Characterising W radiation in JET-ILW plasmas

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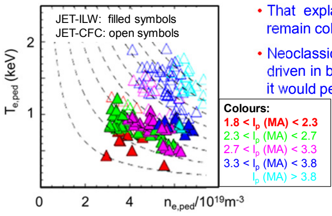
* See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

MOTIVATION FOR STUDY: pedestal in JET-ILW colder tan in JET-C

- JET-ILW (with W divertor): typically $T_{e,ped}$ ~ 0.7-1.2 keV. JET-C (CFC divertor) $T_{e,ped}$ ~ 1.5-2 keV [1,2]
- This is due in part to the much larger fuelling rates required to maintain the ELM frequency up and avoid W events and accumulation. At larger fuelling, pedestals have larger n_e, lower T_e



- That explanation is insufficient: at same fuelling levels, pedestals remain colder, particularly at higher densities.
- Neoclassical transport: H-mode pedestal can be W accumulator. W is driven in by inward pinch from ∇n_e, but once it reaches the top of ∇n_e it would penetrate much more slowly, by diffusion.

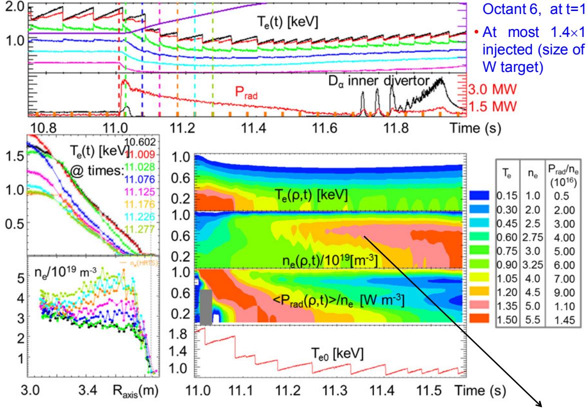
W can accumulate, in between ELMs, near $T_{e,ped}$.

W-associated radiation would slow down the rise of $T_{e,ped}$ in between ELMs, while density continues to rise until an ELM is triggered, resulting in colder pedestals.

W Ablation into L-mode plasma: JET 90472, 2 MA, 2.4 T, 1.2 MW NBI

To investigate to what extent the difference in $T_{e,ped}$ is due to W radiation in the pedestal region we injected W (by laser ablation) into cold **L-mode** plasmas at JET.

- W injected at outer midplane, Octant 6, at t=11 s.
- At most 1.4×10^{18} W atoms injected (size of hole left in the W target)

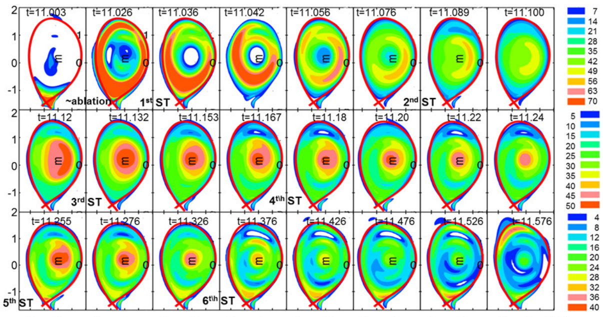


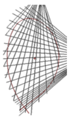
T_e	n_e	P_{rad}/n_e (10^{16})
0.15	1.0	0.5
0.30	2.0	2.00
0.45	2.5	3.00
0.60	2.75	4.00
0.75	3.0	5.00
0.90	3.25	6.00
1.05	4.0	7.00
1.20	4.5	9.00
1.35	5.0	1.10
1.50	5.5	1.45

- T_e collapses at plasma edge: radiating mantle.
- Below 100 eV radiation dominated by D, Be.
- Power detachment, collapse of $T_{e,edge}$ ➔ $T_{e,core}$ drop
- Langmuir probes: plasma detaches as soon as W reaches plasma edge, $T_{e,SOL}$ drops from 13 to 5 eV.

- Hollow n_e profile would prevent penetration of W into ρ<0.6.
- D, V adjusted to simulate effect of sawteeth bringing W inward and force $n_W(\rho,t)$ at 11.2 s.

BOLOMETRY, time averaged +/- 5 ms, kW/m^3





Persistent poloidal structures and plumes

Centrifugal effects produce in-out asymmetry: n=1 MHD, 500 Hz: Mach ~0.3

W ions propagate along field line by collisional diffusion, PS regime.

Random walk estimate of time required for W to spread poloidally

$$t = L^2/D_{||}$$

With $L=\pi(qR+a)$, q=3, $n_e=3\times10^{19}m^{-3}$ typical times are ~7-85 ms

These are comparable to radial transport times.

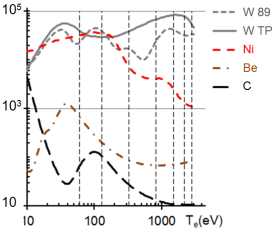
Z_W	$T_e=T_i$ eV	$D_{\|\|}$ 10^4 m^2/s	time ms
W^{8+}	160	1.1	85
W^{10+}	210	1.4	67
W^{13+}	290	1.9	51
W^{17+}	420	2.8	34
W^{19+}	500	3.4	28
W^{23+}	685	5.1	18
W^{27+}	881	7.0	14
W^{30+}	1230	13.0	7

W RADIATION, COOLING FUNCTIONS $L_Z(T_e)$

$$P_{rad} = \sum_Z n_e n_Z L_Z(T_e)$$

W is generally a very good radiator in the 0.5-2 keV T_e range. Calculation is challenging.
One way of representing the information is via the cooling functions $L_Z(T_e)$.

Radiated power density, W/m^3, assuming $n_e=3\times10^{19}m^{-3}$, $n_Z/n_e=2\times10^{-4}$, $n_{Be}/n_e=1\%$



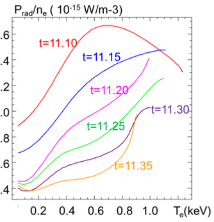
For low and medium Z impurities (C, Be, Ni) radiation is a decreasing function of T_e from 250 eV: burn through.

For W, two ADAS-based curves are shown:

- W 89: ADAS 89 baseline data, with only low level configurations used to estimate line radiated power;
- W TP: similar to W 89, but with a different choice of configurations, adjusted recombination coefficients to match ASDEX measurements in W^{24+}-W^{46+} range and more sophisticated ionization rates [3,4].

Both curves have regions of positive slope: when plasma is heated radiation increases, and it is harder for T_e to rise.

But both $L_W^{89}(T_e)$ and $L_W^{TP}(T_e)$ omit important effects, particularly below 1 keV.



Experimental observations indicate major flaw in dielectronic recombination (DR) coefficients for mid-range ions with an open 4f shell in the ground state. This can increase DR rates in W by a factor of 10. It would significantly move the ionisation balance to higher T_e with the expectation that structure would emerge in $L_W^{TP}(T_e)$ near ~600 eV. Work is in progress to incorporate these effects

As a first cut on the data, we plot P_{rad}/n_e as a function of T_e from 11.1 s. The n_W profile is convolved with these curves, but excepting the first timeslice, all exhibit an increasing character from T_e> 0.6 keV, steeper above 0.8 keV, and a bump at 0.4 keV, possibly revealing some structure in $L_W(T_e)$.

TRANSPORT MODELLING: radiation from different W models

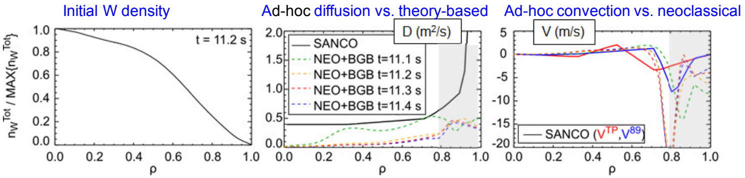
Ad-hoc D and V used in SANCO to compute P_{rad} from experimental n_e,T_e and two sets of atomic data, like W 89 and W TP.

Modelling starts at t=11.2, with the same diffusion and $n_W(\rho)$ for both cases.

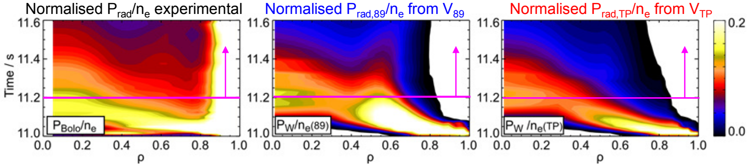
Convection needed to match radiation data near ρ=0.6 changes with atomic models: V^{89}, V^{TP}

JETTO-NEO+BGB [5-9] used to calculate theory-based transport coefficients, for comparison.

Initial W density — Ad-hoc diffusion vs. theory-based — Ad-hoc convection vs. neoclassical



Normalised P_{rad}/n_e experimental — Normalised $P_{rad,89}/n_e$ from V_{89} — Normalised $P_{rad,TP}/n_e$ from V_{TP}



Due to flatness of n_e near ρ=0.6, the V^{89} profile needed to reproduce the structure of P_{rad} in that region provides the best match to the theoretical pinch.

SUMMARY, PRELIMINARY CONCLUSIONS, FURTHER WORK

- W injection can produce detachment and a radiating mantle in the outer 10 cm inside the separatrix.
- Severely cooled edge allows deep penetration of neutrals, raising n_e & producing hollow n_e profiles.
- W motion along and across field lines has similar time scales: plumes seen in bolometry. This effect scales with machine size squared.
- Sawteeth can transport W inward to the core and back out.
- Work ongoing to improve ADAS predictions of W radiation in this relevant T_e range.
- Transport models required to match observed radiation data require less manipulation of the convection terms compared to theory when there is structure in $L_W(T_e)$ in the 0.3-1 keV range
- We hope to carry out more W ablation experiments into nom-sawtoothing plasmas

References:

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