Simulations of the H to L transition in JET plasmas

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Introduction

In ITER the plasma position control system has a relatively slow (~2 s) reaction time to sudden changes in plasma parameters like a rapid H-L transition. In burning plasma this transition to low confinement state is exacerbated by the drop in the alpha-heating which could decrease plasma beta and lead to a swift inward movement of plasma position [1]. This paper describes the development of a simulation and its validation on existing JET H-mode experiments to predict the H-L transition for ITER [2].

A study was made of a database of 229 JET pulses, with a range of JET operation parameters but all beginning in Type I ELMy H-mode during the high power phase and having constant plasma current after the end of the main heating phase until the L-mode back transition (JET plasmas where plasma current is varied after the main heating phase are studies in ref[3].) Four different classes of back transitions were found after the step down of the auxiliary heating. The transition a) Type I→ELM free→Type III→L-mode is more common in the high triangularity plasmas (68 % in $\delta > 0.3$ at the time of the H-L mode transition), while b) Type I→Type III→L-mode is more common in the low triangularity plasmas (54 %). The c) Type I→L-mode back transition, possibly the most challenging for a plasma position control, is only observed in the plasmas with Greenwald density fraction ($\langle n_e \rangle / n_{eGW}$) > 0.6. The fourth, d) and least common (3 % in $\delta > 0.3$ and 11.5% in $\delta \leq 0.3$) back transition is a steady increase in frequency and decrease in amplitude of the ELMs before the return to the L-mode.

	shots	a) (%)	b) (%)	c) (%)	d) (%)
$\delta > 0.3$	65	67.7	23.1	6.2	3.1
$\delta \leq 0.3$	164	20.1	54.3	14.0	11.6

Table1: Table of the back transition classes observed in 229 JET pulses where: a) Type I→ELM free→Type III→L-mode; b)Type I→Type III→L-mode; c) Type I→L-mode and d) steady increase in frequency and decrease in amplitude→L-mode

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[b] See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

Modelling

The temporal evolution, from the end of the main heating phase to the L-mode back transition (~100ms), of the thermal energy (W_{th}) was modelled using the equation: $\frac{dW}{dt} = (P_{in} - P_{loss}) - \frac{W}{\tau_e}$, where τ_e is the energy confinement time. In the model, τ_e was determined by the IPB98(y,2) [4] scaling during the high power phase. After the step down of the input power, τ_e was determined using three different scalings: IPB98(y,2) [4], ITER89-P L-mode [5] and Goldston [6]. The simulated time evolution of W_{th} was closest to experiment over the whole database when $\tau_{eIPB98(y,2)}$ was used.

Four JET pulses, two low (72207, $\delta = 0.18$ and 76466, $\delta = 0.21$) and two high triangularity (77118, $\delta = 0.38$ and 77293, $\delta = 0.45$) plasmas, representing the most common classes of back transition in the database, were simulated using JINTRAC, see figure 1. The 1.5D JETTO transport code and the Monte Carlo orbit following ASCOT, to simulate the NBI particle and energy deposition, are used. In the simulations the experimental density and electron temperature profiles from HTRS and the ion temperature profile from CXSM were used. Figure 1 show that the simulated slowing down of the NBI fast particles varied between 25-100 ms depending upon the density and temperature of the plasma. The time interval between the step down of the NBI and the transitions to L-mode were between 200-500 ms, approximately equal to the confinement time. This indicates that the fast particle energy decay time is not the main factor for the plasma to stay in H-mode after the step down of NBI.

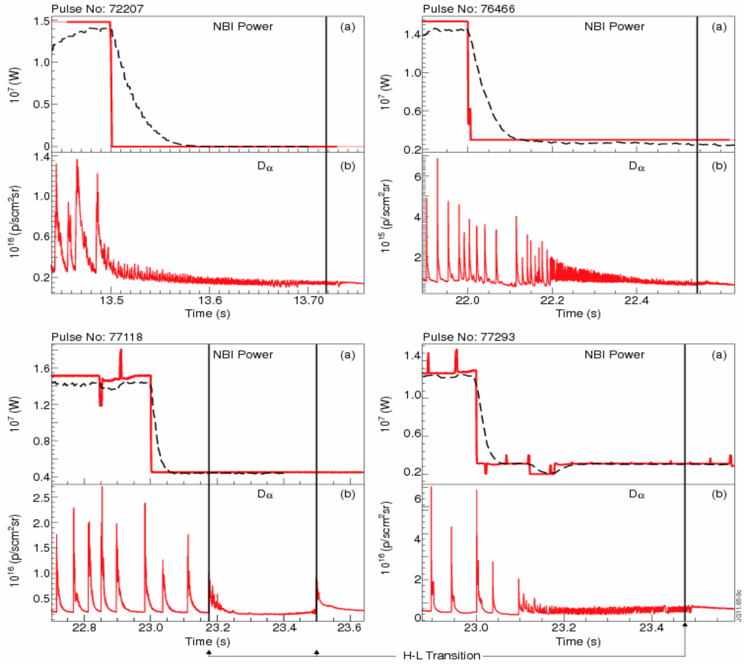

Figure1: a) Time traces of the Injected NBI power (red) and total NBI power deposited in the thermal plasma calculated by JINTRAC (black); b) the respective D_α time trace from the outer divertor target for the JET pulses: 72207; 76466; 77118 and 77293. The H-L back transition is represented by a vertical black line

The L-H transition model implemented in JINTRAC evaluates the sum of the electron and ion heat fluxes at the top of the pedestal, $P=P_e+P_i$, and compares it with a threshold power for the L-H transition, P_{L-H}, to determine whether the plasma is in H-mode or not. In this case, the L-H power threshold is defined from the scaling from Martin et al. J. Phys 2008: $P_{L-H} = 0.0488 n_{e,20}^{0.717} B_T^{0.8} S^{0.941} (M/2)^{-1}$ [7]. The Bohm/GyroBohm empirical model was used for the L and H-mode phases. In the H-mode phase the transport model includes a reduced transport coefficient locally within the edge transport barrier (ETB) width of 4 cm to ion neoclassical levels. In JINTRAC the ELMs are simulated by a significant increase of the transport within the ETB region during a ELM duration of 1ms, and are trigged when $\alpha_{crit}(\rho=0.9)$ exceeds $\alpha \equiv \frac{-2\mu_0 R q^2}{B_\phi^2} \cdot \frac{\partial p}{\partial r}$ [8]. In the simulations, α_{crit} is chosen as such that the level of the experimental W_{th} was reached during the NBI phase. The type III phase starts when $P_{III-I} = A^* P_{L-H}$ where A is a free parameter of the model. A was chosen as such the time of the transition from type I H-mode→type III H-mode coincides with the experiments. The Type III ELMs are trigged at a lower pressure gradient and to best follow the experimental W_{th} time decay after NBI step down $\alpha_{crit}(\rho=0.9) = 0.8$ is used. The density and temperature profiles are predicted except the NBI power deposition that was calculated previously by PENCIL. The JINTRAC simulations were performed for two well diagnosed JET plasmas: one low (76466, $\delta = 0.21$) and the other high triangularity (77293, $\delta = 0.45$). The plasma parameters at the boundary (last closed flux surface) were taken as constant throughout the simulations with $Ti(\rho=1) = Te(\rho=1) = 100$ eV, $n_i(\rho=1) = 5.0e18$ m-3, for $\delta = 0.21$ and $Ti(\rho=1) = Te(\rho=1) = 110$ eV, $n_i(\rho=1) = 1.5e19$ m-3 for the $\delta = 0.45$ plasma. In both plasmas the measured $Ti(\rho) \cong Te(\rho)$.

Figure 2 and 3, show the simulations and experimental times traces for the JET shots 76466 and 77293 respectively. These figures show that the predicted ELM frequency of ≈48Hz was similar to the experiment of ≈55 Hz but only for the $\delta = 0.21$ plasma with a $\alpha_{crit}(\rho=0.9) = 1.9$, while for the $\delta = 0.45$ plasma, even with a higher $\alpha_{crit}(\rho=0.9) = 2.1$, the predicted ELM frequency is two times higher than experimentally observed. In the simulations for the $\delta = 0.21$ plasma found that the power ratio of A = 1.4 matched the experimental time of the back transition between type I→type III H-mode phases, see figure 2. In this figure also shows that the model also predicts the time of the transition between Type III H-mode→L-mode at ≈22.5 s. Although the same parameters were used, A=1.4, the type III ELMy H-mode phase is not observed in the $\delta = 0.45$ plasma simulations, as it is observed experimentally. The simulated plasma changed from Type I ELMs→L-mode plasma, see figure 3. A higher value of A=1.5 was used but the plasma stayed in type III ELMs even during the NBI phase, in figure 3 clearly shows that it is not the case. This model also does not predict the back transition time to L-mode it is 300 ms earlier than experimentally observed. A possible reason to underestimate transition time is overestimation in the δ = 0.45 plasma simulations of $P_{L\text{-}H}$ in comparison with $P_{L\text{-}H}$ calculated from the experimental parameters (see figure 3). $P_{L\text{-}H}$ goes like $n_{e,20}^{0.717}$ and the core transport model does not predict correctly the volume average density (n_{eav}) decay after the NBI step down. To model n_{eav} correctly the Scrape of Layer 2D modelling has to be included. More refined simulations for these plasmas using the core coupled with edge are planned.

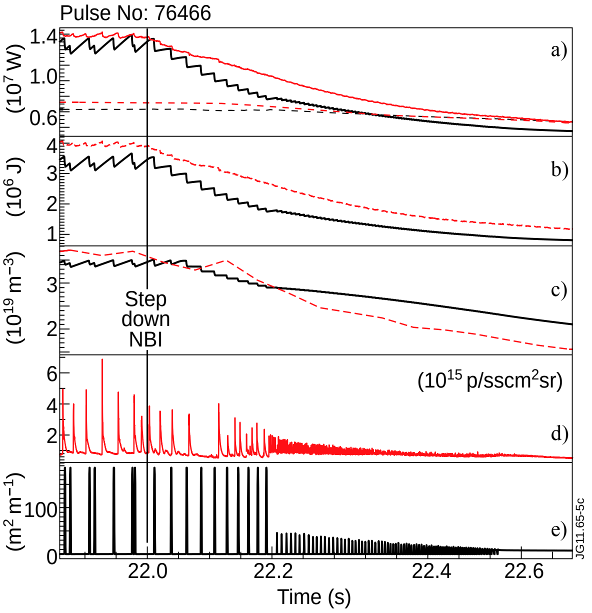

Figure2: Simulated (black) and experimental (red) time traces of JET pulse 76466 with δ = 0.21. a) $P=W_{th}/\tau_{eIPB98(y,2)}$ (continuous line) and the $P_{L\text{-}H}$ threshold (dashed line); b)Thermal energy; c)Volume averaged electron density; c) D_α; d)$\chi_i(\rho = 0.95)$;

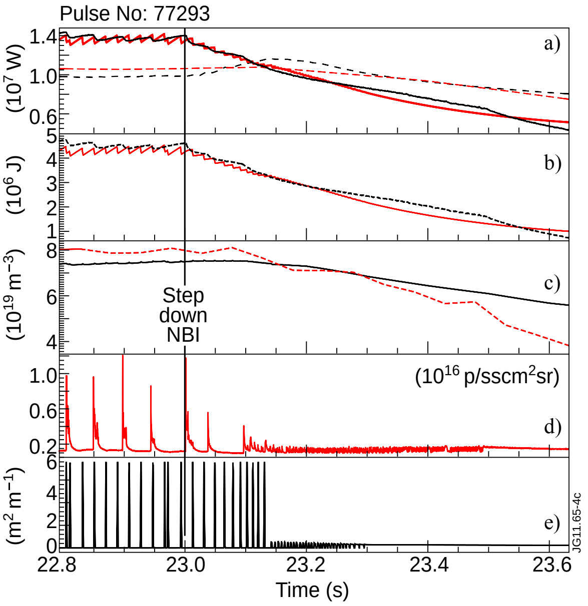

Figure 3: Simulated (blue) and experimental (red) time traces of JET pulse 77293 with δ = 0.45. a) $P=W_{th}/\tau_{eIPB98(y,2)}$ (continuous line) and the $P_{L\text{-}H}$ threshold (dashed line); b)Thermal energy; c)Volume averaged electron density; c) D_α; d)$\chi_i(\rho = 0.95)$;

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