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** See annex of F. Romanelli et al, "Overview of JET Results",*
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1. INTRODUCTION.

Understanding of the physics mechanisms that determine plasma fuelling and core particle transport is required to predict both the plasma density profiles and fuelling requirements for burning plasmas in next step devices, the access to burning plasma conditions and its possible control requirements. The evolution of the plasma density following the H-mode transition is particularly relevant for ITER because it affects the temporal evolution of the alpha heating power level build-up from L-mode conditions, as well as the edge power flow which is required to maintain the H-mode confinement itself [1]. For the alpha heating evolution, the behaviour of the central plasma density and temperature (from where most of the alpha power is produced) in conditions with very low central fuelling (as expected in ITER with Negative Neutral Beam Injection) is of particular interest.

2. EDGE/CORE PLASMA PARAMETERS BUILD-UP FROM L TO H-MODE IN JET EXPERIMENTS.

In order to characterise the physics processes that determine the plasma temperature and density build-up and their timescales, a set of JET H-mode discharges has been analysed. They comprise H-mode discharges with a range of plasma current (I_p) from 1.0MA to 4.3MA, low and high plasma triangularity (δ), with dominant NBI heating and fuelling by gas puffing [2, 3]. For all JET H-modes, the pedestal plasma density and temperature build up in relatively short timescales, which are comparable to the energy confinement time of the stationary Type I ELMy H-mode that follows. The timescale for the core temperature evolution is similarly short, contrary to that of the core density that, for some conditions, evolves in much longer time scales (several s). This slow core density build up leads to the formation of very hollow electron and ion density profiles (i.e., this is not, simply transient edge impurity accumulation), which can persist for $\gtrsim$1s in the H-mode phase, as shown in Fig.1 a-c. The duration of this hollow density profiles phase (i.e., when $n(\rho = 0.8)/n_e(\rho = 0.2) \geq 1$) increases with I_p (which is linearly correlated with plasma density in H-modes), as shown in Fig.2, and usually terminates by a sawtooth crash that causes the density profiles to flatten suddenly (Fig.1). The appearance of long-lived hollow density profiles is concurrent with the NBI particle deposition profiles becoming flat or hollow, which occurs when the edge density at JET exceeds $\sim 6.0\ 10^{19}\ \mathrm{m}^{-3}$. This causes the appearance of long-lived hollow density profiles at lower I_p for higher δ (higher pedestal densities) discharges.

To quantify the physics processes that lead to the formation of long-lived hollow density profiles, the timescale of the edge ($\rho = 0.8$) and core ($\rho = 0.2$) electron and ion temperature and density build-up has been independently determined by characterising their time evolution from the L-mode to the stationary conditions with two methods (evaluating the time interval required to reach 80% of the rise and by fitting the time evolution with a modified hyperbolic tangent fit (mtanh) in time) and they provide similar results, although quantitatively there are small differences. Figure 3 shows these timescales evaluated with the mtanh fitting method for a series of low δ

H-modes at JET illustrating that the findings in Fig.1 are applicable to all JET Type I H-modes; core and edge ion and electron temperatures and edge densities evolve in timescales comparable to the energy confinement time ((0.5-1.5) τ_E) from the L-mode to the stationary H-mode. On the contrary, the core density has a much longer timescale, which increases with plasma current (and plasma density) and decreasing NBI core particle deposition source. Results for high δ H-modes are similar to those at low δ but are shifted to lower I_p (due to the higher edge densities at high δ).

3. MODELLING OF THE H-MODE DENSITY BUILD-UP IN JET H-MODES.

The density build up has been modelled with JETTO, which includes an edge transport barrier model (modelled with $D_{e,i}$, $\chi_{e,i}$ values as given by ion neoclassical transport and no anomalous pinch), modelling of the NBI particle source and from gas puffing. Core transport has been modelled with the Bohm/gyroBohm model for the heat and energy transport as described in [4].

Two assumptions have been used regarding the existence of an anomalous inwards pinch : $v_{pinch} = 0$ and $v_{pinch} = 0.5\ D\ \rho/a$, the latter being required to model the stationary density profiles in JET H-modes over a range of parameters. Contrary to stationary conditions, it is found that the slow rise of the core density build-up for conditions with low NBI core source can only be reproduced by assuming that there is no anomalous pinch during this phase.

In addition, the slow core density rise requires a low value of D in the sawtooth-free core plasma region, typically $D = (0.25\text{-}0.5)\ D_{BgB}$, where D_{BgB} is the value of the Bohm/gyroBohm diffusion coefficient used for the stationary simulations of JET plasma density profiles. The diffusion coefficient required to model the transient density evolution in the outer half of the radius is typically a factor 4-8 times larger than in the core. Figure 4 shows the evolution of the density profiles at various radii with the two assumptions above regarding the particle transport for a high I_p JET H-mode with low core NBI source. Although the physics mechanisms leading to this low level of particle transport in this transient phase remain to be studied in detail, it is important to note that $T_e \sim T_i$ and that the plasma collisionality during the H-mode density build-up phase of JET high current discharges with low NBI source course is very low and close to that of that of the ITER $Q_{DT} = 10$ stationary conditions, for which a significant inwards pinch is expected. The lack of pinch in these low collisionality conditions is most likely due to the negative scale length of the density profiles (hollow), as indicated by gyrokinetic modelling of JET H-modes that show a very low value of the anomalous particle flux for flat density profiles (i.e. $v_{pinch} = 0$) [5].

4. IMPLICATIONS FOR ITER, FURTHER ANALYSIS/MODELLING AND CONCLUSIONS.

Modelling of the access to the full performance phase of ITER in the 15MA scenario with $P_{additional} = 53$MW has been carried out with the same transport assumptions which have been used to model the JET H-modes. In the ITER case, core plasma fuelling is evaluated from the negative NBI deposition and pellet fuelling to a level of $3.0\times10^{22}s^{-1}$ following the same procedure in [6]. As shown in Fig. 5, the evolution of the core plasma density is slow enough to allow the plasma temperature and fusion power to build up to full performance. The inclusion of an inwards particle pinch in this phase ($v_{pinch} = 0.5$ D ρ/a) leads to a higher core density and lower core temperature and fusion power build up thus extending the duration (by a period of $\sim \tau_E$) of the phase in which the core input power remains close to the L-H transition threshold power, during which a loss of the H-mode may occur in experiment.

The major issues that remain to be understood for ITER are the physics processes which may lead to the appearance of a pinch in low collisionality H-modes with low core fuelling starting from hollow/flat density profiles after the H-mode transition. JET experiments indicate that the change of density profiles caused by the sawteeth plays an important role by terminating the phase of hollow density profiles with negative scale lengths. If this applies to ITER, given the low sawtooth frequency expected, long periods (~50s) in which density profiles remain flat could be expected. Similarly, it is important to determine if the long timescales for the core density evolution seen in the L-H transition are also found in the H-L transition. This influences to a significant degree the evolution of the alpha heating and the decrease of the plasma energy after the H-mode, which remains a challenge for plasma position control in ITER.

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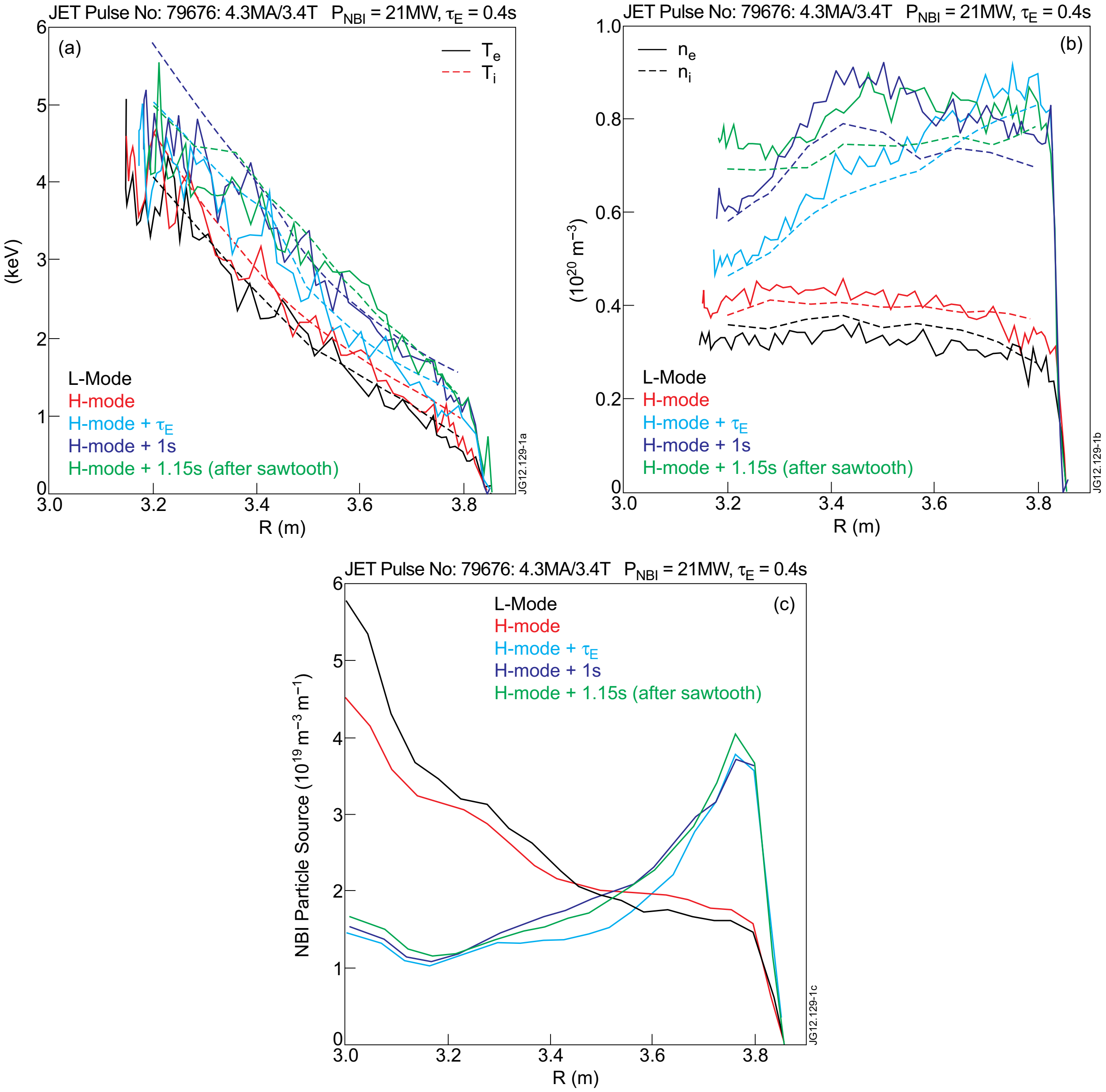

Figure 1: Electron and ion temperatures (a), densities (b) and NBI particle deposition (c) profiles at five times in the evolution of a JET high current discharge (from L-mode to the first sawtooth in the steady-state phase of the H-mode) showing the formation of hollow density profiles and their evolution in time up to their termination by a sawtooth. During the hollow density profile phase, the NBI particle deposition profiles are also hollow.

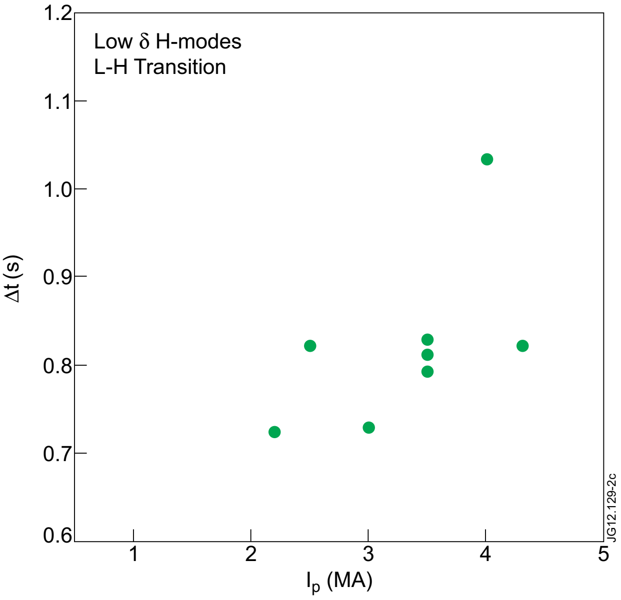

Figure 2: Duration of the hollow density profile phase versus plasma current for JET low δ H-modes showing an increase of the duration with I_p.

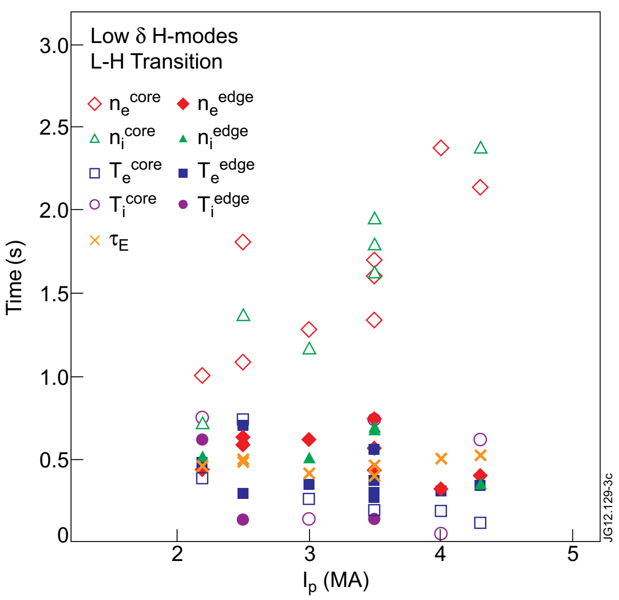

Figure 3: Timescales for the evolution after H-mode transition of edge and core electron and ion temperature and density for a range of low δ H-modes at JET. The energy confinement time for stationary conditions (τ_E) is shown for comparison.

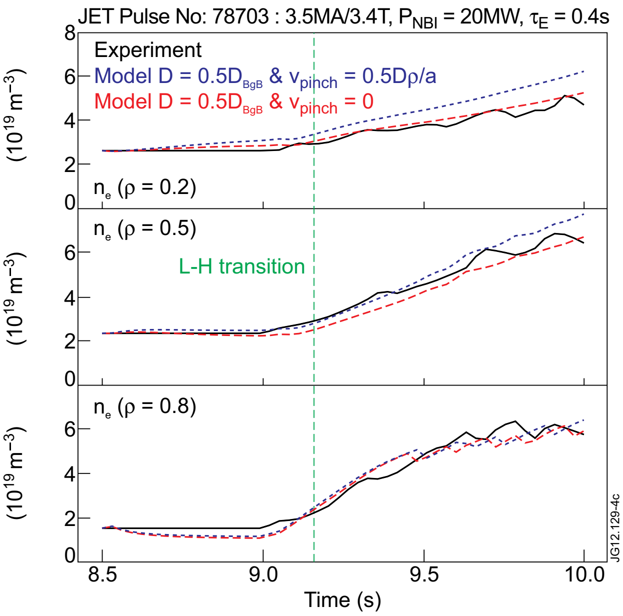

Figure 4: Experimental and modelled electron density evolution following the H-mode transition at three radial positions for a high I_p JET H-mode with low NBI core source showing the lack of anomalous pinch during this phase.

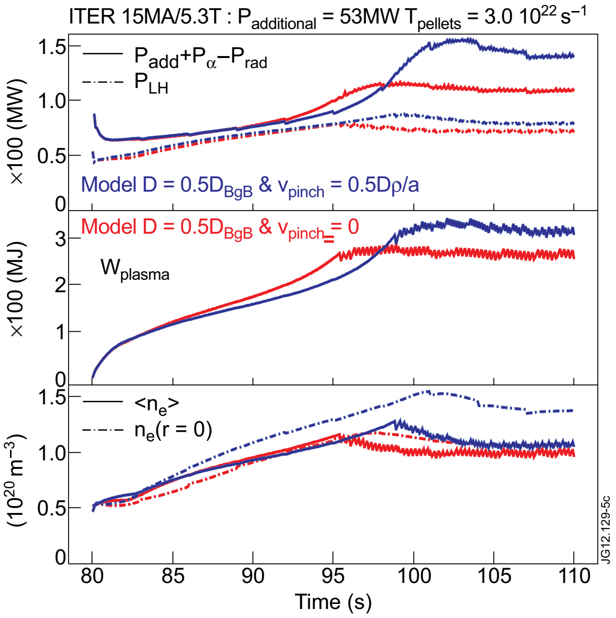

Figure 5: Simulation of access to burn conditions in ITER with two transport assumptions illustrating the effect of the low diffusion coefficient during this phase and the effect of a particle pinch.