Modelling of Transitions Between L- and H-Mode Including W Behaviour in ITER Scenarios

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INTRODUCTION

The dynamics for the transition to a stationary H-mode regime and for its controlled termination in ITER is expected to be qualitatively different to present experiments. Therefore detailed modelling studies have been carried out with the JINTRAC suite of codes [1] in order to better understand under which ITER-specific conditions these transitions can be achieved, how the plasma evolution to / from H-mode can be optimised, and to assess the problem of possible core W accumulation in these transient phases.

SIMULATION SETUP

JINTRAC core and core+SOL simulations were performed with the JETTO+SANCO and EDGE2D+EIRENE codes.

- Fully predictive modelling of current density, momentum, plasma ion and electron pressure, main ion, Be and Ne / W impurity density evolution.
- Core transport in L-mode predicted by standard Bohm/gyroBohm model.
- Core transport in H-mode predicted with GLF23 or Bohm/gyroBohm retuned to fit with predictions from GLF23 [2]; sawteeth are modelled with a continuous sawtooth model.
- Neoclassical transport modelled with NCLASS.
- L-H transition model: exponential reduction of anomalous transport in ETB as function of $(P_{sep}-P_{L\text{-}H})/P_{L\text{-}H}$ for $P_{sep} > P_{L\text{-}H}$, $P_{L\text{-}H}$ determined by scaling from [3].
- ELM-induced transport applied in a time-averaged way (continuous ELM model [4]).
- Extension of ETB into the SOL by a few mm on outer midplane; further away from the separatrix the plasma transport is increased to a constant level ($\chi_e = \chi_i = 1.0$ m²/s, $D_{D/T} = D_{imp} = 0.3$ m²/s). Pinch velocities and drifts in the SOL are not included in the simulations.

OPTIMISATION OF DENSITY RAMP FOR ACCESS TO HIGH Q_{DT} H-MODE @ 15 MA

- Access to high Q_{DT} H-mode at P_{AUX} = 53 MW requires a delay time before the application of increased pellet fuelling and a moderate n_e ramp rate.
- Core ion temperature needs to be kept > ~10 keV to keep alpha heating at a level required to maintain $P_{sep} > P_{L\text{-}H}$ during the transition.
- Increased poloidal flux consumption during the transition to high Q_{DT} H-mode at P_{AUX} = 53 MW in range of $\Delta\Psi$ ~3.5-7.5 Wb.
- Fast transition to high Q_{DT} predicted to be feasible at increased P_{AUX} = 73 MW at ~50 % reduced $\Delta\Psi$.
- Quantitative predictions depend on initial conditions (n_e at start of transition, pre-heating) and uncertainty in $P_{L\text{-}H}$ scaling.

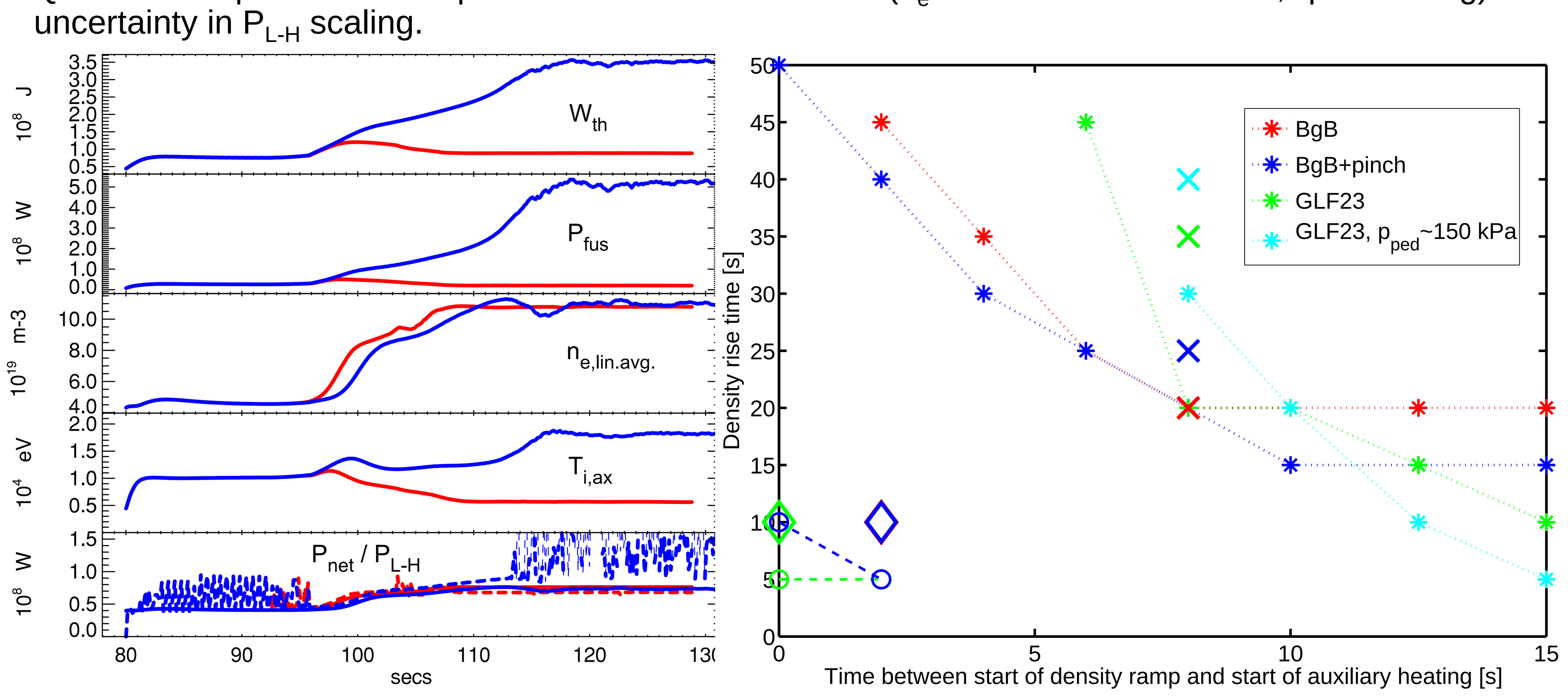

Figure 1: Left: successful (blue) and unsuccessful (red) transition to high Q_{DT} H-mode at P_{AUX} = 53 MW, modelled with GLF23 predicted core transport. Right: Limit for the achievement of a transition to high Q_{DT} H-mode in terms of nominal density rise time and delay of the ramp in density with respect to the start of the L-H transition, at P_{AUX} = 53 MW (stars) and P_{AUX} = 73 MW (circles), obtained with BgB (blue), BgB with anomalous inwards pinch (red) and GLF23 (green) at $p_{ped,max}$ ~ 120-130 kPa, and with GLF23 at $p_{ped,max}$ ~ 150 kPa (cyan). Density ramp configurations with minimum resistive + sawtooth-induced flux consumption are indicated as crosses (P_{AUX} = 53 MW, same colour code) and diamonds (P_{AUX} = 73 MW).

W CONTROL DURING THE ACCESS TO HIGH Q_{DT} H-MODE IN ITER

- Temperature screening of W in ETB is improved if $dn_i/d\rho$ / $dT_i/d\rho$ is reduced by a delayed start of the increase in core density after the H-mode transition by pellet injection, by low n_e ramp rates and by increased gas puff yielding a higher n_e at the separatrix (cf. [5]).
- Moderate DT gas injection at a rate of ~ $2{\cdot}10^{22}$ s^{-1} can help to keep the divertor plasma temperature below ~ 10 eV and W sputtering at a negligible level in the ELM-free phase.
- W core accumulation during the transition to high Q_{DT} H-mode can thus be minimised by simultaneous control of SOL and pedestal density by gas and pellet fuelling.

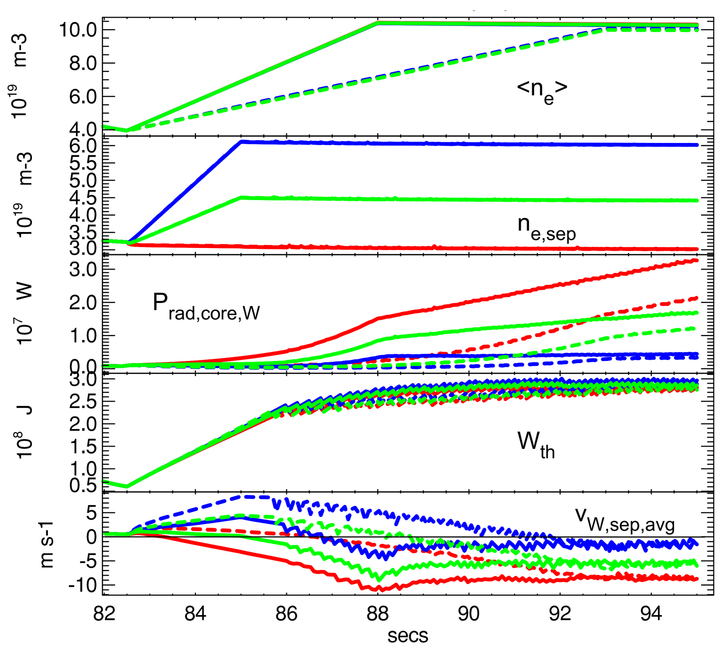

Figure 2: <n_e>, $n_{e,sep}$, W core radiation, thermal core energy content and W pinch velocity at the separatrix (from top to bottom) for cases with $n_{e,sep}$ ~ 3.0 (red), 4.5 (green) and $6.0{\cdot}10^{19}$ m^{-3} (blue) at pellet injection rates of S_{pellet} = $1{\cdot}10^{22}$ s^{-1} (solid) and S_{pellet} = $5{\cdot}10^{21}$ s^{-1} (dashed).

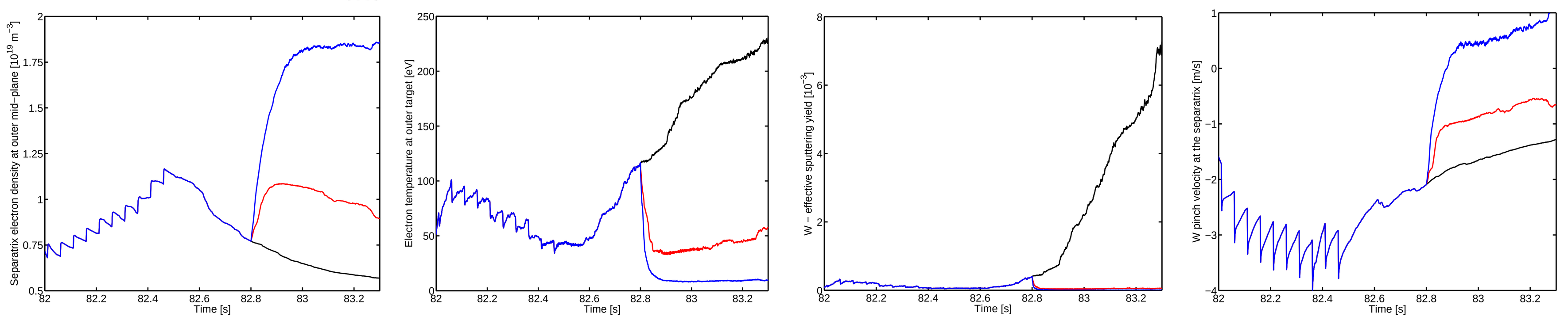

Figure 3: From left to right: n_e at the separatrix on the outer mid-plane, T_e on the strike point position of the outer target plate, effective W sputtering yield and W impurity pinch velocity at the separatrix, for three integrated JINTRAC-core+SOL simulations with pellet fuelling at t < 82.5 s and DT gas puff injection at a rate of G_{DT} = $0{\cdot}10^{22}$ s^{-1} (black), G_{DT} = $1{\cdot}10^{22}$ s^{-1} (red) and G_{DT} = $2{\cdot}10^{22}$ s^{-1} (blue) for t > 82.8 s.

ACCESS TO TYPE I ELMY H-MODE IN 7.5 MA / 2.65 T HELIUM PLASMAS

- According to results from JINTRAC core simulations with boundary conditions from modelling studies with B2-EIRENE (cf. i.a. [6]), H-mode can be accessed at P_{AUX} > ~ 40 MW due to low n_e caused by inefficient core fuelling by He gas puff only. n_e remains close to the NB shine-through limit.
- The presence of a moderate influx of W influx to the core (≤ $1.5{\cdot}10^{19}$ s^{-1}) does not affect adversely the plasma due to an efficient screening of W that is caused by low density gradients in the ETB .

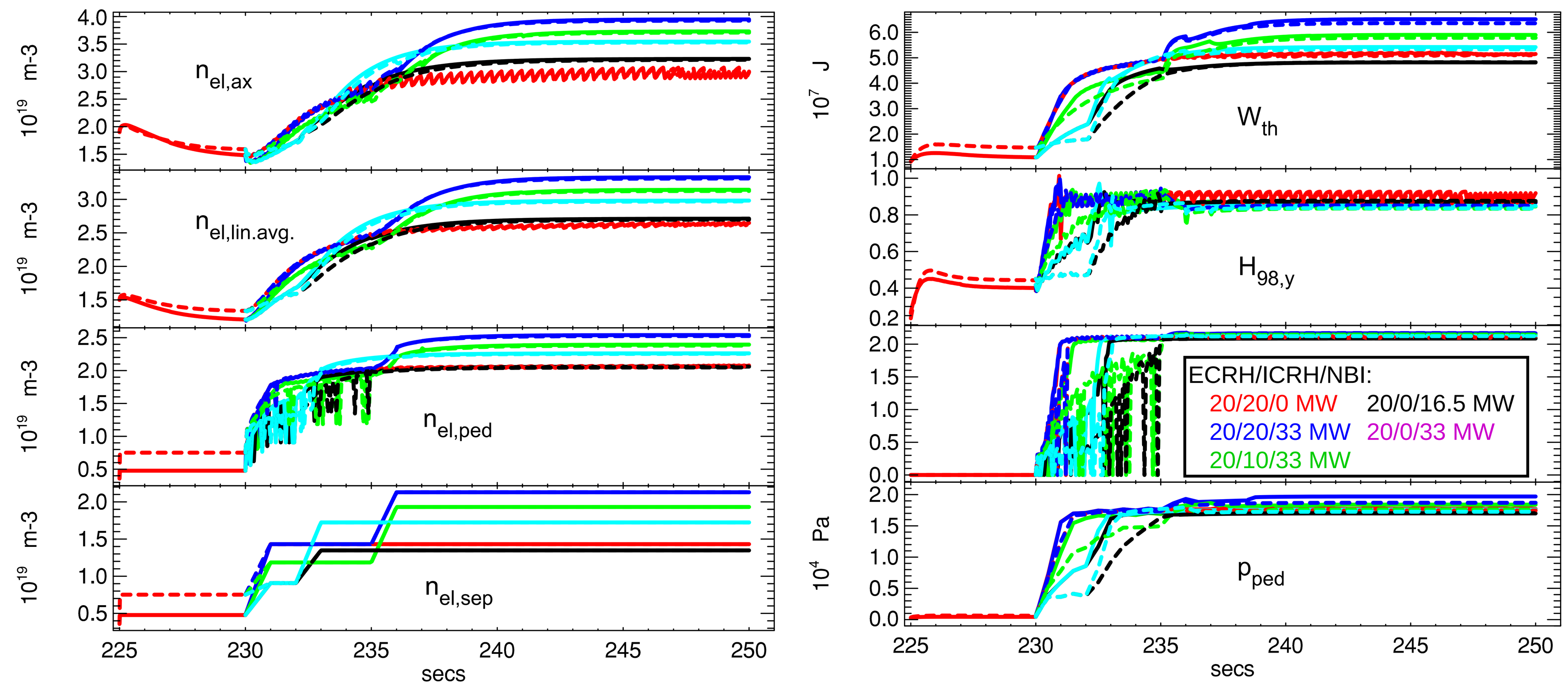

Figure 4: Evolution of n_e (left) and (right) W_{th}, normalised confinement, maximum normalised dp/dρ in the ETB and p_{ped} for a range of He H-modes. P_{ECRH} = 20 MW and P_{ICRH} = 0-20 MW are applied at t = 230 s. In addition P_{NBI} = 16.5 MW or 33 MW is applied at t = 232 s or 235 s. Various levels of He and W influxes into the core plasma are considered. In these simulations $P_{L\text{-}H}{}^{He} = P_{LH}{}^{D}$ and $P_{L\text{-}H}{}^{He} = 1.4{\cdot}P_{LH}{}^{D}$ from [3] is assumed. For the lowest P_{AUX} and higher $P_{L\text{-}H}$ there is a long dithering L-H phase in the access to H-mode shown by the oscillations in max(α_{ETB}).

TRANSITION FROM HIGH Q_{DT} H-MODE TO L-MODE IN 15 MA / 5.3 T PLASMAS AND FROM H_{98} ~ 1 TO L-MODE IN 7.5 MA / 2.65 T PLASMAS

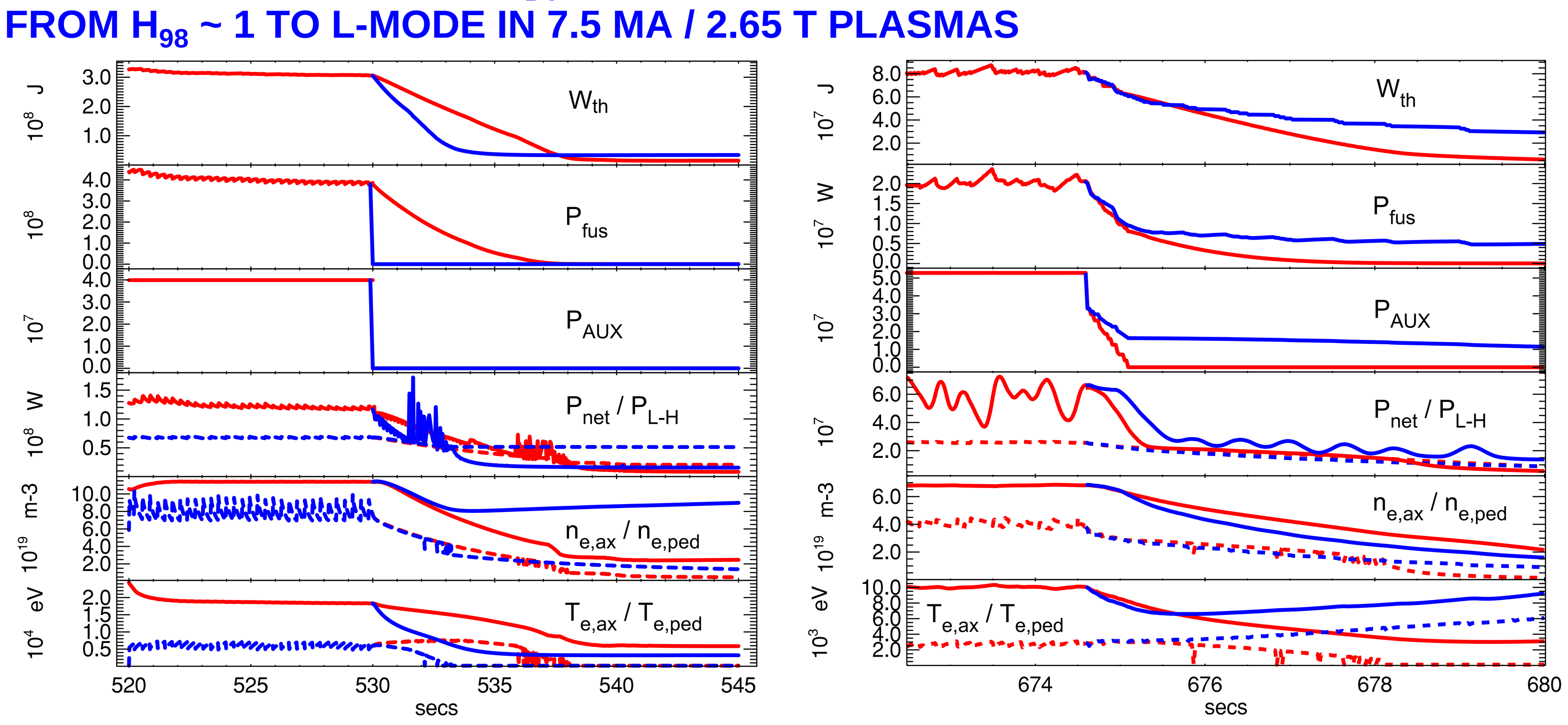

Figure 5: From top to bottom: W_{th}, P_{fus}, P_{AUX}, P_{net} (solid) and $P_{L\text{-}H}$ (dashed), $n_{e,ax}$ (solid) and $n_{e,ped}$ (dashed), $T_{e,ax}$ (solid) and $T_{e,ped}$ (dashed), left: for the case of a regular H-L transition with controlled ELMs in the flat-top phase of a 15 MA / 5.3 T DT plasma with (red) and without (blue) consideration of alpha heating and without heating and fuelling for t > 530 s; right: for the case of a regular H-L transition in the flat-top phase of a 7.5 MA / 2.65 T DT plasma without fuelling and P_{AUX} = 0 MW (red) or P_{AUX} = 16.5 MW of NB heating (blue) for t > 674.6 s.

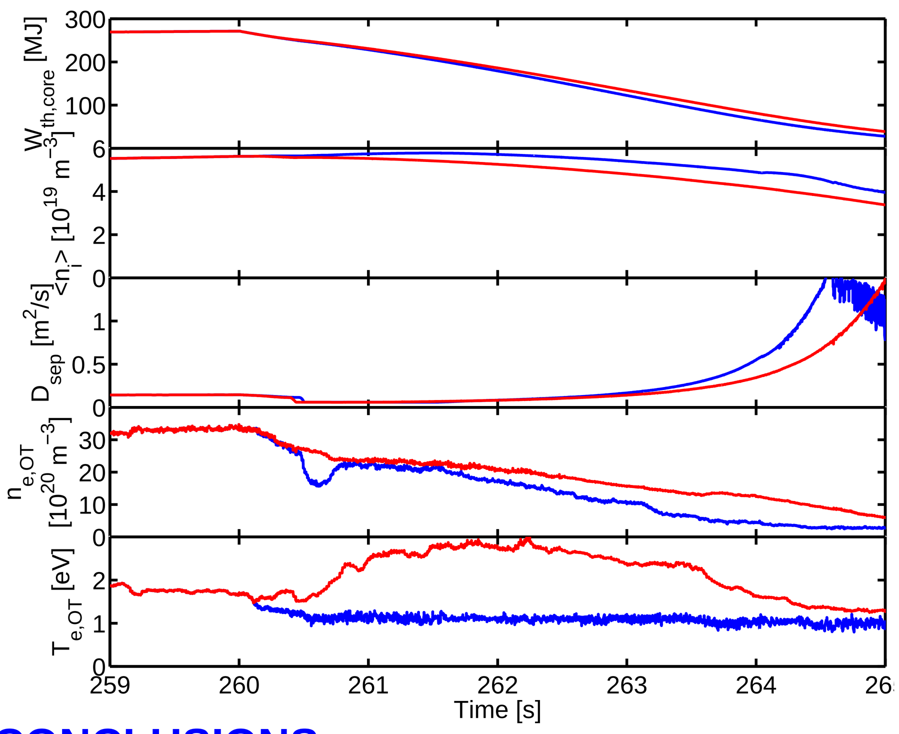

Figure 6: From top to bottom: thermal core energy content, volume averaged ion density, particle perp. diffusivity at the separatrix, electron density and temperature at strike point location on the outer target plate, for an H-L transition occuring in a 15 MA / 5.3 T DT gas fuelled plasma (G_{DT} = $2{\cdot}10^{22}$ s^{-1}, cf. [6]) with controlled ELMs. The transition is triggered by removal of auxiliary heating (33 MW NBI + 20 MW ICRH) at t = 260 s. Gas fuelling is either stopped (red colour) or maintained (blue colour) after the start of the transition. Due to the slow reduction in P_{sep}, the plasma remains in H-mode for a few seconds. The duration of the transition is long enough to keep the heat flux to the divertor at a tolerable level and to control the position of the plasma to avoid contact with the inner wall. However, loss of ELM control could lead to significant W core accumulation and W radiation reducing the transition time to ~1.0 s. [7]

CONCLUSIONS

- Limits for n_e ramp rate / delay time before application of increased pellet fuelling wrt. P_{AUX} for the transition from L-mode to high Q_{DT} 15 MA H-mode plasmas in ITER have been established. Delayed start of n_e ramp and moderate n_e ramp rates and injection of gas in addition to pellet fuelling are required to ensure reliable access to high Q_{DT} and to prevent W contamination of the plasma in the high Q_{DT} access phase due to improved screening of W in the ETB and reduced W sputtering.
- n_e increase following H-mode transition in He plasmas is found to be moderate due to inefficient He neutral penetration to the core, allowing for robust access to type-I ELMy H-mode with P_{AUX} > ~40 MW and efficient W screening. <n_e> might stay close to the NB shine-through limit though.
- Predicted duration for H-L transition at 15 MA / 5.3 T and 7.5 MA / 2.65 T with ELM control during the H-mode termination phase does not seem to be critical for divertor and plasma position control, as the plasma is remaining in H-mode for a substantial period after the decrease of P_{AUX} which is supported by alpha heating. The reduction of fuelling or maintenance of reduced P_{AUX} helps to prolong the transition. Without ELM control, the duration of the transition might be shortened due to W contamination, however local deposited power fluxes would remain low due to large radiated power. [7]

REFERENCES

[1] Romanelli M, Plasma and Fus. Research 9 (2014) 3403023.
[2] Garzotti L., Nucl. Fusion 52 (2012) 013002.
[3] Martin Y R, Journ. of Phys.: Conf. Ser. 123 (2008) 012033.
[4] Parail V, Nucl. Fusion 49 (2009) 075030.
[5] Dux R, this conference, TH/P3-29.
[6] Kukushkin A S, Nucl. Fusion 53 (2013) 123025.
[7] Romanelli M, this conference, PPC/P3-22.
[8] Loarte A, to be published in Nucl. Fusion.

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