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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT
Developing safe, non-disruptive plasma termination scenarios is essential for the preparation of ITER operation. The ITER Poloidal Field (PF) system, internal Vertical Stability (VS) coils and Central Solenoid (CS) will have to provide plasma position control (slow and fast) and respond to plasma disturbances within a range of plasma internal inductance (l_i). In addition, the central solenoid will have to provide adequate magnetic flux for the entire discharge; however, little or no transformer flux may be available for the plasma ramp-down. JET has investigated the ITER rampdown in both ohmic and in H-mode, and methods for controlling li staying within the limits of the PF system as well as avoiding any resistive flux consumption. These discharges have been modelled using JETTO and fully predictive simulations with the standard JETTO Bohm/gyro-Bohm transport model.

1. INTRODUCTION
During the ramp-down phase, as l_i increases with decreasing plasma current, there is a reduction of the plasma coupling with the surrounding conducting structures increasing the plasma vertical instability and requiring a stronger action from the VS system to control the plasma position. Also important is the control of magnetic flux consumption. For the ITER long pulse, none or very little flux is available for the ramp-down phase [1, 2]. The resistive flux during the plasma current ramp-down depends on the ramp-down rate, the level of additional power, the confinement regime and the plasma geometry [3, 4]. The plasma current ramp-down scenario has to be able to cope with two different situations: (1) standard termination and (2) fast termination to avoid a possible disruption or contact between plasma and first wall. For both terminations, the plasma current ramp-down scenario has to be nondisruptive hence able to control the growth of l_i and density in order to maintain stable conditions. Also important during this phase is the control or avoidance of flux consumption. For the fast termination, similar requirements apply with the additional constraint of having to ramp-down the plasma current as fast as possible but still controlling l_i, density as well as the flux consumption [5, 6]. The work presented here shows how the plasma inductance can be controlled either in ohmic or H-mode plasmas during the ramp-down phase and simultaneously avoid net flux consumption.

For these experiments, the ITER plasma parameters were scaled, using plasma resistivity as guide, to JET plasmas with $B_T = 2.4T$, $I_P = 2.66MA$ and minor radius of $a = 0.95$. The range of plasma current ramp-down rates performed in this experiment extrapolates to ≈300s for the slowest ramp rate and ≈80s for the fastest ramp-down rate in ITER from a plasma current of 15MA at the flat-top, corresponding to JET values of 38s (0.07MA/s) and 5.35s (0.5MA/s) respectively. The assessment of the magnetic flux evolution is carried out based on the value and time evolution of the average current of the JET central solenoid. The experiments include plasma current ramp-down in ohmic, L-mode and H-mode at four different rampdown rates (0.07, 0.14, 0.28 and 0.5MA/s) with ion cyclotron or neutral beam heating at various levels of heating power. The plasma shape used in these experiments has an average triangularity of 0.25 with an elongation of ~1.7. The effect of reducing the plasma elongation during the ramp-down phase on li and net flux consumption is also assessed for all the plasma current ramp-down rates in ohmic and H-mode. All experiments were carried out with diverted plasmas.

2. EFFECT OF ΔIP/ΔT RAMP-DOWN RATES

The effect of the plasma current ramp-down rate is assessed for two cases; ramp-down in ohmic and in H-mode (with constant input power). The variation of l_i during the ramp-down phase in ohmic for the two ramp-down rates is shown in figure 1. The increase of l_i after the transition from H-mode to ohmic at the start of the ramp-down depends strongly on the I_p ramp-down rate. For the faster I_p ramp-down rate, l_i rises to high values early in the ramp-down phase despite the low nominal starting value (~0.8). The increase of l_i for the slower I_p ramp-down rate is slower. Therefore, for an ohmic ramp-down phase, in order to control the rise of l_i, the plasma current ramp-down rate must be slow enough to avoid loss of vertical stability. On the other hand, the behaviour of the average current in the ohmic transformer shows that for slow rampdown rates, flux needs to be provided, contrary to the faster ramp-down rates. Varying the rampdown rate may not be enough to achieve the aim of both minimizing the transformer flux consumption as well as controlling the l_i excursion. One way of slowing down the increase of l_i during this phase is by applying additional heating during the ramp-down phase as shown in figure 2. Although l_i still varies with the plasma current ramp rate, its rise is now slower even for the fastest I_p ramp-down rate when compared with the analogous ohmic discharge. As the plasma current decreases, the H-mode regime changes from type I to type III ELMs. However, as long as this phase is in H-mode, the l_i rise is controlled. Figure 3 shows a comparison of three discharges with different levels of additional heating. In these examples, and during the plasma current ramp-down phase, discharge #72209 is in Type I ELMy H-mode, #72238 is still in H-mode but with type III ELMs and discharge #72210 is in L-mode. Both discharges in H-mode show a similar time evolution of l_i contrary to the discharge in L-mode where li rises, similar to the ohmic discharges. For all cases the transformer average current either decreases (H-mode discharges) or stays constant (L-mode) contrary to the ohmic discharge at the same Ip rampdown rate (0.14MA/s) where an increase is observed.

3. EFFECT OF ELONGATION

In the case of an event requiring a rapid termination of the discharge, a fast current termination may be required in order to reduce the plasma energy as fast as possible in a stable way. Moreover, additional heating may not be available for such “off-normal” fast ramp-down forcing a ramp-down phase in ohmic. A scenario with fast ramp-down of the plasma current in ohmic is then desirable. As shown previously, the increase rate of l_i is proportional to the increase of the rampdown rate in ohmic, indicating that a fast rampdown rate would increase l_i to values possibly outside the VS system capabilities. In terms of magnetic flux consumption, it was shown that for fast plasma current ramp-down rates there is no flux consumption, even for ohmic plasmas. Decreasing the plasma elongation reduces the plasma vertical instability growth rate allowing a smaller request of voltage/current from the VS system and hence a larger margin for this system operation. To assess this possible scenario, the plasma elongation was reduced from 1.7 to 1.61, 1.56, 1.48 and 1.44, at constant plasma current ramp-down rate (0.5MA/s), as shown in figure 4.

With decreasing elongation, the increase of li slows down up to values of elongation of 1.56 where no further reduction of the rate of increase is observed. In addition, also the increase of q_{95} is slower with decreasing elongation suggesting that the variation of l_i is in this case dominated by the variation of q_{95}. This example shows that at JET is possible to control simultaneously li and flux consumption with a fast plasma current ramp-down rate in ohmic plasmas.

4. MODELLING OF THE CURRENT RAMP-DOWN EXPERIMENTS

A study has been performed to assess whether the current ramp-down in ITER can be adequately simulated by using the predictive transport modeling with similar assumptions as those employed for the flat-top simulations. Discharges with the plasma current ramp-down in H-mode and L-mode have been modelled using a combination of fully predictive transport modeling (including density and temperature evolution) and MHD stability analysis. For the transport analysis, the 1.5D core transport code JETTO has been used with a standard Bohm/gyro-Bohm transport model for H-mode plasmas. The marginally stable level of the pressure gradient in the simulations has been determined with the MHD stability codes HELENA and MISHKA-1. The transport simulations have subsequently been run with the correct stability limits. An ad hoc model has been used for simulating ELM crashes upon violation of the determined critical level of the pressure gradient. The electron thermal energy content and internal inductance are compared against experimental time traces derived from fully interpretative JETTO runs (figure 5). MHD analysis shows that the marginally stable level of pressure gradient increases as the current decreases during the ramp-down, which is typical for all the H-mode plasmas with current ramp-down. However, even by using a fixed critical pressure gradient during the current ramp-down, the thermal energy content in the predictive simulations compares very well with interpretative modelling, which reproduces the experimental evolution. The figure clearly shows how the predictive transport simulation fairly accurately reproduces the evolution of the electron thermal energy content. The evolution of the internal inductance is generally slightly faster in the modelling studies than in the experimental measurements but is well matched for the fast ramp-down rates. The modelling also shows consistency between the time evolution of the net flux consumption and the measured average current on the ohmic transformer. Only the ELM behaviour is not adequately reproduced during the ramp down. This can in part be attributed to the simplicity of the ad hoc ELM model used in the exercise.

CONCLUSIONS

These experiments show that it is possible to ramp-down the plasma current with diverted configurations controlling l_i and flux consumption simultaneously by varying the plasma current ramp-down rate with different confinement regimes where the li variation is proportional to Ip (q_{95}) or by varying the plasma elongation in ohmic where the li variation can be, to some extent, controlled independently of the plasma current ramp-down rate by varying the plasma elongation. For these cases the variation of li is, apparently, dominated by q_{95}. Both these methods have demonstrated that for the fast ramp-down rate of the plasma current (0.5MA/s), corresponding to the fastest ramp-down rate in ITER, it is possible to maintain plasma vertical position and avoid flux consumption leading to a good plasma landing. From the modeling results it can be concluded that a number of important characteristics of the current ramp down, including the H-L transition and evolution of the thermal content and internal inductance can be reproduced to an acceptable degree of satisfaction with the available models and modelling tools.

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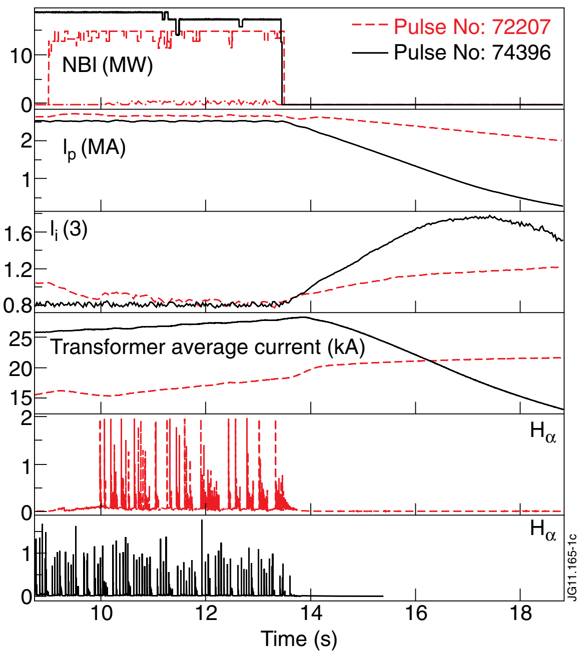

Figure 1: variation of li for a plasma current ramp-down in ohmic for two ramp-down rates, 0.14MA/s (red) and 0.5MA/s (blue)

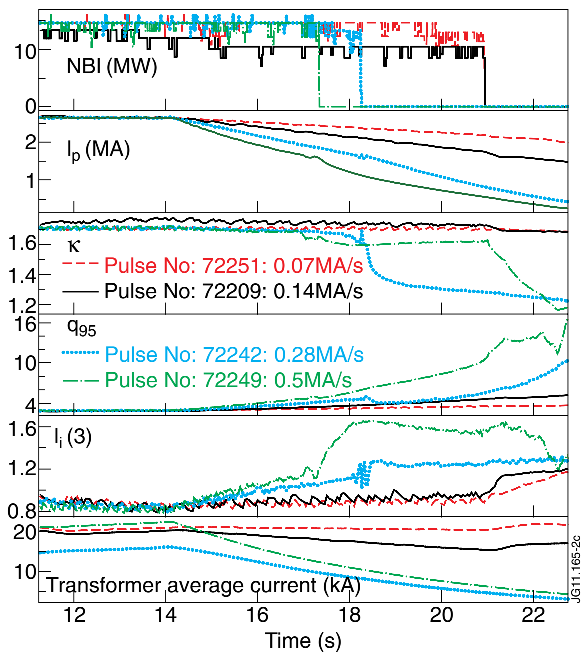

Figure 2: Temporal evolution of li and transformer average current during the plasma current ramp-down phase in H-mode for four ramp-down rates of plasma current.

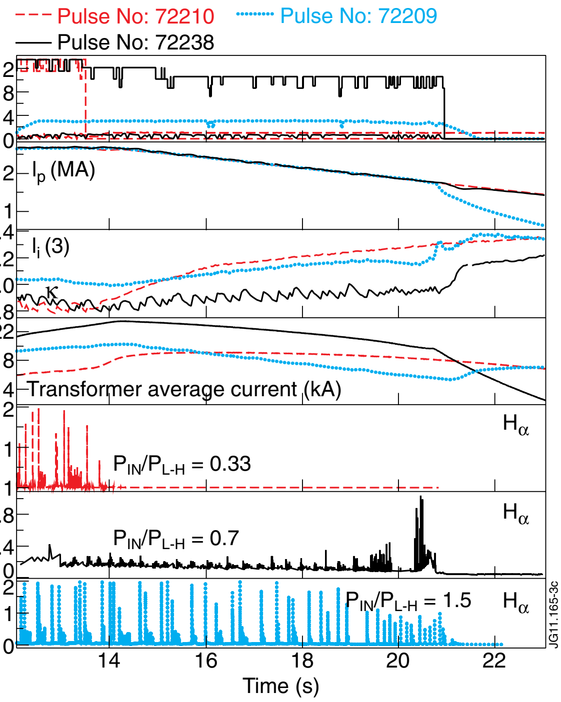

Figure 3: comparison of the l_i and transformer average current for the ramp-down phase in Lmode (red), and H-mode with type I (black) and type III (cyan) ELMs.

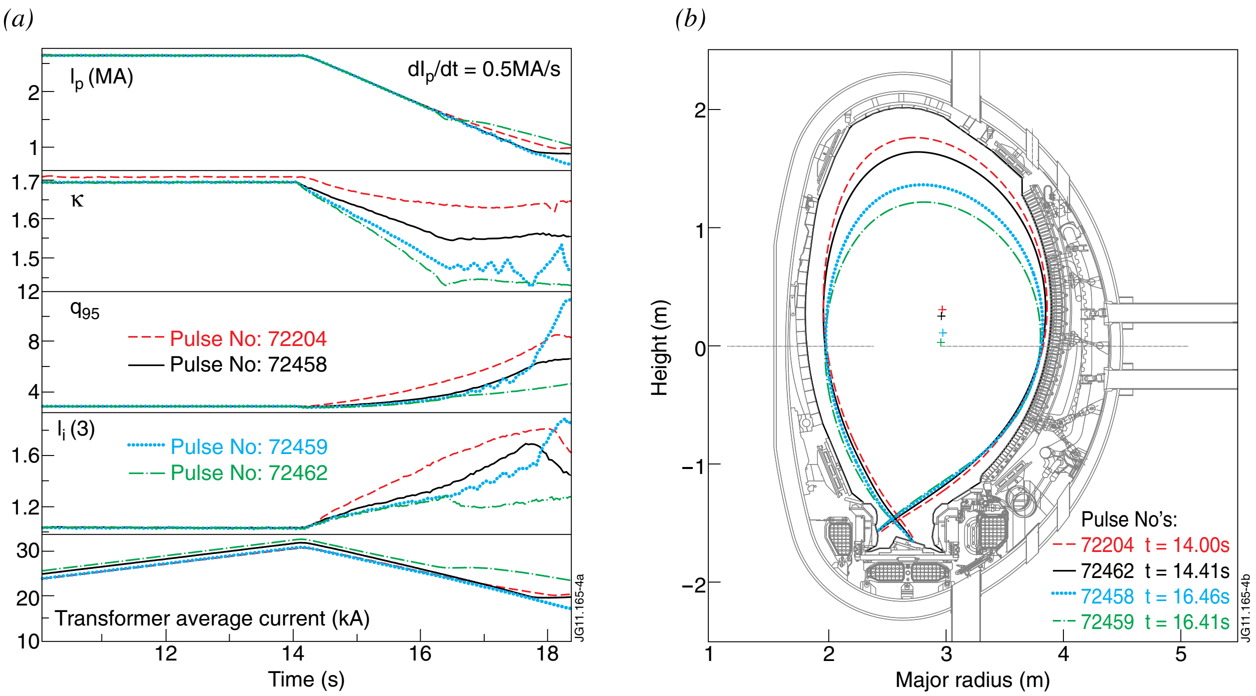

Figure 4: (a) Variation of li and transformer average current as a function of elongation for ohmic discharges and (b) plasma configuration for the different values of elongation

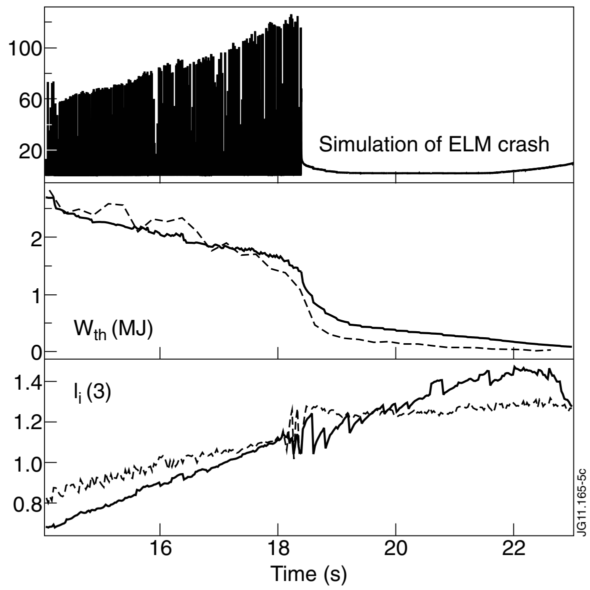

Figure 5: Time traces for the simulation results (full line) and experimental measurements (dotted line) for a discharge (Pulse No: 72242) with the plasma current ramp-down in H-mode