Comparing the bulk radiated power efficiency in carbon and ITER-like-wall environments in JET.

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1) Abstract

We use a parameter β_r for all plasmas that allows detecting the pollution of the plasma bulk by highly radiative impurities. This parameter is defined as the radiative loss of the mixture of impurities relative to their mean Z^2 and was used in the past to characterize the efficiency of radiative mantles in Neon seeded discharges [1,2]. We show that this parameter, though global, is very sensitive to the presence of highly radiative impurities in the bulk of the discharge. In the carbon environment of JET, the value of β_r is around 10^{-40} MW.m^6, indicating the absence of highly radiative impurities in the plasma. In the ILW machine, the value of β_r is found to depend on the type of additional heating and confinement state of the plasma. We observe that neutral-beam injection (NBI) introduces little W into the plasma, with a β_r between 2 and 3 10^{-40} MW.m^6. Ion-cyclotron radio-frequency (ICRF) waves yield a β_r of order 5 in L-mode and 10^{-39} MW.m^6 in H-mode when no edge-localized modes (ELMs) are present.

2) The definition of βr.

Following references [1,2] a parameter characterizing the quality of cooling of the impurities in the bulk of the plasma can be written as:

$$\beta r = P_{\text{radbulk}}/(\text{Zeff}-1)\, n_e^2 \qquad (1)$$

where n_e is the line-averaged density provided by high-resolution Thomson scattering and Z_{eff} is calculated from bremsstrahlung emission measured along a horizontal line-of-sight crossing the plasma centre (i.e. not passing through the divertor region). P_{rad} in the bulk is evaluated by bolometry. In JET, we neglect the bremsstrahlung and cyclotron radiation; however, in a machine such as ITER, they will have to be calculated or measured and removed from the total radiated power before evaluating β_r. We give the expression for β_r in a general case with different types of impurities in a deuterium plasma. First the bulk radiated power can be written as:

$$P_{\text{rad bulk}} = n_e V \sum_k n_{\text{imp}}^k \sum_i a_i^k b_i^k c_i^k L_{ti}^k ,$$

In this expression n_{imp} is the total impurity density, n_e the electron density, $a_i = n_i/n_{\text{imp}}$ the fraction of impurity ions with charge Z_i, $b_i = n_{ei}/n_e$, the fraction of the density in the volume

*See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US where the ion with charge Z_i radiates and $c_i=V_i/V$ the fraction of the volume in which the same ion radiates. L_{ti} is the radiative cooling function for the same ion with charge Z_i. We suppose in this expression that the electron temperature T_e is homogenous in the volume where the ion of charge Z_i is radiating, as well as the density of impurity ions and electrons. Here k denotes different types of impurities. We can write the expression for Z_{eff} as:

$$Z_{\text{eff}} = 1 + \frac{1}{n_e} \sum_k n_{\text{imp}}^k \sum_i a_i^k \, Z_i^k \, (Z_i^k - 1)$$

If we combine these expressions in relation (1), we find

$$\frac{\beta_{\text{r}}}{V} = \frac{\sum_k \varepsilon_{\text{imp}}^k \sum_i a_i^k b_i^k c_i^k \, L_{ti}^k}{\sum_k \varepsilon_{\text{imp}}^k \sum_i a_i^k \, Z_i^k (Z_i^k - 1)} \quad (2) \qquad \text{where } \varepsilon_{\text{imp}}^k = \frac{n_{\text{imp}}^k}{\sum_k n_{\text{imp}}^k} .$$

We notice that β_r/V has the dimension of L_t and can be expressed in $W.m^3$.

<u>3) The physical meaning of β_r</u>

The radiative loss parameter of an impurity k is defined in reference [3] as $S_k = \hat{P}_{\text{rad}\,k} / (n_e \, n_k)$, where $\hat{P}_{\text{rad}}$ is radiated power density (W/m^3). It can be calculated using the same notations used in section 2.

We find in this case that for an impurity k, $S_k \approx \sum_i a_i^k \, b_i^k \, c_i^k \, L_{ti}$ where i takes account of the different ionization states. Hence β_r can be expressed as a function of the radiative loss parameter S_k of the impurities as:

$$\frac{\beta_{\text{r}}}{V} \approx \frac{\sum_k \varepsilon_{\text{imp}}^k \, S_k}{\sum_k \varepsilon_{\text{imp}}^k \sum_i a_i^k \, Z_i^k (Z_i^k - 1)} . \quad (3)$$

For W, the radiative loss parameter increases moderately for T_e above 100 eV (about a factor of 2 between 100 eV and 3 keV), while it decreases by a factor of 10 for carbon in the same range. In the case of W pollution, the rather weak dependence of S_W with T_e leads to the conclusion that an increase of β_r must be associated with an increase of the relative concentration of W in the bulk $\varepsilon_{\text{imp}}^{\text{W}}$ (even if this increase is not sufficient to have a measurable impact on Z_{eff}). The second point is that the value of β_r is liable to be very resilient to T_e changes with tungsten pollution. Finally, in the ILW changes in the values of β_r will always indicate a change in the bulk impurity mixture.

<u>4) Carbon environment in H-mode.</u>

In Figure 1, β_r is plotted for an H-mode shot with ELMs. Two heating phases are present, the first with 9 MW of NBI power, the second with 19 MW of NBI power. Figure 1 shows that the 9 MW phase has a value of β_r close to 10^{-40} $MW.m^6$,value usually obtained in L-mode. At 19 MW, β_r decreases to 0.5 10^{-40} $MW.m^6$. This decrease may be attributed to the behaviour of the radiative loss parameter of the light impurities and carbon (S_C) in particular. As the additional heating power is increased, T_e increases in the whole bulk including the pedestal region.

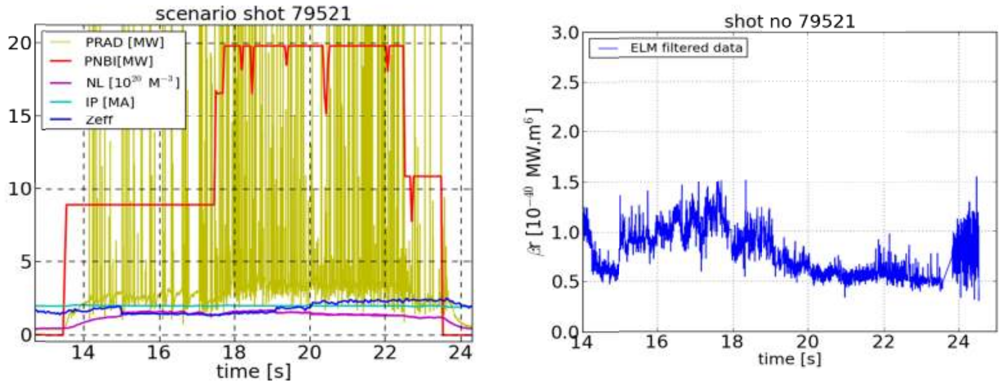

Figure 1
Left) scenario of shot 79521, carbon environment.
Right) β_r calculated during the NBI additional heating phase.

As a consequence, the radiative loss parameter of carbon decreases (numerator of relation (2)), thus yielding lower β_r values. This simply indicates that the low-Z impurities become even less efficient at radiating in the bulk when T_e is increased. We observe that at NBI heating power below 10 MW, the β_r value is the same in L or H-mode.

<u>5) ILW transition from L- to H-mode with NBI only.</u>

Figure 2 illustrates the behavior of βr when there is an L-H transition with NBI heating. We notice first that the value of β_r during the L-mode phase (8s<t<10s) is around 2.2 10^{-40} MW.m^6. We have measured values as low as 1.3 10^{-40} MW.m^6 for some ILW plasmas during NBI heating, close to those measured in carbon pulses. During the H-mode phase (10s<t<14s), β_r increases from 2.2 to an average 3.7 10^{40} MW.m^6, a 68% increase, though the additional heating power is increased from 1.5 MW to 10 MW. This result illustrates the fact that in this scenario, NBI heating increases moderately the amount of high-Z impurities from L to H-mode. The fact that Z_{eff} remains unchanged also indicates that the pollution by low-Z impurities does not increase either.

<u>6 ILW transition from L to H-mode with ICRF only</u>In Figure 3, a plasma where only ICRF is

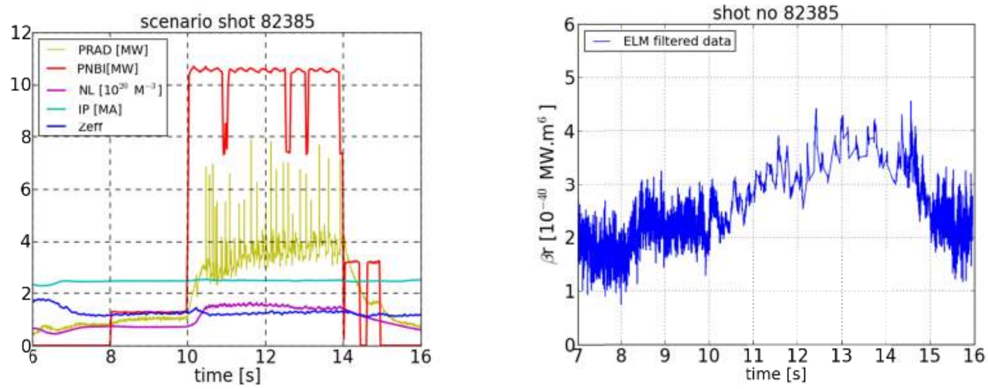

Figure 2
Left) scenario of shot 82835in ILW, L-H transition, NBI heating.
Right) value of β_r calculated during the additional heating phases.

used triggers an L-H transition. This is visible in the plasma traces where the D_alpha signal drops at *t*=17.27s. The energy stored in the discharge is not sufficient to trigger ELMs. After the transition, β_r increases from 5 to 10, a 100% increase. β_r around 10^{-39} MW.m^6 is the level commonly observed in the JET database when ICRF triggers H-modes without ELMs. It is one of the highest values obtained so far for β_r. As the level of β_r jumps to 10^{-39} MW.m^6 immediately after the ICRF power has reached the threshold, it can be speculated that this is partly the effect of the transport change. As transport decreases in the bulk after the H transition, the amount of impurities there increases.

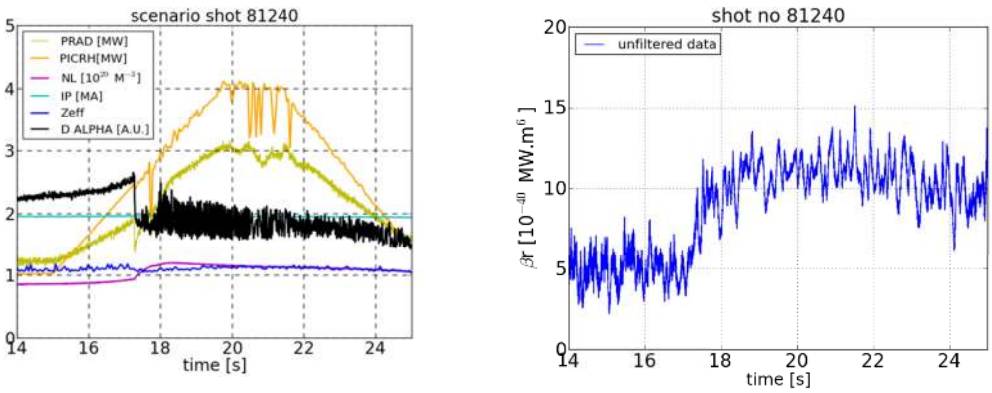

Figure 3

Left) scenario of shot 81240 in ILW, L- H mode transition , ICRF heating.

Right) value of β_r calculated during the additional heating phases.

7) Conclusions

We have shown that a global time-dependent parameter can give reliable information about the presence of highly radiative impurities in tokamak discharges. It can be calculated for all plasmas regardless of the scenario and of the confinement state. We have compared JET shots in the carbon environment with ones in the ILW. The very low values obtained in the carbon environment clearly indicate the absence of significant radiation from highly radiative impurities in the bulk plasma, with an average value of $\beta_r \approx 10^{-40}$ MW.m^6. When switching to the ILW environment, we observe that plasmas heated with NBI have relatively low β_r values of order 2 to 3 times those measured in the carbon environment. During the L-H transition the β_r parameter is observed to increase moderately even with a sevenfold increase of the NBI power. In the case of ICRF heating, the plasmas systematically yield β_r values of order 5 10^{-40} in L-mode and 10^{-39} MW.m^6 in H-mode if no ELMs are present.

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