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ABSTRACT

In 2006, the hybrid scenario at JET has been extended to duration of 20s with good confinement properties ($H_{98}y2=1$) and a fusion figure of merit $G = H_{89}.\beta_N/q_{95}^2 = 0.4$. 186MJ of neutral beam energy has been injected in these discharges and more than 50% of the total current is driven non-inductively. The 3/2 Neoclassical Tearing Mode (NTM) is observed to degrade the confinement by typically 15% and its triggering depends closely on the q profile at the time when the main heating is applied. Boundary flux control has been applied for 15s during these discharges together with strike point sweeping for spreading the heat load on the divertor target. In addition this control has been coupled with total plasma current control by the neutral beam power for shorter times (10s). This experiment demonstrates the potential of the hybrid scenario to become a reference scenario for stationary long duration operation.

1. INTRODUCTION

The Hybrid scenario is an alternative H-mode to the conventional ELMy H-mode for inductive operation of ITER and pulse length beyond 400s. In this scenario, the central value of the safety factor is kept close to unity with very low central magnetic shear with low or no sawteeth activity thus avoiding the triggering of large Neoclassical Tearing Modes (NTM) at high normalised kinetic pressure. It offers the prospect of higher stability, high neutron fluency and long pulse inductive operation without a full steady-state capability. In the recent years, the performance of the Hybrid regime has been operationally validated and the physics basis established in several experiments such as DIII-D [1], ASDEX Upgrade [2], JT-60U [3] as well as in JET experiments [4]. In previous JET experiments, stationary conditions have been achieved for duration less than 5s typically smaller than the resistive time (6 to 7s) with the fusion figure of merit G reaching 0.42 at $q_{95} = 3.9$ only.

The recent 2006 campaigns at JET have investigated experimentally key physics issues such as core and pedestal transport, MHD limits at high normalised pressure (up to $\beta_N = 3.6$), the development of benign edge stability conditions and current profile control in 20s discharges. The question of the stationary q profile and why this q profile remains close to unity has been the subject of dedicated experiment in several machines. So far it is not clear why the current profile in the hybrid scenario becomes stationary with a broad safety factor profile close to unity. Off-axis current from the bootstrap current could be large enough to flatten the q profile and maintain q slightly above unity. However, in ASDEX Upgrade, current balance simulation predicts $q_{min}<1$ in contrast to the q profile measurements from Motional Stark Effect diagnostic (MSE) [2]. The effectiveness of off-axis neutral beam current drive in some conditions has also been questioned [5]. In DIII-D [2], the 3/2 island has been shown to modify the current distribution and acts to raise the central q_o above 1. However, the island size does not seem large enough to change the central current by more than a few percent and the 3/2 island can have a deleterious effect on the stored energy. JET has not resolved these issues yet partly because of its long resistive time (>6s) resulting from its large volume ($80m^3$). The optimisation of the q profile formation and evolution in hybrid scenario is necessary to prevent the development of a large q=1 surface or to investigate systematically the effect of sawtooth on NTM triggering or on the effective β limit that this scenario can reach. For these reasons, JET has developed a specific experimental set up to extend the hybrid scenario up to 20s. In addition this experiment has integrated novel control schemes specifically design for long duration discharges such as loop voltage control with the ohmic voltage and also sweeping techniques to mitigate the power load on the divertor targets.

This paper reports first the experimental details of the 20s hybrid scenario operated in JET in last year campaign. The current balance analysis is detailed followed by the study of the relation between the 3/2 NTM and the target q profile formed in the current ramp up prior to the main heating. The control techniques applied to this scenario are also described and their benefit evaluated in the prospect of establishing the techniques for running a relevant stationary discharge for the next step.

2. EXPERIMENTAL SET UP

Figure 1 illustrates a typical 20s long hybrid scenario achieved in JET. This discharge is operated at a plasma current of I_p = 1.3MA and a toroidal field B_T = 1.5T with a high triangularity (~0.4) ITER-like magnetic configuration and q_{95} = 3.5. The current ramp-up is pre-heated by Lower Hybrid Current Drive (LHCD) up to a level of 1.2MW and has been used as a tool to broaden the target q profile and this will be explained in a next section. Because of the poor lower hybrid current drive efficiency at this toroidal field strength, the LH-wave essentially heats the electron channel but does not produce any significant amount of off-axis non-inductive current drive. Neutral Beam Injection is injected at the time the current plateau is reached for duration of 20s at a level of about 10MW. Because of power supply hardware limitations it is not possible to use all beams at the sme time for more than 10s. Therefore, in this experiment, the 14 beams available were divided into two groups of 7 beams, each covering 10s of the pulse. With this set up a record of 186MJ of NBI energy has been injected in the plasma. As a consequence, beam diagnostics such as charge exchange spectroscopy (for ion temperature and rotation measurements) and MSE (for the q profile) are only covering respectively the second and first 10s of the pulse.

The pulse shown in figure 1 reaches a normalised pressure β_N of 2.5 for almost 20s. The resistive time is calculated from the Mikkelsen reference [6] and is of the order of 5.5s. This discharge therefore lasts for more than three resistive times. It is operated at 70% of the Greenwald density, an ion temperature of 4keV and electron temperature of 3.5keV with type I ELMs. There are some signs of sawtooth crashes in the plasma core preceded by long n=1 precursors lasting up to 0.5s, but there is no sign of 3/2 MHD activity. This pulse has a thermal H factor just above 1 with respect to the ITER scaling H98(y,2) [7], making a fusion merit factor $G=H_{89}.\beta_N/q_{95}^2$ of 0.4. The discharge stays below the estimated ideal wall limit (4×li~3). More power would be necessary to investigate the no-wall limits for such long plasma duration.

For long duration stationary discharges, the control of plasma wall interaction both during transients (such as ELMs) or local power flux (for example at the strike points) is a critical issue. The present carbon targets are usually very resilient in terms of power load. However JET is planning in the future to change the carbon divertor targets tiles with a combination of tungsten and tungsten coated tiles thus limiting the surface temperature to 1600C and the plasma operating target temperature to less than 10eV [8]. A new wide angle infrared and visible camera has been installed on JET [9]. This diagnostic observes the inner wall, the outer wall, the outer and upper limiters, de divertor target tiles and the ICRH antenna with a typical space resolution better than 1cm at a distance of 3 metres and a temperature range of 200C to 2300C. A frame rate of up to 100Hz can be achieved at full image size. For the 20s duration hybrid stationary discharge, it was used to monitor the power load on the divertor target and assess the effect of strike sweeping.

In order to make this pulse compatible with long duration, several new key plasma control features have been simultaneously integrated. The new JET shape controller recently installed and validated for accurate control of the plasma boundary has been integrated with boundary flux control [10]. The shape controller guarantees that the plasma shape does is not modified as the poloidal β (βp) and internal inductance (li) are varying. On its side, boundary flux control is the best way to achieve the control of the flux consumption and discharge duration. In addition, the new shape controller includes a new strike point sweeping facility specifically designed to spread the heat load on the divertor target and examine its potential usefulness with the future tungsten wall.

3. CURRENT PROFILE BALANCE ANALYSIS

Current balance analysis has been inferred from the CRONOS [11] codes. The main non-inductive current components are the bootstrap current reaching a level of 500kA (40% of the total current) and the beam current with a level of 150kA (10 to15% of the total current). As shown on figure 2a, the loop voltage evolution is well reproduced by the CRONOS calculation using the neoclassical resitivity and bootstrap current from the NCLASS code [12]. Experimentally, this discharge shows infrequent low amplitude sawteeth (see figure 2a) with an inversion radius of 20 to 25cm and fishbones indicating that the q profile is close to unity. However, the current diffusion calculation predicts a central q value constantly below 1 after t = 10s and a q = 1 surface of r/a = 0.2. On one hand this suggests that the non-inductive current from bootstrap and neutral beam is sufficient to maintain a stationary q profile throughout the 20s. On the other hand, it appears (fig 2b) that the peaked beam current prediction by CRONOS is driving q down too far inconsistently with the observations on the n = 1 m = 1 mode. Here it should be stressed that there exists some uncertainties in the calculation of the beam driven current and plasma conductivity that may account for the observed differences between current diffusion calculations and measurements in the plasma centre. The beam current calculations from TRANSP [13] and CRONOS respectively use the NUBEAM [14] Monte Carlo code and the SINBAD [15] code. The model in NUBEAM self consistently handles classical guiding centre drift orbiting, collisional and atomic physics effects during the slowing down of the fast ion population.

SINBAD uses an accurate but simplified beam model and a Fokker Planck module and not taking into account first orbit effects. This could lead to less broad beam current density profile and therefore to the prediction of a more peaked q profile and larger q = 1 flux surface.

Also, the electric neoclassical conductivity used in current diffusion codes can be inferred from several sources: the NCLASS code using Shaing viscosity coefficients [16], or the standard analytic Hirshman formula [17]. The latter is valid in the limit of low collisionality only and can overestimate the conductivity in the plasma core [18]. Therefore, this expression is likely to over-estimate the conductivity in the plasma core and produce more peaked current density profiles.

In contrast to studies elsewhere [2], it does not seem necessary to invoke in the current diffusion calculation other processes like the redistribution of current by fishbone activity to explain the evolution of the q profile. Within r/a = 0.3 where the current density is small and the bootstrap and beam driven current of the same order of magnitude in hybrid scenario, it is essential that extrapolations and modelling of this scenario are made with validated models including all the necessary physics effects in the plasma core.

4. NTM STABILITY DEPENDENCE WITH TARGET Q PROFILE.

Access to the hybrid scenario requires the formation of a q profile with low magnetic shear in the plasma core and qo~1 in order to minimise the triggering of neoclassical tearing modes by sawteeth. The formation of the q profile is therefore essential. Since NTMs are pressure driven modes, the access to high normalised pressure requires the optimisation of the q profile in order to avoid the creation of a seed island on q = 1. As in DIII-D or ASDEX Upgrade hybrid scenario, low amplitude n = 2, m = 3 MHD activity is recorded in JET.

To investigate the effect of the target q profile on the stability of the 20s hybrid scenario a scan of the LH power has been carried out. Varying the LH-power in preheat has the effect to modify the poloidal flux diffusion in the current ramp-up before t = 4.0s when the main heating (NBI power) is applied as confirmed by MSE measurements. In this way, the optimum target q profile can be determined. The LH power was varied from 0 to 1.2MW. Discharges with an LH-power below 0.5MW in general do not show any significant 3/2 mode but sometimes intermittent sawteeth accompanied with fishbones activity. On the other hand discharges with LH-power above 0.5MW show strong 3/2 activity and a degraded confinement by typically 15% on average, but no sawtooth activity.

These data are summarised in figure 3 showing the confinement degradation related to the presence of the 3/2 mode. This result first suggests that high values of β_N are reached when the q profile is just touching the q = 1 surface and not when a 3/2 mode is present. This is also consistent with the latest ASDEX Upgrade results [19] showing the difference in confinement between the late heating timing (with fishbone activity) and the early timing (with m = 3 n = 2 MHD activity). Secondly, this study helps in quantifying the effect of the presence of a 3/2 mode on confinement. Applying the confinement degradation expected for an island located at 3.45m [20], the island size produced in this discharges are of the order of 10 to 15cm which is consistent with the MHD measurement of the island size using magnetic pick-up-coils.

Experiments in DIII-D have shown evidence of the beneficial effect of the 3/2 island on the current profile: stabilisation of the m=3, n=2 NTM by localised ECCD provides a small decrease of the core q profile by typically 0.05. This relatively small effect is also probably present in JET and could explain the absence of sawtooth when the LH-power exceeds 0.5MW. Nevertheless, significant off-axis non-inductive current (~50%) and possibly current profile control is still a necessary condition for keeping a stationary q profile close to unity. In addition, the analysis above also suggests that keeping an island exceeding more than 1/10th of the minor radius introduces a too large penalty on confinement.

Finally, the occurrence of the 3/2 mode when the q profile is modified by the LH power in the preheat phase suggests that magnetic shear is playing a dominant role in the destabilisation of this mode in the early phase of the discharge. Comparison of q profiles reconstructions using EFIT constrained with MSE data for two pulses without and with 1.2MW of LH power shows a significant change in magnetic shear at the location where the 3/2 is expected. Δ' effects could be responsible for the onset of the mode even before the pressure drives it more unstable through the neoclassical effect. This underlines that current control in the early phase of the q profile formation will be a key tool for operating this scenario in a reliable way.

5. BOUNDARY FLUX AND TOTAL CURRENT CONTROL

One important feature of the experiment reported in this paper is that the 20s hybrid scenario uses boundary flux control in the time window 8-23s, meaning that during this window the flux consumption is solely controlled at the boundary and the plasma current is floating.

The boundary flux control is performed by means of a SISO (Single-Input-Single-Output) loop acting on the current in the transformer circuit. The other poloidal circuits are devoted to shape control. This SISO loop uses a Proportional-Integral (PI) controller whose gains have been tuned by standard design techniques on the basis of the linearised CREATE-L model [21]. To set up the experiment, a pre-assigned boundary flux reference is designed on the basis of a previous reference pulse. Here the flux reference has a slope in time of 0.02Weber/s. In can be noted from figure 1 that the plasma current is slightly increasing up to 1.4MA, indicating that the plasma conditions have changed with respect to the reference discharge. The pulse in figure 1 is not showing any m = 3, n = 2 MHD activity like the reference pulse. Therefore, the confinement and normalised pressure are higher by typically 15% and more bootstrap and ohmic current are generated as a result. This control scheme has been successfully applied in several 20s hybrid scenario pulses.

When the boundary flux is controlled by the transformer current, the plasma current is in principle left floating. Hence, a further feedback loop has been added, that controls the plasma current using the NBI power as actuator. For this, another SISO PI controller has been designed on the basis of a first-order plasma response model, which parameters have been empirically tuned (proportional gain = 12MW/MA and integral time constant = 0.1s) before the actual experiments using the results obtained on a different plasma configuration. The target plasma current is set to 1.5MA, implying that the demand on the NBI power is likely to exceed 10MW. Therefore, this double control loop has been attempted on a shorter pulse of 10s. On top of the two controllers strike point sweeping has also been set up with a frequency of 4Hz and an amplitude of 7cm. The control scheme successfully drives the total current up to its target of 1.5MA (q_{95} = 3.2) (figure 4); it must be pointed out that the neutral beam demand is limited to 16.5MW by the beam plant after 8s. The high demand to the beam plant is partly explained by the onset of a large island (width close to 15cm located at 3.45m at t = 8s) with n = 2 m = 3 mode which degrades the confinement and the amount of generated bootstrap current. This combined control of the boundary flux and non-inductive current through the bootstrap current, have been applied to the hybrid regime for the first time at high normalised pressure up to β_N=3.

6. POWER LOAD MEASUREMENTS ON DIVERTOR TARGETS

Long duration pulse also implies that the first wall must be able to cope with the power deposited on plasma facing components and in particular on the target plate in the divertor region. Mitigating local power on the divertor target is not a major issue when using carbon tiles since this material can survive very high surface temperature (above 2000C). However the use of Berylium or tungsten tiles (as foreseen in the future JET-wall [8] and in ITER) will require a more refined surface temperature control to avoid any melting of the target tiles. To mitigate the power load falling on target plates, strike sweeping technique has been tested in the 20s long hybrid scenario. The strike points are swept with peak to peak amplitude of 7cm and a frequency of 4Hz on two tiles of the divertor. On average, no significant confinement losses related to the sweeping of the strike points (figure 1) are observed. However, looking in more details on the ELM behaviour, it appears that the sweeping leads to a decrease of the ELM frequency (figure 5) and sometimes to short (<100ms) ELM free phases as the outer strike reaches the divertor corner.

On the other hand, measurements with the new infrared camera show that the local temperature at the target is lower than that observed on a pulse without sweeping. Typically the maximum temperature measured by the infrared camera on the outer divertor tile (figure 5) is lowered by 25 to 30% close to thermal equilibrium conditions. The infrared camera data also show a broadening of the foot print on the tile resulting also in a lower power load density from typically 5MW/m^2 to 3.5MW/m^2.
The amount of energy dumped into the tile is not different than if the strike had remained at the same position. This can be explained by the fact that the strike point stays on the same tile throughout the whole sweeping. This is confirmed experimentally by the thermo-couples data which do not show any difference with and without sweeping.

By spreading the heat load on the tile, this sweeping technique can prove a useful and valuable tool for minimising the temperature with more sensitive plasma facing component material such as Beryllium or Tungsten. It could also help in keeping peak temperature due to transients (like ELMs) within the allowable limits.

CONCLUSIONS

Recent experiments in JET have successfully extended the duration of the Hybrid scenario well beyond the resistive time (typically ~ 5s) to 20s with normalised pressure up to†$\leq_N$ = 2.5. More than 50% of the total current is generated non-inductively in these discharges. The modelling of the core q profile is very sensitive to the conductivity and neutral beam current models used as source terms in the current diffusion equation. The bootstrap current appears as the main non-inductive component to sustain the broad central q profile in the core.

Using a dedicated LH-preheat scan, the confinement degradation related to the presence of a m=3 n=2 island has been quantified to about 15%, confirming that the 3/2 and also 4/3 island are not desirable to optimise the hybrid scenario performance. The scenario is best optimised when q is broad and just touching the q=1 surface. In these conditions intermittent sawteeth and fishbone activity are not strong enough to trigger an NTM. The optimisation of the target q profile is a key in avoiding the classical destabilisation of the tearing mode.

The hybrid scenario pulses in JET has been operated at high normalised pressure with the simultaneous application of several control features relevant for long discharges: the control of flux consumption with the transformer current as actuator, the total plasma current control using neutral beam injection as actuator and finally the strike points sweeping for spreading the power on divertor targets. The strike sweeping procedure provides a mean to decrease the target temperature by typically 25 to 30%. It has no apparent impact on confinement but seems to affect the ELM behaviour.

This 20s duration hybrid scenario is a first step towards the integration of more control schemes and techniques in ITER relevant scenario such as the hybrid regime. As already mentioned, the control of the q profile appears to be a key in optimising the confinement and its control would be required. Long discharges like the hybrid 20s run at JET are also showing the importance of the control of divertor target temperature [22]. The integration work of different operational parameter for discharge performance and limit avoidance is a necessary step for the validation of the ITER scenario.

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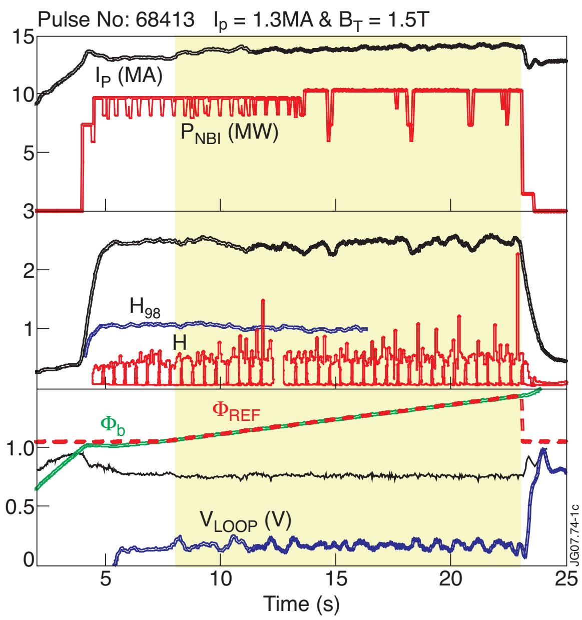
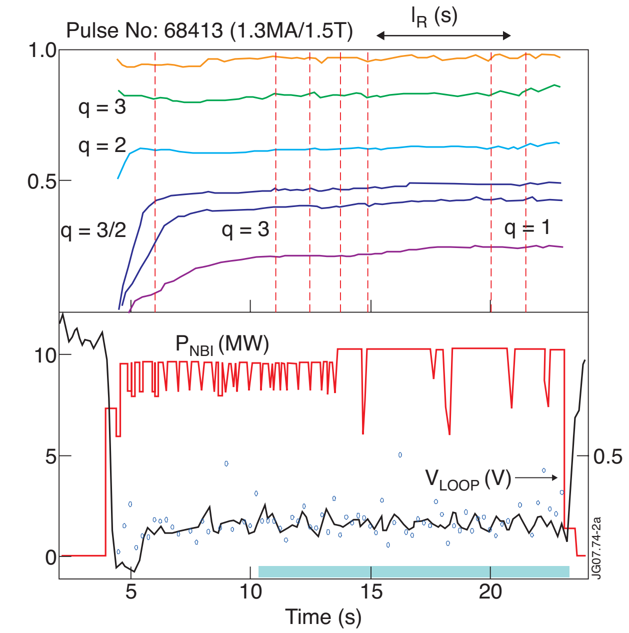


Figure 1: Typical 20s pulse with boundary flux control and strike sweeping. The control window is indicated by the shaded area. Note that the plasma current increases slightly during the flux control window.



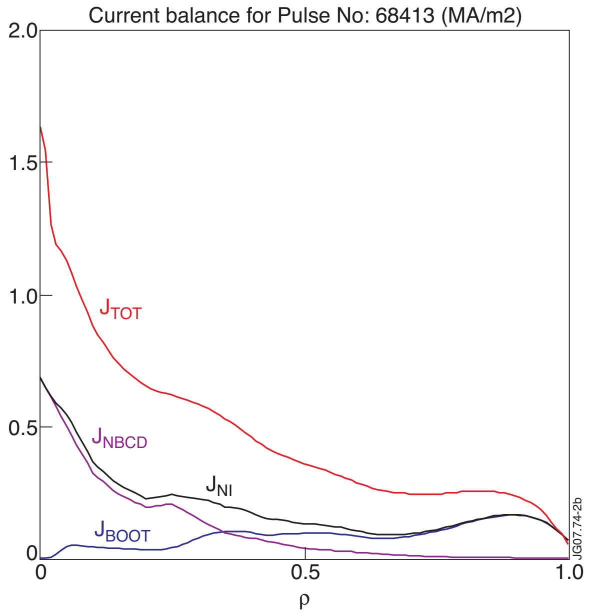
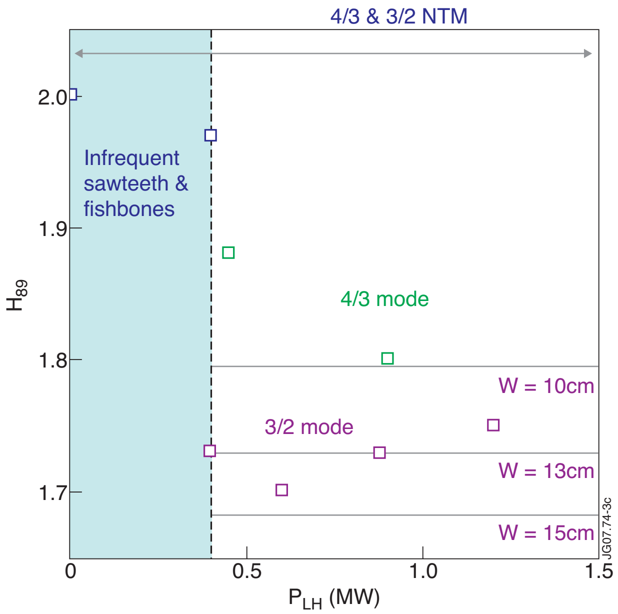


Figure 2a: CRONOS analysis of Pulse No: 68413. Vertical dashed lines indicate the times of sawteeth. Blue dots in the lower box are the V_{loop} calculation from the CRONOS simulation. The resistive time for this pulse is of the order of 5.5s.

Figure 2b: Current balance analysis from the CRONOS code at 10s.



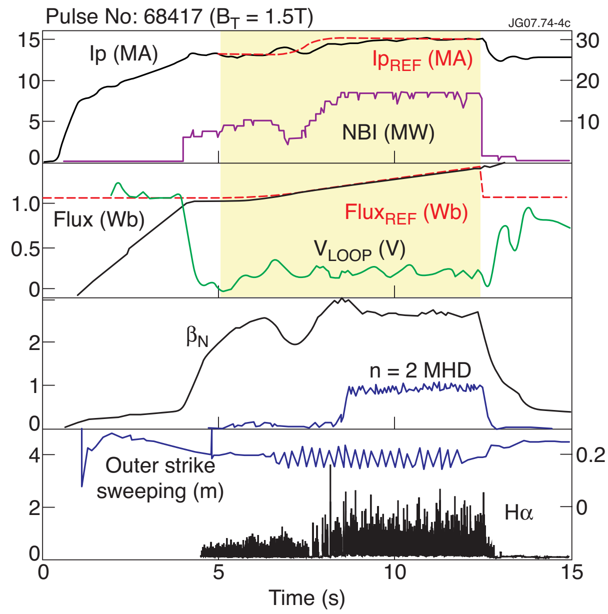


Figure 3: Dependence of confinement with the LH-power in the preheat phase. The horizontal lines are showing the typical confinement level arising from the presence of a 3/2 island of 10, 13 and 15cm located at 3.45m as calculated from reference [18].

Figure 4: Double control loop achieved in a 10s pulse in JET. The plasma current is controlled by the beam power (top box) and the boundary flux by the current transformer (2^{nd} box). Note that the beam power is limited to 16.5MW by the beam plant. Strike point sweeping is also applied between 7s and 12s.

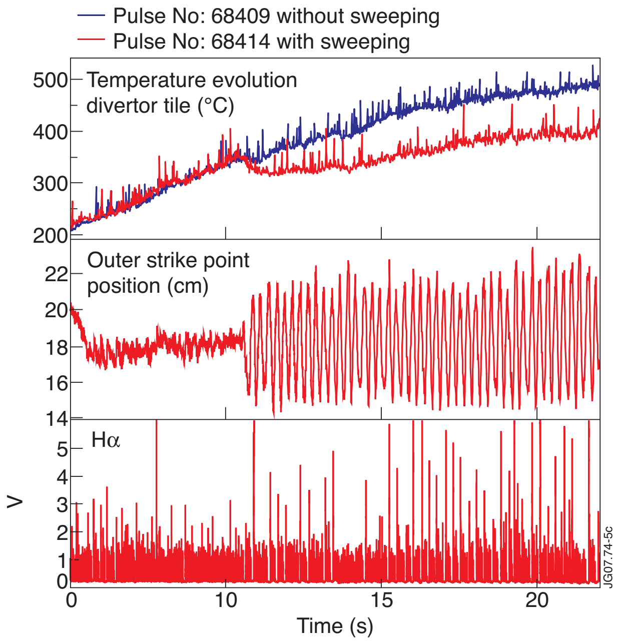


Figure 5: Effect of sweeping on the target temperature as measured by the infrared camera. Note that the ELMs activity (bottom trace) ais also somewhat affected by the sweep: short ELM free phases are produced.