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ABSTRACT.

The study of ELM pacing by means of vertical kicks has been extended in JET to heating power levels marginally above the H-mode power threshold, allowing steady-state conditions to be established for particles and energy at lower power than normally observed in the absence of kicks. The experiments shows that inter-ELM dynamics and radiation have to be included in a detailed power balance to account for the variation of the total power required to maintain H-mode conditions and H98~1. Progress in identifying the mechanism responsible for the kick-triggered ELM is shown and the implications of these findings for JET operation with the Be/W wall and ITER are discussed

1. INTRODUCTION

ITER is expected to operate at powers close to the H-mode threshold power scaling. This might leave ITER with very little margin in terms of the available power flux crossing the separatrix (~30% above the predicted H-mode threshold power as reported in [1]) to drive the plasma into H-modes with normalized energy confinement time $H_{98} \geq 1$, required to achieve $Q = 10$ or higher. Since a theory-based and experimentally verified transport model for the L-H transition and the subsequent confinement evolution does not yet exist, the experimental study of H-mode plasmas with heating powers marginally above the H-mode threshold power and the characterisation of their performance and ELM behaviour in these conditions become an essential tool to increase confidence in the extrapolability of such regimes to ITER. The JET experience (with CFC wall and also with the new ITER like-wall) is that such operation leads to a transient behaviour of the H-mode, with transitions from Type I ELMs to Type III or L-mode [2,3] and reduced confinement. One question relevant to the extrapolation to ITER is to which extent this transient behaviour is related to the ELM dynamics (loss power/transport in between ELMs, ELM crash) and therefore if it can be changed, and how, with ELM amelioration/suppression methods.

This paper concentrates on the results of experiments carried out in JET before the installation of the ITER-like metallic wall (Be wall and W divertor) to investigate the influence of ELM pacing methods on the power requirements to obtain and maintain target H-mode confinement (H_{98}~1, based on the ITER-98(y,2) reference scaling law[4]) in steady state conditions. ELM pacing is obtained by fast vertical movements of the plasma column (so called 'vertical kicks') induced by a controlled variation of the PF coil current [5,6]. A description of the initial results obtained using vertical kicks with the Be/W wall is also presented.

2. EFFECT OF VERTICAL KICKS ON THE ACCESS TO STEADY-STATE H-MODE WITH H_{98}~1 (CFC-WALL)

For discharges with heating powers marginally above the H-mode power threshold, cyclic transitions to lower confinement at constant P_{IN} are typically observed in JET [2,3]. This is illustrated in figure 1 with one of the most recent NBI power scan experiments performed in JET with the carbon wall. In this scan ($B_T = 2T$, $I_P = 2.2MA$, $q_{95} \sim 3$, $\delta_{av} \sim 0.4$, $f_{GW} \sim 0.6$), the data is in the range P_{loss}>1.2-2×P_{th}, where $P_{loss} = P_{abs}$-$\partial W/\partial t$ and P_{th} is the predicted H-mode threshold power [7] evaluated in the fully developed H-mode. In all the pulses shown in figure 1, no external fuelling is applied during the H-mode. At low input power (with P_{loss}/P_{th} <1.6 in this example), the plasma does not reach steady state and low frequency (~1Hz), large compound ELMs (large ELM crash followed by a short burst of type III ELMs and sometimes brief back transitions to L-mode) appear. This is accompanied by large variations in the density and stored energy (up to ~25%). For theses pulses, with non-stationary behaviour, the time averaged H98 factor remains below that obtained in steady state conditions (~10%) with temporal variations of ~10–15%. Adding gas fuelling or reducing the power even further leads to a permanent transition to type III ELMs with a significant loss in confinement (H_{98}<0.8). Only when the input power is increased to $P_{loss}>1.8\times P_{th}$ stationary H-mode operation with good confinement (H_{98}~1) is achieved, in broad agreement with earlier observations [2]. These plasmas typically exhibit regular type I ELMs (with f_{ELM}>10Hz) which maintain stationary density and stored energy (time-averaged over ELM period), with temporal variations of <5%. Earlier experiments in JET shown that, for the CFC-wall, the type I ELM threshold power scaled in a similar manner than the Pth scaling law, increasing with I_p (n_e) and BT [2] (and also the isotopic mass[8]), allowing this threshold to be expressed as $P_{loss} \sim \alpha P_{th}$. However, it was also found that the proportionality factor was not constant but depended on plasma parameters, such as triangularity and maybe collisionality [2]. This variation of the proportionality factor is also evident from a more recent analysis carried out in JET [9] to map out the operational space of good confinement H-mode plasmas at $q_{95} \sim 3$ (ITER reference baseline scenario), where the power margin above Pth found for the access to steady state ELMy H-mode plasmas is smaller than that obtained in the experiments shown here. Therefore there is an uncertainty in the prediction of what is a sufficient margin in terms of P_{loss} over P_{th} to achieve the steady-state ELMy H-mode regime in ITER. In addition, as it is shown in this paper, this margin can also be affected by the ELM behaviour (ELM crash and inter-ELM transport).

Control of plasma density and radiation is a key aspect in the achievement of the H-mode stationary regime. It is well known from AUG experiments [10] and more recently from JET experiments with the new Be/W wall [11] that increasing the ELM frequency is beneficial in reducing the net influx of impurities from the plasma edge. In H-mode with low type I ELM frequency (as observed when operating at input powers near the H-mode threshold power) the radiation is seen to increase through the ELM-free periods, as a result a large fraction of the input power is being radiated before reaching the separatrix. With this in mind, kicks with frequencies ~10-20Hz were applied to pulses at input power marginally above P_{th} in order to investigate if it was possible to reduce the inter-ELM density and radiation increase seen in those conditions.

The plasma response to the vertical kicks can be seen in more detailed in figure 2. Shortly after the start of the NBI heating the plasma makes a transition to H-mode (~13.34s), and after a short period of type III ELMs, the plasma enters into an ELM-free period. During this phase, both density and the radiation rise rapidly, causing significant edge cooling and keeping the edge pressure below the critical value for the ELMs to be triggered. When the radiation losses become dominant (P_{rad}/P_{tot}>50%), the stored energy saturates. The net power flux crossing the separatrix (P_{net} = P_{loss}-$P_{radbulk}$, where $P_{radbulk}$ is the radiated power from within the separatrix determined from the bolometer system) is shown in figure 2 to decrease during the ELM-free period until it becomes too small to sustain the edge barrier. At this point the edge barrier collapses (ELM-like crash) and the plasma reverts back to L-mode, followed by a long-lasting (~15ms) phase of type III ELMs. After the transition to L-mode the edge density and the stored energy sharply drop, which in turns reduces the radiation, allowing the cycle to repeat again. The transition to low confinement is seen to occur when Pnet decreases to similar values to that measured during the Type III ELM phase after the H-mode transition, which is strong evidence that P_{net} (and the edge temperature) is controlling the H-L transition. Indeed, the edge T_e profile measured by Thomson scattering just before the large ELMs drops to L-mode like values (not shown). The situation changes dramatically with the application of the vertical kicks (at t = 17.3s). Vertical kicks reliably trigger ELMs (with ~70% of the kicks triggering an ELM) at a frequency of 10Hz, changing the ELM behaviour from large and infrequent ELMs to small regular ELMs. In this pulse, with $P_{loss}/P_{th} \sim 1.2$, some of the triggered ELMs are still accompanied by a train of type III ELMs, however this compound phase disappears when the power margin over P_{th} increases and, in those conditions, every single kick triggers an ELM (see Pulse No: 76875 in fig.1). The appearance of the triggered ELMs rapidly brings the density and radiation power under control, allowing the discharge to evolve into a stationary ELMy H-mode that lasts several confinement times (~$7\tau_E$), while still maintaining good energy confinement ($H_{98y} \approx 1.1$). We note that time-averaged level of line radiation does not drop after application of kicks probably because impurities already reach the core plasma. In this case, the averaged power necessary to attain good H-mode performance (stationary, H98~1) is reduced by ~40% when compared with reference pulses without kicks (Pulse No: 76872 in Fig.1). As can be seen in figure 2, the appearance of the triggered ELMs is accompanied by a decrease in the edge ne due to the additional ELM driven particle losses.

However, the plasma pressure is partially compensated by an increase in $T_{e,ped}$ (~15%), which extends to the core via profile stiffness, and an increase in core ne, causing the density profile to become more peaked ($<n_e>/n_{e,ped} \sim 1.3$), resulting in an increase (<8%) of the stored energy. Similar density peaking factors to those found in this example are routinely observed in ELMy H-mode plasmas with regular type I ELMs [12] and are not a peculiar feature of the ELM pacing provoked by the vertical kicks. Reducing the ELM size to avoid transition to long compound ELM phases in plasmas where the edge power flux is marginally above the H-L boundary is also a key element in achieving stationary conditions. As expected, the more frequent triggered ELMs are associated with smaller energy loss per ELM [6]. While up to 25% of the thermal energy can be lost during the large compound ELMs in the initial phase of the discharge, the relative loss in energy content is rather modest ($\Delta W_{ELM}/W$<7%) in the case of the triggered ELMs. The large variation in the stored energy seen in the absence of kicks is due mainly to a collapse of the edge density profile (see figure 2), which affects a large radial region ($\rho < 0.6$). Similar effect is observed on the transition to stationary type III ELMs using gas fuelling [12] without kicks. In contrast, the ELM affected region of the density profile for the triggered ELMs is smaller, limited to the outer ~20% of the minor radius, similar value to that typically measured for spontaneous type I ELMs of similar size [13].

Figure 3 describes the widening of the operational space, in terms of the minimum power required to access the steady-state ELMy H-mode regime with good confinement, which is obtained with the vertical kicks for both low and high triangularity (δ) pulses. P_{net} is used in this analysis because, while radiation losses are relatively small in L-mode plasmas and therefore P_{th} can be taken as a good approximation of the net power crossing the separatrix at the time of the transition, this not necessarily apply to fully developed H-mode plasmas where radiation losses are much higher. The figure shows that, when the radiation is larger than ~30% of P_{loss}, the H-mode has transient behaviour. In these conditions the loss power required to maintain stationary conditions with H_{98}~1 is P_{loss}>1.8×P_{th}. The effect of the application of kicks (increase in f_{ELM}) is that by reducing the bulk impurity level and radiation, they increase the power flux crossing the separatrix for a given input power, therefore reducing the overall power requirement in terms of loss power above Pth (P_{loss} > 1.2×P_{th}) for good H-mode confinement (H_{98}~1) access.

3. MODELLING OF KICK TRIGGERED ELMS

Vertical kicks are produced by applying a radial field to the plasma using controlled voltage variation in specific PF coils currents, which causes the plasma to move towards the lower X-point. Successful ELM triggering is obtained in JET with displacements of the current centroid (Δz_{cc}) ~0.5-1.5cm and velocities ($\nu \cong dz_{cc}/dt$) in the order of 5-10ms/s [6]. While moving down, the plasma also shrinks which produces a deformation of the plasma shape which is more noticeable in the upper region of the plasma column. This is done with the vertical stabilization (VS) controller switched off. After a pre-determined time interval the VS controller is switched on again rapidly reducing the plasma velocity, the position being recovered on a slower timescale.

In an effort to understand the mechanism responsible of the ELM triggering, simulations combining the free boundary equilibrium CREATE-NL [14] and the JINTRAC [15] suite of codes have been carried out. The plasma equilibrium is solved with CREATE-NL for the pre-kick phase by fitting external magnetic measurement only. The flux surfaces are passed to the transport code where the plasma profiles are evolved. Every 0.5ms a new equilibrium step is calculated predictively with CREATE-NL, updating the plasma boundary and the average boundary loop voltage ($\partial\psi_{ext}/\partial t$) induced by the varying PF coils and vessel eddy currents. This provides update boundary conditions in the transport code. The CREATE-NL equilibrium calculation includes eddy current, but ignores plasma evolution. Ongoing work aims to produce closed-coupled simulations, in which equilibrium reconstruction benefits from updated information on plasma characteristics and time-evolving experimental magnetic measurements. For now, the interleaved steps provide a simplified model of the plasma evolution during a kick cycle. The plasma behaviour after the ELM is not considered in this analysis.

Initial results [16] suggest that edge current density induction may play a role in the triggering of ELMs. The evolution of the edge current during the kick cycle for realistic plasma parameters in JET is shown in figure 4. With the application of the kick the plasma begins to move downwards, and this is accompanied by a decrease in plasma volume. In this phase $\partial\psi_{ext}/\partial t < 0$ and the edge current in the boundary is reduced. However, this phase was preceded by the recovery phase of the previous kick, a time of plasma expansion with $\partial\psi_{ext}/\partial t > 0$, causing the boundary current to increase. This positive edge current perturbation diffuses inwards and typically reaches the top of the pedestal in a few milliseconds. These two mechanisms combine during the downward plasma movement, with the current density decreasing in the vicinity of the separatrix, and simultaneously increasing close to the top of the edge barrier. As seen in figure 4 the appearance of the ELM seems to be correlated with an increase in edge current density at the separatrix (green line), whose origin is related to the increase in loop voltage predicted by the simulation during the downward movement. This might be explained by a counter-reaction of the plasma to the reduction in total plasma current, causing the edge current at the boundary to increase and reducing the magnetic shear. According to the simulations results available so far, the edge pressure perturbation caused by the deformation of the boundary caused by the kick appears to be too small to be responsible for the ELM triggering.

A major difficulty in verifying the picture that emerges from the simulations is the lack of direct edge current measurements in JET. In the absence of a direct confirmation, growing experimental evidence is accumulating in support of the modelling predictions. Both in JET [5] and AUG [17] ELMs were triggered in the phase of the kick cycle when the plasma is moved downward and the plasma volume decreases and also the finding that typically the first kick in JET does not trigger an ELM (without a preceding kick, the positive current perturbation close to the top of the pedestal might be too small). In JET, the delay between the start of the kick cycle and the onset of the ELM was found to increase (with Δt varying from ~1.5 to ~3ms) with decreasing temperature, which is consistent with the penetration of a current density perturbation on a resistive time scale.

Further evidence that the kick-triggered ELMs are related with the edge current density comes from the comparison of the effect of kicks in H-mode plasmas with and without gas fuelling. An example of such comparison is shown in figure 5. Except for the addition of gas fuelling in Pulse No: 76946, the rest of the plasma parameters and kick amplitude are kept identical for this comparison. In contrast with the increase in ELM frequency provoked by kicks seen in the unfuelled discharge, very few ELMs were triggered at higher ne. With the increase in n_e, the edge T_e decreases at similar edge pressure, resulting in smaller edge current, from both the ohmic (lower resistivity) and the bootstrap (higher collisionality) component. If one assumes that the effect of the vertical kicks is to add current in the edge region, the smaller the edge bootstrap current the larger amount of edge current needs to be induced by the kicks to destabilize the current-driven peeling mode for a given pressure gradient, which is qualitatively consistent with the experimental observations described above.

In order to check the validity of our hypothesis, peeling-ballooning (P-B) mode stability analysis has been performed (see figure 6) using the MISKA-1 code [18] for the two pulses shown in figure 5. The ne and Te measured Thomson scattering profiles just before the start of the kick cycle were used in the MHD analysis. To deal with the uncertainty in the location of the separatrix calculated by EFIT, the assumption of T_e ~150-200eV at $\psi = 1$ [19] is used to locate the measured profiles with respect to the equilibrium boundary. This analysis shows that although the edge plasma is marginally stable (close to the ballooning boundary) at a given instant before the beginning of the kick cycle, it crosses the stability boundary towards the low-n peeling modes unstable region when a finite edge current similar to that predicted by the simulations is included in the stability analysis. This illustrates the strong sensitivity of edge stability to the edge current density in the separatrix. The operational point for the Pulse No: 76946, with lower edge temperature, is found to be stable to peeling ballooning modes, located far away from any stability boundary (not shown here).

4. ACCESS TO STATIONARY H-MODE OPERATION WITH THE BE/W WALL USING VERTICAL KICKS

The experience in the first year of operation in JET with the Be/W wall has shown us that maintaining a sufficiently high ELM frequency (f_{ELM} >10-15Hz) [11] is critical to achieving robust steady state H-mode operation with tolerable core W concentration, in line with the AUG results [10]. The increase in ELM frequency is typically achieved in JET by adding gas fuelling, with the corresponding decrease in confinement (H98<0.9 for the majority of the H-mode plasmas obtained so far). Indeed, low gas fuelled (and low input power) H-mode plasmas in JET are impurity-dominated, with relatively long ELM free phases followed by back transitions to L-mode [20], which is similar to what was observed in the carbon wall operating close to the H-mode power threshold. Hence, the ability to trigger ELMs in order to reduce the inward transport of tungsten from the edge region and reduce the length of the ELM-free phases during the initial phase of the H-mode is clearly desirable. Besides gas fuelling other methods such as pellets [21] and vertical kicks have been employed to control the ELM frequency. An example is given in figure 7 where kicks are shown to be effective in controlling the core W accumulation. Initial experiments have shown that the ELM frequency can be effectively locked to that of the vertical kicks ($f_{kick} \leq 45$Hz) in stationary gas fuelled H-mode plasmas, but larger kick size was required for effective ELM triggering. The difference in kick size is likely to be related with the difference in pedestal temperature between the present experiments in the Be/W wall (gas fuelled plasmas, with $T_{e,ped} < 0.6$keV) [22] and the previous ones carried out in JET with the carbon wall (unfuelled plasmas, with $T_{e,ped} \sim 1$keV). Lower pedestal pressure and higher collisionality implies reduced edge bootstrap current which is consistent with the observations discussed in the previous section. In the experiments conducted so far, the increase in ELM frequency was marginal. In those conditions no significant changes on ELM size or plasma confinement are observed, as seen in previous experiments [6]. The ELM pacing experiments with vertical kicks has just started and it will continue in the coming campaigns, with emphasis on the application of the vertical kicks in low power/gas plasmas where the natural plasma behaviour is non stationary.

DISCUSSION AND CONCLUSIONS

The ability to confidently predict the power required to access and sustain steady H-mode operation with good confinement (H_{98}~1) is a critical issue for ITER. It is worth noting that in the carbon wall the access to H_{98}~1 in stationary conditions was linked to the onset of regular type I ELMs (f_{ELM} >10Hz). The analysis shown here has identified that inter-ELM dynamics and radiation (and therefore density and edge impurity content) have to be included in a detailed power balance to account for the variation of the total power required to maintain stationary H-mode conditions and H_{98}~1. A similar conclusion has been recently drawn in [23]. It follows that ELM control with kicks may be effective to reduce the required Ploss to access stationary H-modes. It is not clear however that core density/impurity accumulation is the only cause for the observed variation of the average power requirements for attaining H~1 in JET ELMy H-modes [2,9]. We cannot rule out that additional mechanisms might pay a role and work is ongoing to clarify this issue and to address the scaling to ITER

The experiments carried out at JET have shown that effective ELM triggering via vertical kicks (f_{kick}~10-20Hz) can be achieved in H-mode plasmas at power levels marginally above the H-mode power threshold, which provides sufficient degree of impurity content and radiation control to maintain stationary conditions, with no additional penalty in terms of confinement. These results suggest that the use vertical kicks may provide a potential route towards minimizing the W impurity build-up during the early phase of the H-mode in ITER during current ramp up/down phases. A major advantage of the vertical kicks with respect to the rest of the available ELM frequency control methods is that the ELM frequency can be controlled without affecting any other plasma parameter (no added impurities or density). Feasibility studies for ITER have shown that plasma vertical excursions similar to those obtained in JET at a maximum frequency of 20-30Hz could be delivered with the existing internal VS coil system during the current ramp up/down phase (with I_p below 10MA) [24], which opens up the possibility of using vertical kicks as a tool for ELM frequency control in ITER. Nevertheless, extrapolation of the JET results to the ITER conditions is difficult as long as the mechanism for the triggering of the ELMs is not better understood. On this topic, a substantial progress has been made on the capability to model the underlying physics involved in the kick-triggered ELM. The initial results of the simulations suggest that the mechanism by which vertical kicks trigger ELMs is strongly linked to edge currents and their effect on edge stability. We must, nevertheless, wait for the more accurate closed-coupled simulations to confirm this hypothesis. A positive trend for the kick probability to trigger an ELM with increasing edge T_e is deduced from the modelling (at lower edge resistivity the induced edge current increases faster) and confirmed experimentally, which is encouraging in view of ITER. Further modelling and experimental work are needed to improve the predictive capability of a physics basis model of the ELM triggering mechanism via vertical kicks.

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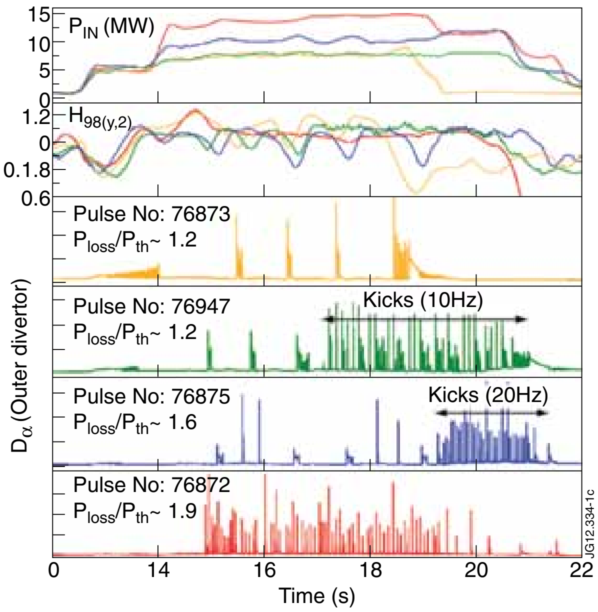

Figure 1: ELM behaviour during a P_{NBI} scan in JET (CFC-wall, 2.2MA, 2T, δ_{av} ~ 0.4, f_{GW} ~ 0.6). The time windows were vertical kicks were applied are shown.

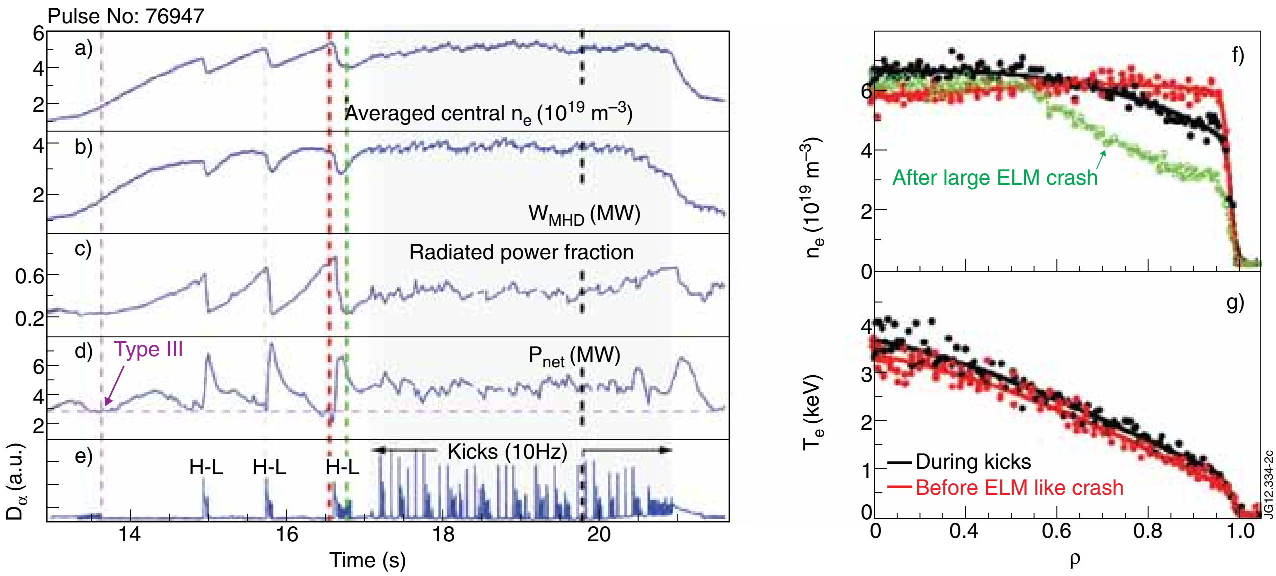

Figure 2: Time traces of several plasma parameters illustrating the plasma response to the application of vertical kicks (at t~17.3 sec) in a JET discharge (2.2MA, 2 T, P_{NBI} = 8 MW, CFC-wall, also shown in figure 1) with input power marginally above P_{th} (P_{loss}/P_{th} ~ 1.2). The n_e and T_e profiles, as measured by Thomson scattering, at the times marked in the figures on the right are also shown.

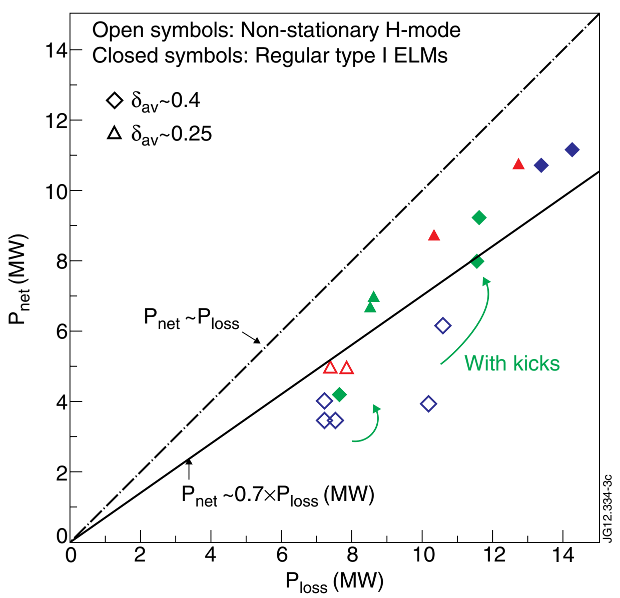

Figure 3: P_{net} versus P_{loss} for two P_{NBI} scans at low and high δ (2.2MA, 2T, q_{95} = 3), including the discharges shown in fig.1. Pulses with kicks are marked in green.

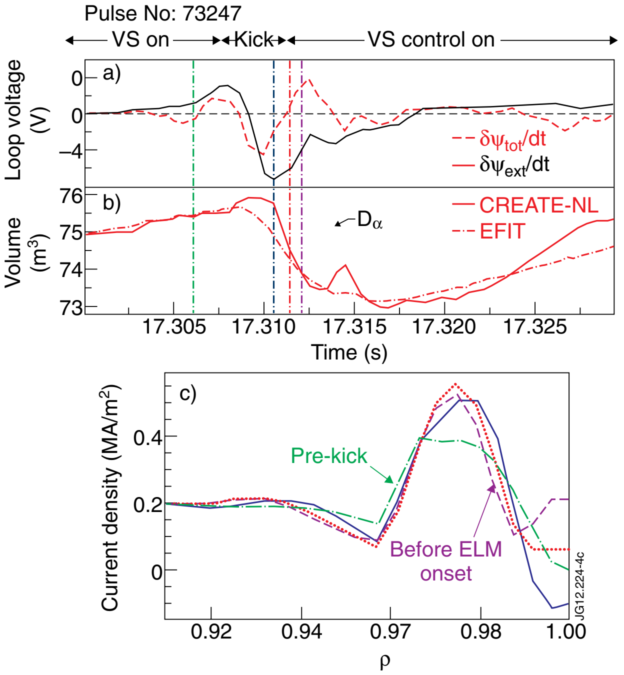

Figure 4: Temporal evolution of (a) loop voltage and (b) plasma volume during a kick event. (c) current density profile for the times marked in the upper plots. The ELM onset is also included in (b).

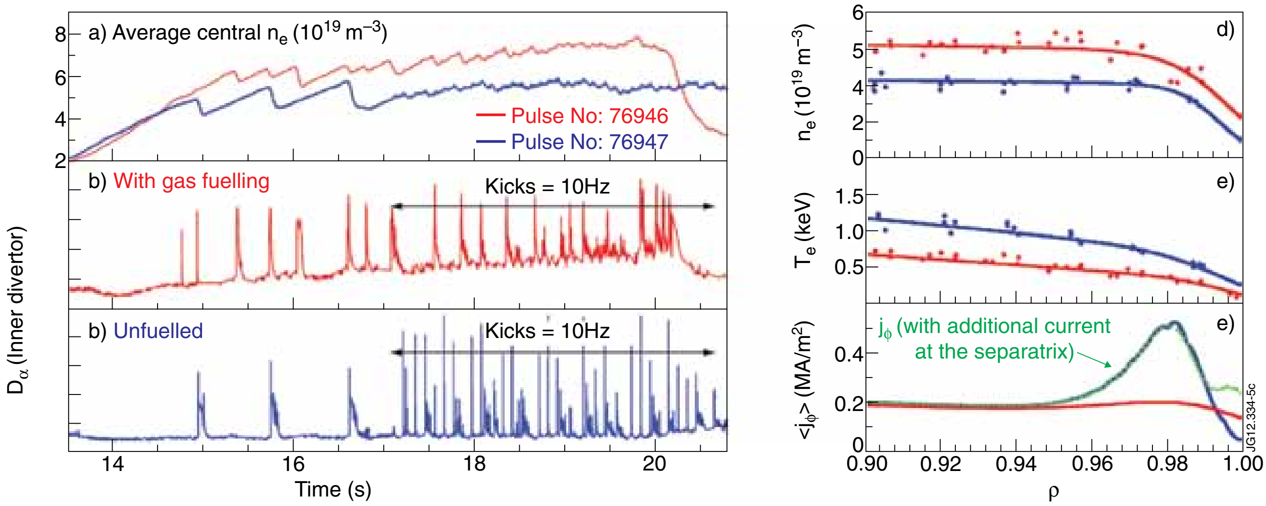

Figure 5: The efficiency of ELM triggering by vertical kicks reduces in plasma with lower $T_{e,ped}$ (and higher collisionality). The impact of gas fuelling in the measured (d)T_e, (e)P_e profiles and the calculated (f) j_ϕ profile is shown. The j_ϕ profile used in the MHD stability analysis shown in figure 7 is plotted (green) in (f)

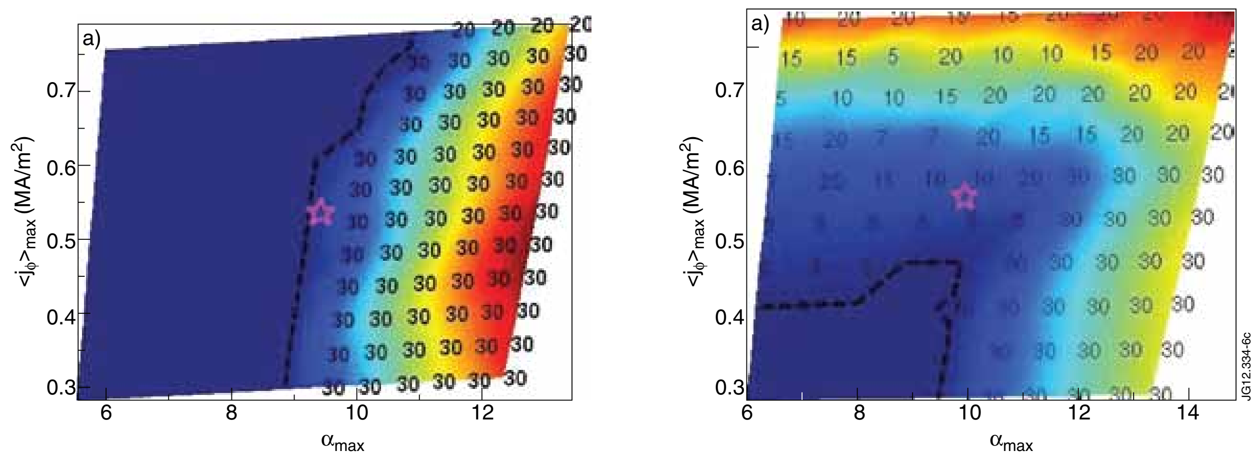

Figure 6: P-B stability diagrams for JET Pulse No:76947 (see figure 6 for more details) (a) jz calculated from measured ∇P and (b) j_ϕ profile including additional current at the separatrix (as shown in the simulations). The stability is plotted in terms of normalized edge pressure gradient (α) and the edge current density. The blue region is stable to P-B modes. The numbers show the toroidal number of the most unstable mode. The operating point is shown by the stars.

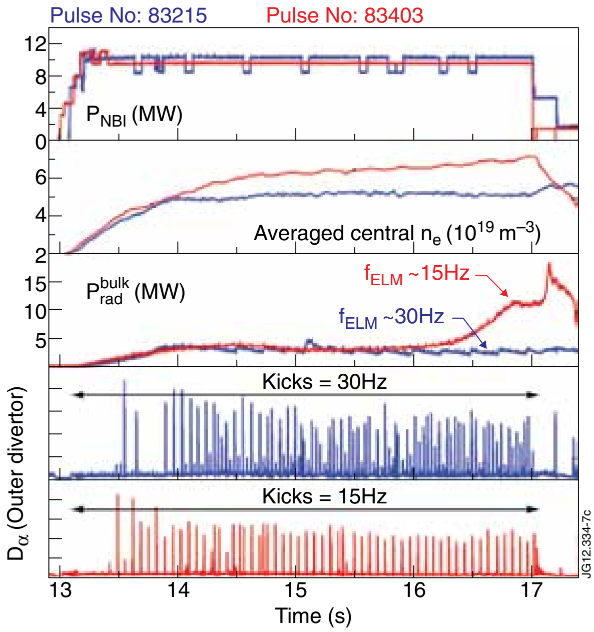

Figure 7: ELM pacing experiments using vertical kicks in gas fuelled H-modes plasmas in JET with the Be/W wall (I_p = 2MA, B_T = 2.2T, q_{95} = 3.6, H_{98}~0.9, δ_{av}~0.3). Core W accumulation is seen with f_{ELM} = 15Hz but not with f_{ELM} = 30Hz.