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ABSTRACT

The influence of the ITER-like Wall (ILW) with divertor target plate made of tungsten (W), on plasma performance in JET H-mode is being investigated since 2011(see [1] and references therein). One of the key issues in discharges with low level of D fuelling is observed accumulation of W in the plasma core, which leads to a reduction in plasma performance. To study the interplay between W sputtering on the target plate, penetration of W through the SOL and edge transport barrier (ETB) and its further accumulation in plasma core predictive modelling was launched using a coupled 1.5D core and 2D SOL code JINTRAC [2]. Simulations reveal the important role of ELMs in W sputtering and plasma density control. Analyses also confirm pivotal role played by the neo-classical pinch of heavy impurities within the ETB.

INTRODUCTION, EXPERIMENTAL RESULTS

It was observed in JET experiments that W accumulation depends critically on a number of factors, such as: magnetic configuration, D fuelling rate and use of seed impurities (see [1] and references therein). In particular, it was shown recently that with the modest level of cold D fuelling (with $\Gamma \sim 1.5*10^{22}s^{-1}$) and fixed NBI heating power the plasma stays in a good quality type-I ELMy H-mode with $H_{98}y = 1$ without W accumulation inside separatrix in the case when the strike points sit in the corners of the horizontal targets (lower triangularity plasma, see Fig. 1). However, the main ion and W densities start to increase in plasma core as soon as the inner strike point moves to the vertical target (higher triangularity plasma). Simultaneously, the ELM frequency drops to a very low level and the confinement deteriorates. We select one recent JET H-mode Pulse Number: 85300 with $B_T = 2.1T$, $I_P = 2MA$ ($q_{95} = 3$), without impurity seeding, in which position of the inner strike point moves from horizontal to vertical tile in the middle of the discharge (see Figure 2, please also note that not only lower but coincidentally upper triangularity increases in the second part of the H-mode). To study the interplay between the change in magnetic configuration, level of recycled and external D flux, ELM frequency, plasma performance and W source on W accumulation, we launched predictive modelling of JET plasmas using a coupled 1.5D core (from magnetic centre to separatrix) and 2D SOL code JINTRAC [2]. The results of the modelling will be presented in this paper.

TRANSPORT MODEL

The simulation domain include both plasma core (from magnetic axis to separatrix with 1D description of time evolving plasma current, electron and ion temperatures, main ion density and two impurities- Be and W) and 2D modelling of SOL plasma (describing electron and ion temperatures, main ion and impurities densities and velocities and all neutrals). Core and SOL codes exchange boundary conditions at the separatrix at every time step and evolve plasma in line with the selected transport model. Standard Bohm/gyroBohm transport is used in plasma core [3] in combination with the neo-classical transport. Anomalous transport is reduced near the separatrix to account for the ETB. The ELM-free period is interrupted by periodic ELMs when normalised edge pressure gradient α exceeds fixed critical level needed to trigger peeling-ballooning instability. Transport in the SOL consists of the classical transport along the magnetic field lines in Braginskij approximation. Transport across the magnetic field is taken from the core (both between and during ELMs). Neutrals for both main ions and impurities are treated by the 3D Monte Carlo code EIRENE, which also includes package for plasma-wall interaction.

It is important to note that due to a limited knowledge about transport processes both in the core and the SOL our transport model uses a few adjustment parameters, which allow us to make better agreement between modelling and experiments. For example, there is no theory, which would prescribe ELM amplitude and duration so we vary ELM duration (or better to say the duration of elevated transport within edge barrier) from 1ms in low triangularity to 5ms in high triangularity to adjust ELM frequency and obtain better agreement with experiment. The same argument is valid for the way we specify anomalous transport across the magnetic field in the SOL. We use the model, which was proposed in [4] and tested on a number of JET discharges with C wall. Another uncertainty worth mentioning is wall recycling. We usually assume that both Be and W are fully reflective for hydrogenic atoms and inert gases. However, it might not be correct in transient phenomena like ELMs when strong transient particle flux to the wall might return back to plasma after some delay.

RESULTS FOR LOWER TRIANGULARITY PLASMA.

Taking into account limitations described above, we run full JINTRAC simulations of low triangularity JET plasma. The comparison of simulated main plasma parameters with experimental data is shown on Figure 3 and allows us to claim a decent level of agreement. One can see (on a Figure 4, zoomed on an individual ELM) that each ELM releases significant amount of W from the target plate and this W does penetrate through the SOL to the main plasma (actually W stays close to the separatrix as one can find from Fig.5). However, despite good penetration of W through the separatrix during the ELM, most of W ions return back to SOL and are subsequently lost on the target plate. This is generic feature of the “short, frequent” type-I ELMs, which is observed in many experiments. The explanation to this feature is twofold. On one side, ELM is a source of W since it generates a short burst of large particle fluxes of main ions and impurities onto target plates combined with higher electron temperature at the target cause strong W sputtering. However, simultaneously ELM redistributes main ion density and temperature profiles, which control neo-classical pinch velocity of W near the separatrix [5]. Qualitatively, this pinch velocity is proportional to the difference in the relative gradients of main ion density and temperature:

$$V_W \; {}^{n_D}\!/_{n_D} \; 1/2 \; {}^{T_i}\!/_{T_i} \qquad (1).$$

Close to separatrix (within ETB) both gradients are strong before ELM. Analysis shows that, if there is no strong D fuelling, neo-classical pinch velocity is negative between ELMs so that W should be drugged into the plasma core. However W sputtering between ELMs is very small in our simulations (with effective sputtering yield being below 10^{-5}). This is a result of the low level of heat and particle fluxes during ELM-free period, obtained in our simulations, which keeps electron temperature at the inner strike point at the level 1eV < Te < 2eV. This is below the W sputtering threshold even for Be ions. (unfortunately it is not possible to test this result on present experiment due to lack of experimental data). If electron temperature would stay above sputtering threshold between ELMs this would offer an alternative way to explain W accumulation between ELMs, particularly in plasma with low ELM frequency. Situation changes though during and, in particular, shortly after ELM. W pinch velocity generally becomes weekly positive during the ELM (see Figure 5) and it increases to a very large level shortly after the end of ELM. The reason for this is easy to see from equation (1) and the fact that unlike density, ion temperature at the separatrix drops to its pre-ELM level very quickly (within the parallel connection time in the SOL). Ion density at the separatrix, on the contrary, should stay elevated much longer since it can be removed only by the pumping (or by the temporary particle storage in Be wall after the burst of ELM).

RESULTS FOR HIGHER TRIANGULARITY PLASMA.

Plasma dynamics changes dramatically when magnetic configuration is switched from low to high triangularity. First of all, ELM frequency drops down significantly and individual ELM duration increases (see Figures 1b). It is fair to say that ELM becomes a composite one, in which first strong ELM is followed by an extended period of smaller ELMs. Simultaneously main ion density start rising and so does core W radiation. Continuous increase in W radiation eventually reduces heat flux through the separatrix to the level, which does not support H-mode.

As we discussed earlier, one of the possible way to explain W retainment after the ELM and subsequent accumulation in the core is to extend ELM duration. This would allow pumping the density near the separatrix out before the end of the ELM thus avoiding generation of a very strong positive neo-classical pinch velocity, which leads to W pump out after the end of short ELM. Another possible way to retain W in plasma core after ELM could be to increase density pumping by the Be wall. We test both abovementioned ideas. Figure 6 shows time evolution of plasma parameters in the simulations when ELM duration was extended to reproduce experimental ELM. One can observe that lengthening ELM duration (see Figure 7 for the details) dramatically increases W accumulation in line with what was observed in experiments. Reduction in wall recycling works in a very similar way. Finally, it is worth mentioning here change in magnetic configuration potentially could offer another explanation to experimentally observed difference in W accumulation. We leave this investigation for further work.

CONCLUSIONS.

Predictive modelling of W accumulation in JET ELMy H-mode plasma using integrated 2D SOL and 1D core transport code JINTRAC reveals a critical role played by the ELM. Analysis shows that plasma with fast frequent type-I ELMs is more resilient to W accumulation while plasma with long, infrequent, composite ELMs are easily contaminated by W, which is sputtered from W plate during the ELMs. The main mechanism of W retention in the core is edge-localised neo-classical pinch velocity, which becomes inward directed shortly after ELM.

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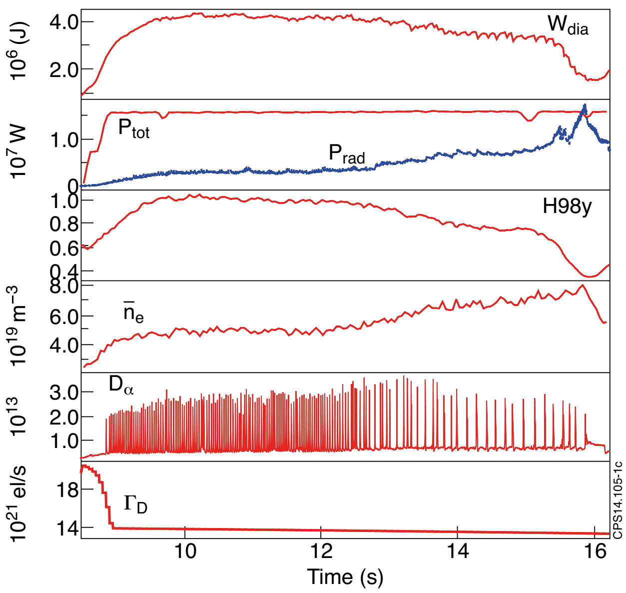

Figure 1. Time traces of main plasma parameters in JET Pulse No: 85300. From top: diamagnetic energy, NBI power (solid) and core radiation (dash), $H_{98}y$, line-average electron density, D ionisation source and D fuelling rate.

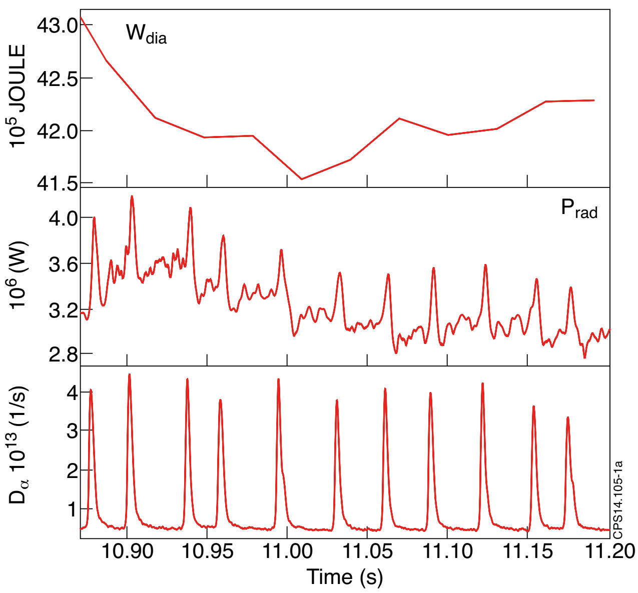

Figure 1a. Time traces of diamagnetic energy (top), radiated power (middle) and D ionisation source (bottom) zoomed on the magnetic configuration with low triangularity.

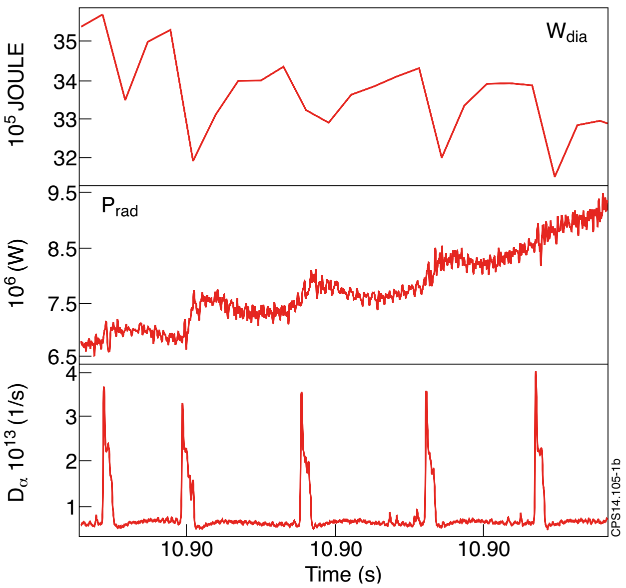

Figure 1b Time traces of diamagnetic energy (top), radiated power (middle) and D ionisation source (bottom) zoomed on the magnetic configuration with high triangularity

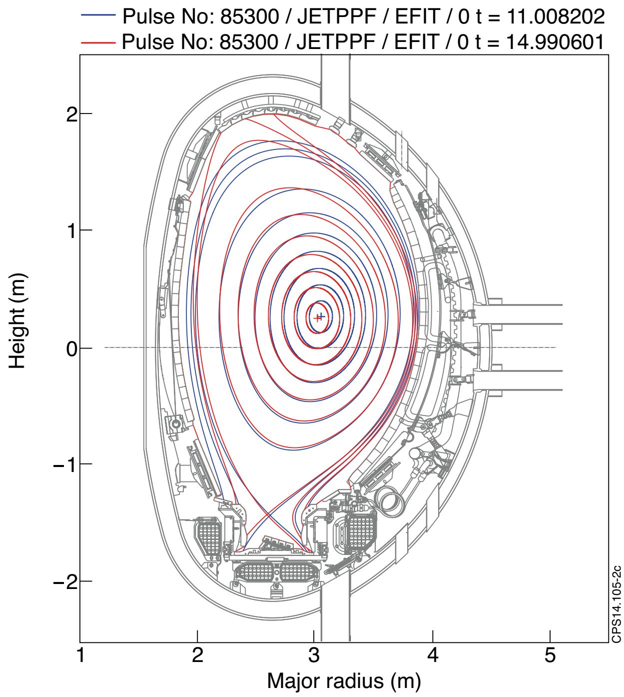

Figure 2. Contour plot of poloidal flux surfaces for two magnetic configurations for JET Pulse No: 85300 (solid-low triangularity, dash-high triangularity).

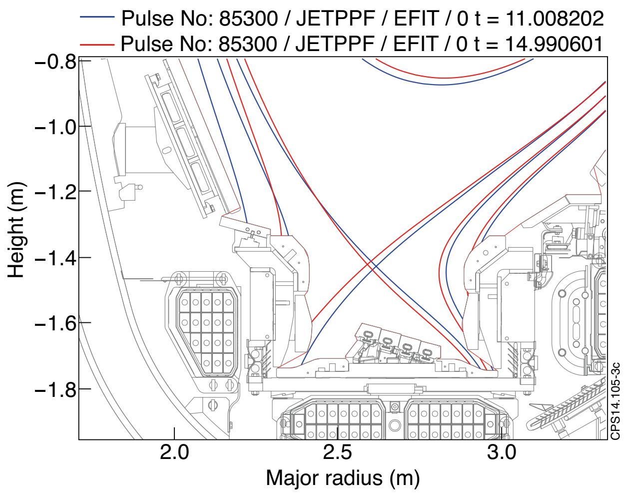

Figure 2a. Same as Figure 2 but zoomed in on the divertor.

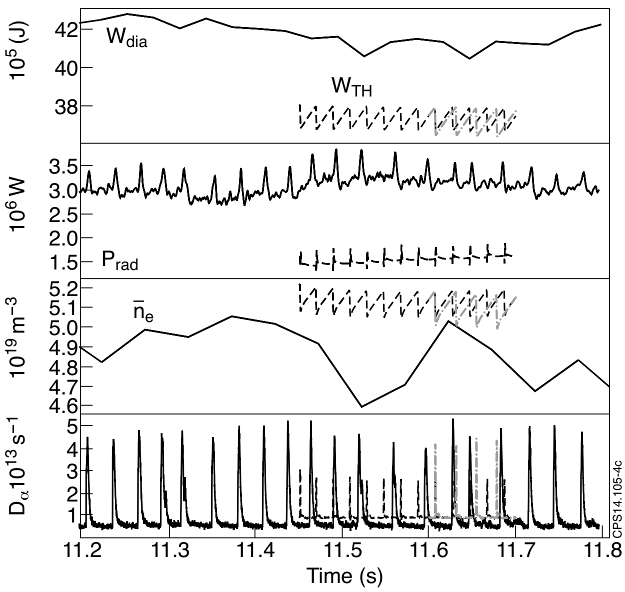

Figure 3. Comparison between experimental time traces (solid) and simulated one (dash) for the low triangularity plasma. From top to bottom: diamagnetic/thermal energy, radiated power, volume-average density and ionisation source. Time traces in chain correspond to a simulation with two times higher ELM amplitude.

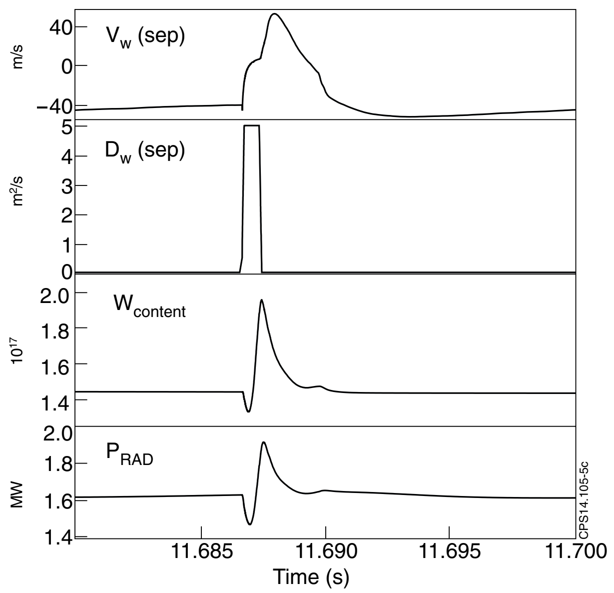

Figure 4. Time evolution of plasma parameters during the ELM cycle simulation (from top to bottom): W neo-classical pinch velocity at the separatrix, particle diffusivity at the separatrix, total core W content and core radiation.

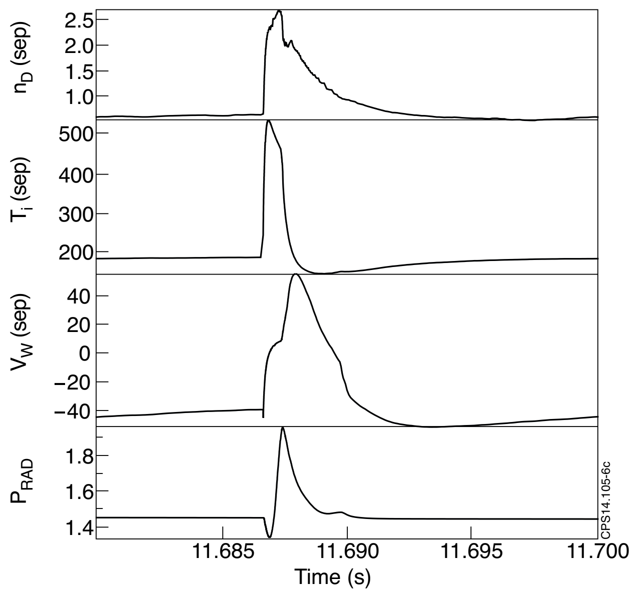

Figure 5. Time evolution of plasma parameters during the ELM cycle simulation (from top to bottom): ion density at the separatrix, ion temperature at the separatrix, W neo-classical pinch velocity at the separatrix and core radiation.

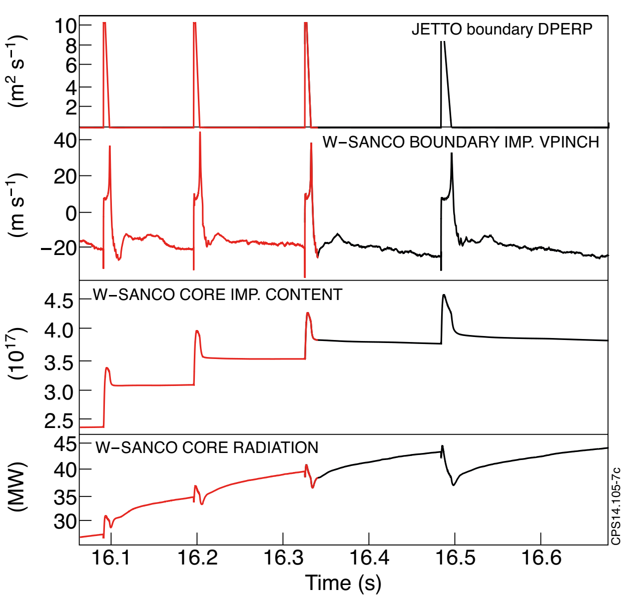

Figure 6. Time evolution of plasma parameters during the ELM cycle simulation with high triangularity (from top to bottom): particle diffusivity at the separatrix, W neo-classical pinch velocity at the separatrix, total core W content and core radiation.

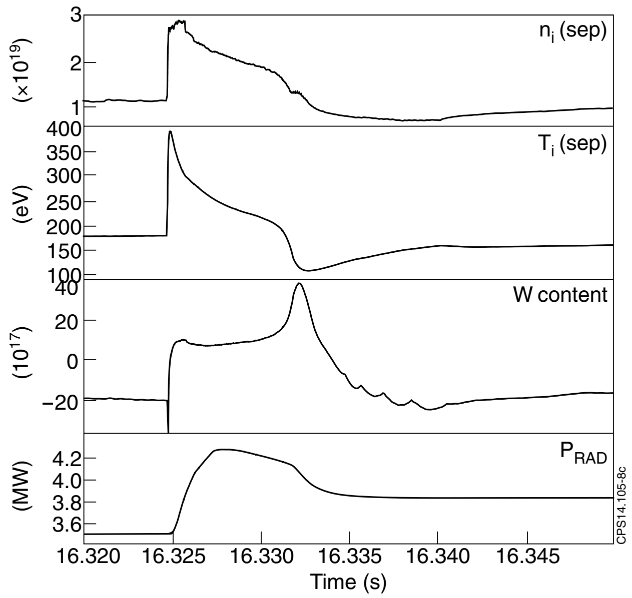

Figure 7. Time evolution of plasma parameters during the ELM cycle simulation with high triangularity (from top to bottom): particle diffusivity at the separatrix, W neo-classical pinch velocity at the separatrix, total core W content and core radiation.