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Preprint of Paper to be submitted for publication in
43rd European Physical Society Conference on Plasma
Physics (EPS)

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*See Appendix of F Romanelli et al. Proc. of the 25th IAEA Fusion Energy Conf. 2014, Saint Petersburg, Russia

A fundamental change of plasma behaviour in JET since the installation of the ITER-like-Wall (ILW) is that the pedestals in ELMy H-modes are considerably colder than in the Carbon phase of JET, even for comparable fuelling levels [1,2]. This is interesting in itself, and also has implications for scenario development, since reduced core confinement is correlated with the lower pedestal electron temperature, $T_{e,ped}$, in ELMy H-mode plasmas. H-mode pedestals exhibit strong gradients in electron density, n_e, which drive a neoclassical inward pinch of W from the SOL towards the pedestal top. From there n_e is typically flat, so further penetration of W would be much slower. Thus, in between ELMs, W could peak in the $T_{e,ped}$ region, where now typically $T_{e,ped}$< 1.5 keV. W is known to be a good radiator in the 0.5-2 keV T_e range, where calculation of the W radiation from first principles is challenging.

In figure 1 we illustrate the dependence of radiated power density on T_e for various plasma species, based on ADAS atomic models: $P_{rad,Z} = n_e n_Z L_Z(T_e)$ for each species, where $L_Z(T_e)$ is the cooling function. Be "burns through" below 100 eV: this means that from then on, as T_e rises $P_{rad,Be}$ drops, so T_e can continue to rise. In contrast we see that for both W curves, there are regions with positive slope: as T_e rises, $P_{rad,W}$ rises, so it is harder for T_e to continue to rise.

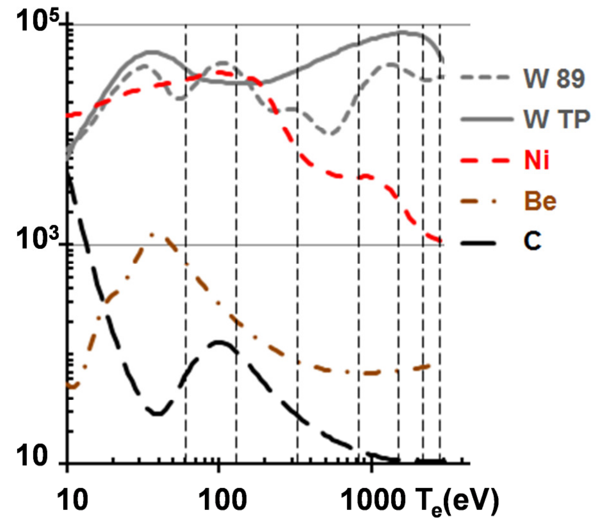

Fig. 1: Computed radiated power density (MW/m^{-3}) for various species, with two different curves shown for W. It was assumed that $n_e=3\times10^{19}m^{-3}$, $n_Z/n_e=2\times10^{-4}$, except for Be, $n_{Be}/n_e=2\times10^{-4}$. We do not advocate that either W curve is correct: they just illustrate types of behaviour in the interesting T_e range.

Calculations from two rather different cooling functions for W are shown: W 89 is based on the JET-ADAS working version (commonly referred to as ADAS 89, unpublished). The ADAS 89 data included only low level configurations for estimation of the line radiated power. It was created as a starting point. W TP is based on more recent work [3,4]: a different choice of configurations was made, and recombination coefficients were adjusted to match ASDEX measurements in the W^{24+}-W^{46+} range (>1 keV). W TP also has more sophisticated ionization rates. Further studies, using configuration average estimates of omitted power from further configurations, indicate that both ADAS 89 and TP had important omissions, likely to introduce/modify the structure of the T_e dependency of W radiation below 1 keV.

Additionally the ionization balance must be re-examined. Recent experimental studies of dielectronic recombination (DR) [5, and references therein] indicate a major flaw in the DR coefficients for mid-range ions with open 4f shell in the ground state. This effect, known as the low-temperature DR effect, is greatly enhanced in tungsten, such that it can increase the rate, at the temperatures considered here, by a factor of 10. This would significantly move the ionisation balance towards temperatures of interest in the JET pedestal region (0.5-1keV), with the expectation that structure may appear in the cooling function below 1 keV.

Both W curves would be affected by the modified ionisation balance and improved configuration modelling. Work is ongoing to incorporate these effects into new W radiation calculations. Here we use the two existing models as test cases, to investigate the evidence for or against structure below 1 keV, as in W 89, or in W TP, respectively.

To gather experimental data in relevant plasma conditions we used laser ablation to inject W into cold L-mode plasmas. We injected ~10^{18} atoms (estimated from the size of the hole left in the target) of W at t=11.005 s into 2.4 T, 1.7 MA JET plasmas, heated by P_{NBI}=1.2 MW and P_{ohm}~0.9 MW. Soon after injection we observed a fast rise in radiation (Fig. 2a) and

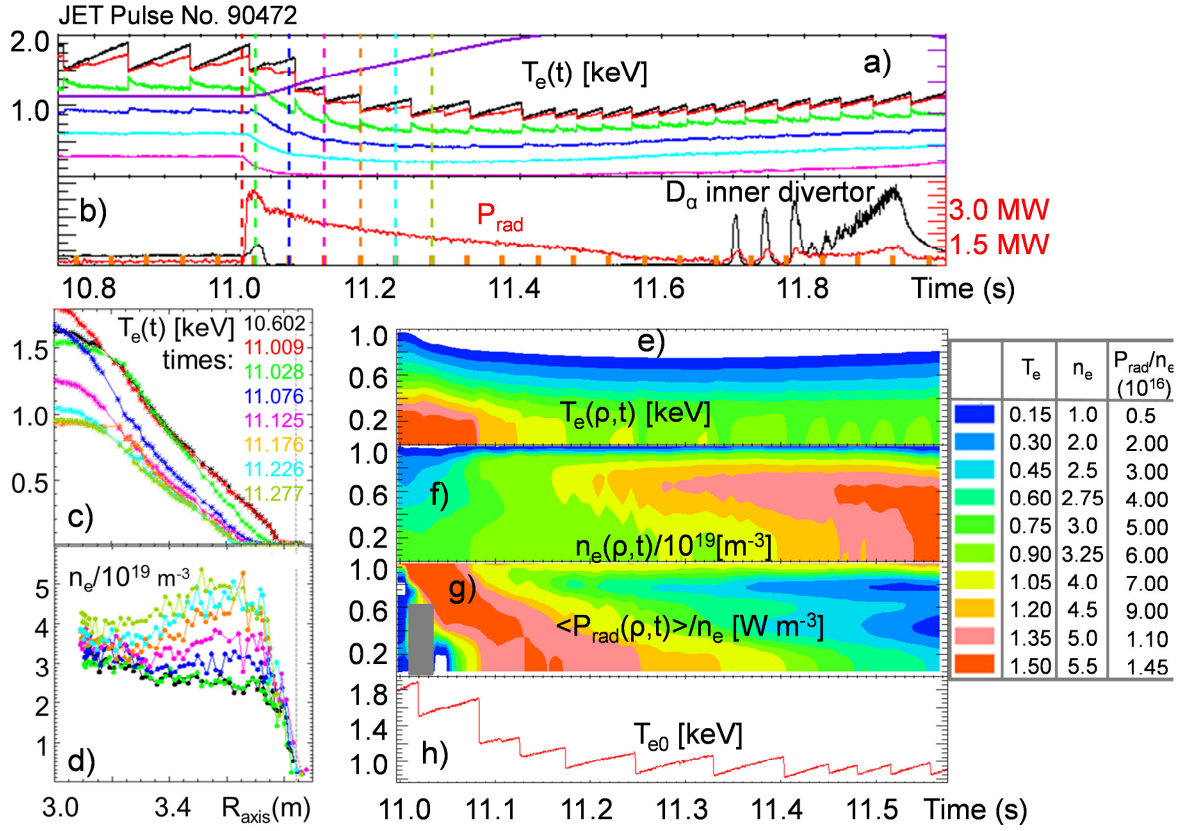

Fig. 2: a: temporal evolution of T_e, ; b) total radiated power and D_α, showing W injection at 11.005 s and its effects. c) and d) profiles of T_e and n_e at the times indicated a,b. e) evolution of profiles of T_e, f) n_e and g) P_{rad}/n_e, normalised radius in vertical axis , 0 on axis, contour level values on left. h) T_e on axis. Note that P_{rad}/n_e ~ $n_W L_W(T_e)$: we can see W penetrating into core after 3rd sawtooth.

drastic cooling of the plasma edge, as shown in Figs. 2c, 2e. The outer 15 cm of the plasma becomes power detached from 11.05 till 11.55 s (ρ>0.9, R>3.65 m), with T_e below 100 eV. This low T_e allows deep penetration of neutrals leading to a rise in edge n_e, and hollow n_e profiles, Figs. 2d, 2f. Near the edge T_e is so low that radiation has contributions from Deuterium and Be, not only W. But inside of ρ<0.8, and after t=11.1s, the low Z species have burnt through and only W remains as a radiator. This is the area of interest for our study.

Tomographic reconstruction of bolometry from vertical and poloidal arrays shows poloidally and radially localised structures. Because W is very collisional, it can take a long time for n_W to become poloidally symmetric. Assuming classical collisional diffusion, a random walk estimate of the time required for W to propagate along a full poloidal arc would be given by $t = L^2/D_{||}$, with $L = \pi(qR + a)$. We show some typical values in Table 1, assuming q=3, $n_e=3\times10^{19}$ m^{-3}. Here we must note that the two bolometer cameras at JET are separated toroidally by 135°, about 9 m, resulting in W propagation times of order 1-10 ms: thus toroidal propagation time is not a concern for diagnostic interpretation.

Z_W	$T_e=T_i$ (keV)	$D_{\|\|}$ $10^4 m^2/s$	time (ms)
W^{8+}	0.160	1.1	85
W^{10+}	0.210	1.4	67
W^{13+}	0.290	1.9	51
W^{17+}	0.420	2.8	34
W^{19+}	0.500	3.4	28
W^{23+}	0.685	5.1	18
W^{27+}	0.881	7.0	14
W^{30+}	1.230	13.0	7

Table 1: Collisional random-walk estimate of time required for W to spread poloidally.

From the tomographic reconstruction of bolometry we computed the flux-surface averaged radiation density as a function of normalised minor radius and time, which we divided by n_e to estimate $n_Z L_Z(T_e)$. Looking at P_{rad}/n_e in Fig. 2 it is evident that sawteeth play an important role carrying W inward until the 3rd sawtooth, and outwards from then on. From t=11.3 s we see clear evidence of structure in P_{rad}/n_e near 0.5<ρ<0.8, where 150<T_e (eV)<800. Is this structure due to the cooling function?

To investigate this we turn to transport modelling. We can't model the interaction of W with sawteeth, so we enhance the inward particle flux during the time period 11.-11.2 s, to mimic the effect of the sawtooth carrying W inwards. This allows a centrally peaked n_W profile to form. Starting with that initially peaked n_W profile at t=11.2 s the subsequent temporal decay from t>11.2 s is modelled with SANCO [6] using two different sets of atomic data taken from the ADAS baseline data (W 89) and from Pütterich (W TP), including recombination, ionisation and line power rate coefficients. In each case, the radial diffusion profile is the same, shown in Fig. 3a, while the radial convective velocity profile is varied, for both W 89 and W TP, to match both the 2D reconstructed bolometry profiles and the mid-plane, line-integrated bolometry trace. As shown in Fig. 3c, the convective velocity profile associated with the W 89 model gives rise to a strong inward pinch around ρ=0.8 and a weak outward velocity at ρ=0.7, where ∇n_e is outward. When using the W TP atomic data the inward pinch is smaller and changes sign twice inside of ρ=0.8.

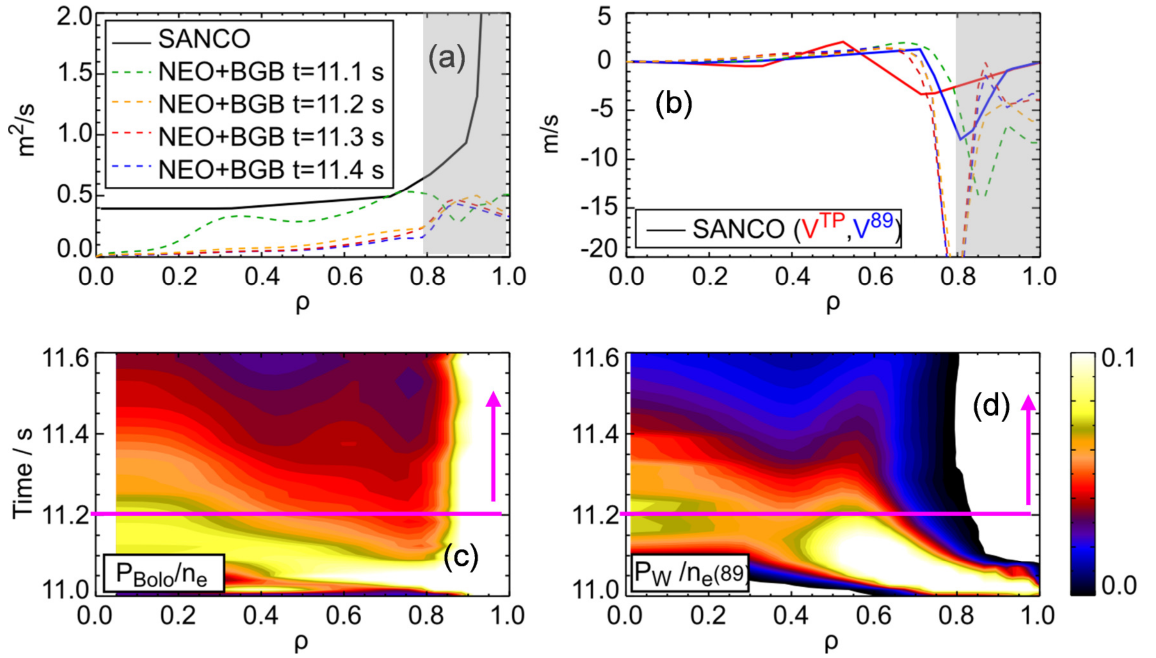

Fig. 3: a) diffusion coefficient used in SANCO during the 11.3-11.6 time window, compared with theoretical calculations; b) convection used to fit radiation data for the two atomic models considered; c) P_{rad}/n_e measurement, normalised to its maximum value. d) modelling result for W 89, from 11.2 s. The shaded areas in 1,b indicate regions were radiation from low Z species may also be present, but is ignored in models.

Calculations of the particle flux at each radial location have been carried out in the transport code JETTO [7,8] using the mixed Bohm/gyro-Bohm model [9] to compute the anomalous diffusive transport and the local drift kinetic neoclassical code NEO [10,11] to calculate the convective velocity. The inward pinch needed to match the radiated power calculated using the W TP atomic data with the reconstructed bolometry profile is hard to justify between ρ=0.6-0.7 in comparison to NEO, because only a strongly peaked density profile can facilitate an inward pinch. Due to the flatness of the electron density profile around ρ=0.6-0.7, the convective velocity profile associated with the W 89 model provides the best match to the theoretical calculations. These results could imply that there is structure in the shape of the tungsten cooling function between T_e=100 – 1000 eV, but, alas, they are not conclusive.

In summary: Different ADAS-based atomic models can lead to very different distribution of W radiation. Work is ongoing to improve ADAS predictions of W radiation in the 0.1-2 keV range of T_e, of interest for pedestal studies in JET-ILW. Transport models required to match observed radiation data require less manipulation of the convection term when there is structure in $L_W(T_e)$ in the 0.3-1 keV range, but the results are still inconclusive. We also note how slow diffusion of W along a field line can be.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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