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Edge fluctuations in the absence of large ELMs on JET

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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 Type II 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 42 MHz minority ICRF heating, shown in Fig.1 (#50492, 2.7 T, 2.5 MA, $\kappa = 1.67$, $\delta^u = 0.43$, $\delta^l = 0.35$, $q_{95} = 3.2$). 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

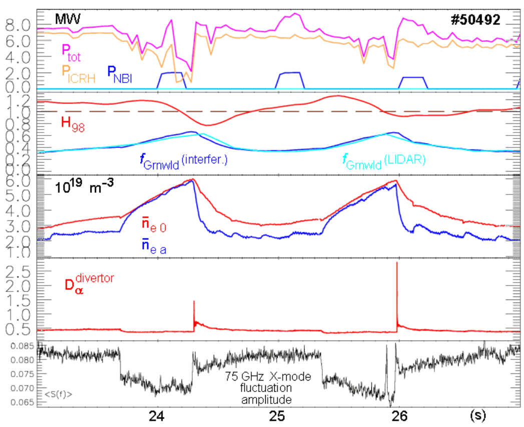

Fig.1 Input power, normalized confinement and density, central and edge density, divertor Dα, reflectometer fluctuation amplitude, for two ICRH ELM-free H-mode phases.

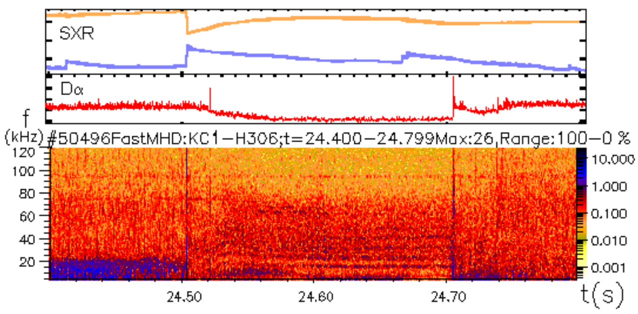

Fig.2 SXR, divertor Dα, power spectrum of magnetic fluctuations spanning an ELM-free H-mode interval in a very similar ICRH plasma. "Washboard" modes are visible as multiple coherent frequency stripes.

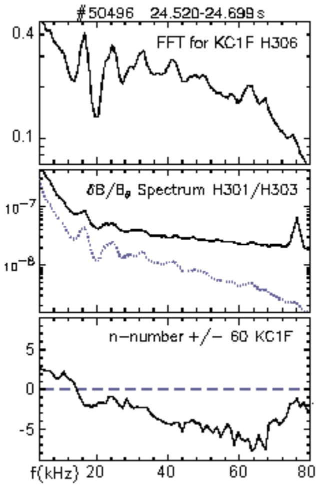

Fig.3 Power spectrum, out/in coil signals, estimated toroidal mode numbers during ELM-free phase.

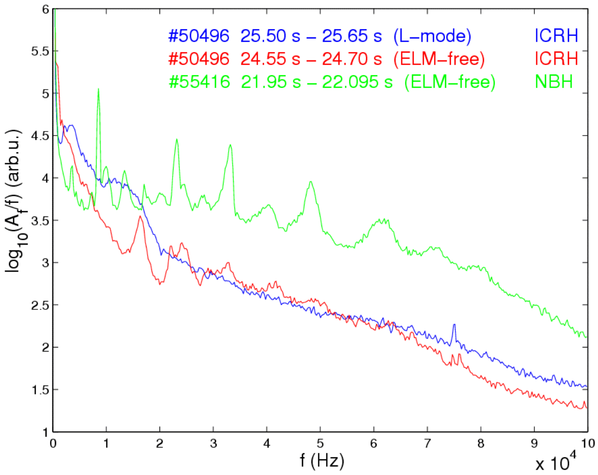

Fig.4 Frequency-normalized averaged power spectra of magnetic fluctuations in ICRH and NBH ELM-free H-modes, plus L-mode reference.

a very similar plasma at slightly higher density (#50496) is depicted in Fig.2, and clearly reveals multiple coherent oscillations with frequencies between ≈ 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 96 GHz and 75 GHz 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 (#55416, 2.0 T, 2.0 MA, $\kappa = 1.73$, $\delta^u = 0.36$, $\delta^l = 0.31$, $q_{95} = 3.1$, 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 50 GHz 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 (#50492, #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 42 MHz ICRH (#53421, 2.8 T, 2.0 MA, $\kappa = 1.70$, $\delta^u = 0.46$, $\delta^l = 0.43$, $q_{95} = 3.9$) is shown in Fig.5. Ballooning-like WBMs in the electron direction are still evident from ≈ 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} (#58909, 2.7 T, 1.5 MA, $\kappa = 1.73$, $\delta^u = 0.56$, $\delta^l = 0.40$, $q_{95} = 6.1$) 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

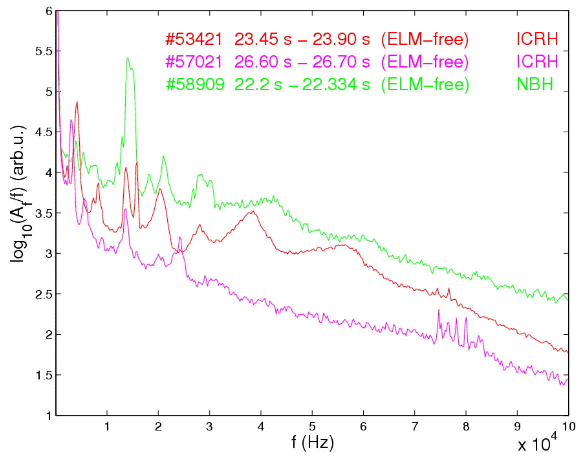

Fig.5 Frequency-normalized averaged power spectra of magnetic fluctuations in higher shaping and C-Mod identity (#57021) cases.

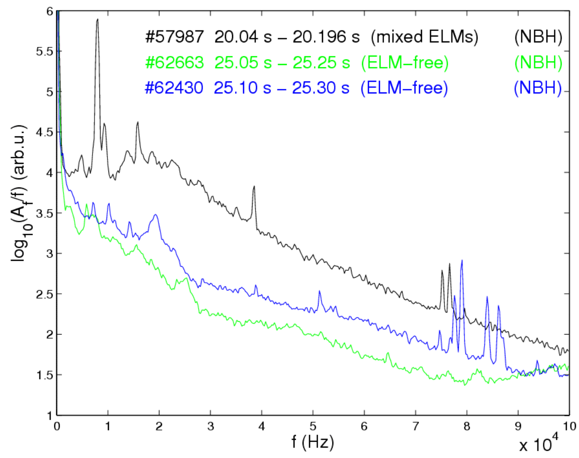

Fig.6 Corresponding spectra (all NBH): between large ELMs in reference "mixed" regime; ELM-free phases at higher edge ν_{*e}.

NBH (#62663, 0.9 T, 0.7 MA, $\kappa = 1.67$, $\delta^u = 0.41$, $\delta^l = 0.38$, $q_{95} = 4.3$) displays a very long ($\approx 10\,\tau_E$) nearly ELM-free period, with a prominent new feature that <u>stored energy and pedestal density</u> (though not core density or radiation) <u>remain almost constant</u> [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 28 MHz $2\,\omega_{c\,i}$ 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 (#57021, 1.3 T, 0.81 MA, $q_{95} = 5$, 42 MHz $2\,\omega_{c\,i}$ ICRH) is added in Fig.5 and now contains only 2 - 3 strong modes at ≈ 14, 24 kHz. These appear powerfully on all O-mode reflectometer signals (19 - 45 GHz) 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] (#62430, 1.15 T, 0.87 MA, $\kappa = 1.74$, $\delta^u = 0.50$, $\delta^l = 0.37$, $q_{95} = 4$). 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, 20 kHz are briefly seen on an O-mode reflectometer channel at 34 GHz reaching the mid gradient region, but coherent

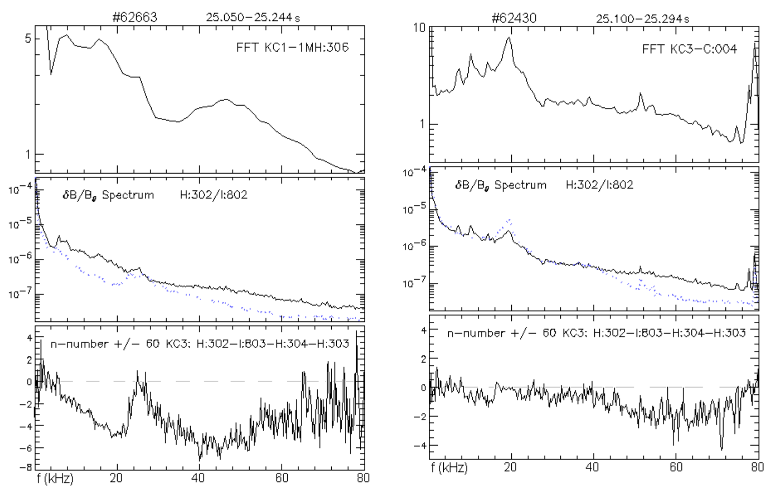

Fig.7 Magnetic power spectra, out/in coil signals, estimated toroidal mode numbers for ELM-free phases in identity plasmas to C-Mod (left) and ASDEX-U (right).

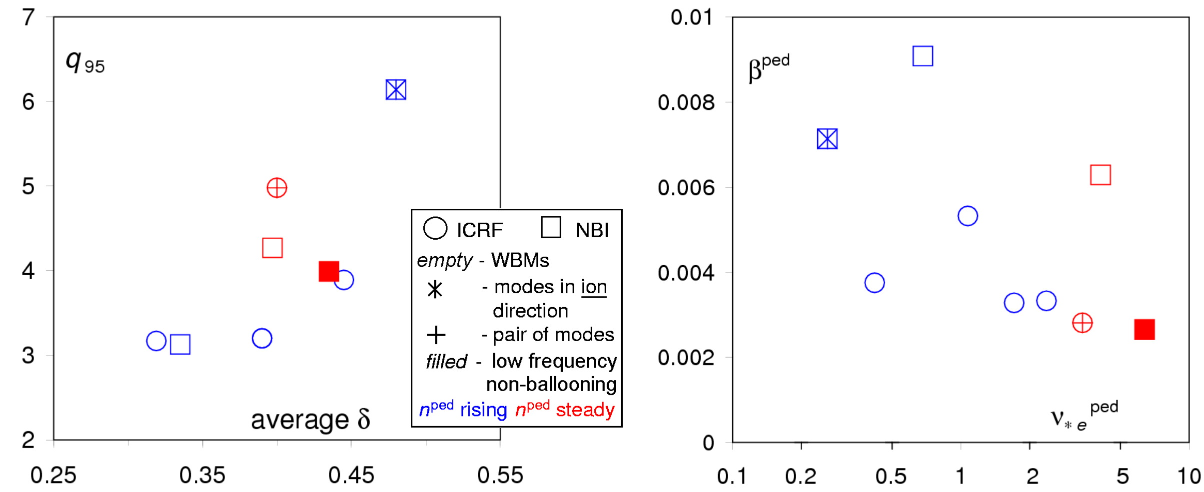

Fig.8 Summary of ELM-free H-mode periods surveyed, in terms of magnetic equilibrium parameters and pedestal dimensionless quantities.

density fluctuations are otherwise absent in both this and the preceding case (#62430, #62663).

3. 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 ν_{*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 eg to lead to ion thermal diffusivity comparable to the total effective coefficient $-q_{\mathrm{loss}}/(n_e \nabla T_e + n_i \nabla T_i)$ in the periphery of pulse #62430. Hence it may account for (much of) its enhanced pedestal transport even without turbulence effects, while high $\nu_{*e}{}^{\mathrm{ped}}$ 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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References

1 J Stober *et al*, 20th IAEA FEC, Vilamoura, 2004, IAEA-CN-116/EX/P1-4, *accepted for* Nucl Fusion
2 G Saibene *et al*, Nucl Fusion **45** (2005) 297
3 P Smeulders *et al* Plasma Phys Control Fusion **41** (1999) 1303
4 C P Perez *et al* Plasma Phys Control Fusion **46** (2004) 61
5 A Mazurenko *et al* Phys Rev Lett **89** (2002) 225004
6 G Maddison *et al* Proc 30th EPS Conf Control Fusion Plasma Phys, St Petersburg, 2003, P-1.109
7 A Loarte *et al* Plasma Phys Control Fusion **44** (2002) 1815