Influence of impurity radiation loss on the L-H transition power threshold

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Since the discovery of the high-confinement mode (H-mode) significant work has been devoted to study the conditions for entry to this mode, especially the threshold power, characterised by $P_{loss}=P_{ohm}+P_{Aux} - dW/dt$. The effect of radiation on the power threshold is accounted for by subtracting the power radiated inside $\mathrm{Psi_N}=0.95$, P_{rad}, and constructing $P_{sep} = P_{loss} - P_{rad}$ ([1], [2], [3]). $\mathrm{P_{rad}}$ can't be neglected, and in predictions for ITER it has to be factored into the pulse scenarios, both for the H-mode entry and for possible re-entries after drop-out of the H-mode.

Electromagnetic radiation in the plasma comes from electron transitions – free-free, free-bound (continuum spectrum) and bound-bound (line radiation). The amount of power radiated from the different plasma regions depends on electron density and temperature, and also on plasma composition in the region itself. An unseeded fusion plasma contains predominantly hydrogen isotopes (pure or mixed), which are completely ionized in the pedestal and core regions, about 1% or less of light impurities (in the current JET ITER-like wall case mostly beryllium) which are also in most parts of the plasma completely ionized, and heavier impurities, with total concentration below 0.1%. Despite this low concentration they can dominate the total radiated power, as the mid-and high-Z impurities are not fully ionized even in the plasma core (especially in L-modes used to study L-H transitions) and their radiated power per ion is high. In this contribution we show the impact of impurities on radiation loss for different plasma fuel gases – isotopically pure hydrogen/deuterium/tritium plasmas, and helium plasmas.

This analysis is carried out in NBI and RF heated JET L-H plasmas, all with the same shape (Horizontal Target), $\mathrm{B_{tor}}=1.8\mathrm{T}$, $\mathrm{I_p}=1.7$ MA (see more data about it in [4]).

Experiment

The L-H transition power threshold is identified by gradually increasing the auxiliary heating power during the flat-top phase of the plasma pulse. Typically at the transition there is an increase of the edge plasma density and also a drop in Balmer alpha light (see example in figure 1). $\mathrm{P_{rad}}$ during the power ramp just before the transition is a primary object of this study.

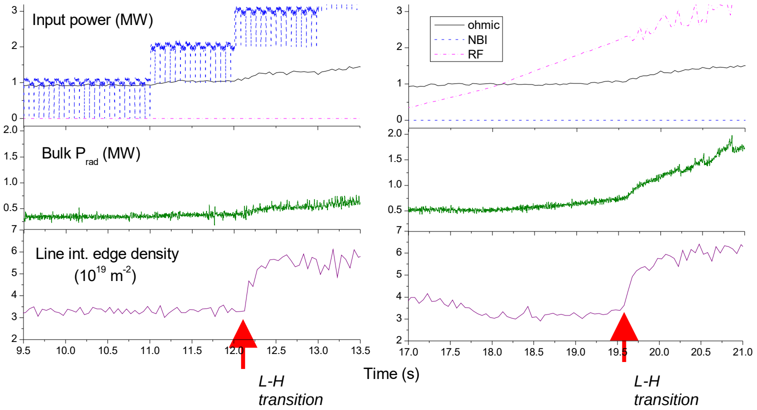

Figure 1: Power ramps in JET pulse 100847 – NBI heating (left) and RF heating (right)

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[1] See the author list of Mailloux et al, Nucl. Fusion **62** (2022) 042026

Total power lost by plasma via electromagnetic radiation is estimated using bolometers. In JET there are two sets: with approximately horizontal lines of sight in one octant, and vertical lines of sight in the other. The data can be then either processed via complete tomography code under human supervision (very costly in time and manpower) or by simplified codes using weighted sums of certain lines of sight to quickly estimate total radiated power and so-called bulk radiated power (estimated as coming from within the 0.95 region). The total power contains radiation from all sources, including line radiation from light impurities, but in the bulk power, apart from free-free electron radiation, only the heavy impurities contribute to the power loss. This bulk radiated power, P_{rad}, is the one used in [1-3] as a correction for the L-H power threshold estimation.

Radiation loss due to each impurity is estimated using its radiation in the VUV/XUV region. In the case of tungsten, the unresolved transition array of many spectral lines located in XUV region of 4 to 6 nm is used to estimate the total tungsten concentration along the line of sight, and then the result (assuming flat tungsten concentration distribution) is used to estimate the total tungsten radiated power with model cooling curves [5]. In the case of mid-Z metals, the concentration is calculated using the appropriate lines from Na-like ion radiation. The method of estimation, though for higher temperature and Li-like ions is described in [6]. The total radiated power from each impurity is then obtained using their cooling curves.

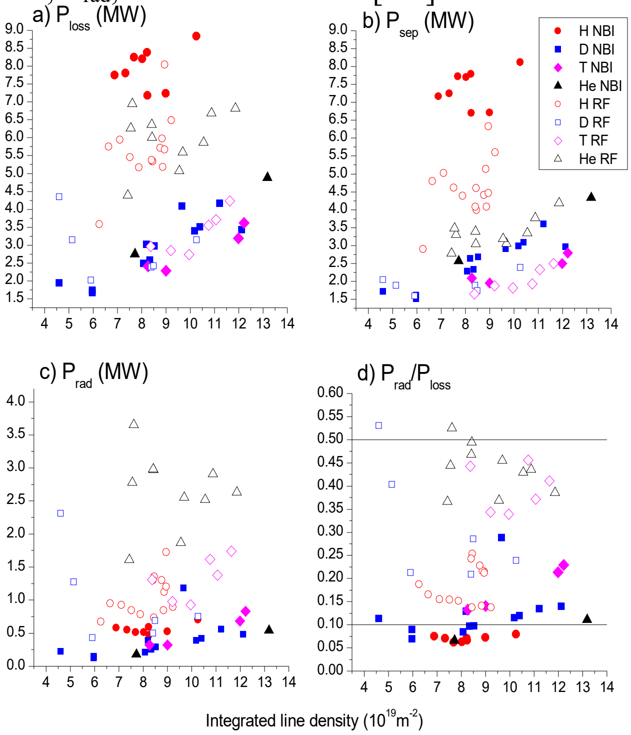

Figure 2: a) P_{loss} as a function of density just before L-H transition. b) P_{sep}, c) bulk radiated power P_{rad}, d) P_{rad}/P_{loss}. Hydrogen is represented by red circles, deuterium by blue squares, tritium by magenta diamonds, He by black triangles. Full symbols denote NBI heating, hollow symbols RF.

Results and discussion

As can be seen from figure 2, P_{rad} can affect P_{sep} considerably in certain L-H transitions.

In general, the bulk radiation in NBI heated plasmas is low– apart from one deuterium pulse (where there was an identified tungsten influx). So the radiation loss in such heating scheme is minimal. In the case of RF heated plasmas the bulk radiation can be very high, especially for low-density pulses, exceeding 50% of the total power loss. The dependence on fuel mass is conflated with the RF heating scheme: in H we use H-majority heating, in other plasmas H minority. In H plasmas at low density P_{rad} can be large due to enhanced sputtering from faster ion tails, while slower tails will be present in H-minority heated D, He, T plasmas. The strength of the fast ion tail in H-minority heated plasmas increases with main ion mass. Note that there is no data at low density for He because P_{loss} was too high to obtain transitions, and at low density in T the transitions were ohmic, with very low P_{loss}.

The results for specific impurities are visible in figure 3. The estimated radiated power per impurity are scaled to bulk P_{rad}. This variable was chosen because it is used in [1-3] to calculate power threshold, and also because of the popular assumption that high and mid-Z impurities radiate from bulk plasma. In fact, at least 1/3 of the mid-Z (Ni, Cu) radiated power comes from the regions very close to the separatrix, and therefore also regions which are outside the Psi_N=0.95 boundary, so the sum of those contributions frequently exceeds the bulk radiation itself.

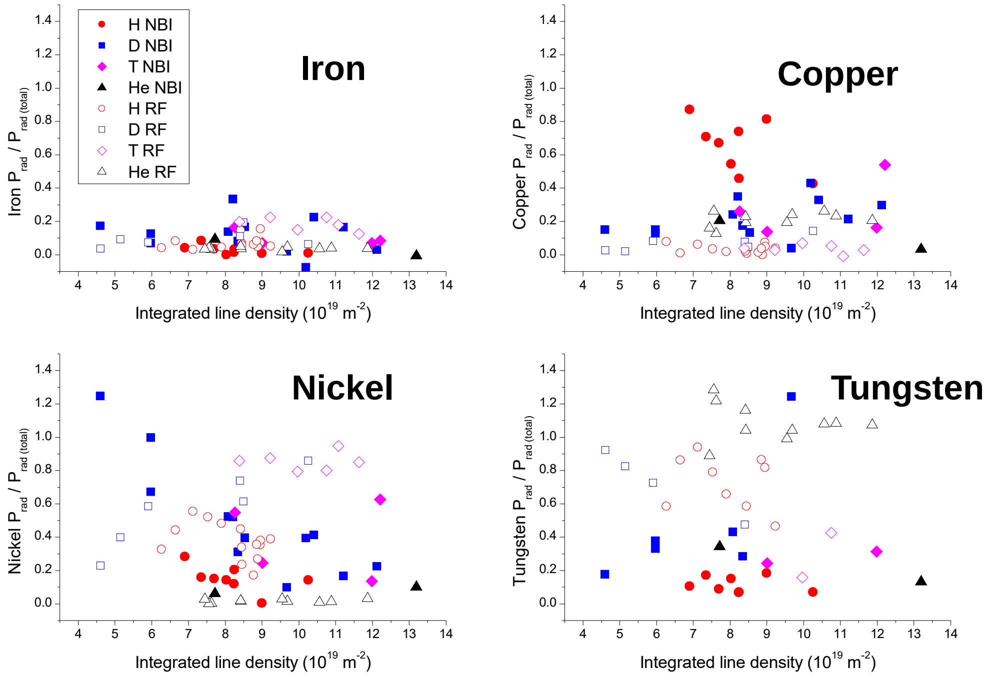

Figure 3: Radiated power of specific impurities, scaled to bulk radiated power

The results are shown for iron, copper, nickel and tungsten, because other impurities radiate either only from external regions (e.g. beryllium), or their contributions can be neglected (e.g. molybdenum). In principle, iron is also an impurity that does not strongly contribute to radiation in JET-ILW, with Fe P_{rad} consistently below 20% of the bulk P_{rad}. For Cu, there is a strong difference between RF and NBI heated plasmas – in the RF heated plasmas traces of copper can be found only in helium pulses, in all hydrogen isotopes copper contribution is negligible. The strong copper radiation in NBI heated H plasmas is due to Cu being injected by NBI during that H campaign (duct source). Its impact on the plasma edge may explain the unexpectedly high P_{loss} in those plasmas.

Nickel and tungsten contributions are strongest in RF heated pulses. Unfortunately, we don't have the tungsten data for all presented pulses – during the early tritium campaign the spectrometer measuring the XUV tungsten feature had to be frequently switched off, and later, during the deuterium-tritium pulses, its detector was destroyed by strong neutron fluxes. Nevertheless, we can say that W and Ni together radiate frequently more power than the estimated bulk P_{rad}. This means, that even if their contributions are overestimated due to non-flat impurity profiles or uncertainties in cooling curves, any other radiative loss during those pulses is negligible compared to their summed up contribution and control of those impurities is essential for reaching H-mode in RF heated plasmas. Ni and W P_{rad} have different dependence on the working gas. In the case of helium, for any heating, the Ni contribution to radiated power is negligible when compared to tungsten. This is also true in the case of the W-poisoned deuterium NBI pulse. In the case of hydrogen, for NBI heated plasmas both contributions are low, but for RF heated they determine total radiation, with similar contributions (slightly more W than Ni). In tritium data we see high estimated power from Ni, much lower from W, at least for existing data (only high density pulses). Data from deuterium, where the density dependence is measured in the largest region, suggest that the nickel contribution is decreasing with density for NBI-heated pulses and increasing for RF-heated, whereas the tungsten contribution is roughly the opposite/complementary.

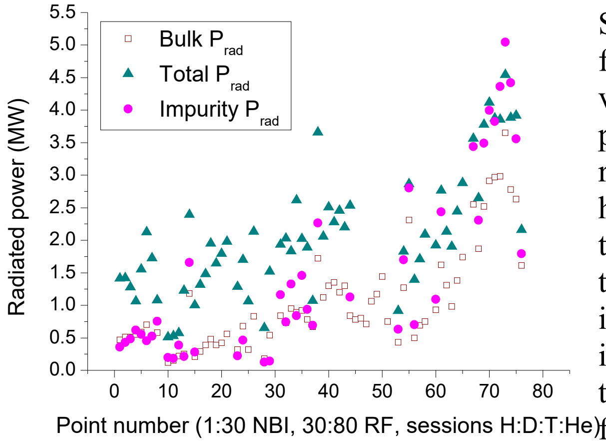

Figure 4: Sums of the estimated impurity radiated power, compared to bulk and total radiated power of the same pulse.

Summarizing, total estimated impurity P_{rad} from those four mid and high-Z elements is very rarely lower than the bulk radiated power, and frequently is comparable with total radiated power (Fig. 4). Impurities presented here are therefore the dominant component of the radiation loss in the plasmas close to L-H transition. Which of the impurity is dominant in which pulse depends on a complex interplay of impurity sources and transport. In the case of RF heated plasmas, Ni is eroded from RF antennas, and its concentration for high-density plasmas is ~0.02%, whereas for low density deuterium plasmas it may rise ~ 0.1%. In the case of tungsten, there are two possible sources – divertor and NBI beam shine-through in the inner wall. Its density dependence is very similar to nickel, with roughly flat high density part and strongly increasing low density part, but with one difference – helium pulses have much higher W content than the hydrogen (any isotope) pulses with similar density. The possible explanations of this behaviour include many steps, because most probably none of the metals are eroded directly by fuel ions. Most common description for hydrogen is that fuel ions sputter beryllium from the walls, limiters and beryllium deposits in the inner divertor, and most of the main plasma source of impurities is beryllium erosion of heavier metals. In the case of helium, there may be also direct sputtering by the working gas. Ni sputtered from the RF antennas may (due to the magnetic configuration) reach the divertor and therefore, contrary to the copper ions from beam ducts, those ions increase tungsten source. This would explain the fact, that in RF heated plasmas there is a strong correlation between Ni and W concentrations (not radiated powers!), but with different slope for hydrogen isotopes and for helium. Any possibility of diminishing the impact of this radiation loss has to take into account those complex production and transport mechanisms.

Conclusions

Our study shows, that in JET-ILW the loss of power via impurity radiation is an important part of the total input power needed to enter the H-mode (up to 50%), and we show also which impurities contribute most to this loss. The radiative loss is highest for pulses heated by RF, with antennas sending significant amounts of Ni into the plasma, where it erodes the tungsten divertor. For those RF-heated pulses, the main radiator is most often tungsten, with Ni as a close contender. The NBI heated pulses have lower direct radiation losses, with copper as a main impurity. Their total power loss is smaller, though as [1] discusses, the impurities can still contribute to increase of the power threshold by some other mechanisms. The more detailed study is in plans for a future publication.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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