H-mode and L-H threshold experiments during ITER-like plasma current ramp up/down at JET with ILW

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1. Introduction

ITER plasma scenario studies [1] have shown that the optimisation of the flux consumption from the poloidal field coils requires control of the plasma inductance, used here l_i=l_i(3) [1]. This control was achieved in ITER demonstration discharges (at DIII-D, C-Mod, AUG and JET-C) using a combination of full bore start up with early X-point formation and current ramp-up in H-mode. H-mode during current decay down has been shown also instrumental to maintain low inductance in order to minimise flux consumption [2]. Moreover variation of plasma inductance in ohmic discharges can be controlled, independently of the plasma current ramp-down rate, by varying the plasma elongation, as reported in [2]. An all-metal ITER-like wall (ILW) [3], consisting of beryllium in the main chamber and tungsten surfaces in the divertor, has now been installed in JET. Its implementation has offered the opportunity to assess if the flux consumption and plasma inductance evolution is modified by Be-wall and W-divertor during the current rise and current decay (e.g. current profile evolution, plasma controllability issues as W accumulation in the transient phase, L-H transition, etc.). Details of the experimental results obtained in 2012 with the ILW and comparison with carbon-fibre reinforced carbon (CFC) wall (JET-C) will be given here. The CRONOS suite of codes has been used to interpret JET-ILW experimental results and make predictions for ITER.

2. Experimental set-up.

The JET scenario used was 2.5MA/2.4T (q_{95}≈3) at low triangularity δ≈0.25, low voltage breakdown (E_{axis}≈0.37V/m), early X-point formation, with additional heating applied from plasma current I_P = 1.5MA. This matches, using the plasma resistivity as guide, as discussed in [1], the proposed baseline inductive scenario for ITER of 15MA/5.3T (q_{95}≈3), X-point formation at ~4MA and additional heating applied from I_P~9MA. This scenario was also used for JET-C studies [1, 2]. The following parameters were varied in the experiments: input power (ohmic, low power L-mode and H-mode during the ramp-up and down phases); density: the Greenwald fraction n_e/n_{eGW} was varied from 0.2 to 0.4; I_P ramp rate: the ramp-up rate was dI_P/dt = 0.36 MA/s, 0.28MA/s and 0.19 MA/s, to match the ITER I_P rise phases of 50s, 80s and 100s, respectively [1]. The current ramp-down rate was varied between -0.14 and -0.5MA/s along the same guide lines; elongation was reduced from κ~1.68 to κ~1.54 in a few pulses to control the l_i evolution. The eXtreme Shape Controller (XSC) including the new Current Limit Avoidance (CLA) system was used from the X-point formation to the termination of the discharge in order to achieve a better plasma shape control [4]. Compared with the standard JET Shape Controller (SC, see also [4]), which has been used in the JET-C ramp-up/down experiments [1, 2], the XSC improves the plasma shape control, since it allows to control

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(in the least mean square sense) more than 30 plasma shape descriptors, whilst at most 4 plasma shape descriptors are controlled with SC. Indeed, current L-H threshold scaling law [5] and used for ITER assumptions, predicts for D, in MW:

$$P_{thr,08} = 0.049 B_T^{\ 0.80} n_{20}^{\ 0.72} S^{0.94}, \qquad (1)$$

where B_T [T], n_{20} [$10^{20}m^{-3}$] and S [m^2] are respectively the magnetic field, line-averaged density, plasma surface area. From (1) it turns out that it is important to have a good control of plasma shape. Initial ramp-up ohmic experiments have been setup to assess the improvement on plasma shape control by using XSC. During the ramp-up phase the variation on the plasma surface is ~%5 for the pulse 83014 (XSC), whilst is ~%10 for the pulse 83011 (SC). Furthermore, the XSC improves also the control of plasma shape during disturbances due to the poloidal β variation induced by the additional heating in current rise and decay, as discussed in [6].

3. L-H transition studies during plasma current ramp-up.

The effect of non – zero dI_P/dt on the access conditions for H-mode is not well known, since L-H threshold work has generally focused on discharges at constant plasma current [7]. Initial dedicated experiments have been set up at JET with ILW to assess the lowest power necessary for the L-H transition during a current ramp up (never done at JET before), in comparison with the L-H power in the same conditions (low delta, toroidal field B_t, q_{95}, plasma electron density) without a current ramp, at the same plasma current where the transition occurs during the ramp. Such studies are of relevance for ITER, where the available auxiliary heating will be limited and the predicted $P_{th,08}$ extrapolated from scaling laws at fixed I_P, as discussed in Section 2. First, slow NBI power ramp (1MW/s) were used to measure the L-H transition at constant I_P values,: I_P after X-point formation (low current 1.5 MA, beginning of current ramp-up (RU)) and I_P=2.5MA (flat top (FT) value for q_{95}≈3, end of current ramp-up). All the data used in the present analysis have been averaged over ~40 ms in the L-mode phase just before the L-H transition. The values for the power threshold P_{thr} are provided in the normal way as the loss power though the separatrix, $P_{LOSS}=P_{OHM}+P_{AUX}-dW_{DIA}/dt$, where P_{OHM} is the ohmic power dissipated in the plasma, P_{AUX} is the absorbed auxiliary heating and dW_{DIA}/dt is the rate of change of the diamagnetic energy W_{DIA}. In the present analysis n_e is the interferometer measured line integrated divided by the central chord length in the plasma. It was found P_{thr}(1.5MA)≈2.4MW at $n_e=2.5\times10^{19}m^{-3}$ for pulse 83193, and P_{thr}(2.5MA)≈3.9MW at $n_e=3.1\times10^{19}m^{-3}$ for pulse 83194. These results are in line with the results obtained for the L-H transitions studies at the same toroidal field and shape, discussed in [8], that show a P_{thr} for the ILW lower ~30% than the CFC results and the $P_{thr,08}$ (see Fig.1).

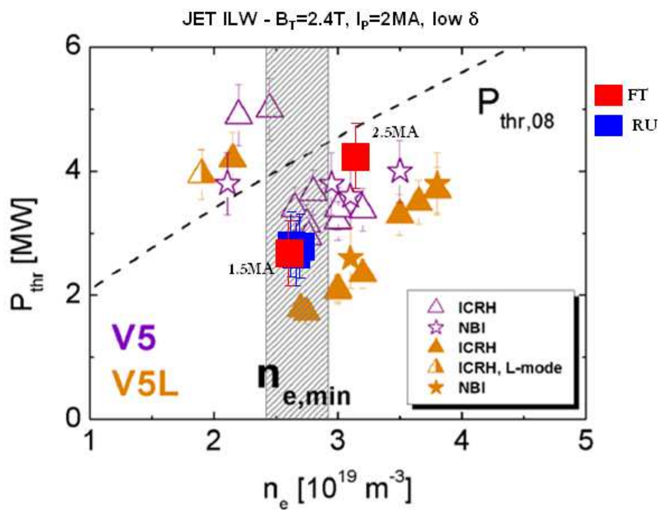

***Figure 1**. Variation of P_{thr} with ne in JET with ILW (2.4T/2.0MA) at low δ for two divertor configurations [8] with different strike point positions, and superimposed results at 1.5MA and 2.5MA in I_P flat top (red square) and the values during I_P ramp discussed in the paper (blue square).*

The second part of the experiment was to vary the level of P_{AUX} (NBI) in small steps around the found P_{thr}(1.5MA) in subsequent discharges (83195, 83200, 83199, 83196) to study L-H threshold during I_P ramp-up, with dI_P/dt = 0.28MA/s. The measured power threshold during I_P ramp up was $P_{thr,ramp-up}$=2.5-2.8MW at n_e=2.45-2.55 x $10^{19}m^{-3}$, is similar to that obtained in I_P flat top conditions, discussed above (see Fig.1). Recently, C-mod has found similar results on to JET ones for L-H transition studies during current rise compared to flat-top conditions [7].

Studies to determine the influence of current ramps (from 0.19MA/s to 0.36MA/s) on the L-H threshold will be addressed in the next experimental campaign at JET (2013-2014). These experiments should be done at higher L-mode density in order stay away from this weak H-mode and raise P_{thr} for more experimental headroom as suggested also from C-mod results [7].

4. H-mode during plasma current ramp-up and ramp-down.

In parallel to the study of L-H transition during I_P ramp-up, JET has carried out dedicated experiments to investigate the H-mode in ramp-up and in ramp-down phase with the new wall. These studies, already done with CFC wall, can provide needed input for ITER: assessing if the flux consumption and l_i evolution can be controlled within some margin (range of l_i = 0.7–1.0 possible for ITER [1], see Fig. 3) and how the results are modified by ILW compared to CFC wall; documenting the main plasma parameters, Z_{eff} and radiation fraction for validation of models. The range of l_i in ohmic and H-mode at the end of the current rise with ILW was found comparable to that obtained with the CFC wall (an overview of all the results are summarized in Fig.2). The lowest l_i~0.62 value obtained for JET-ILW is referring to the case of 0.36MA/s (not investigated in CFC wall) and P_{NBI}=5MW.

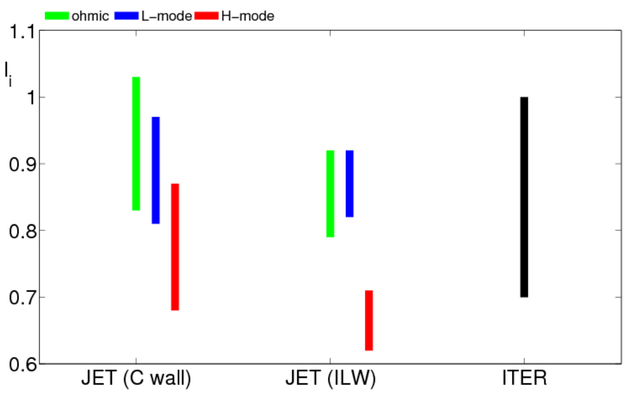

Figure 2*. Range of l_i obtained at the end of the current rise phase for JET-C and JET-ILW, for ohmic current rise experiments and compared with results obtained in heated discharges. ITER range for l_i is indicated by the black bars. Note that: only two H-mode discharges are available for JET-ILW, dI_P/dt = 0.28 and 0.36MA/s with P_{NBI}=5MW. The slowest dI_P/dt =0.19MA/s that gives an l_i above 1(ohmic discharge) with JET-C was not tried with ILW.*

Comparison between heated discharges in CFC wall and ILW at the same dI_P/dt=0.28MA/s is given, in details, in Table I. Although the ILW pulses shows a lower Z_{eff} respect the CFC wall ones, at T_e(keV)≈2-3keV the effect of W on radiation is much higher the C, suggesting a current profile less peaked with respect to CFC wall, therefore lowering l_i. It should be said that n_e for pulse with ILW is ~20-30% higher than the CFC wall ones, and so, further analysis is needed (including total radiation for a given value of n_W/n_e), and interpretative transport simulation runs. JET-ILW discharge with H-mode current rise phase save ~25% of the transformer flux required for an ohmic current rise [3] that is comparable to CFC wall results [1]. The H-mode current rise discharges with ILW show a low H_{98}~0.7 in line with the values obtained for the H-mode baseline experiments at low plasma β discussed in [3].

JPN	P_{NBI} (MW)	$P_{rad,bulk}$ (MW)	T_{e0} (keV)	Z_{eff}	l_i
72516 (CFC)	4.1	~0.4	3.6	1.7	0.87
72511 (CFC)	7	~0.7	4.9	1.5	0.73
72512 (CFC)	**9.8**	~0.9	5	1.6	**0.68**
83224 (ILW)	**5**	~1.0	2.8	1.2	**0.68**

Table I: CFC discharges Vs ILW at the same dI_P/dt=0.28MA/s at JET.

Next JET ITER-like plasma experiments foreseen for 2013-2014 will be also focused on the power scan (from 1.2 to 2*P_{thr}) during the current rise to reach H_{98}~1 during the current rise. The effect of sustaining H-mode or reducing the elongation on l_i control and flux consumption reduction during the ramp-down was modelled by transport CRONOS suite of codes [9], in order to give an interpretation of the experimental observations. A Bohm-gyroBohm transport model (original L-mode form, [10]) was used. Experimental value of n_e, T_e and Z_{eff} were used in the simulations. First the H-mode current decay (-0.28MA/s) with P_{NBI}=5MW with ILW, discharge 83225, has been modelled and compared to the ohmic ramp-down at the same ramp-rate, discharge 83224. The results of the modelling and comparison to the experimental data are shown in Fig. 3 and they are in good agreement. Although l_i increases from 0.9 to ~1.3, the increase is limited as long as the discharge stays in H-mode. In addition a strong flux consumption is achieved in the H-mode discharge.

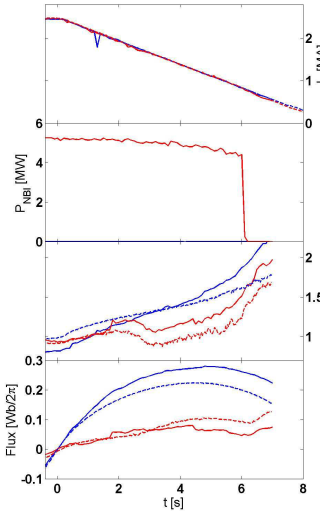

***Figure 3**. Interpretation of the current decay results from JET-ILW using CRONOS suite of code: effect oh H-mode. The simulations starts (t=0sec) at the start of ramp-down. Shown are modelled (solid line) and experimental time traces (dashed line) for pulses 83224 (ohmic reference, -0.28MA/s, blue), 83225 (H-mode, -0.28MA/S, red). Given is the total flux consumption calculated as described in [11].*

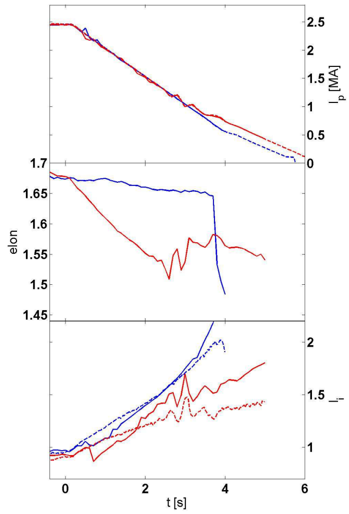

***Figure 4**. Interpretation of the current decay results from JET-ILW using CRONOS suite of code: effect of elongation scan. The simulations starts (t=0sec) at the start of ramp-down. Shown are modelled (solid line) and experimental time traces (dashed lines) for pulses 83449 (ohmic, -0.5MA/s, blue), 83447 ohmic, (-0.5MA/s, κ scan, red).*

In the case of an event requiring a rapid termination of the discharge, a fast current termination may be required in ITER in order to reduce the plasma energy as fast as possible in a stable way as discussed in [2]. Moreover, additional heating may not be available for such "off-normal" fast ramp-down forcing a ramp-down phase in ohmic. For this reason, an ohmic elongation scan has been done with ILW as in CFC wall (from κ~1.68 to κ~1.54), during the faster ramp-down phase (-0.5MA/s), showing that the increase of l_i is slowed down (see Fig.4). In addition, also predictive simulations have been performed by CRONOS to study the influence of increasing W radiation on the discharge evolution during the ohmic current ramp-up by varying the concentration n_W/n_e. The following assumptions have been down on simulations: n_W/n_e independent from radius and model from [12], W as only radiator to compute the radiated power (P_{rad}).

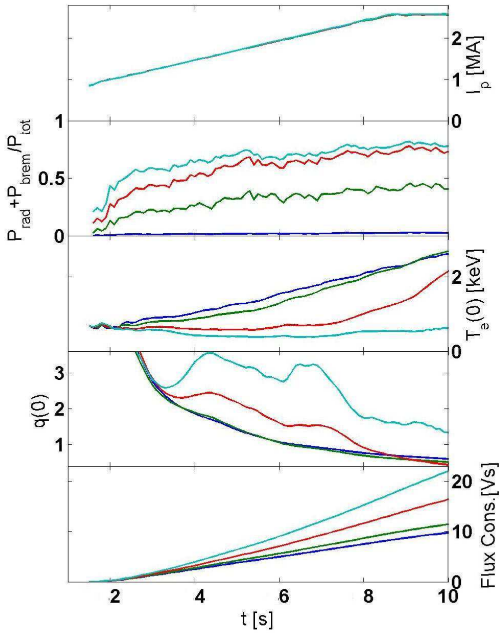

***Figure 5**. Effect of adding traces of W in a typical ITER-like ohmic JET current ramp-up (pulse 72723, 0.28MA/s). Shown are time traces of I_P, $(P_{rad}+P_{brem})/P_{tot}$, $T_e(0)$, q(0) and flux consumption, for n_W/n_e = 0 (blue), 5 10^{-5} (green), 1 10^{-4} (red) and 2 10^{-4} (cyan). Given is the resistive flux consumption only [11].*

Experimental value of n_e and Z_{eff} have been used in the simulations. It was shown that the critical concentration is $n_W/n_e \approx$ 1-2 10^{-4} (see Fig.5). Above this value, the plasma cannot cross the radiation barrier, thus staying at a flat/hollow T_e profile below 1 keV, with very high flux consumption and strongly distorted q profile (see Fig.5). For experimental ohmic ramp-up, it was found that measured radiation level of normally P_{rad}<1MW can only be compatible with $n_W/n_e < \sim 3\cdot 10^{-5}$ < critical n_W/n_e, assuming all radiation is from W. In conclusion, these initial studies with ILW on current ramp-up/down phases of ITER-like discharge have provided valuable information for the ITER working groups (ITPA and ITER design review team) when moving from CFC wall to Be-wall and W-divertor, in particular for the controllability of l_i and flux consumption, and provide adequate experimental basis for ITER, in particular for the modelling codes used in preparing ITER scenarios.

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