

Evolution and control of tungsten transport in the termination phase of JET H-mode discharges and implications for ITER

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Abstract. Operation of tokamaks with W PFCs presents specific challenges for impurity control. In the transition from stationary H-mode to L-mode, W control may be particularly demanding due to unfavourable core W transport conditions. To assess W transport and methods for the mitigation of W core accumulation in the H-mode termination phase a series of dedicated experiments have been performed at JET including the variation of the decrease of the power ramp rates, gas fuelling and central ICRH, and applying active ELM control by vertical kicks and pellets. The experimental results obtained demonstrate the key role of maintaining ELM control with ICRH-assisted heating to control the W concentration in the exit phase of H-modes with slow (ITER-like) ramp-down of the NBI power in JET. Without ELM control, W accumulation takes place even with central ICRH (~1 MW). Modelling studies performed with JINTRAC have shown that the existing models may appropriately reproduce the accumulation of W in the termination phase of JET H-modes. The lengthening of the H-mode termination phase by maintaining a low level of NBI heating, which provides sizeable core particle sources and peaks the core density profile, reduced time-averaged edge particle transport and increased W influx without ELM control, ICRH heating and core W transport enhancement due to plasma rotation caused by NBI were found to be the key to differences in W behaviour found in the experiment.

1. Introduction

Operation of tokamaks with tungsten (W) plasma facing components in the H-mode confinement regime presents specific challenges regarding the control of the impurity concentration in the main plasma. Lack of impurity control can lead to the loss of the H-mode, the radiative collapse of plasmas by W accumulation and increased disruptivity, which is detrimental to ITER operation. Control of W in H-mode plasmas requires, as a first step, the control of W production and of its transport into the core plasma through the SOL and edge transport barrier. In addition, even when the concentration of W at the pedestal is kept at low levels, unfavourable core W transport can lead to its uncontrolled accumulation and to loss of the H-mode due increased radiation. Strategies have been developed in present experiments to avoid W accumulation in stationary phases of H-mode discharges by controlled ELM triggering to control the edge W density and central RF heating to prevent core accumulation. Such schemes are also expected to be effective in ITER, where strong core W accumulation is not expected to occur due to the low particle source provided by the 1 MeV negative-NBI injection, which is in agreement with H-mode experiments with low core source [1]. On the other hand, the control of W transport can be more challenging during the confinement transient phases between L-mode and H-mode and in particular in the transition from stationary H-mode to L-mode. During this phase the pedestal plasma density and

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temperature decrease as the input power is decreased and this can lead to long-ELM free phases causing uncontrolled increase of the edge W density and peaking of the core density profile, which is favourable for W accumulation. To avoid this, a frequently followed approach in present experiments is to cause a fast H-L transition and in this way increase the W outflux from the core preventing its accumulation. This approach is, however, not applicable to ITER high Q regimes both due to the impossibility to suddenly stop alpha heating and because the associated change in plasma energy would lead to direct contact of the plasma with the inner wall [2] and a slow decrease of the plasma energy in H-mode termination is required, which is prone to W accumulation [3].

In order to address W control issues in the H-mode termination phase a series of dedicated experiments have been performed at JET and modelled with JINTRAC [4]. In these experiments several H-mode termination scenarios with constant plasma current have been explored including variation of the decrease of the power ramp rate, gas fuelling level and central ICRH heating with and without active ELM control by vertical kicks and pellets. The influence of certain aspects that were found to be crucial to explain differences in core W accumulation behaviour in the H-mode termination phase such as ELM control, NBI momentum and particle sources and ICRH is highlighted and described in detail in sections 3-6.

2. Simulation conditions

For the analysis of the H-mode termination experiments, fully predictive JINTRAC core transport simulations (solving transport equations for q , p_e , p_i , n_D , n_{Be} , n_W , v_{tor}) have been carried out. Neoclassical transport is calculated by NCLASS [5] including the dominant correction terms for the consideration of poloidal asymmetry for high Z impurities at high core rotation from [6], while anomalous transport is modelled by GLF23 [7] in H-mode (considering impurity specific anomalous transport predictions) and by the standard Bohm/gyroBohm model [8] (including an inwards pinch term proportional to $0.5 \cdot D_{i,BGB}$) in L-mode. Impurity reaction cross-sections are evaluated by ADAS, with W cooling rates being calculated from recent ADAS datasets based on [9]. A gradual increase of anomalous transport in the ETB for $P_{net} := P_{in} - dW_{th}/dt - P_{rad}$ approaching P_{L-H} as described in [2] is taken into account, applying a factor 0.7 to P_{L-H} from [10] that is specific for JET ILW discharges [11]. ELM transport is modelled in a time-averaged way with the continuous ELM model [12]. The Be and W core influx are feedback controlled against the experimental Z_{eff} and P_{rad} resp.. Sawtooth reconnections are described by Porcelli model [13].

3. Effect of ELM control on W transport in H-mode termination

The experimental results obtained demonstrate the key role of maintaining ELM control to avoid core W accumulation in stationary H-mode for all considered scenarios (especially at low gas puff rates) but even more so in the exit phase of H-modes with slow (ITER-like) ramp-down of the NBI power in JET, as shown in Fig. 1. Without ELM control, the ELM frequency is reduced, long ELM-free phases may occur and W accumulation takes place despite the application of central ICRH heating (~ 1 MW), while a safe H-mode termination with only modest W core contamination can be realised with continued ELM control even without ICRH. The required ELM frequency to avoid W accumulation can be achieved at JET through adjustment of the gas fuelling level (unlikely to be effective in ITER) or by active ELM control with pellets or kicks [14] at levels of gas fuelling for which W accumulation occurs when pellets / kicks are not applied. The latter scenario provides an integrated solution regarding the control of W concentration and plasma energy evolution in the termination of H-modes that can be readily extrapolated to the corresponding phase of 15 MA $Q = 10$ plasmas in ITER.

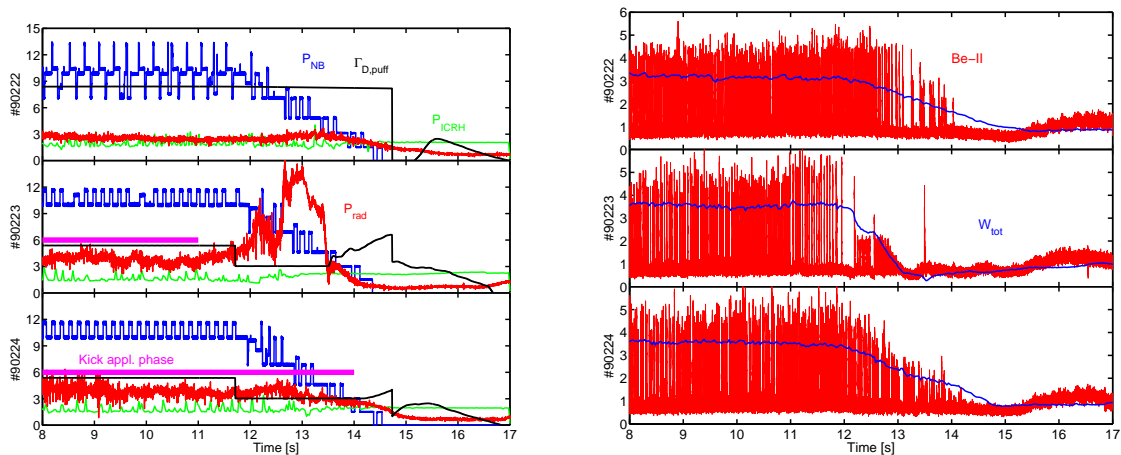


Figure 1. JET H-mode plasma terminations with a slow NBI power ramp-down at $I_{pl} = 2$ MA simulating the slow decrease of the alpha heating in ITER. #90222: high gas fuelling, no kick application, #90223: low gas fuelling, kick application until $t = 11$ s, #90224: low gas fuelling with extended kick application until $t = 14$ s. Left: P_{NB} (MW), P_{ICRH} (MW), applied gas puff rate $\Gamma_{D,puff}$ ($2 \cdot 10^{21}/s$) and P_{rad} (MW). Right: Be-II photon flux near outer divertor (a.u.), W_{tot} (blue, MJ). Terminations without W accumulation (correlated with large radiation levels) have been achieved with high gas puffing levels or by extended active ELM control for lower gas fuelling levels.

Modelling results obtained for the H-mode termination phase in discharges with and without continued ELM control by kick application (#90224 vs. #90223) suggest that the reduction in ELM frequency without ELM control might induce reduced time-averaged edge particle vs. heat transport due to lower D/χ in the ETB in the ELM free phase and possibly less convective natural ELMs. This would give rise to the formation of increased density gradients in the ETB and less efficient temperature screening. As a consequence, a larger amount of W is transported to the plasma core, leading to W accumulation and increased radiation near the magnetic axis, the appearance of hollow temperature profiles and a radiative collapse associated with an early H-L transition due to strongly enhanced core radiation.

A comparison between measured and modelled time traces for #90224 vs. #90223 is shown in Figs. 2-5. The variation in the duration of kick application in the experiment is translated in the simulations into a difference of the applied W influx at the separatrix and reduced time-averaged (ELM induced) particle diffusivity in the ETB in the phase without ELM control in #90223. Otherwise, the two discharges are identical both in terms of experimental and modelling conditions. Although the time for the appearance of hollow temperature profiles and for the H-L transition cannot be exactly matched and the core W concentration seems to be reduced more quickly in the experiment in the L-mode phase for #90223, the main core plasma properties can reasonably well be reproduced for the H-mode termination phase in the simulations. These results strengthen the hypothesis that the probability for core W accumulation might increase for reduced ELM frequency due to reduced neoclassical screening in the pedestal. In addition, they might confirm the general validity of the model assumptions applied for the prediction of the plasma evolution in the H-mode termination phase, although dedicated validation studies need to be pursued to make a firm conclusion.

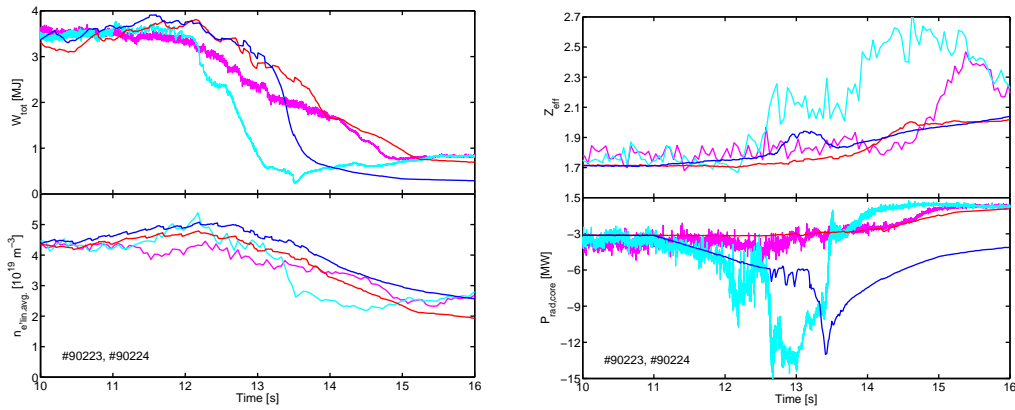


Figure 2. Comparison of measured (magenta/cyan) vs. simulated (red/blue) time traces for the H-mode termination phase in #90224 (magenta/red) and #90223 (cyan/blue). Left: total energy content (top) and line-averaged electron density (bottom), right: Z_{eff} (top) and core radiation (bottom).

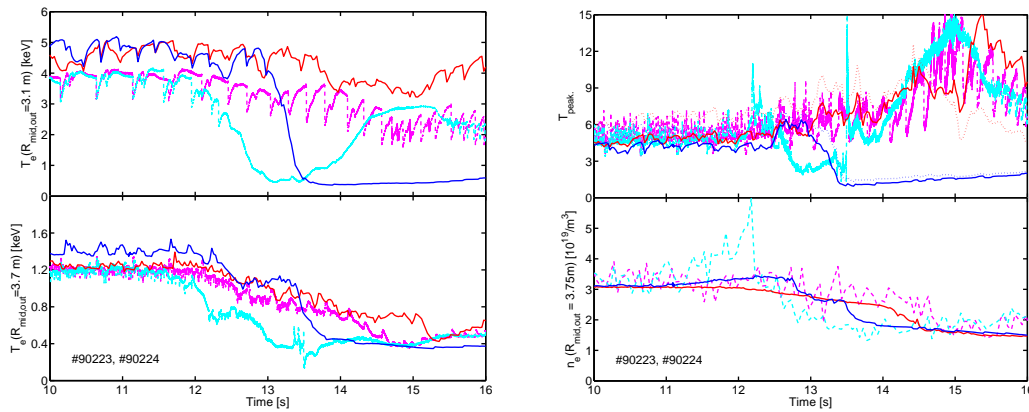


Figure 3. Comparison of measured vs. simulated time traces for the H-mode termination phase in #90224 and #90223, same colour code as for Fig. 2. Left: core electron temperature (top, evaluated at $R_{\text{mid,out}} = 3.1$ m) and edge electron temperature (bottom, evaluated at $R_{\text{mid,out}} = 3.7$ m), right: peaking factor for electron (solid/dashed) and ion temperature (dotted), evaluated as $T(R_{\text{mid,out}} = 3.1 \text{ m})/T(R_{\text{mid,out}} = 3.75 \text{ m})$ (top) and edge electron density (bottom, evaluated at $R_{\text{mid,out}} = 3.75$ m).

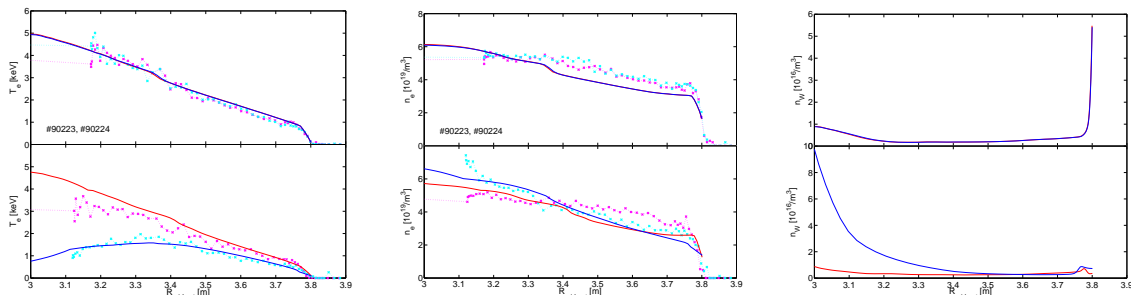


Figure 4. Comparison of measured vs. simulated T_e , n_e and n_w profiles (from left to right) at $t = 10$ s (top) and $t = 12.75$ s (bottom) in #90224 and #90223, considering a time shift for the modelled data to match experimental H-L transition times, same colour code as for Fig. 2.

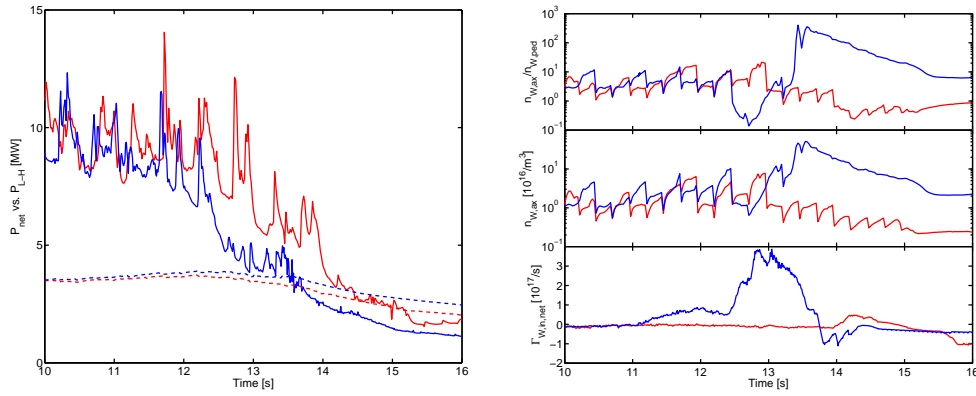


Figure 5. Simulated time traces for the H-mode termination phase in #90224 (red) and #90223 (blue). Left: P_{net} (solid) vs. $P_{\text{L-H}}$ (dashed), right: W density peaking factor $n_{W,\text{ax}}/n_{W,\text{ped}}$, W density on axis and net (smoothed) W core influx.

4. Effect of NBI momentum sources on W transport in H-mode termination

As mentioned in section 1, a prolonged heating scheme needs to be foreseen in the H-mode termination phase for extrapolation to ITER. In the JET experiments presented here, the auxiliary heating is mainly provided by NBI, which is associated with particle and momentum sources. Both sources have a significant impact on W transport, which may deserve separate investigation in view of extrapolation to ITER, as these sources may be important at JET but only marginal in ITER.

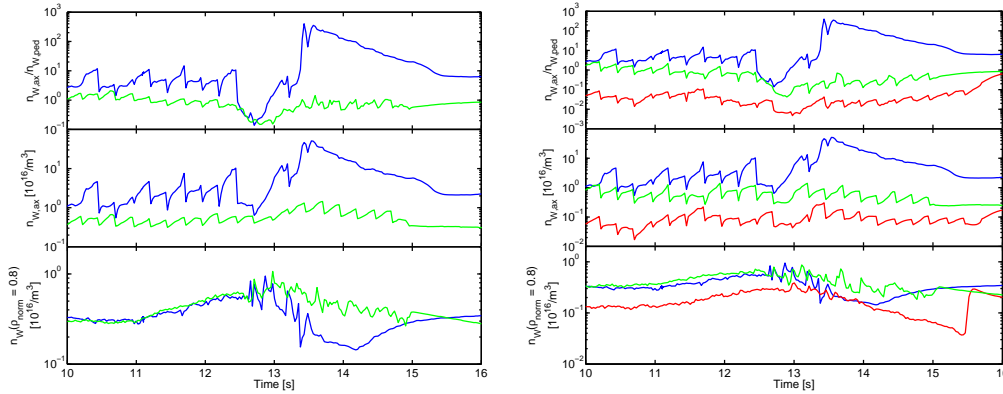


Figure 6. Simulated time traces for the H-mode termination phase in #90223. From top to bottom: W density peaking factor $n_{W,\text{ax}}/n_{W,\text{ped}}$, W density on axis and W density in the outer core region ($\rho_{\text{norm}} = 0.8$). Left: comparison of results obtained with (blue) and without (green) consideration of rotation driven poloidal asymmetry in W distribution affecting neoclassical W transport, right: comparison of results with anomalous core W transport being artificially reduced by 100% (red), 50% (green) and 0% (blue).

As described in [15], neoclassical transport enhanced by poloidal asymmetries can be a crucial mechanism responsible for tungsten accumulation in the central core region of plasmas at high rotation. For the H-mode termination in #90223, this is confirmed by a test simulation in which the neoclassical W transport has been calculated assuming that there is no rotation driven poloidal asymmetry in W distribution (i.e. neglecting the correction terms from [6]). As shown in Fig. 6 (left), W core accumulation can be avoided in that case. One can thus conclude that the toroidal rotation produced by NBI indeed seems to play an essential role providing enhanced unfavourable inwards directed neoclassical transport in the central region where maximum rotation values are achieved, while outer regions with

favourable outwards directed convective neoclassical transport due to temperature screening are only marginally affected, as rotation is low in the periphery.

In addition to neoclassical W transport, the net time-averaged anomalous W transport to the core also seems to be critical for core W accumulation though as shown in Fig. 6 (right), where simulations with and without artificially reduced anomalous core W transport are compared. If D_W and v_W are reduced by $>\sim 50\%$, W does not accumulate near the magnetic axis in #90223 despite rotation driven neoclassical transport enhancement.

5. Effect of NBI particle sources on W transport in H-mode termination

In addition to the momentum source, the particle source associated with NBI heating may also affect core W transport. It increases the core density gradient leading to a more inwards directed neoclassical convective W velocity. The importance of this effect has been assessed for the H-mode termination phase in #90223 by comparison of JINTRAC simulations with and without artificial removal of the NBI particle source as illustrated in Fig. 7. In line with previous findings for the stationary phases of hybrid scenarios [16], it is shown that the NBI particle source needs to be considered as an important constituent in the mechanism responsible for core W accumulation in JET ILW discharges.

For ITER, these results together with those from the previous sections may indicate that the risk of W accumulation in the H-mode termination phase with extended heating may be less severe compared to direct extrapolations from JET experiments due to low relative NBI momentum and particle sources which would lead to a reduction in neoclassical W transport to the core.

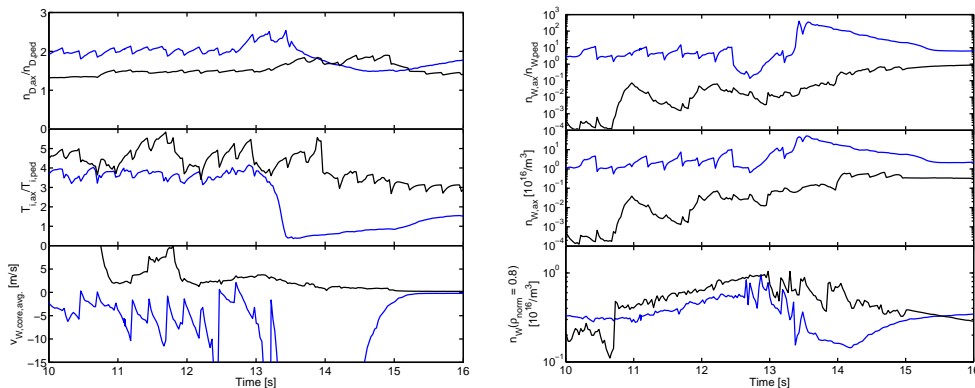


Figure 7. Simulated time traces for the H-mode termination phase in #90223. Comparison of results with (black) and without (blue) artificially removed NBI particle source. Left: D density peaking factor $n_{D,ax}/n_{D,ped}$, ion temperature peaking factor $T_{i,ax}/T_{i,ped}$, line-averaged total convective W velocity in the core region. Right: W density peaking factor $n_{W,ax}/n_{W,ped}$, W density on axis and W density in the outer core region ($\rho_{norm} = 0.8$).

6. Effect of ICRH on W transport in H-mode termination

Although measurement results clearly indicate that core W contamination control is significantly improved with ICRH-assisted auxiliary heating especially in the late H-mode termination phase (where a pronounced increase in core temperature gradients can be observed), it was not possible to prevent W accumulation with ICRH without the active ELM control, as the ICRH power available for this experiment was $\sim 1-2$ MW due to limitations in ICRH power coupling efficiency in ELMy conditions. Compared to NBI heating, the influence of ICRH in these discharges has therefore been modest. To test the effect of enhanced ICRH heating on W transport, simulations for the H-mode termination in #90223 have been repeated with artificially varied ICRH power. Results are presented in Fig. 8. The

simulations confirm that neoclassical core W transport properties may be improved even for a small increase in ICRH power of $\sim 1\text{-}2$ MW due to a reduction in core ion density vs. ion temperature gradients as described in [15,16], while W transport conditions deteriorate and core W accumulation takes place at an earlier stage with reduced ICRH heating. The modelling results suggest that it may be possible to assure core W contamination control without ELM control at higher levels of ICRH power compared to those applied in the experiment. Compared to NBI heating, ICRH may certainly be advantageous for the avoidance of core W accumulation due to the absence of core particle and momentum sources.

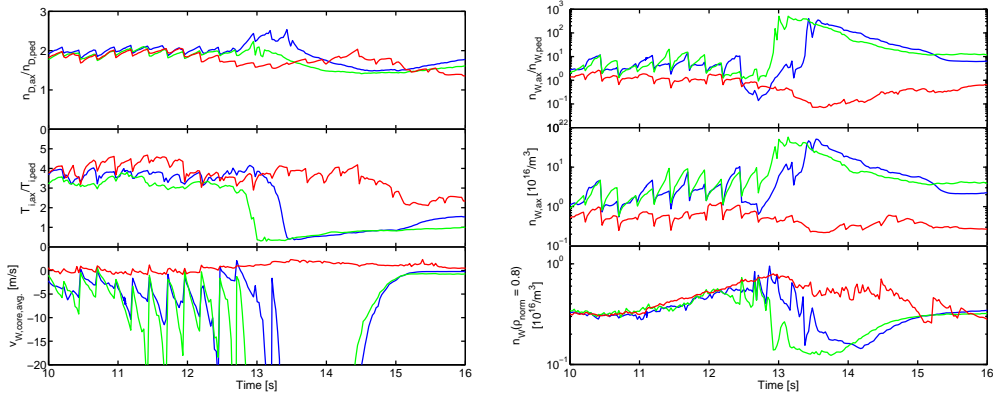


Figure 8. Simulated time traces for the H-mode termination phase in #90223. Scan in applied P_{ICRH} : ~ 1 MW (green), ~ 1.9 MW (blue, experimental value), ~ 4 MW (red). Left: peaking factors $n_{D,\text{ax}}/n_{D,\text{ped}}$ and $T_{i,\text{ax}}/T_{i,\text{ped}}$, line-averaged total convective W velocity in the core region. Right: W density peaking factor $n_{W,\text{ax}}/n_{W,\text{ped}}$, W density on axis and W density in the outer core region ($\rho_{\text{norm}} = 0.8$).

7. Effect of continued heating in H-mode termination phase

Two JET discharges without ELM control and different heating schemes for the H-mode termination phase (#84714 vs. #84716), one with immediate removal of NBI heating and the other with a more gradual reduction, have been studied as well with JINTRAC. A comparison between measurement data and simulation results is shown in Fig. 9.

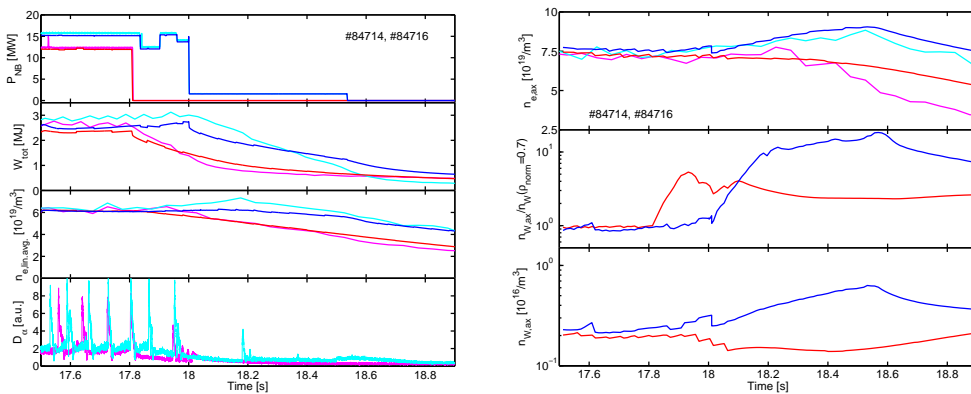


Figure 9. Two JET H-mode plasma terminations with a different P_{NB} ramp-down waveform leading to a fast H-L transition (#84714, magenta/red) and to a long low confinement H-mode before the H-L transition (#84716, cyan/blue). W accumulation is found in #84716. Measured (magenta/cyan) vs. simulated (red/blue) time traces are shown for P_{NB} , W_{tot} , the line-averaged electron density and the D_{α} signal (left, from top to bottom) as well as for the electron density on axis, the W peaking factor $n_{W,\text{ax}}/n_{W,\text{ped}}$ ($\rho_{\text{norm}} = 0.7$) and the W density on axis (right, from top to bottom).

Again, satisfactory agreement is obtained, demonstrating the adequacy of the selected model assumptions for the description of the time evolution of plasma properties in the H-mode termination phase. The lengthening of the H-mode termination phase by maintaining a low level of NBI heating without ICRH, which provides an extended phase at low or zero ELM frequency at sizeable core particle and momentum sources is the key to the different W behaviour found in the experiment as described in the previous sections.

Conclusions and outlook

Dedicated experiments have been performed at JET for the assessment of W transport and possible schemes for the mitigation of W core accumulation in the H-mode termination phase including (amongst others) scans in auxiliary heating schemes and active ELM control methods. It could be demonstrated that the maintenance of ELM control with ICRH-assisted heating may be crucial for the control of the W concentration in the exit phase of H-modes with slow (ITER-like) ramp-down of the NBI power in JET. This may imply that active ELM control may also need to be foreseen for the H-mode termination phase in ITER, although W core transport properties may be more favourable there due to the absence of significant NBI momentum and particle sources.

Modelling of experimental results carried out with JINTRAC has highlighted the importance of certain aspects such as the effect of ELM control on particle transport and edge temperature screening, NBI momentum and particle sources and ICRH-assisted heating for the explanation of observed differences in core W transport properties in the H-mode termination phase. In addition, it has shown that the existing core transport models may appropriately reproduce the plasma evolution in general and the accumulation of W in particular in the termination phase of JET H-modes. The model assumptions may thus be adequate for the prediction of the W transport behaviour in the H-mode termination phase in ITER as presented in [2,17]. More detailed modelling investigations involving SOL transport are currently being pursued as a follow-up study.

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