The radiative power in Tore Supra and its link with Zeff

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This study aims to find parametric dependencies for the radiated Power and Zeff to predict the values expected after the completion of the upgrade of the LHCD power (CIMES project). It also revisits the link between Zeff and P_{rad} in the configuration of Tore Supra. Similar work for divertor configuration can be found in [1, 2].

A large data base of several hundred shots covering the last 3 years of operation is used to study the dependences of the total radiated power with global plasma parameters such as mean electron density, total plasma power, LHCD and ICRH power. It has to be noted that all the discharges are fuelled only by deuterium.

The effective charge (Zeff) calculated from the visible Bremsstrahlung is also investigated.

The data is recorded every 50 or 100 ms on the current plateau of the discharges and the range of parameters covers variations of ne from 0.8 to 5.3 10^{19} m^{-3},variations of Te from 0.9 to 4 keV and plasma currents from 0.5 to 1.2 MA. It is to be noted that the Greenwald ratios span from 0.2 to 0.81 and that the plasma is never in a state where radiative instabilities are triggered at the edge leading to MARFES, detachment and/or disruptions.

Finally all these shots have in common that the plasma is operated with additional heatings and that the plasma is leaning on the Toroidal Pumped Limiter (TPL). The ohmic plasmas present different dependencies that are not discussed here.

1) Dependences of the radiated Power:

The radiated power in a tokamak is composed of different contributions i.e.; line radiation, Bremsstrahlung and cyclotron radiation. However in all the tokamaks in operation at the moment, the most important term is the line radiation, the other contributions being very small. FIGURE 1 shows a tomographic reconstruction of the bolometers measurements. It shows that the radiation occurs at the plasma edge with a very strong poloidal asymmetry, a large fraction of the radiation being located just above the TPL (about 50%). The concentration of the radiated power above the limiter indicates that what is radiating in this region is the material of the limiter i.e. carbon. As a consequence, in Tore Supra the main impurity contaminating the discharge is believed to be the carbon that is eroded during the discharge from the TPL on which the plasma is leaning. This erosion has been experimentally studied in a previous work and the carbon flux at the TPL has been found to scale linearly with the total power (P_{tot}) independently from the type of additional heating used [3].

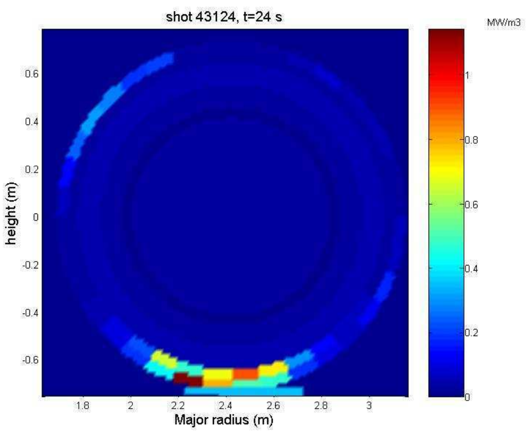

Figure 1: tomographic reconstruction of the Radiated Power during additional heatings.

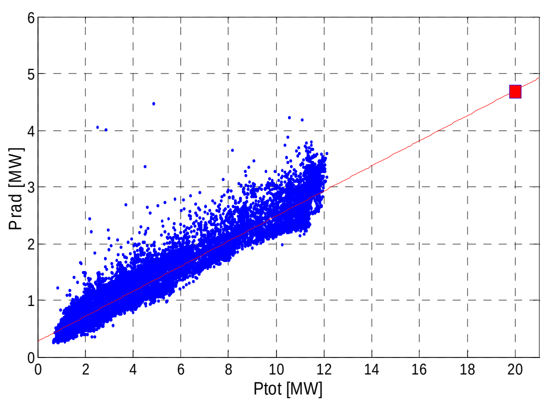

Figure 2: Plot of Prad as a function of Ptot with linear fit. Also shown, extrapolation of Prad with Ptot=20 MW.

If we assume that carbon is the main source of impurity, we can write that locally the radiation scales as $P_{\rm rad}= n_{\rm e}\ n_{\rm C}\ L(T_{\rm e})$ where $L(T_{\rm e})$ is the radiative function that takes into account the contribution of the different ionization states of the carbon to the radiation as a function of $T_{\rm e}$. We can try to extend such dependence to the global case by assuming that $n_{\rm C} \propto P_{\rm tot}$ so that $P_{\rm rad}$ scales as:

$$P_{\rm rad} = n_{\rm e}\, P_{\rm tot}\, G \qquad [1]$$

In this expression G is an unknown function, plasma parameters dependant that integrates the contribution of the different carbon lines along the profiles. Figure 2 represents $P_{\rm rad}$ as a function of $P_{\rm tot}$ and this figure shows that in fact above 1 MW $P_{\rm rad}$ is a linear function of $P_{\rm tot}$ so that G scales as $1/n_{\rm e}$.

However this result is ambiguous as $n_{\rm e}$ and $P_{\rm tot}$ are not independent variables in Tore Supra. To illustrate this, we plot the distribution of $n_{\rm e}$ and $P_{\rm tot}$ within the database (Figure 3). Figure 3 shows that $P_{\rm tot}$ increases with $n_{\rm e}$ so that the increase of $P_{\rm rad}$ with $P_{\rm tot}$ could also be attributed to a change in $n_{\rm e}$. However, the database contains sufficient data to de-correlate the effect of both parameters and the result is shown in Figure 4, where the effect of a change of $n_{\rm e}$ on $P_{\rm rad}$ is observed with $P_{\rm tot}$ at a fixed value of 6 MW.

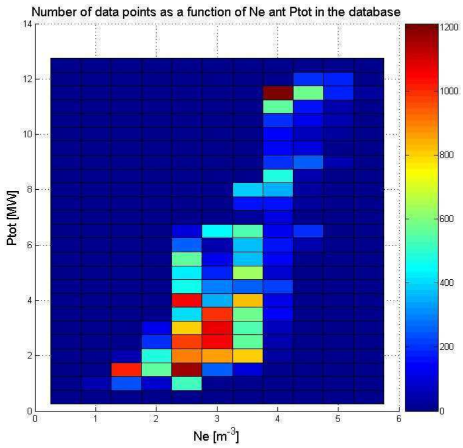

Figure 3: Distribution of $n_{\rm e}$ and $P_{\rm tot}$ in the database.

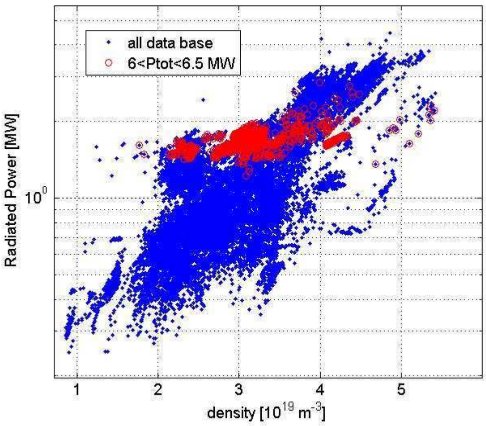

Figure 4: radiated power as a function of $n_{\rm e}$. In red, data points corresponding to $P_{\rm tot} = 6$MW.

Figure 4 shows that a change of $n_{\rm e}$ by more than a factor of 2 at $P_{\rm tot} = 6$ MW does not produce a corresponding change in $P_{\rm rad}$ as only an increase of about 25% is observed. If we assume that relation 1 indeed holds, this results confirms that the weak dependence of Prad with Ne finds its root in the fact that G scales as $1/n_{\rm e}$.

A linear fit has been applied to the data plotted in Figure 2 and yields $P_{\rm rad} = 0.22\ P_{\rm tot} + 0.27$ where $P_{\rm tot}$ and $P_{\rm rad}$ are in MW. The dispersion of the data around the fit has a standard deviation of 0.19 MW. This relation can be used to predict the radiated power expected for operation of the upgraded additional heatings in Tore Supra as shown in Figure 2. $P_{\rm tot}$=20 MW yields $P_{\rm rad}$= 4.7 MW.

2) Dependences of Zeff

If carbon is the dominant impurity, we can write

$$Zeff \approx 1 + \frac{\sum_{i=1}^{i=6} nc_i\,(Z_i^2 - Z_i)}{ne} \quad \text{With } n_{Ci}=\alpha_i\, n_C \quad \text{and} \quad \sum \alpha_i = 1$$

$$Zeff = 1 + \frac{nc}{ne}\sum \alpha_i \cdot (Zi^2 - Zi)$$

Finally if $n_C = M\,P_{tot}$, where M is an unknown constant, Zeff should be about:

$$Zeff - 1 \propto \frac{Ptot}{ne}\sum_{i=1}^{i=6} \alpha_i\,(Z_i^2 - Z_i) = M\,\frac{Ptot}{ne}.Fi \qquad [2]$$

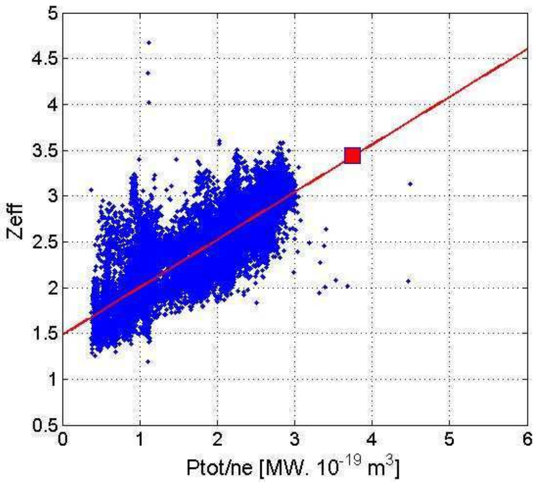

Figure 5: *Zeff* as a function of P_{tot}/n_e. P_{tot} is in MW, n_e in 10^{19} m^{-3}, Deuterium case, data from only 2008 campaign.

Where Fi is the fully ionized state of the carbon in the core and is equal to 30. In order to check this, we plot Zeff as a function of P_{tot}/n_e in Figure 5.
Provided that relation 2 holds *Zeff* should be linear with P_{tot}/n_e. Figure 3 shows that this is roughly the case as some dispersion exists (the standard deviation of the data around the fit is 0.30) that could be explained by the presence of other types of impurities in the discharge. From the slope of Figure 5, it is possible to calculate an experimental value for *M* and to estimate the fraction of Carbon in the discharge (n_C/n_e). *M* is found to be 1.73 10^{17} m^{-3}/MW and n_C/n_e spans from less than 1% up to 5%. The data has been extrapolated to the additional heatings upgrade foreseen in Tore Supra where 15 MW will be applied at n_e=4e^{19} m^{-3} and yields a Zeff value of 3.44 +/- 0.30.

3) Link between *Zeff* and P_{rad}

A link between P_{rad} and Zeff can be considered provided that the ratio of the edge Zeff upon the core one remains constant. This is necessary as the Zeff currently measured corresponds to the value in the core where no line radiation is expected. With this restriction in mind, the dependence with P_{tot} in expressions 1 and 2 can be eliminated yielding the following dependence between P_{rad} and *Zeff*:

$Zeff = 1 + A\,F_i/G\,P_{rad}/n_e^2$ Where *A* is some unknown constant.

This expression is similar to the multimachine law [2], the additional term F_i/G is parameter dependent and mostly describes the change of the volume integrated radiative function with density and total power. If F_i is approximately constant, we have found that *G* has a $1/n_e$ dependence. In fact it is possible to obtain the parametric behavior of F_i/G by computing (Zeff-1)*n_e^2/P_{rad}. The result plotted in Figure 6 shows that F_i/G is an increasing function of n_e (roughly linear as expected). The consequence is that Zeff-1 does not scale as P_{rad}/n_e^2 but has dependence closer to P_{rad}/n_e.

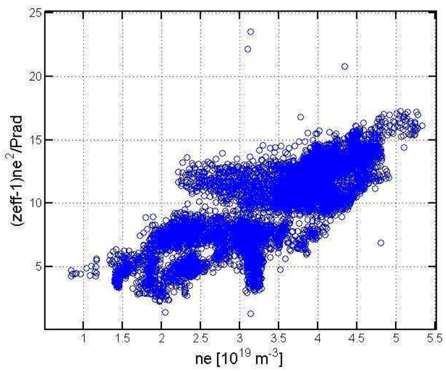

Figure 6: Plot of the experimental Fi/G as a function of ne.

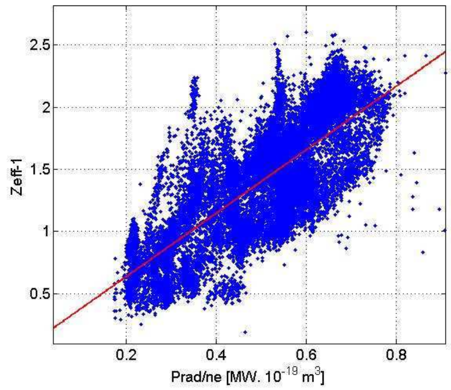

Figure 7 : Plot of Zeff-1 as a function of P_{rad}/n_e. Also represented a linear fit of the data

In order to emphasize this point, we plot in Figure 7 Zeff-1 as a function of P_{rad}/n_e. An approximate linear dependence is observed so that the data can be fitted by a straight line and yields the following dependence:

$$\text{Zeff} \approx 1 + 2.6\, P_{rad}/n_e$$

The standard deviation of the data around the linear fit is large (standard deviation = 0.33) and is equivalent to the dispersion that was observed around the fit of Zeff versus P_{tot}/n_e.
Finally, these results indicate that in limiter configuration both the behavior of the radiative power and Zeff are consistent with a picture where the density of impurities in the discharge depends linearly on the total Power. The change of the carbon concentration in the discharge modulated by the erosion on the TPL is a good candidate to explain the behavior of both P_{rad} and Zeff. However, the large spread observed in the data indicates that other parameters like impurity profiles, other intrinsic impurities, etc. also contribute but to a lesser extent.

[1] Mc Kracken G M et al, Nucl. Fusion 39 (1999) 41
[2] Matthews G F et al, J. Nucl. Mater. 241-243 (1997) 450
[3] Hogan J T et al, *Mechanisms for carbon migration and deuterium retention in Tore Supra CIEL Long discharges,* 21st IAEA Fusion Energy Conference (2006)