EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(04)03-46

G. Saibene, P.J. Lomas, J. Stober, R. Sartori, A. Loarte, F.G. Rimini, Y. Andrew, S.A. Arshad, P. Belo, M. Kempenaars, H.R. Koslowski, J.S. Lonnroth, D.C. McDonald, A.G. Meigs, P. Monier-Garbet, M.F.F. Nave, V. Parail, C.P. Perez, P.R. Thomas and JET EFDA Contributors

Small ELMs Experiments in H-mode Plasmas in JET

Small ELMs Experiments in H-mode Plasmas in JET

G. Saibene[1], P.J. Lomas[2], J. Stober[3], R. Sartori[1], A. Loarte[1], F.G. Rimini[4], Y. Andrew[2], S.A. Arshad[2,5], P. Belo[6], M. Kempenaars[7], H.R. Koslowski[8], J.S. Lonnroth[9], D.C. McDonald[2], A.G. Meigs[2], P. Monier-Garbet[4], M.F.F. Nave[6], V. Parail[2], C.P. Perez[8], P.R. Thomas[4] and JET EFDA Contributors*

[1]*EFDA Close Support Unit (Garching), 2 Boltzmannstrasse, Garching, Germany*
[2]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
[3]*Association EURATOM-IPP, MPI fur Plasmaphysik, 2 Boltzmannstrasse, Garching, Germany*
[4]*Association Euratom-CEA, Cadarache, F-13108 St. Paul-lez-Durance, France,*
[5]*EFDA Close Support Unit, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
[6]*Associação EURATOM/IST, Centro de Fusão Nuclear, Lisbon, Portugal*
[7]*FOM-Rijnhuizen, Association EURATOM-FOM, TEC, PO Box 1207, Nieuwegein, The Netherlands*
[8]*Forschungszentrum Jülich GmbH, Institut fur Plasmaphysik, EURATOM Association, Trilateral Euregio Cluster, Jülich, Germany*
[9]*Association EURATOM-Tekes, Helsinki Univ. of Techn., P.O. Box 2200, 02015 HUT, Finland*
** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002).*

Preprint of Paper to be submitted for publication in Proceedings of the
31st EPS Conference,
(London, UK. 28th June - 2nd July 2004)

INTRODUCTION.

Access conditions and plasma performance of H-modes with acceptable ELM size (extrapolated to ITER conditions) have been one of the main research lines in recent experimental campaigns at JET. Earlier experiments were dedicated to the study of the pedestal and ELM behaviour of high density/high confinement ELMy H-modes [1,2,3]. These experiments focussed on the exploration of the effects of the plasma edge magnetic geometry (triangularity δ, as well as proximity to double null, or quasi double null plasmas, QDN) and of q_{95} on the pedestal parameters, edge stability and ELM size. In Single Null (SN) configuration at high δ and modest values of the safety factor (q_{95}~3 3.6), the plasma pedestal accesses a regime of reduced Type I ELM frequency, and enhanced inter ELM losses, named the mixed Type I-II regime. In this regime, H_{98}~1 and n/n_{Gr} ~0.9 are obtained routinely. In Asdex-Upgrade [4], steady state Type II ELM H-modes at high confinement and density (H_{98}~0.95, n/n_{Gr}~0.85) are obtained in QDN plasmas, at β_N~1.8 and a minimum q_{95}~4. Attempts to reproduce this regime by modification of the magnetic configuration (from SN to QDN) and by varying the edge safety factor up to 4.5 in high shaped plasmas at medium plasma current (2.0 to 2.5MA) were not successful, leading to reduced plasma confinement and eventually to a transition to Type III ELMy H-mode regimes.

This paper presents the results of new experiments carried out to further investigate the physics of small ELMs in JET. These experiments explored two main directions: the first had the aim to further investigate the role of QDN in JET to reproduce the Asdex-U Type II regime, by making a dimensionless identity with a Type II ELMy H-mode of Asdex-U. The second line of investigation was to study the effect of β_p on the pedestal MHD stability, in analogy with results from JT-60U [5], where "grassy ELMs" spontaneously replace Type I ELMs in H-modes, when β_p>1.7, in high δ plasmas with q_{95}>4.

1. ASDEX-UPGRADE/JET TYPE II IDENTITY EXPERIMENTS.

The JET dimensionless identity with the Asdex Upgrade Type II ELMy H-mode is a 0.87MA/ 1.17T plasma, with average δ ~0.44 and QDN configuration (distance between first and second separatrix Δx~1cm). Neutral beams were the dominant additional heating (up to ~4MW), with small amounts of ICRH (<1MW). In these conditions, long phases of H-mode confinement with no Type I ELMs and steady state pedestal parameters were observed with H_{98}~1 and pedestal densities ~$0.85n_{Gr}$. The duration of the period at constant pedestal parameters was limited by plasma core instabilities. In fact, at these low input powers, the core plasma suffered from progressive density peaking leading to radiative collapse of the discharge. When either the input power or the plasma current and field (in steps up to 1.5MA/2.0T at constant q_{95}~4.1) were increased, ELM activity typical of standard ELMy H-modes reappeared, and no ELM-free phases with constant pedestal parameters were obtained.

These findings are illustrated in more detail in figure 1, showing selected time traces of two plasma discharges at 0.87MA/1.17T (Pulse No's: 62428 in red, and 62430 in blue). After a very similar initial H-mode transition and long ELM free phase, the NB power was stepped up at about 24s in Pulse No: 62428 by~1MW, while it was kept constant for 1s longer in Pulse No: 62430. The power increase in the Pulse No: 62428 has two clear effects: T_{ped} increases and the pedestal goes into a standard Type I ELMs phase. At the same time, the average plasma density (and core radiation) level off, and the plasma reaches stationary conditions. In contrast, the delayed power step up in Pulse No: 62430 corresponds to a Type III ELM phase followed by >1.5s with ~constant nped and Tped and no Type I ELMs. The continuous rise in the core radiation keeps the power across the separatrix below that of Pulse No: 62428, even after the power is increased to the same level of Pulse No: 62428, and the pedestal temperature remains ~250eV (T_{ped}~320eV for Pulse No: 62428). A close examination of H trace in the divertors and at the plasma outer midplane for Pulse No: 62430 shows that the typical bursts correlated to Type I ELMs are essentially absent, and only small and irregular oscillations are detected, similarly to what previously observed in Type II ELM phases of JET mixed Type I-II H-modes. As characteristic of Type II ELMs, an increase of magnetic turbulence [1,7] (figure 2a and 2b) is observed during the quiescent phase of Pulse No: 62430, identified as washboard modes (wb). The JET pedestal parameters in the Type II ELM phase of Pulse No: 62430 are near to the identity values with Asdex-Upgrade, in particular ν^*~1-2. In these identity conditions, the additional loss mechanism correlated to *wb* modes is sufficient to stabilise the pedestal density rise and both Tped and nped are constant in time. These are, to date, the only conditions in JET where the increase in wb mode intensity (correlated to increased inter-ELM power losses) is sufficient to reach steady state nped. On the other hand, the power flux carried by Type II ELMs in these conditions is limited, as demonstrated by the pedestal behaviour of Pulse No: 62428. Finally, increasing I_p/B_t at constant q and shape of the JET/Asdex-U identity closes off the operational space for pure Type II edge between the L-H transition and standard Type III-I H-mode regimes.

2. HIGH β_p H-MODES.

The second line of investigation on small ELM regimes in JET was to study the effect of β_p on the pedestal and ELM activity, in analogy with results from JT-60U, where "grassy ELMs" spontaneously replace Type I ELMs in H-modes, when a b a threshold value of β_p is exceeded (β_p >1.7). In JT-60U, high q_{95} and δ are also required to access the Grassy ELM regime, but a trade-off has been identified experimentally between the value of the safely factor and shape [6]. In contrast to the JET/Asdex-Upgrade identity, no attempt was made to obtain a dimensionless match in JET of the JT-60U plasma parameters, with the exception of β_p. In particular, the experiments in JET were carried out in plasmas with a fully penetrated current profile and no ITB, with l_i>1 for β_p>1.3. The plasma shape was QDN, with Δx~1cm. In this experiment, β_p was increased in steps from 1.1 to 1.9, by increasing the input power (NB and ICRH combined heating) and, at the maximum input power, reducing the plasma current. At β_p ~1.7 (at 1.2MA/2.7T, q_{95}~6.8), a change in the ELM activity was observed, both in the divertor D signature and in the magnetic spectrum (figures 3 and

4): type I ELM disappeared to be replaced by high frequency, very small and irregular oscillations, strongly reminiscent of the grassy ELMs of JT-60U. This change in the ELM behaviour occurs at high confinement (H_{98} ~1) and high density (n~85% n_{Gr}); edge losses associated to these small ELMs are sufficient to maintain the edge and the core in steady state, and are compatible with high global confinement (H98~1.2 at high β_p). The comparison of the MHD spectrogramme in figure 4, top (Pulse No: 62406, Type I ELMs, β_p~1.35) with that of a high β_p plasma (Pulse No: 62413, β_p~1.9, figure 4, bottom) shows that MHD bursts are associated to Grassy ELM activity, although the extent in frequency of the MHD perturbation is much reduced compared to Type I ELMs. Contrary to Type II ELMs, grassy ELMs do not seem to be associated to "continuous" broadband magnetic turbulence.

To understand the reasons for the change in ELM behaviour at high β_p, the high-li H-modes are compared to standard ELMy H-modes at low β_p (β_p<1) and to a series of discharges carried out at 1.2MA/2.7T (like most of the high l_i H-modes), and where β_p was varied over a similar range, from ~1.1 to ~1.9. In the latter, LH pre-heating and early main heating was used to control the q profile, and resulted in plasmas with q_o>2 and broad current profile (l_i ~0.85), with some of these discharges having a weak ion ITB. The discharges in this series will be called "low-li H-modes". These plasmas were standard lower SN, with the same δ, κ and similar q_{95} as the QDN used for the high-li H-modes (δ ~0.45. κ ~1.62 and q_{95}~6-7). The divertor H traces for the low-li H-mode β_p scan are shown in figure 5: in contrast to the previous case, increasing β_p does not cause a change in the ELMs, and Type I ELMs are observed up to β_p~1.9. MHD spectrogrammes show the typical type I ELM signatures, consistently with the H traces.

A comparison of the global plasma confinement shows that, at low β_p, the low-l_i H-modes have reduced H_{98} (H_{98}~0.7-0.9), but for β_p >1.5, the global confinement of high- and low-l_i plasmas is very similar, with H_{98}~1.1-1.2. The pedestal pressures of the two groups of high β_p plasmas are compared in figure 6. Since some of the plasmas of the high-li series had I_p≠1.2MA, P_{ped} is normalised (I_p^2 normalisation [3], to 1.2MA), to allow a direct comparison of all the data. In the case of the high-l_i H-modes, P_{ped} is ~constant with β_p, indicating that the onset of the small and high-frequency Grassy ELMs does not reduce the pedestal energy content, in contrast to what is observed at the Type I→Type III ELM transition [8]. For the low-l_i H-modes, P_{ped} increases with β_p, consistently with the global plasma confinement behaviour and, for β_p~1.9,P_{ped} is very similar to that of the high β_p high-l_i H-modes. Figure 6 also shows a potentially important difference between the two groups of plasma discharges, namely that the pedestal of the high-l_i H-modes is more collisional than that of the low l_i-H-modes. This difference is largest for the highest β_p high-l_i plasmas with grassy ELMs compared to low-l_i plasmas at the same β_p, with ν*~0.4-0.7 with grassy ELMs and β_p ~1.7-1.9, compared to ν*~0.15 for low-l_i plasmas at β_p~1.8-1.9. This difference is due to the stronger edge fuelling used in the high-l_i plasmas, to bring the pedestal density up in the range of ~70% n_{Gr} at high β_p. The fact that grassy ELMs are only observed above ν*~0.4 does not in principle represent an "existence limit" in ν* for such ELMs, but only reflects the range of pedestal parameters investigated so far.

3. ANALYSIS OF ELM LOSSES.

Prompt ELM energy losses, temperature and density drop at ELMs have been analysed for both high- and low-l_i H-modes and compared to the existing database from standard ELMy H-modes (Type I and Type III, β_p<1) [3]. The results of this analysis are summarised in figures 9a, b and c. These figures show that high-l_i H-modes ELM losses are comparable to those of standard H-modes up to β_p~1.6. At higher β_p, the energy loss of grassy ELMs is below detection limit (~50kJ), corresponding to a maximum Δ_{WELM}/W_{ped} of ~4-5%. The low energy losses due to grassy ELMs are confirmed by the analysis of Te and ne drop at the ELM (figures 9b and 9c). Both temperature and density drop for grassy ELMs are below those of Type I ELMs with similar ν*, and even lower than those measured with Type III ELMs, although the global confinement and pedestal pressures with grassy ELMs are similar of higher than what expected for a type I ELMy H-mode. By contrast, ELM losses of the low-li H-modes are similar to those of standard Type I ELMs, although the lack of data on the ELM density losses does not allow making a more detailed comparison.

The reduction of the size of grassy ELMs compared to Type I ELMs may be explained by comparing the ELM affected depth, L_{ELM}. L_{ELM} is calculated by subtracting the post-ELM Te profile from the pre-ELM T_e profile, and then normalising the difference to its maximum. Figure 7 compares LELM for a density scan in standard H-modes (at fixed I_p/B_t, shape and P_{in}), as well as for ELMs at low and medium q_{95} (3.6 and 4.5). Although increasing the density (ν*) reduces ELM losses by factor ~3 (~2 normalised to W_{ped}), and increasing q_{95} reduces Type I ELM losses even more (factor of 3-4), LELM does not change. A reduction of the ELM affected depth is observed only for Type III ELMs. By contrast, figure 8 shows that the increase in β_p and the reduction of the ELM losses observed with grassy ELMs corresponds to a shrinking of the ELM affected depth, strongly suggesting that a change in the MHD instability in the pedestal may be at the root of the reduction in the ELM size. Such a reduction of LELM with β_p is not observed for the low-li H-modes that present a picture similar to standard H-modes.

As discussed in [5,6], strong Shafranov shift (s) is a possible reason for the change in the MHD stability of high β_p plasmas. In fact, for both high- and low-l_i H-modes, Δs of plasmas with β_p>1.7 is high, ~22-26% of the minor radius, but grassy ELMs are only observed for the high-li H-modes. This observation suggests that in JET, high Δs (high β_p) may be a necessary but not sufficient condition for access to the grassy ELM regime. The different current profile (l_i~0.85 vs. l_i~1.1) in the two cases may play a role in determining the edge current values, and prevent or make more difficult the access to the grassy ELM regime at lower l_i.

CONCLUSIONS AND OUTLOOK.

The role of QDN plasma configuration in achieving Type II ELMs has been further investigated in JET by carrying out JET/Asdex-U identity experiments. Type II ELMs and constant n_{ped} and T_{ped} are obtained at the identity point (ν*~1-2), although the core does not reach steady state. Increasing P_{in} and/or I_p/B_t causes Type I ELMs to reappear. Even with QDN, high ν* and/or low T_{ped} (resistive

MHD) may be required to obtain Type II ELMs and sufficient losses to maintain the pedestal in steady state, casting doubts on the extrapolation potential of this ELM regime to hot plasmas.

The investigation of the effect of high β_p on the pedestal and ELM of H-modes has shown that grassy ELMs appear in high-li, high β_p H-modes, for β_p>1.6-1.7. Grassy ELMs cause very low energy losses, below those of Type I ELMs at the same collisionality, pedestal pressure and global confinement. The reduction of ELM losses is attributed to the shrinking of the ELM affected depth. This finding (in contrast to the case of Type I ELMs, where changes in ELM size occur at constant L_{ELM}) suggests that the onset of grassy ELMs may be due to a change in the mode(s) making the pedestal MHD unstable. Comparison between low- and high-l_i H-modes indicates that high β_p is a necessary but not sufficient condition for obtaining grassy ELMs.

The operational space for grassy ELMs in JET needs to be explored further to establish the relevance of the grassy ELM regime as ELM mitigation scenario. The conditions of the experiments described in this paper are such that all the high β_p discharges with grassy ELMs were obtained at high q_{95} and relatively high ν^*. Moreover, a QDN configuration was used for the high-li experiments, in contrast to the SN used for the low-li H-modes. Future experiments should focus on obtaining high β_p plasmas with lower ν^* and q_{95}. In those conditions, the systematic investigation of the role of edge currents and plasma shape in determining the operational space of grassy ELMs would also be required, to clarify the extrapolation potential of this regime.

REFERENCES

[1]. G. Saibene et al., Plasma Phys Cont Fus **44** (2002) 1769.
[2]. G. Saibene et al., EPS 2003
[3]. A. Loarte et al, Phys of Plasmas **11** (2004) 2668
[4]. J. Stober et al, Nucl Fus **41** (2001) 1123
[5]. Y. Kamada and JT-60U Team, Nucl Fus **41** (2001) 1311
[6]. Y. Kamada et al, Plasma Phys Cont Fus **44** (2002) A279
[7]. C.P. Perez et al, Plasma Phys Cont Fus **46** (2004) 61,
[8]. R. Sartori et al., Plasma Phys Cont Fus **46** (2004), 723

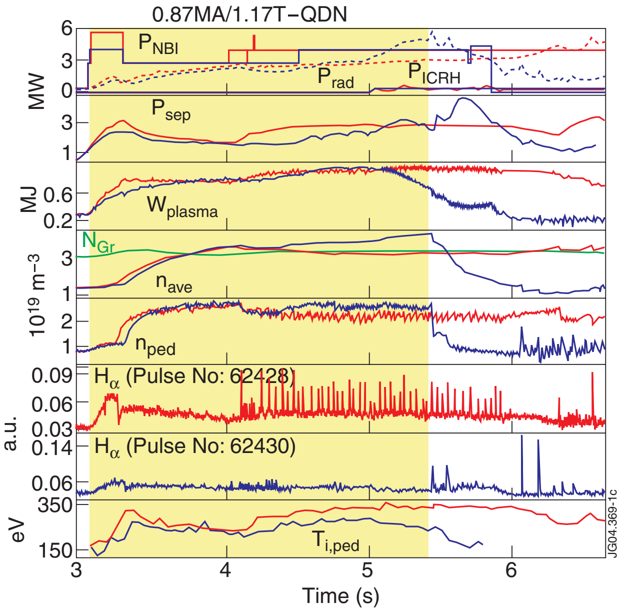

Figure 1: selected time traces for 2 pulses of the JET/Asdex-Upgrade identity experiments: in red Pulse No: 62428 (Type I ELMs) and in blue, Pulse No: 62430. The yellow box highlights the H-mode phase of Pulse No: 62430 until the loss of confinement due to core radiative collapse.

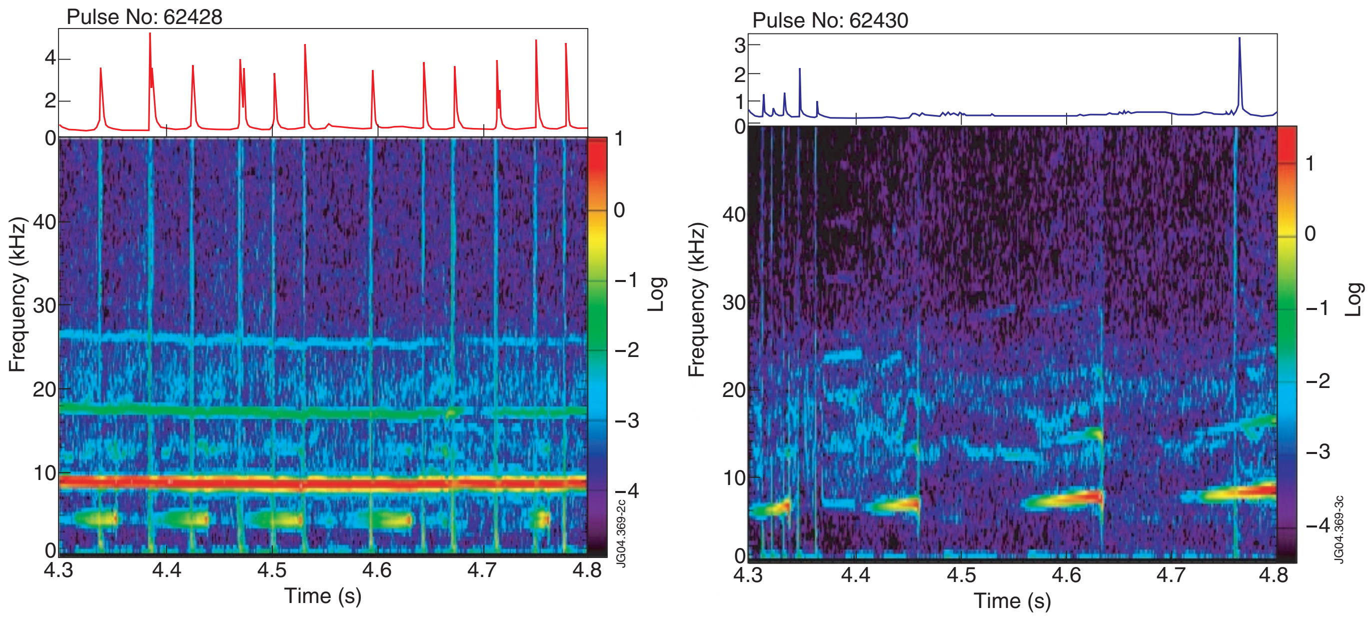

Figure 2: a): H_α time trace and MHD spectrogramme showing Type I ELMs and core MHD, Pulse No: 62428. b): Pulse No: 62430, same signals, showing the wb modes (broadband fluctuations, 10-25kHz) and core MHD replacing the MHD activity typical of Type I ELMs.

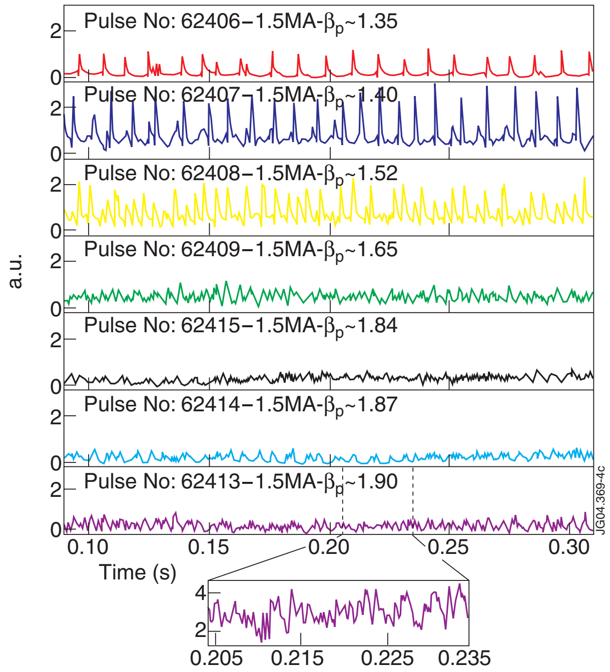

Figure 3:Divertor H_α traces for the β_p scan in high l_i H-modes: Grassy ELMs observed for β_p>1.6 1.7

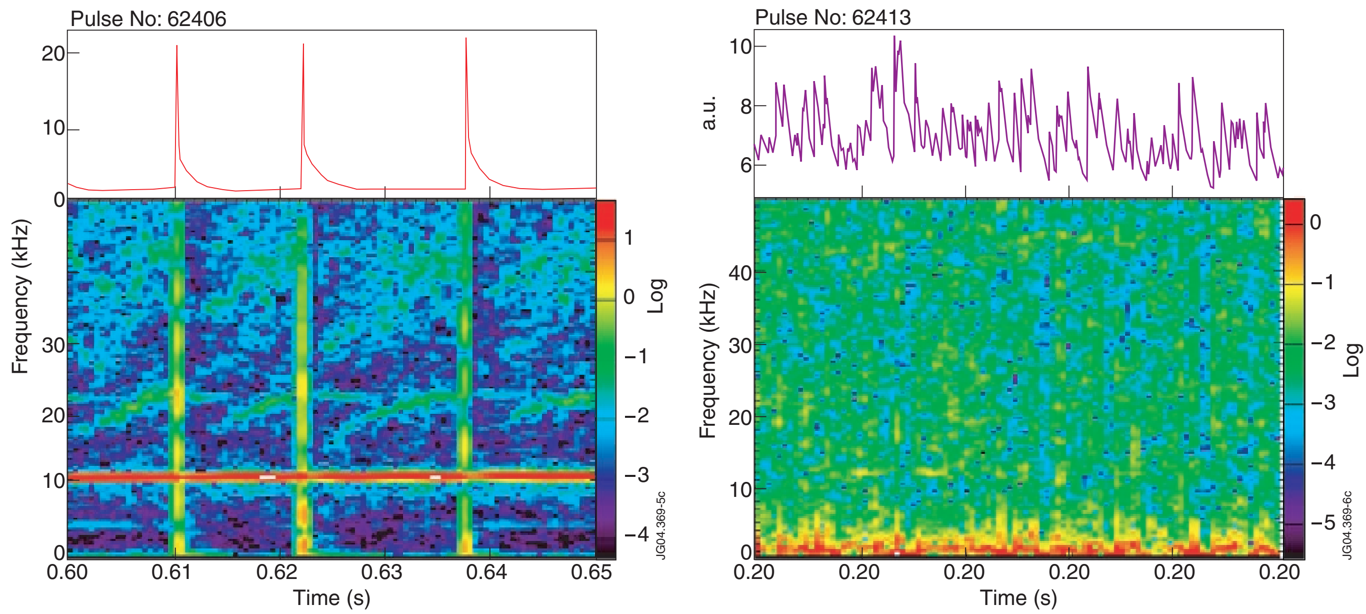

Figure 4: MHD spectrogrammes for Pulse No: 62406 (Type I ELMs, β_p~1.35) and Pulse No: 62413 (Grassy ELMs, β_p~1.9)

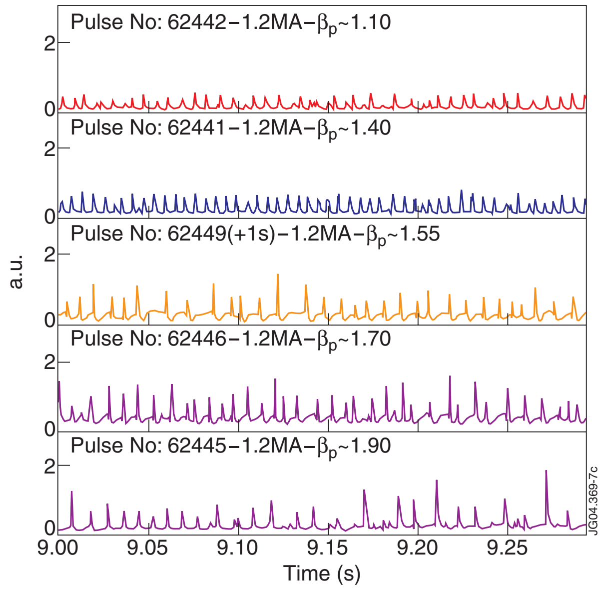

Figure 5: Divertor H_α traces for the β_p scan in high l_i H-modes: Type I ELMs observed up to the highest β_p

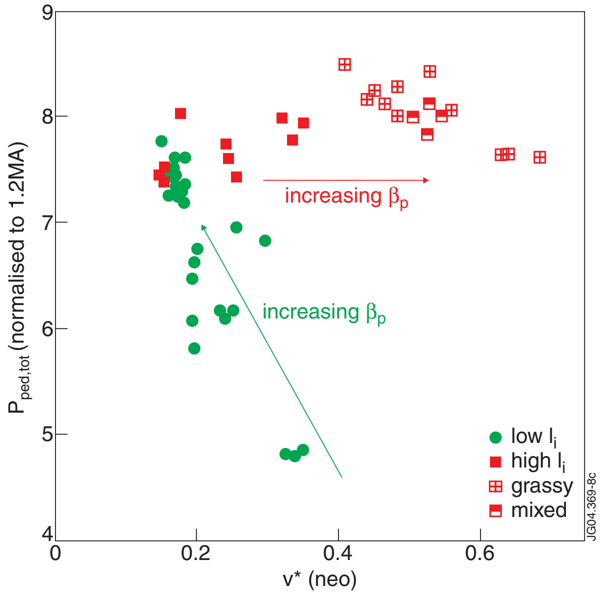

Figure 6: P_{ped} (normalised to I_p^2) for the high l_i and low l_i H-modes β_p scans.

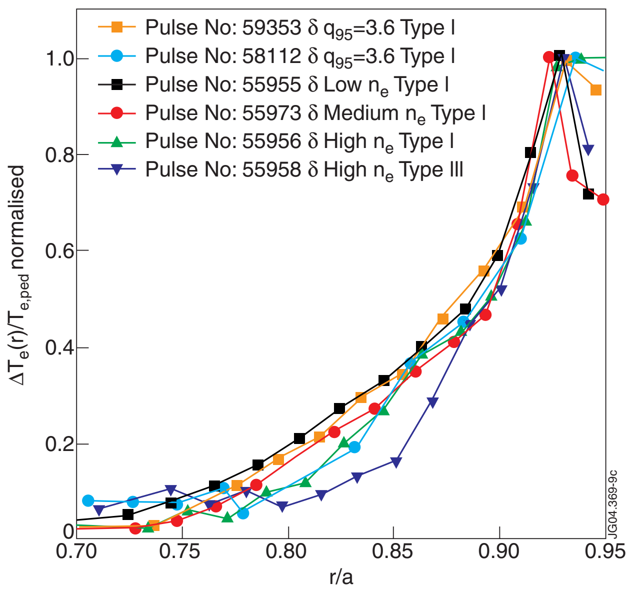

Figure 7: ELM perturbation of T_e profiles for standard H-modes: density scan (Type I and Type III ELMs)

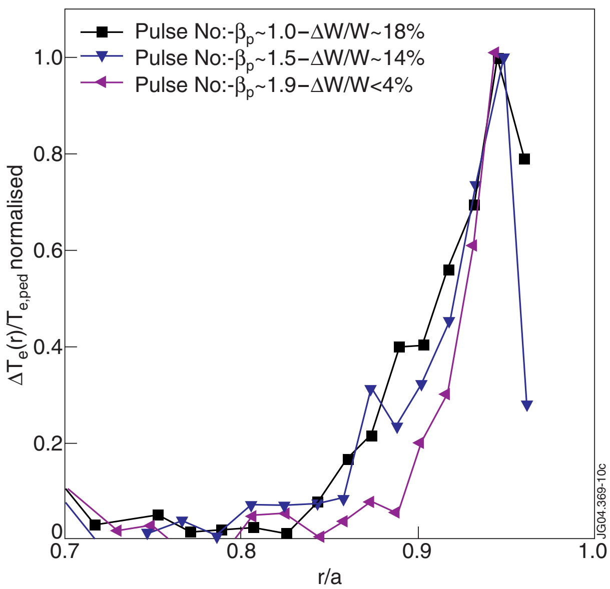

Figure 8: ELM perturbation of T_e profiles for low-medium and high β_p, high l_i H-modes.

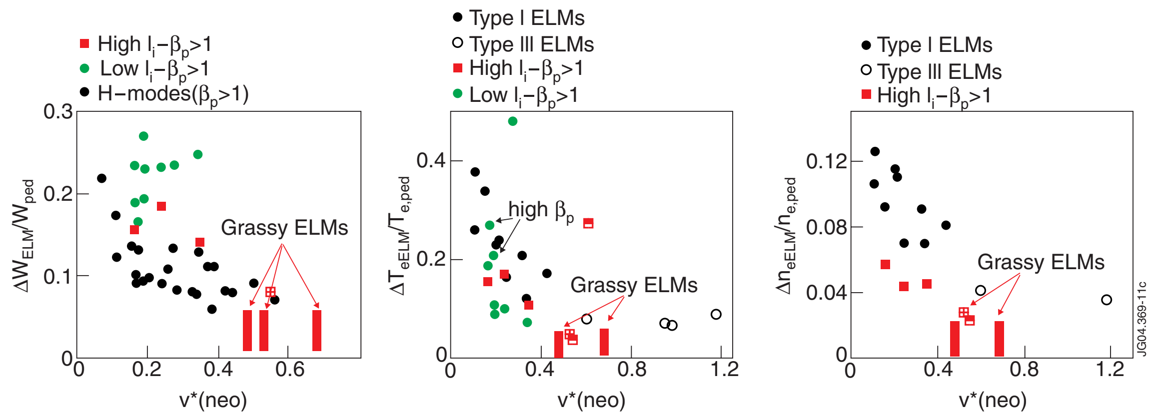

Figure 9: from left to right: ELM energy losses, normalised to W_{ped}, ELM temperature drop, normalised to T_{ped} and ELM density drop and, left, normalised to n_{ped}. Standard H-modes [3] in black, low-l_i H-modes in green, high-l_i H-modes in red. The red bars are calculated from estimated ΔW_{ELM}, ΔT_{ELM} and ΔN_{ELM}, with the top of the bar being the upper value for those quantities.