Scaling of Prad with density and Zeff in the bulk of JET

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Test of the original multi-machine scaling law in ILW

The original multi-machine scaling [1] establishes a link between total Prad, Zeff and density. A reduced form of the scaling that was found to be a good approximation reads as:

$$Zeff \approx 1 + 7\,\frac{Prad}{S\,Ne^2} \qquad (1)$$

with Prad in MW and Ne in 10^{20} m^{-3}, S envelope of the plasma in m^{-2}. This scaling was found to hold in many different machines of all sizes, equipped with divertor or limiter [1].

In JET with its new ITER-Like Wall (ILW) configuration [2], we found that this scaling in Ohmic, H or L mode gives relatively good predictions at high density values near or close to detachment and during impurity seeding. The main experimental condition for the multi-machine scaling to be close to the data is that the radiated power in the divertor is significantly larger than the radiated power in the bulk. In Limiter case this is also observed when most of the radiation is located at the edge of the machine. This is illustrated for two Ohmic divertor shots near the detachment limit in Figure 1, where the histogram of $Prad_{div}/Ne^2$ and $Prad_{bulk}/Ne^2$ is plotted.

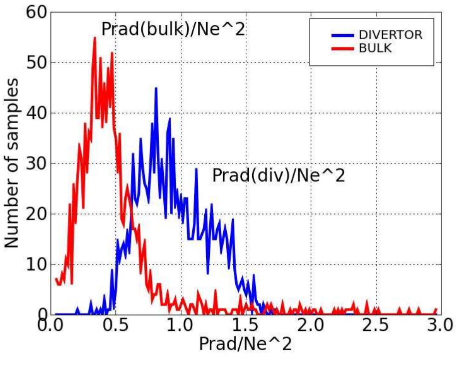

Figure 1
Histogram of $Prad_{div}/Ne^2$ and $prad_{bulk}/Ne^2$ in $MW/(10^{40}\ m^4)$ for shots 80821 and 80822

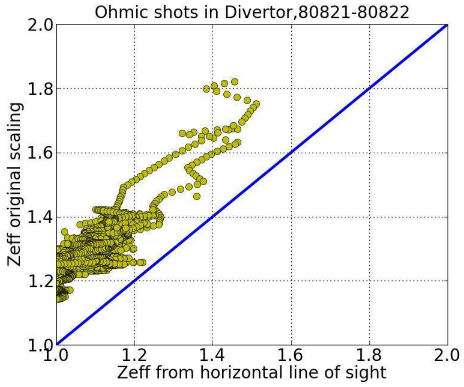

Figure 2
Zeff predicted by original multi-machine scaling versus Zeff from Bremsstrahlung signal and profiles

Figure 2 shows the Zeff values predicted by the original multi-machine scaling versus Zeff obtained from a Bremsstralhung signal, density and temperature profiles. Although the values predicted are slightly too large (by 0.2) the slope is correct. A closer look at both divertor and bulk regions reveals that for these two shots, there is no correlation between divertor radiated power and Zeff while the radiated power in the bulk is very well correlated with Zeff (Figure 3). The multi-machine scaling in this case describes the correlation of the bulk radiated power with Zeff, but the slope of the scaling (the factor 7 in (1)) is given mostly by the amplitude of the $\mathrm{Prad}_{div}/\mathrm{Ne}^2$ term that is larger than the $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ one. The surprising result is that the multi-machine scaling does not imply that all the radiation is correlated to Zeff.

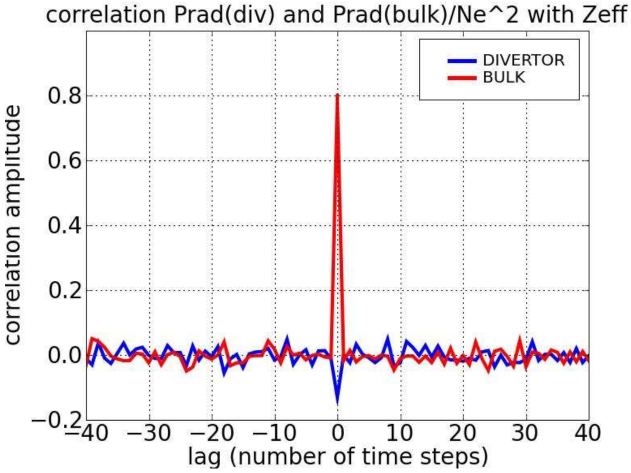

Figure 3
Normalized cross-correlation function of $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ and $\mathrm{Prad}_{div}/\mathrm{Ne}^2$ with Zeff. Ohmic shots 80821 and 80822 during detachment.

Divergence with the original multi-machine scaling

The slope of the original scaling is not recovered anymore when the radiated power in the bulk increases and becomes of the same order or larger than the divertor radiated power. This situation is encountered in the ILW in L and H mode and is associated to the presence of high Z impurities in the bulk. This is illustrated for a series of shots with ICRH heating in Figure 4 where the histogram of $\mathrm{Prad}_{div}/\mathrm{Ne}^2$ and $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ is displayed. If $\mathrm{Prad}_{div}/\mathrm{Ne}^2$ remains bounded between 0 and 4, values of $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ up to 10 are observed. Figure 5 (top) shows the Zeff calculated with the multi-machine scaling versus the experimental one. A general result is that the shift of Zeff from the prediction of the multi-machine scaling is found to increase linearly with the value of $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ (Figure 5, bottom).

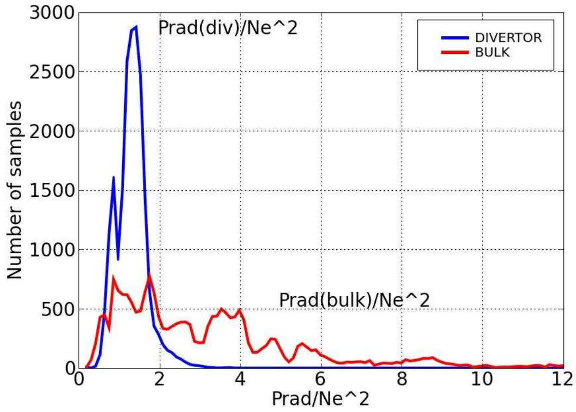

Figure 4
histogram of $\mathrm{Prad}_{div}/\mathrm{Ne}^2$ and $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ for series of shots 80770-80778

Scaling of $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ with Zeff

As was discussed previously, $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ is always well correlated with Zeff and the two can be plotted against each other. The systematic result that is found is that Zeff is always a linear function of $\mathrm{Prad}_{bulk}/\mathrm{Ne}^2$ and secondly that the slope of the scaling depends on the nature of the impurity mixture contaminating the bulk. The robustness of this dependence differs with the behaviour

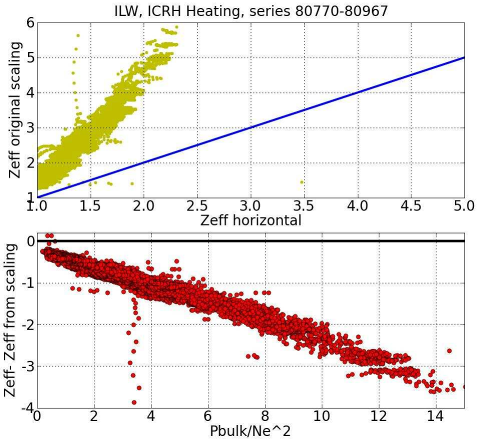

Figure 5
top: Plot of Zeff predicted by original multi-machine scaling versus Zeff obtained from Bremsstrahlung and profiles.
bottom: Departure of Zeff from multi-scaling prediction as a function of $\mathrm{Prad}_{\mathrm{bulk}}/\mathrm{Ne}^2$.

of the divertor radiation that is not systematically correlated with Zeff. The linear dependence is found to hold, in Ohmic, L or H mode, limiter or divertor configuration. In order to understand the meaning of the scaling, we write it in the following way:

$$\alpha \approx \frac{\mathrm{Pr}\,ad_{bulk}}{Ne^{2}\,(Zeff-\beta)} \tag{2}$$

The parameter α characterizes the radiated power per Zeff at a given density. The parameter β is always close to 1 and mostly subtracts from Zeff the deuterium contribution. To illustrate the validity of relation 2, we plot in Figure 6 $\mathrm{Prad}_{\mathrm{bulk}}$ as a function of Ne^2(Zeff-β) with the value of β set to 1. The parameter α is the slope of the linear fit. Figure 6 is from a series of shots heated by ICRH only, where the discharges switched from L to H mode forth and back. The value of the α parameter determined from the slope of the fit is 14 and this is one of the highest values that we have measured, indicating that the impurities contributing to Zeff are rather efficient radiators in the bulk. This result is compatible with the presence of high Z impurities in the bulk such as W but not exclusively.

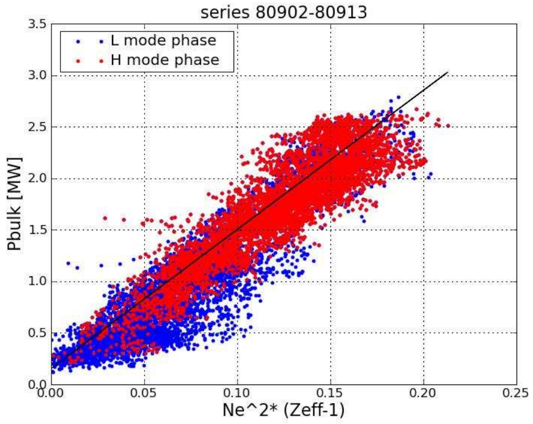

Figure 6
$\mathrm{Prad}_{\mathrm{bulk}}$ as a function of Ne^2 (Zeff-1),
slope of the fit: α=14

Figure 7 shows another example of a series of shots ran during the same day where both limiter and divertor configurations were tested. We use in that case the traditional multi-machine scaling plot of relation 1. Two different slopes corresponding to the 2 plasma configurations were found. The one in limiter has a low value of α (3.3) indicating that the bulk is contaminated by light impurities that do not radiate efficiently at high temperatures. When the X point is formed, the divertor washes away the light impurities and whatever remains in the bulk is more efficiently radiating (α=14.5) and is again compatible with the presence of impurities such as W, Cu, Fe or Ni.

Independence of the α parameter with the confinement quality of the discharge.

Another result is that in the ILW, the radiated power per effective charge (α) is not sensitive to the confinement properties of the discharge. This is shown in Figure 6 where both L and H mode phases are plotted on the same graph. The slope of the scaling is unchanged by going from L to H mode. This result indicates that the impurity mixture in the bulk is not modified by the change of confinement and therefore the radiated power per Zeff measured by the parameter α remains the same.

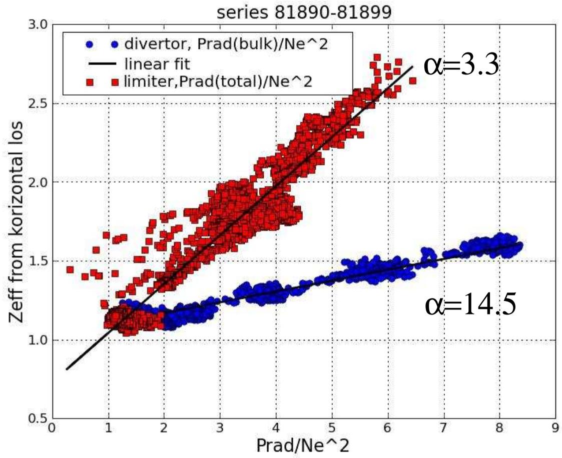

Figure 7
Zeff as a function of $\mathrm{Prad}_{\mathrm{bulk}/}\mathrm{Ne}^2$ for limiter and L mode Divertor discharges with ICRH and LH heating.

Conclusion

In ILW, the multi-scaling is found to hold at very high densities close to the detachment. The main condition for this scaling to give Zeff values close to the ones deduced from measurements was identified: The divertor radiation must be much larger than the bulk one. For this reason, the slope of the original multi-machine scaling characterizes mostly the impurities radiating in the Divertor at low temperature. As far as the bulk radiation is concerned, a relationship of the same type than the multi-machine scaling is found to hold. A difference with the original scaling is that the slope of the scaling is very sensitive to the impurity species of the bulk. The α parameter defined in (2) that characterizes the radiative efficiency of the bulk impurities relative to Zeff is a useful tool to get an idea about what type of impurity is radiating in the plasma bulk. For example a high value of α indicates very efficient radiators and points towards high Z impurities being responsible for a good part of the radiation. On the other end, a low value of α indicates contamination of the bulk by light impurities that are not efficient at radiating at these high temperatures.

In ILW, the α parameter does not carry information about the confinement state of the discharge probably because with divertor screening the composition of the bulk impurity mixture does not change from L to H mode.

*See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

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[2] Matthews G F et al, Phys. Scr. **T128** (2007) 137–143