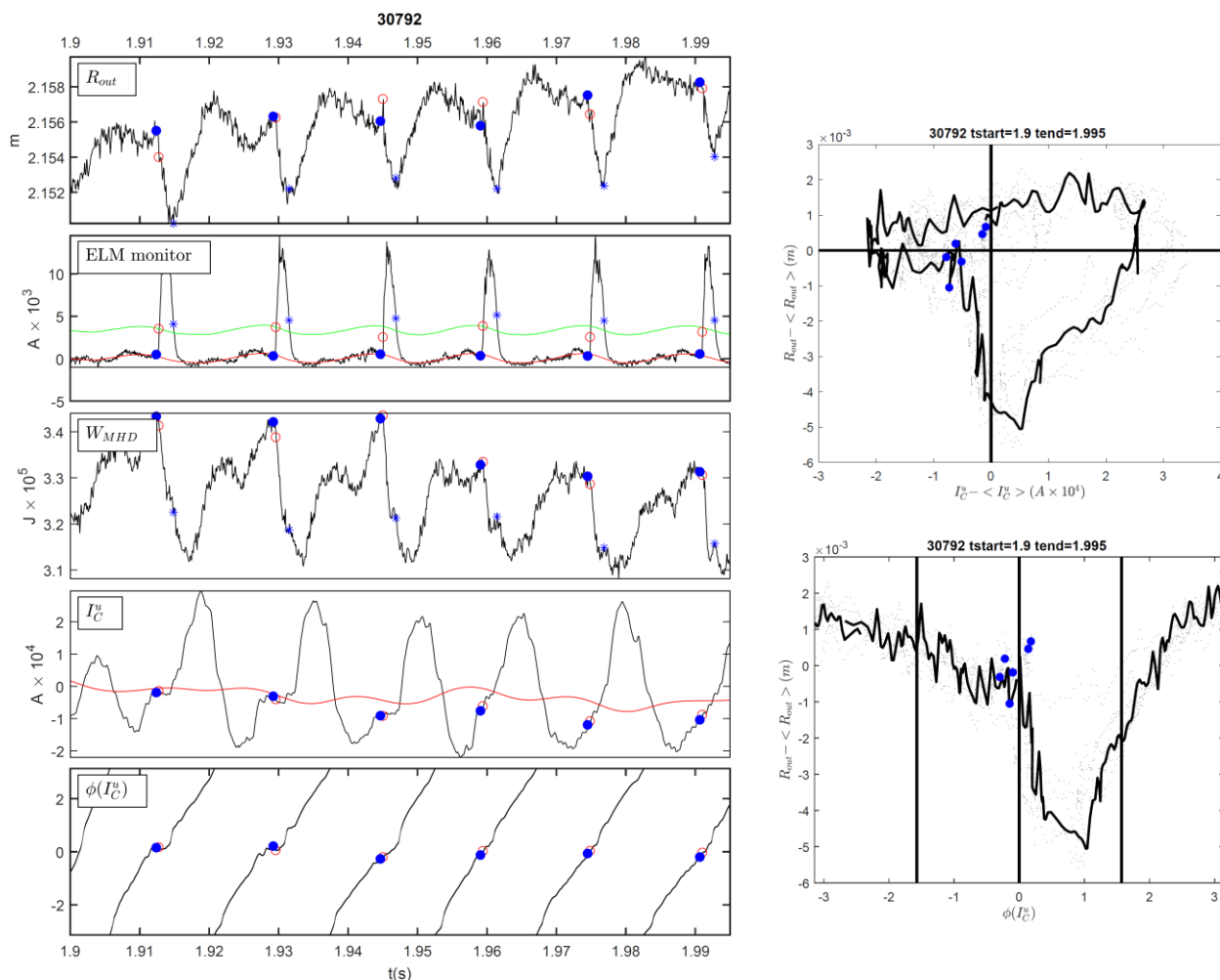


Fig.2 (left): A zoom of Fig.1 to show an interval of synchronous dynamics.

Fig.2 (right): The location of the plasma outer edge (R_{out}) plotted versus the mean-subtracted current in the control system field coils (I_C^u , top plot) and its phase (bottom plot). Except for the I_C^u phase, the plotted traces have their respective running means subtracted, and the signals are plotted for the interval of synchronous dynamics in the left hand panels (grey dots). One cycle of this dynamics, that is, from one ELM to the next, is overplotted (solid black line). For each ELM, the signals at the time just before ELM onset t_B are plotted (blue filled circles).

In Fig.1 the timeseries can be characterized as short intervals of the fully synchronous dynamics as shown in Fig.2, interspersed with phase slips. The phases at which ELMs occur are far from random. In the right hand panels of Fig.1 we plot a histogram of the I_C^u phases at the times of ELM onset (t_R , upper plot) and 350 μ s before this (t_B , lower plot). To check statistical significance, we calculate the Rayleigh R statistic (see [7,8] for details) at t_R and t_B . A value $R = 1$ would indicate that all phases are exactly aligned; for the interval $t = 1.8 - 2.5$ seconds we find $R(t_R) = 0.67$ and $R(t_B) = 0.65$, implying high significance. Importantly, we see strong phase alignment not only when ELM onset has begun, but also at a time 350 μ s before it. Hence this phase relationship is not simply due to the response of the control system to

each ELM crash: there is synchronized dynamics of control system and plasma, shown e.g. in the right panels of Fig.2. Here the upper plot is the mean-subtracted location of the plasma outer edge (R_{out}) versus the mean-subtracted current in the control system field coils (I_C^u), for the interval of synchronous dynamics shown in the left panels. The signal values just before each ELM, at time t_B , are plotted with blue circles. For each ELM, the plasma and control system together execute a cycle. The lower right panel plots the mean-subtracted value of R_{out} versus the phase of I_C^u , which can be seen to be a natural co-ordinate variable for the ELMing process. Just before the ELM onset, at time t_B (blue circles), the I_C^u phases cluster about zero, and we can see that the build-up and recovery occur over two halves of the phase cycle of the control system current.

3. Conclusions

We have identified intervals of natural ELMing in ASDEX Upgrade tokamak plasmas, during which the current in the control system vertical field coils continually oscillates, and is synchronized with oscillations in the plasma edge position and total MHD energy. In these synchronous states, ELMs all occur when the control system coil current is around a specific phase. In the example analysed here, while the synchronous motion is not perfectly maintained, since there are phase slips which disrupt the phase pattern, the control system vertical field coil current phase just before ELM onset is far from random. At minimum, this suggests that the control system current phase is a useful ELM cycle ‘clock’: the same phase relationship will persist even if the ELM frequency is drifting. Additionally, these results suggest a synchronous state, in which continual nonlinear feedback between global plasma dynamics and the control system is intrinsic to the natural ELMing process. On JET we previously found a class of prompt [9] natural ELMs which rapidly follows the preceding ELM, synchronized by the combined response of the plasma and control system to the first ELM. We would thus expect that, under certain conditions, natural ELMing reflects fully synchronous dynamics between the control system and global perturbations in the plasma. We have found just such a synchronous dynamics here. This supports the paradigm shift [6] in which interaction between the control system and the plasma can be part of the natural ELMing process.

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- [1] P T Lang, A W Degeling, J B Lister et al, Plasma Phys. Control. Fusion **46** L31–L39 (2004)
- [2] T E Evans, R E Moyer, K H Burrell, M E Fenstermacher *et al.*, Nature Phys. **2** 419 (2006)
- [3] Y Liang, H R Koslowski, P R Thomas, E Nardon *et al.*, Phys. Rev. Lett. **98** 265004 (2007)
- [4] E de la Luna, I T Chapman, F Rimini, P J Lomas *et al.*, Nucl. Fusion **56** 2 (2016)
- [5] W Treutterer, R Cole, K Lüddecke, G Neu *et al.*, Fusion Eng. Des. **89** 146 (2014)
- [6] S C Chapman, R O Dendy, A J Webster, N W Watkins, T N Todd, J Morris & JET-EFDA Contributors, *Proc. 41st EPS Conference on Plasma Physics, Europhysics Conference Abstracts (European Physical Society)*, Vol. **38F**, ISBN 2-914771-90-8, paper 101 <http://ocs.ciemat.es/EPS2014PAP/pdf/P1.010.pdf> (2014)
- [7] S C Chapman, R O Dendy, T N Todd, N W Watkins *et al.*, Phys. Plasmas **22** 072506 (2015)
- [8] S C Chapman, R O Dendy, P T Lang, N W Watkins *et al.*, Nucl. Fusion **57** 022017 (2017)
- [9] S C Chapman, R O Dendy, T N Todd, N W Watkins *et al.*, Phys. Plasmas **21** 062302 (2014)