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1. INTRODUCTION

One avenue towards an integrated H-mode regime suitable for standard operation on ITER is development of well-confined states with intrinsically small ELMs. Significant progress has been made with the “Type II” and “mixed” regimes on ASDEX-U and JET, high β_p “grassy” regime on JT-60U and JET, “EDA” H-mode on Alcator C-Mod and JFT-2M, and “QH”-mode on DIII-D and ASDEX-U (see eg [1,2] and references therein). An important feature these all have in common is an increase in continuous edge turbulence compared to usual intervals between Type I ELMs, which mediates steadier exhaust through the pedestal region. The aim in the present study is to open a systematic examination of edge fluctuations in ELM-free periods on JET, in order to clarify their evolution towards the former benign properties. We compare behaviour in “standard” cases with plasmas coming progressively closer to the conditions of C-Mod EDA and ASDEX-U TypeII pedestals.

2. VARIATION WITH HEATING SCHEME, PLASMA SHAPE AND PEDESTAL COLLISIONALITY

Typical ELM-free H-mode intervals on JET are illustrated by the moderately-shaped single-null case, using 42MHz minority ICRF heating, shown in Fig.1 (Pulse No: 50492, 2.7T, 2.5MA, $\kappa = 1.67$, $\delta^u = 0.43$, $\delta^l = 0.35$, $q_{95} = 3.2$). Two clear transitions from L-mode are exhibited, during each of which plasma density (and radiation) rise rapidly until a limit forcing a back-transition is reached. The power spectrum of magnetic fluctuations during one such interval in a very similar plasma at slightly higher density (Pulse No:50496) is depicted in Fig.2, and clearly reveals multiple coherent oscillations with frequencies between $\approx 10 - 80$ kHz throughout the ELM-free phase, but disappearing immediately at the terminating ELM and into the subsequent L-mode. Estimated toroidal mode numbers in Fig.3 indicate $n \approx -1$ to -10 , signifying rotation in the electron diamagnetic drift direction. Contrasting coil signals from differing poloidal locations also are consistent with a ballooning character. These features all epitomize a class of edge MHD instabilities prevalent between ELMs in JET designated “washboard” modes (WBMs)[3,4]. Here they are not detected on X-mode reflectometer channels at 96GHz and 75GHz probing the upper half of the pedestal gradient region, although the latter does display a pronounced drop in integrated fluctuation amplitude in each ELM-free period (Fig.1), again as often observed. Similar WBMs are seen in ELM-free intervals with NBI heating, as demonstrated by multiple peaks above ≈ 35 kHz in the frequency-normalized power spectrum superimposed in Fig.4 (Pulse No:55416, 2.0T, 2.0MA, $\kappa = 1.73$, $\delta^u = 0.36$, $\delta^l = 0.31$, $q_{95} = 3.1$, also (4,2), (5,3), (6,4) modes in ion direction at lower frequencies). In this case, they also just become visible on O-mode reflectometry at 50GHz sensing close to the pedestal top. Preliminary analyses with the JETTO/HELENA/MISHKA transport/stability code suite find no ideal MHD instabilities in the edge for either instance (Pulse No:50492, Pulse No:55416), actually consistent with an expectation from their electron-drift motion that WBMs are resistive (though not tearing[3]) in nature.

Small ELMs, particularly Type II and “mixed” regimes, are promoted by stronger magnetic shaping[2]. The magnetic normalized power spectrum during recurrent ELM-free phases in such a plasma with dominant 42MHz ICRH (Pulse No:53421, 2.8T, 2.0MA, $\kappa = 1.70$, $\delta^u = 0.46$, $\delta^l = 0.43$, $q_{95} = 3.9$) is shown in Fig.5. Ballooning-like WBMs in the electron direction are still evident from $\approx 30 - 60$ kHz, ie fewer frequency bands are concentrated in a smaller range. They are also detected by X- and O- polarization reflectometer channels returning from the upper half of the gradient region. However, an NBH plasma at extreme shaping / q_{95} (Pulse No:58909, 2.7T, 1.5MA, $\kappa = 1.73$, $\delta^u = 0.56$, $\delta^l = 0.40$, $q_{95} = 6.1$) exhibits modes only in the ion direction below ≈ 60 kHz, suggesting WBMs are then suppressed (averaged spectrum in Fig.5). “Quasi-Coherent” Mode (QCM) turbulence[5] mediating EDA H-regime is obtained with higher edge collisionality, and this has further been tested by adapting JET conditions to yield plasmas non-dimensionally identical to C-Mod in the pedestal^[1,6]. An example using NBH (Pulse No: 62663, 0.9T, 0.7MA, $\kappa = 1.67$, $\delta^u = 0.41$, $\delta^l = 0.38$, $q_{95} = 4.3$) displays a very long ($\approx 10 \tau_E$) nearly ELM-free period, with a prominent new feature that stored energy and pedestal density (though not core density or radiation) remain almost constant[6]. Magnetic fluctuations are concentrated in a low frequency range up to ≈ 25 kHz (Fig.6), while mode analysis recalls WBM-like out/in asymmetry and rotation (Fig.7). In contrast, when heating is switched mid-way through the pulse to 28MHz $2 \omega_{ci}$ ICRF, there is a marked change in ELM behaviour, ie here a definite effect of heating scheme does arise. Repetitive ELM-free phases with initially rising recycling re-emerge, separated by short bursts of possibly Type III ELMs. The magnetic spectrum for another such case (Pulse No:57021, 1.3T, 0.81MA, $q_{95} = 5$, 42MHz $2 \omega_{ci}$ ICRH) is added in Fig.5 and now contains only 2 - 3 strong modes at ≈ 14 , 24kHz. These appear powerfully on all O-mode reflectometer signals (19 - 45GHz) covering the whole pedestal, implying localization in the edge, but at least the lower frequency oscillation is not ballooning-like and not definitely electron-drift directed. Hence there are no longer clear signs of WBMs. Longest ELM-free period of all with steady pedestal density is derived in an NBH plasma alternatively designed for dimensionless identity to Type II regime in ASDEX-U, using quasi-double-null geometry^[2] (Pulse No: 62430, 1.15T, 0.87MA, $\kappa = 1.74$, $\delta^u = 0.50$, $\delta^l = 0.37$, $q_{95} = 4$). Again magnetic fluctuations are concentrated below ≈ 25 kHz (Fig.6), but mode analysis in Fig.7 suggests a totally distinct pattern of non-ballooning like disturbances in fact more reminiscent of L-mode characteristics than of WBMs. Two modes decreasing in frequency from initially ≈ 10 , 20kHz are briefly seen on an O-mode reflectometer channel at 34GHz reaching the mid gradient region, but coherent density fluctuations are otherwise absent in both this and the preceding case (Pulse No:62430, Pulse No:62663).

SUMMARY

Each ELM-free H-mode period presented, plus one extra, is summarized in terms of equilibrium and estimated pedestal dimensionless quantities in Fig.8. The higher values of triangularity (≥ 0.35) and q_{95} (≥ 3.5) where EDA regime occurs on C-Mod[5] have indeed been

covered, but without any signs here of QCM activity. Electron-drift directed WBMs, however, seem clearly to emerge irrespective of heating scheme for a wide middle range in pedestal collisionality, perhaps disappearing only at lowest (< 0.5 , or highest shape / q_{95}) and highest (> 5) figures included. Similarly pedestal density tends to become constant at high edge v_{*e} . The extent to which WBMs actually contribute to plasma transport remains uncertain[4]. It should be noted though that neo-classical transport is already substantial in this last condition, and is estimated with the JETTO/NCLASS codes e.g. to lead to ion thermal diffusivity comparable to the total effective coefficient $-q_{\text{loss}}/(n_e \nabla T_e + n_i \nabla T_i)$ in the periphery of Pulse No: 62430. Hence it may account for (much of) its enhanced pedestal transport even without turbulence effects, while high v_{*e}^{ped} is also known itself to favour reduced ELMs[7]. A next step in studying fluctuations between ELMs will therefore be to compare their behaviour in QH-mode like cases, where quasi-stationary ELM-free H-mode is sustained at significantly lower pedestal collisionality.

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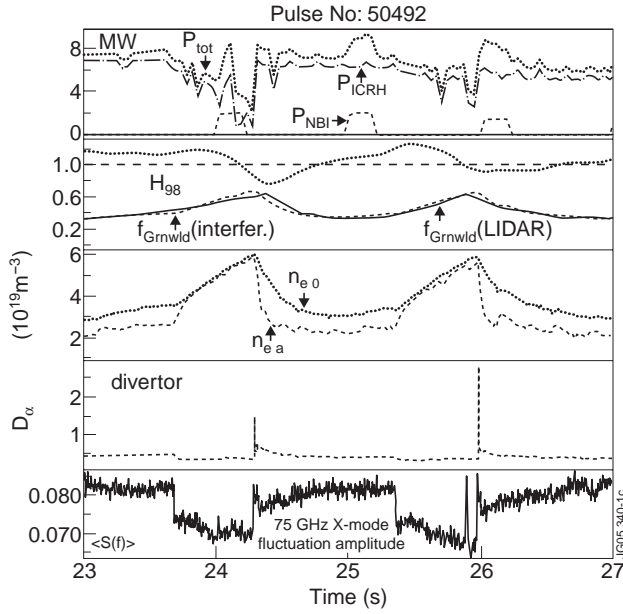


Figure 1: Input power, normalized confinement and density, central and edge density, divertor D_α reflectometer fluctuation amplitude, for two ICRH ELM-free H-mode phases.

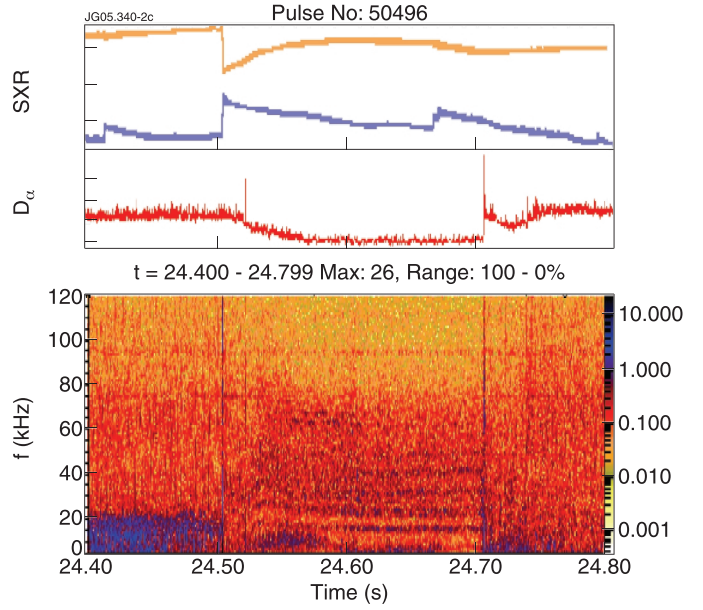


Figure 2: SXR, divertor D_α power spectrum of magnetic fluctuations spanning an ELM-free H-mode interval in a very similar ICRH plasma. “Washboard” modes are visible as multiple coherent frequency stripes.

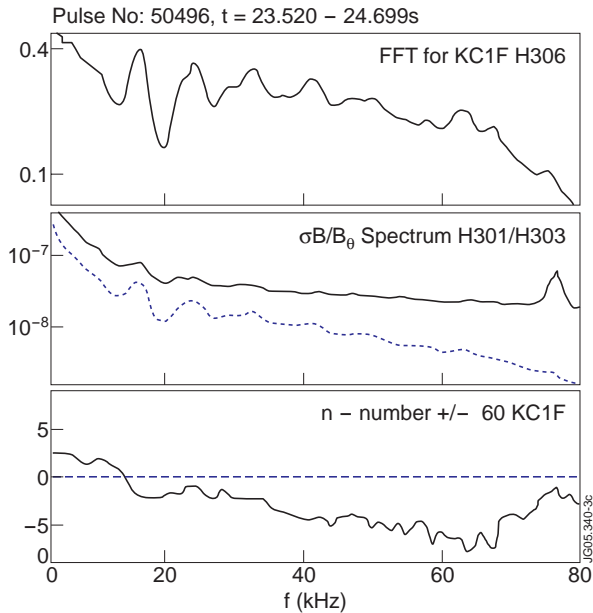


Figure 3: Power spectrum, out/in coil signals, estimated toroidal mode numbers during ELM-free phase.

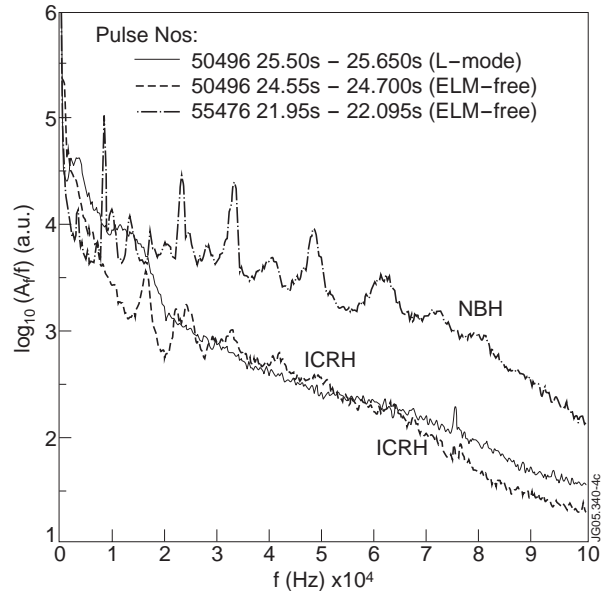


Figure 4: Frequency-normalized averaged power spectra of magnetic fluctuations in ICRH and NBH ELM-free H-modes, plus L-mode reference.

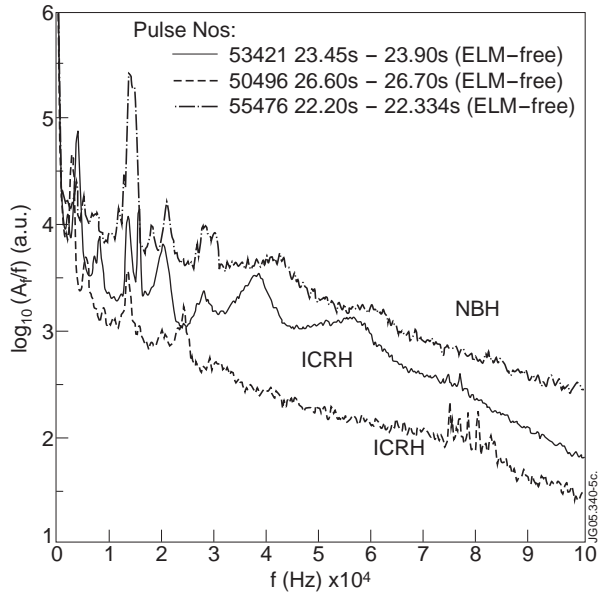


Figure 5: Frequency-normalized averaged power spectra of magnetic fluctuations in higher shaping and C-Mod identity (Pulse No: 57021) cases.

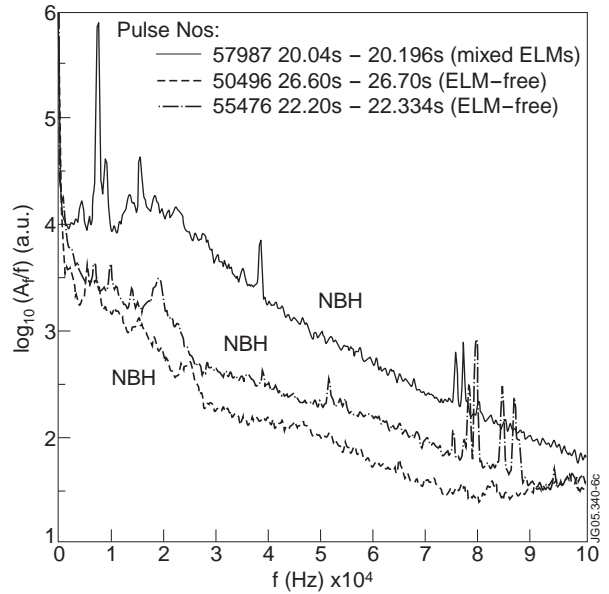


Figure 6: Corresponding spectra (all NBH) between large ELMs in reference "mixed" regime; ELM-free phases at higher edge v_{*e} .

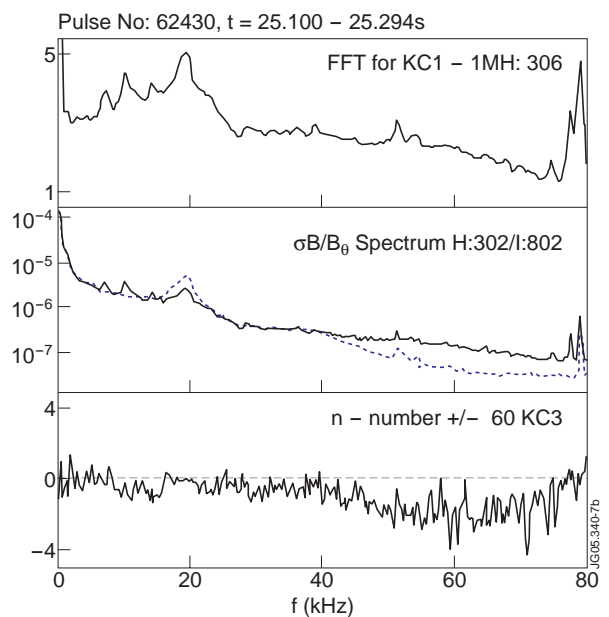
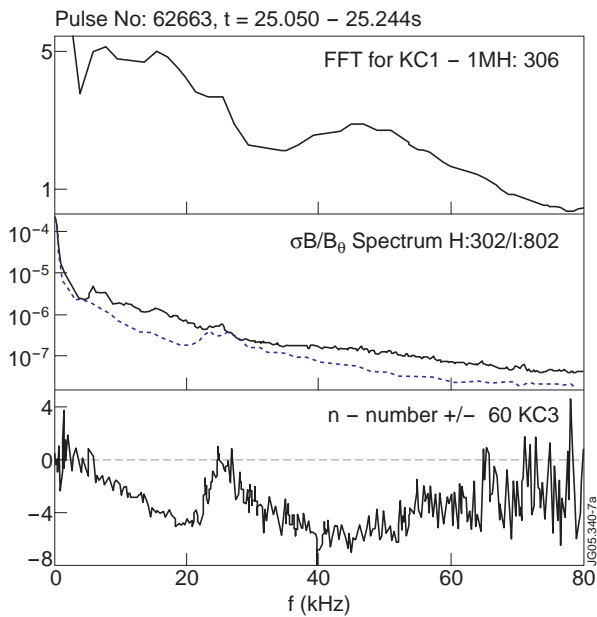


Figure 7: Magnetic power spectra, out/in coil signals, estimated toroidal mode numbers for ELM-free phases in identity plasmas to C-Mod (left) and ASDEX-U (right).

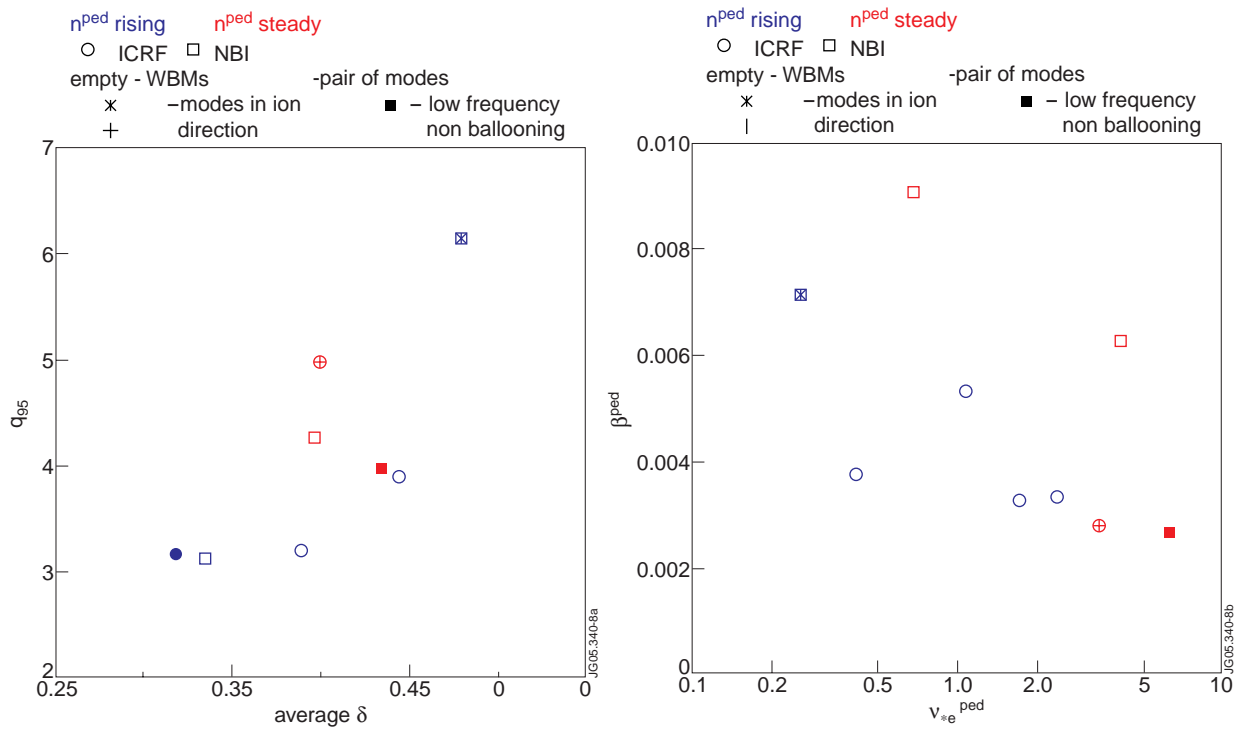


Figure 8: Summary of ELM-free H-mode periods surveyed, in terms of magnetic equilibrium parameters and pedestal dimensionless quantities.