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# Effect of PFC Recycling Conditions on JET Pedestal Density

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# Effect of PFC recycling conditions on JET pedestal density

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There is experimental evidence that the pedestal dynamics in type-I ELMy H-mode discharges in a metallic environment is significantly affected by a change in the recycling conditions at the tungsten plasma-facing components (W-PFCs) after an ELM event. The integrated code JINTRAC has been employed to assess the impact of recycling conditions during type-I ELMs in JET ITER-like wall H-mode discharges. By employing a heuristic approach, a model to mimic the physical processes leading to formation and release (i.e. outgassing) of finite near-surface fuel reservoirs in W-PFCs has been implemented into the EDGE2D-EIRENE plasma-wall interaction code being part of JINTRAC. As main result it is shown, that a delay in the density pedestal build-up after an ELM event can be provoked by reduced recycling induced by depleted W-PFC particle near-surface reservoirs. However the pedestal temperature evolution is barely affected by the change in recycling parameters suggesting that the presented model is incomplete. A criticism of the used heuristic but integrated approach and suggestions for improvements of the JINTRAC model is given.



## 1 Introduction

JET with its metallic wall consisting of a beryllium first-wall and tungsten armour in the divertor (ITER-like wall, ILW [1,2]) has demonstrated to perform very successfully for plasma-wall interaction studies and plasma operation with the identical plasma-facing material selection foreseen in ITER [3]. It has been proven that with the ILW in JET the goal to minimize long-term fuel retention can be achieved [4,5] and that the plasma-facing components (PFC) also do allow for a fast isotope exchange [6]. However, it has been revealed that the confinement in type-I ELMy H-mode JET discharges has degraded significantly compared to JET with a carbon wall (JET-C). Partly, this is driven by the fact that with the ILW significant W-accumulation must be avoided to avoid a radiative collapse of the main-plasma and thus baseline ILW H-mode discharges demand higher gas-fluxes and thus recycling compared to JET-C. As a consequence in JET-ILW baseline scenarios at elevated current and field a confinement factor H98(y,2) > 0.8 could not be achieved so far [7].

Assuming stiff core plasma transport plasma the confinement is mainly driven by the pedestal performance. With the JET-ILW it was revealed that the change of the wall material has not only an impact on the pedestal parameters itself but also on the dynamics of pedestal degradation and recovery during and after an ELM [8]. For type-I ELMs in JET-C the pedestal temperature $T^{ped}$ degradation time was similar to the MHD time $\tau^{MHD}$ ~ 0.2ms. However with the ILW for plasmas with comparable stored energies $T^{ped}$ drops for about >1-2ms after the ELM event, followed by a further but slower $T^{ped}$ drop characterized by a time-scale ~8-10ms depending on the level of recycling. In parallel the pedestal density $n^{ped}$ in ILW also degrades on longer time-scales compared to JET-C. The duration to reach the lowest $n^{ped}$ after the ELM does depend on the level of $n^{ped}$ itself. At higher $n^{ped}$ and thus recycling the duration until full recovery of $n^{ped}$ after the ELM increases and

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†See Appendix of F. Romanelli et al., 25th IAEA Fusion Energy Conference, 2014, Russia

comes with ELM durations of a few to several ms or more. In high-recycling conditions pedestal degradation times of 8ms or more and total recovery times >20ms have been observed [11] leading to reduced confinement as the level of recycling increases [12]. The effect of reduced confinement is somewhat mitigated by N-seeding in discharges with high triangularity [9,10] in which the the degradation of $n^{ped}$ can be partially mitigated.

The physical mechanism behind these observations is barely understood, if at all. State-of-the-art pedestal models like EPED1 for pure deuterium fuelled plasmas with high-triangular shape predict a good agreement for the pedestal height, but the pedestal width cannot be reproduced [13]. In JET-ILW discharges with increased deuterium fueling there is no improvement in the pedestal pressure $p^{ped}$ height but the the pedestal width $\Delta$ widens that is inconsistent with the $\beta_{pol,ped}{}^{1/2}$ scaling expected from JET-C. Also, EPED1 does not have a reliable recycling model in place and since recycling plays such a dominant role in the pedestal dynamics it is clear that EPED1 on its own cannot reproduce the change in the dynamics including the effect of recycling.

It is well appreciated that the pedestal fueling capability is directly linked with processes in the scrape-off-layer (SOL) that includes the interaction with recycling neutrals in the SOL/divertor region. We hypothesize that the change in the pedestal performance is not only connected with a change of $Z_{eff}$ in ILW discharges (compared to JET-C $Z_{eff}$ has decreased significantly due to the lack of C in the system) but particularly driven by the change in recycling behaviour on W/W-coated divertor plates. The experimental evidence that the recycling characteristics in the ILW is different from JET-C was discussed in [14] arguing that indeed particle recycling on W PFCs is different: the lack of co-deposited carbon layers which act as large particle reservoir is missing and high energetic particles with pedestal energies of 1keV or more can deeply penetrate (>100nm) into the W-PFC where particles can be confined in traps in the W solute leading to a delayed diffusive outgassing, for example, after an ELM event.

In this work, an integrated approach is followed using the JINTRAC integrated code package [15]. In the following section 2 the model setup of the coupled core-pedestal-edge physical system is briefly summarized. The recycling model being used has been revised by heuristic arguments and a short reasoning is given in section 3. Although the employed model by far cannot be regarded as complete it does allow a proof-of-principle study which exposes the fact that a change in the recycling conditions in the model has the potential to impact the pedestal fueling capability in JET-ILW H-mode discharges as will be presented in section 4. The concluding section 5 is dedicated for a discussion of the results highlighting some further model improvements for the future.

## 2 Integrated Model Description

The JINTRAC integrated code [15] is employing the 2D EDGE2D-EIRENE plasma-edge code package [16,17,18] which is coupled self-consistently to the 1.5D JETTO-SANCO core plasma code [19,20]. In JINTRAC radial heat and particle fluxes (plasma and neutrals) are exchanged dynamically at a common boundary (i.e. the separatrix) and redistributed in poloidal direction [21]. The setup of the time-dependent JINTRAC integrated code model for a typical JET-ILW H-mode discharge including ELM dynamics is described in detail in [22]. In this section give a brief description of the employed JINTRAC coupled core-pedestal-edge system, including details on the description of the extended recycling model in EDGE2D-EIRENE mimicking a delayed outgassing effect after an ELM event as proposed in [14].

The core plasma fluid transport is solved on a 1D radial grid assuming Bohm/gyro-Bohm values for particle and heat diffusion. For the inter-ELM phase within the pedestal region an edge-transport barrier (ETB) is imposed by suppressing the transport to low levels close to neo-classical values for the ions. Electron heat transport within the ETB is assumed to be elevated by turbulent transport and imposed. The pedestal width $\Delta$ is fixed in the model and set to ~4cm mapped at the outer-midplane. The ELM model in JETTO is adhoc: an ELM is assumed to be triggered by unstable ballooning MHD modes in the edge, i.e. when the critical radial pressure gradient $\alpha_c=(2\mu_0 q^2/B^2\varepsilon)dp/d\rho$ is exceeded within the ETB. The level of $\alpha_c$ was acquired from the JET high-resolution Thomson scattering system (HRTS) and for the ILW type-I ELMy H-mode discharge analyzed ($I_p/B_t$ = 2.0MA/2.0T, $P_{NBI}$=12MW, unseeded discharge taken from the JET-ILW C30C campaign, [4]) and

$\alpha_c$=1.4 was identified. In JETTO the ELM characteristics are set as such to expel $\Delta W_{ELM}$~200kJ of plasma energy into the SOL by increasing strongly the transport within the ETB for a short time given by the typical MHD activity time during the ELM, $\tau_{ELM}$~200μs (cf. [22] for details on defining $\Delta W_{ELM}$ using the full JINTRAC model). After the ELM, the pedestal transport is instantaneously set back to its original ETB value allowing the pedestal to be refueled by plasma and heat transported from the deep core into the pedestal region by diffusive processes and by neutrals crossing the separatrix. At a given instant in JETTO the integrated neutral influx located at the separatrix coming from the SOL (provided by the EIRENE code) is taken to model an ionization source profile within the pedestal assuming an exponential decay given by the ionization length.

EDGE2D [16] is a 2D Braginskii edge-plasma fluid model, relaxing self-consistently in time the continuity and parallel ion momentum equations for all ionic species as well as electron and ion internal energy equations. The equation set is solved on a non-orthogonal grid with solutions for plasma densities $n_i$, particle fluxes $\Gamma_i=n_i m_i v_i$ (parallel ion momentum densities) and electron and ion temperatures $T_e$ and $T_i$ in both, perpendicular (radial) and projected poloidal direction. Transport in radial direction in EDGE2D is imposed and normally set to anomalous values. Classical Spitzer-Harm transport coefficients ~$T^{5/2}$ are assumed for parallel electron and ion heat conductivity as well as for parallel ion viscosity. Heat-flux and viscosity limiting factors have been disregarded in this work. One can find in [23] a discussion on the limited use of heat-flux limiting factors in EDGE2D-EIRENE in view of the attempt to reproduce convective ELM filamentary transport towards the target plates. The interpretation of experimental data of JET the infra-red system is hard, but the general trend is recovered that EDGE2D-EIRENE overestimates the instantaneous ELM driven parallel target heat flux by a factor 4-8 [22]. This result is not in contrast to the free-streaming approximation suggested in [26] and on time integrated basis EDGE2D-EIRENE is capable in reproducing the power-balance during and after the ELM.

In the JINTRAC coupling scheme, JETTO is requested to provide EDGE2D-EIRENE new boundary conditions as input for the SOL plasma solver. The time-dependent transients of $P_{SOL}$, $\Gamma_\perp$ calculated by JETTO are distributed poloidally along the separatrix in EDGE2D-EIRENE. An anisotropic distribution of perpendicular fluxes between ELMs or during an ELM allowing for ballooning effects have been disregarded for simplicity. For self-consistency of the coupling the values of time varying radial transport coefficients defined by JETTO at the outer-midplane are taken as boundary values of transport in the SOL. The transport in the inter-ELM phase, i.e. the ETB values, are extended slightly into the SOL (0.5cm at the outer mid-plane and mapped along the field lines conserving magnetic flux expansion) to allow for a realistic scaling for the heat decay parameter $\lambda_q$ [24, 25] and thus $q_{||}$ along the field. Beyond $\lambda_q$ in the far-SOL and throughout the divertor region the transport is increased to anomalous values of $1m^2/s$. During the ELM the transport at the separatrix is high and given by a decaying gaussian profile shape of enhanced transport in the pedestal during the ELM in JETTO [27]. A large value of the transport coefficient located at the separatrix during the ELM is reduced towards the far-SOL with exponential decay. The overall setup of the plasma transport model in EDGE2D-EIRENE does allow the plasma to recycle at the main-chamber wall, and the wall-recycling is enhanced during the ELM. The dominant recycling between and at the ELM however occurs at the divertor target plates. The EIRENE Monte-Carlo neutral kinetic code [17] is coupled to EDGE2D and providing source terms for the full set of Braginskii fluid equations. Assuming the Bohm sheath criteria as boundary condition at the target plates, plasma particles are recombining at the surface and recycled either as reflected atoms or thermally emitted molecules.

## 3 Revision of Recycling Model

In edge codes like EDGE2D-EIRENE or SOLPS the assumption of full particle recycling (recycling coefficient $R = \Gamma_r / \Gamma_i = 1$) is a standard assumption for steady simulations. The argument that in a carbon device co-deposited layers built up which act as infinite particle reservoirs support this assumption even for ELMy discharges. However, already a decade ago at JT-60U [28] and recently at DIII-D [29] it was suggested that the assumption of 100% recycling should be relaxed for large type-I ELMy H-mode discharges. For bulk-W or W-coated CFC divertor plates the thickness of co-deposited layers which in principle could act as particle reservoirs is small (that is specifically true for full-W devices, but also for the JET-ILW with Be-deposits from the main-wall [30]) but high-energetic particles with pedestal energies can penetrate into the upper layers of the W PFCs and form near-surface reservoirs of trapped particles. The hypothesis in [14] is the following: as the W target plate is heated up during the ELM each ELM footprint acts as a mini-desorption of stored particles in the near-surface and thus depletes at least partially the reservoir of trapped D particles.

Here, in the presented rather heuristic approach a very simple near-surface reservoir model was implemented into EDGE2D-EIRENE. At each target plates a fixed number of particles can be stored in a 0D-model reservoir with particle capacity C (i.e. the number of trapped particles which can be stored in each reservoir). At an ELM event the code checks for $T_e^{plate}$ or $T_i^{plate}$ at each target plate whether they exceed a given threshold (> 200eV, i.e. taking into account the time-lag of the ELM driven heat pulse as it is transported along the field until arrival at the target plate) and subsequently empties the reservoirs. At the same time the recycling coefficient is reduced to a fixed level, namely $R^{ELM}<1$. This will allow to pump away at least partially any particle flux arriving at a target plate after the ELM event until the reservoir is fully replenished. After filling up the reservoirs the recycling coefficient is set back to R=1. The exact value of $R^{ELM}$ after the ELM event is difficult to assess (cf. discussion in section 5). In this work $R^{ELM}$ is scanned for values between 0.2 and 1.0.

Following the discussion in [3] the value of capacity C at each target is specified as external parameter and of order ~$10^{20}$ D particles. The applied gas flux rate in JET H-mode discharges is typically much lower (order $10^{-2}$) than the recycling flux $\Gamma_r \sim 10^{23}$ D/m$^2$s. Depending on the exact value of C and $R^{ELM}$ and the actual transient of the particle flux after the ELM the effective refill-time of the near-surface reservoirs at the plate can thus vary for a couple of ms as will be shown in the next section.

## 4 Results

JINTRAC is dynamically evolving the 1D core plasma and 2D edge/SOL plasma profiles in time and at each ELM event after exceeding the critical pedestal pressure $\alpha_c$ a significant fraction of the pedestal energy and particle content is flushed into the SOL. The response of the SOL is to transport the ELM driven plasma energy towards the divertor due to steepened parallel T-gradients along the field. At the same time the instantaneous increase of the upstream particle source must be equilibrated by accelerating the plasma towards the target plates. Parallel convective (free-streaming) SOL transport is fast ($\tau^{SOL} \sim L_{||}/c_s < 1$ms) and an adaptive time-step control scheme in the EDGE2D part of JINTRAC ensures overall convergence in time. The time-scale of neutrals can be of similar order or faster ($\tau_{neut} \sim 0.1$-1ms) and in the employed EIRENE model it is assumed that the neutrals can be treated in a time-independent way (in this way one has to ensure that the time between to EIRENE calls by EDGE2D is not larger than $10^{-6}$s). Time-scales in the deep plasma core are much slower given by the confinement time and the inverse of the ELM frequency $1/f^{ELM}$.

By assuming an $R^{ELM}$ smaller or equal unity and a finite amount of particles which can be stored for in the near-surface of the target plates, i.e. a reservoir size C > 0 which is filled up by the target particle fluxes, JINTRAC can mimic the delay in particle recycling shortly after an ELM. Figure 1 shows for the case $C=10^{20}$ (at each target) and $R^{ELM} = 0.3$ the time-evolution of the particle contents in each target near-surface reservoir. After the ELM, i.e. when a strong heat pulse arrives at the targets, the particles are removed from the system (i.e. pumped away). It is apparent that the model predicts a coincident arrival of the heat pulse at both targets and thus depletion of both near-surface reservoirs in the same instant. After depletion of the reservoirs and depending on the strength of the particle flux each reservoir is filled up again. Since the outer target receives a larger ion flux compared to the inner the fill-up process at the LFS target is faster.

In figure 1 b) the corresponding time-evolution of the recycled particle flux $\Gamma_r$ as seen by EDGE2D is shown. At ELM time the occurring peak in $\Gamma_r$ is strongly reduced due to pumping of particles into the previously depleted near-surface reservoirs. After the outer near-surface is replenished, i.e. after ~ 10ms, the recycling coefficient is set back to unity only at the outer target. Then, notably at both targets, $\Gamma_r$ increases steeply and saturates, until the second near-surface at the inner plate is replenished after another ~15ms, too. After full replenishing of both near-surface reservoirs the recycling coefficient is set back to R=1 everywhere.

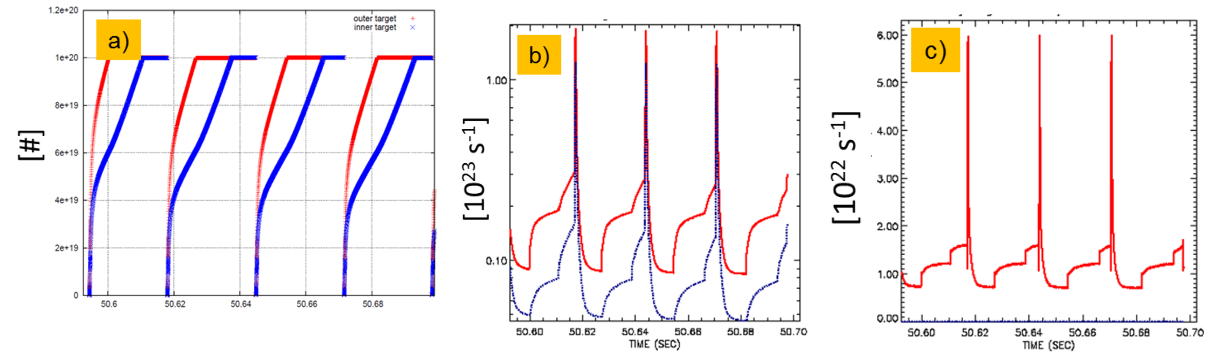


**Fig. 1** For the $C=10^{20}$ case, with $R^{ELM}=0.3$: a) time-evolution of the D-particle number stored in each target near-surface reservoir (red: outer target, blue: inner target), b) resulting recycling neutral flux $\Gamma_r$ [$10^{23}s^{-1}$] at each targets, c) neutral flux [$10^{22}s^{-1}$] crossing the sepratrix $\Gamma_n^{sep}$.

Figure 1 c) displays the evolution of the neutral flux crossing the sepratrix, $\Gamma_n^{sep}$. In the inter-ELM phase shortly after the ELM $\Gamma_n^{sep}$ is decreased down to $0.8{\cdot}10^{22}$ $s^{-1}$. In the approach to reach the maximum of about $1.6{\cdot}10^{22}$ $s^{-1}$ just before the next ELM $\Gamma_n^{sep}$ increases in a step-like manner due to the imposed reduced recycling in the system. As a consequence of the delayed refuel process across the separatrix the pedestal density is retarded as seen from figure 2 a). We observe that $n_e^{ped}$ is directly linked with $\Gamma_n^{sep}$ as the a step-up in $n_e^{ped}$ is synchronous with $\Gamma_n^{sep}$. From this we conclude that the pedestal refueling, although ETB transport is set back to low values shortly after the ELM (i.e. after $\tau^{MHD}$ = 200μs), is driven by the neutrals entering the pedestal zone. Totally unaffected however by the change in neutral influx is the pedestal temperature, as seen in figure 2 b) for $T_e^{ped}$. It is thus concluded that heating of the pedestal for $T_e^{ped}$ is mainly controlled by the power arriving at the pedestal top from the core and the assumed level of ETB transport.

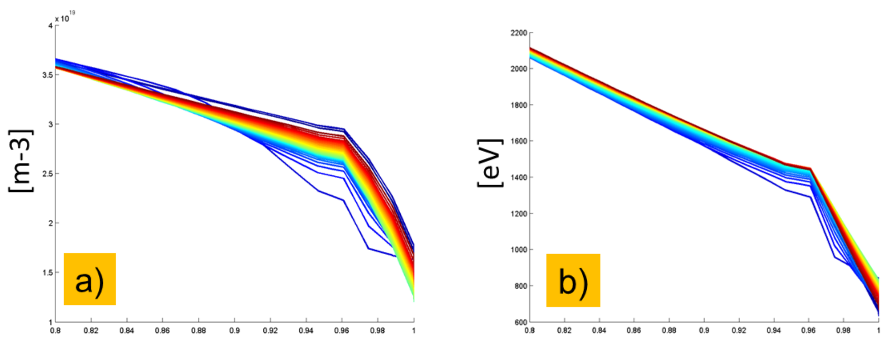


**Fig. 2** Left: Transient of the radial pedestal density profile after the modelled ELM event in JINTRAC, color code after the ELM: blue: 0.4ms, green: 10ms, red: 20ms, black 27ms. Right: Transient of the radial pedestal electron temperature, same color code as in a).

As a result of a sensitivity scan the table 1 summarizes the derived values $f^{ELM}$ as function of $R^{ELM}$ and C (assuming that all other model parameters are kept the same). We observe that by adjusting $R^{ELM}$ and C the amount of delay in pedestal pressure increase can be steered and thus the ELM frequency $f^{ELM}$. $R^{ELM}$ is a strong parameter in the presented JINTRAC simulation and its exact value so far arbitrary. Thus a model parameter constraint based on a sound physics basis for the outgassing process is needed.

| $R^{ELM}$ | Reservoir C | $f^{ELM}$ |
|---|---|---|
| 1.0 | - | 60Hz |
| 0.5 | $1\cdot10^{20}$ | 36Hz |
| 0.3 | $1\cdot10^{20}$ | 50Hz |
| 0.3 | $2\cdot10^{20}$ | 25Hz |
| 0.2 | $2\cdot10^{20}$ | 20Hz |

**Table 1** Sensitivity scan of $R^{ELM}$ and C

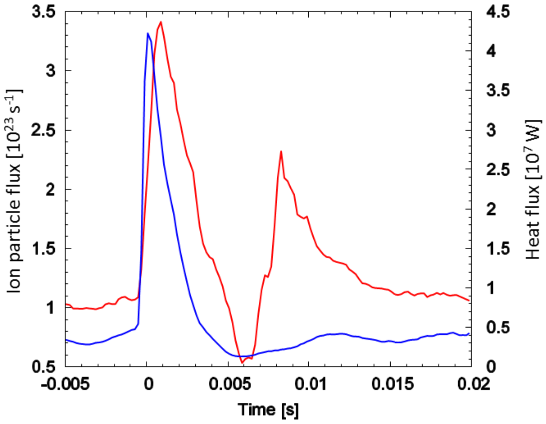


**Fig. 3** Coherently averaged transients of the integrated LFS target power load and particle flux after the ELM event (t=0) taken from the C30C JET-ILW discharges. The averaging procedure is described in [23] and the corresponding non-averaged transients of heat flux and particle flux footprints can be found in fig.4 loc. cit. The particle flux is arriving 1.2ms later than the heat pulse. A pronounced second particle flux peak occurs 7-8ms after the first peak.

## 5 Discussion and Conclusion

By using a heuristic approach we have shown that a change in the recycling conditions can lead to a change in the evolution in the pedestal conditions after an ELM event. Due to unknown constraints on the used near-surface recycling parameter $R^{ELM}$ in the sensitivity study we are currently not capable to state whether a change in the recycling conditions alone is responsible for the degrading change in confinement when moving from JET-C to the JET-ILW. Although the model does predict an impact on the post-ELM evolution of $n^{ped}$ it does not recover the slow response of $T^{ped}$ on the ELM as reported in [8,9,10,11]. It is very likely that other effects like a change in MHD stability after the ELM (as response to changes for example in separatrix or fueling conditions) do also play a role. However in the presented JINTRAC simulations the assumption was made that after the ELM-crash lasting for $\tau^{MHD}$ ~ 200μs the ETB transport is set back to its pre-ELM value which causes the unexpected fast increase of $T^{ped}$ in the post-ELM phase in the model.

A recent work by K. Schmid [31] showed that the recycling coefficient itself after the ELM is actually not changing much from unity. The model utilized in [31] is based on a 1D diffusive-trap model for the W-solute assuming isolated W traps resulting in a 0D value for a time-dependent recycling coefficient. However in [31] it was so far disregarded that a) the ELM flux footprint (target ELM wetted area) is considerably larger than during the inter-ELM phase, and b) that the ELM driven (convective) target particle flux arrives at the same time as the heat pulse. Both assumptions are too idealistic as seen for example in fig. 3. Thus an at least 2D diffusive-trap model taking into account the radial variation in the fluxes and any asynchronicity between heat and particle fluxes is suggested and currently under investigation. A possible coupling of a diffusive-trapping model for W-PFCs with EIRENE is currently under discussion, too. With such an extension the adhoc open parameters $R^{ELM}$ and C can be removed from the JINTRAC integrated model. Further input from dedicated new experiments foreseen for the upcoming JET-ILW campaign will also help to include surface temperature effects on $R^{ELM}$ as well as the effect on sticking impurities like nitrogen as suggested in [14].

ELM driven particles do arrive with at least pedestal energies at the target plates after the ELM event [26] and it was shown that particles with even higher energies up to 4-5 keV can exist in typical JET-ILW type-I H-mode discharges [32]. These energetic particles have the potential to penetrate deep into the material (>> 100nm from TRIM estimates) leading to supersaturation of deeper-lying layers in multi-traps as shown by DFT simulations [33] and thus a delayed outgassing by diffusion out of the W-solute. The increased particle flux during the ELM can potentially compress particles from the near-surface layer deeper into the W-solute, too. To take such effects into account the heuristic model approach could be extended to allow for a secondary deep-surface reservoir allowing for a further refinement of the model for the outgassing process. With the JINTRAC simulations so far the strong secondary peak in the recycling flux 8ms after the ELM could not be reproduced with the existing single-resorvoir model and, as gedankenexperiment, a secondary reservoir with a significant amount particles stored deep W-PFC multi-traps could lead to long delays of outgassed particles after the ELM. For a proper analysis of this effect however extended diffuse-trap models beyond as presented in [31] are required which would lead to further refinements for time-dependent recycling coefficients $R^{ELM}$ and multi-layer reservoirs $C_n$ to be used for example in JINTRAC.

A different explanation for the delayed secondary peak 8ms in the recycling flux after the ELM could be the following: as the estimated target heat-flux from the IR camera system shortly before the secondary peak in the recycling flux is decreased by a factor 2-3 the plasma can drift into a high-recycling regime for a short period (c.f. fig. 3). This intermediate period of enhanced recycling decays over a period of 5-10ms as the heat flux increases over time. As a consequence the upstream conditions might be affected as such that there is a competition between rebuilding the T-pedestal and setting back the level of recycling towards the situation before the ELM. Currently, JINTRAC assumes time-independent neutral transport in EIRENE. Taking the previous considerations on board this approximation might not be adequate enough. Fig 1. b) shows that at the point of replenishing either of the near-surface reservoirs both target plates receive a step in the recycling flux. At a first glance this could be a reminiscent effect of the time-independent assumption for the neutrals. A time-dependent neutral solution with EIRENE would potentially lead to asymmetries in the recycling flux and hence to a further delay in the pedestal refueling dynamics too.

Finally, we must criticize our heuristic approach as a whole since it is obvious from the discussion of the results that the presented integrated model is still incomplete and too oversimplified. It is understood that in order to put an integrated model like JINTRAC on a sound physics basis and to address the complex issue of PFC outgassing effects on pedestal dynamics and plasma confinement an improvement of specific sub-models for the pedestal transport (that includes MHD stability) and the interaction with the W-PFCs is mandatory.

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