*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-4.155 (2007)*

Metallic impurity production during high power RF experiments on Tore Supra tokamak

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One of the objectives of recent experiments on the Tore Supra tokamak has been to inject RF power levels in the range of 10 MW with both Ion Cyclotron Resonance (ICRH, in the H-minority scheme) and Lower Hybrid (LH) heating. Enhanced impurity production, resulting either from fast particles or sheath effects, is known to be a possible limitation in ICRH scenarii[1]. In addition the combination of ICRH and LH heating might possibly generate additional impurity sources. In this paper, we investigate the link between the impurity production and the level of injected RF power. Boronization and H minority concentration effects, because of their possible impact on impurity behaviour in such experiments, have also been studied.

Campaign and measurements: The 2006 campaign has benefited from the use of data from a new protection and monitoring system (the SURVIE device) that uses a VUV spectrometer (Schwob-Fraenkel) operating in the wavelength range 23-30 nm, with 0.02 nm spectral resolution and 10 ms temporal resolution. A real time software has been developed to obtain the time evolution of two line brightnesses: Fe XV (28.42 nm) and Cu XIX (27.33 nm), routinely used to feedback control in real time the injected RF power on the impurity production level. Other line brightnesses, such as C IV (28.92 nm) and O IV (27.99 nm) are also monitored. During the experiments, we collected a database containing the spectroscopic data associated to essential plasma parameters. In order to limit fluctuations, every data point is averaged over a 1 s stationary phase. Selecting similar plasma discharges allows us to assume that the average impurity densities are proportional to line brightnesses. Table 1 gives some information on the most relevant monitored intrinsic impurities. According to the coronal equilibrium model, Fe XV and Cu XIX are located just inside the LCFS; their brightnesses are therefore representative of the Fe and Cu content in the plasma. On the other hand, O IV and C IV are located in the scrape-off layer and depend strongly on the source location with respect to the spectrometer line of sight. Thus, O IV measurements are not

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representative of the oxygen content and will not be presented here. However, the carbon sources, because of the toroidal CFC limiter, are assumed to be toroidally uniform. The C IV emission is therefore used as an indicator of the carbon level in the plasma.

Table 1: major intrinsic impurities monitored during Tore Supra experiments

Element	Ionisation State	Monitored Wavelength (nm)	Temperature of maximum abundance at coronal equilibrium (eV)	Known locations in the vacuum vessel, where these elements are present
Fe	Fe XV	28.42	200	Stainless steel wall components not in close contact with the plasma
Cu	Cu XIX	27.33	300	ICRH Faraday screens (under a layer of B_4C), waveguides of LH grills
C	C IV	28.92	20	Toroidal Pumped Limiter (CFC)
O	O IV	27.99	20	Trapped in all components

Impurity behaviour with RF power:

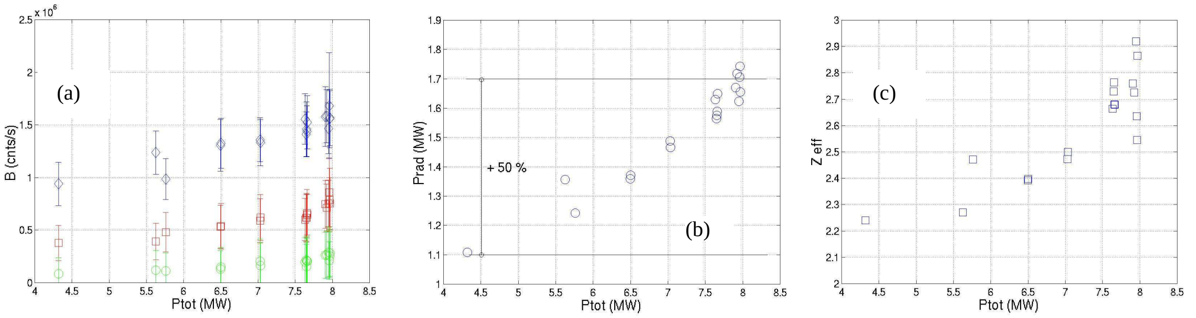

Figure 1 : a) Average Brightnesses of intrinsic impurities versus total injected RF power; error bars represent statistical variations - □: Fe XV ○: Cu XIX ◇: C IV. **b)** Total radiated power (bolometer) versus total injected power**. c)** Effective charge versus total injected power. (nl: 5×10^{19} to 6×10^{19} m^{-2}, Ip: 0.9 to 0.91 MA, It= 1223 to 1225 A)

Fig. 1a shows the evolution of the impurity content with increasing ICRH power (from similar plasma discharges performed during the same day). In this scenario, the LH power was set at approximately 3 MW and the ICRH power was increased from 1 to 5 MW. The level of intrinsic impurities is seen to increase practically linearly with the total injected power (however, the Cu XIX brightness is close to the detection limit). This impurity increase is consistent with the increases of the effective charge, mainly sensitive to light impurities (O, C), and radiated power, mainly sensitive to heavy impurities (Fe, Cu) (figure 1b-1c). Similar observations have been made in other devices [1].

Effect of boronization: During the experimental campaign, boronizations have been performed with a frequency of approximately one per month in order to reduce the plasma oxygen content. The effect of boronization on the Fe XV and C IV brigthnesses is shown in figures 2a and 2b, taken from identical scenarii performed before and after boronization. One point to notice is that the maximum total injected power tolerated by the plasma increases from 8.5 MW before boronization to 9.5 MW after boronization. The limitations of the injected power are generally caused by disruptions or security limitations: maximum allowed temperature reached on the plasma facing components (Infrared), or sudden metallic influx (SURVIE)[2] (the first limitation is the subject of a dedicated study in progress[3]). As has

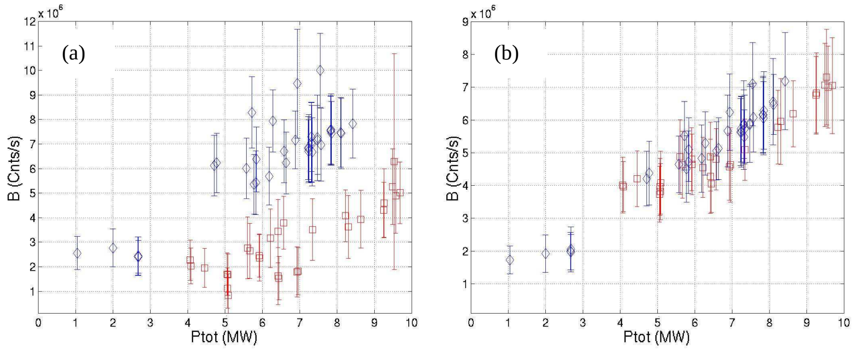

Figure 2 : average Brightnesses of Fe XV (a) and C IV (b) versus total power injected, error bars represent statistical variations from the average □ : After boronization ◇: Before boronization
nl: $5x10^{19}$ to $7x10^{19}$ m^{-2}, Ip: 0.85 to 0.95 MA, It= 1223 to 1226 A

already been shown in Tore Supra[4], the second point to notice is the different effect on iron and carbon. Iron is affected in terms of level and evolution with the total injected power. For a given total injected power up to 6 MW, the iron level is approximately a factor of 2 smaller after than before boronization; its evolution with the injected power is usually characterized by an increase above a threshold around 6 MW. On the contrary, carbon is not affected by boronization. An explanation can be found in the localization of each element (Table 1). Carbon is located on strongly interacting areas, where the thin boron layer is promptly eroded. Iron, on the other hand, is located on areas which are not in close contact with the plasma; boron is therefore not systematically eroded because of the role of other parameters (magnetic configuration, injected power…). Another explanation could be the decrease of iron sputtering due to the lower oxygen content.

Impact of isotopic ratio $n_H/(n_H+n_D)$: An isotopic ratio scan has been performed in consecutive discharges with the same plasma conditions (Fig. 3). The intrinsic impurity production is seen not to depend on the isotopic ratio in the LH-only case. On the other hand, during the LH + ICRH phases, there is a difference as a function of the isotopic ratio: C IV is not affected, but Fe XV increases by ~ 60 % and Cu XIX (not represented here) by ~ 30 % when $n_H/(n_H+n_D)$ increases from 5 % to 11 %. A decrease of Fe XV between 2 % and 5 % could also be assumed. The radiative power increases by 12 % between the minima and the maxima, but no Zeff variation has been observed, confirming the potential role of Fe and Cu (heavy impurities). Several possible causes for this increase of metallic impurities can be identified: fast minority ions, weak wave absorption and near-field sheath effects. 1) Fast

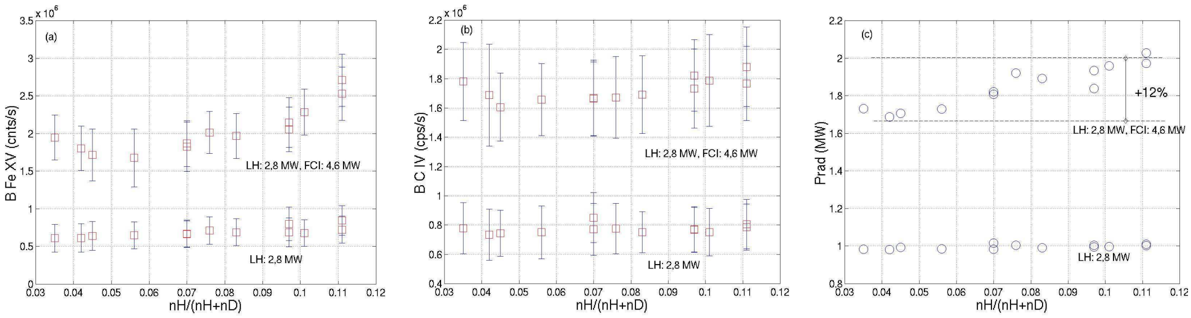

Figure 3 : Experimental measurements during scan of minority concentration. Points are taken with LHCD alone and LH+ICRH
a) Brightness of Fe XV, **b)** Brightness of C IV, **c)** Radiated power

minority ions are due to direct ripple losses and losses induced by stochastic diffusion[5]. Fig. 4 shows the direct ripple ion losses as seen by the ion ripple protection temperature (measured by IR thermography). Direct ripple ion losses have a maximum around an isotopic ratio of 7 %. This measurement is in agreement with a simulation that predicts, in the case of such direct ripple loss behaviour, a decrease of the total losses when the isotopic ratio increases above 5 %[5]. The Fe XV and Cu XIX brightnesses do not seem to be correlated with fast minority ion losses. Moreover, fast ions are accelerated by ICRH up to an energy of 100 keV; the maximum sputtering yield of Fe by D is at approximately 1 keV (~ 3 %) and decreases with energy to reach ~ 0.03 % at 100 keV. 2) As far as wave absorption is concerned, the isotopic ratio constitutes a major parameter as weak single pass absorption results in multiple wave reflections that might induce far-field sheath effects. Fig. 5 represents the single pass absorption for different minority temperatures[6]. In the range 5 % to 15 %, an ion temperature tail up to 10 keV is sufficient to obtain single pass absorption of more than 80 %. Since such temperatures are obtained in ohmic discharges, wave absorption is also probably not in cause. 3) Near-field sheath effects on the ICRH antennae Faraday shields, possibly responsible for the Cu enhancement (Cf. Table 1), have been evidenced by IR thermography.

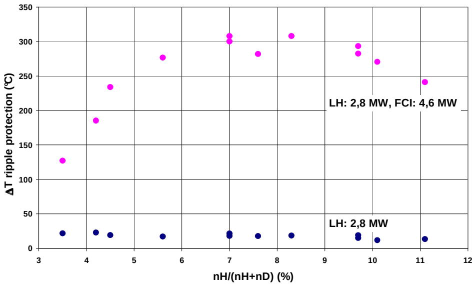

Figure 4: temperature increase of ionic ripple protections located on the low field side part of the Toroidal Pumped Limiter

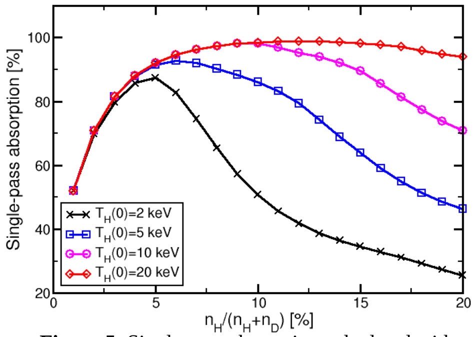

Figure 5: Single pass absorption calculated with METS 1D

The increase of metallic impurities level, especially iron, is therefore not clearly understood. Other possible causes such as magnetic connections to antennae or local increase of edge density have to be explored.

Conclusion: The major issue controlling impurity production is the level of ICRH power, but minority concentration and conditioning are also important parameters. To complete this study and improve the impurity monitoring during experiments, additional work must be done in order to quantify the impurity density profile in such scenarios.

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