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** See annex of F. Romanelli et al, "Overview of JET Results",*
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INTRODUCTION

An ITER-like wall (ILW) of Beryllium and a Tungsten divertor were installed in JET in 2012 (see e.g. [1]) and a first series of experiments in presence of this wall was performed at modest power and thus in L-mode that same year. The logical focus in the 2013 JET campaign was the characterization of high power *H-mode operation*. One of the critical issues to be addressed was whether the influx into the main plasma of high-Z materials coming from plasma facing components can be kept low enough so that reaching fusion-relevant temperatures is not compromised. In the past L-mode experiments [2, 3, 4], it was shown that ion cyclotron resonance heating (ICRH) or radio frequency (RF) waves tend to give rise to *increased* impurity sources from the main chamber, the reason believed to be that ions can be accelerated to high energies in the sheaths that form close to metallic surfaces – and antennas in particular – in contact with a plasma and give rise to increased sputtering of wall material. Although the increased level of ensuing radiation was seen as a bonus for safe operation rather than as a disadvantage (as it allowed to harmlessly radiate away a significant fraction of the power that otherwise is deposited on the divertor), one crucial question to be answered is if high RF power is beneficial for sustaining the H-mode. Just like for the earlier L-mode experiments, Hydrogen minority fundamental cyclotron heating in a Deuterium plasma was chosen as the wave heating scheme. Past experiments [5, 6, 7] with the carbon wall have shown that centrally deposited RF power is able to reduce or annihilate the influx of impurities to the plasma core. Although further confirmation is needed, a series of JET studies seeking optimization of ICRH for W control suggests this is still the case in presence of the ILW [8].

In the context of RF heating and apart from the study presented here, particular attention was paid recently to optimizing the coupling in H-mode conditions (see [9, 10]). This was mainly done by ensuring a sufficiently high density was present in front of the antenna and was realized by tuning the gas mix through which majority ions are injected into the machine. The main finding was that for a given gas injection rate, divertor injection yields the poorest results while mid plane injection yields the best coupling (recall that the RF antennas are located near the equatorial plane); injection from the top yields intermediate results. Distributed main chamber injection not only helps improving the coupling but as it impacts on the sheaths, it also helps to reduce sputtering. A related – be it yet unexplained – observation was that the effect of the gas injection dies away exponentially in function of the distance of the injector to the wave launching structure, hinting at a loss mechanism proportional to the density and inversely proportional to a characteristic loss time.

1. GENERAL DISCUSSION OF THE EXPERIMENTS

The experiments were done using a toroidal magnetic field strength of $B_o = 2.7T$ and a plasma current of $I_P = 2.5MA$. A frequency of $f = 42.5MHz$ was adopted to ensure core minority H fundamental ion cyclotron and majority D second harmonic heating; $0\pi0\pi$ dipole phasing was adopted. H-mode conditions were guaranteed through the use of $14.5MW$ of (D) beam power. Each of the shots contained a phase in which auxiliary heating was absent, a beam phase without ICRH power, then one with low RF power (3MW) and one with high RF power (5MW); finally there was a low power (L-mode) ICRH phase without beam power in the so-called 'landing' at the end of the shot (when the density is decreased while a limited amount of auxiliary heating is kept to avoid a disruption to take place). The Ohmic power was typically $0.5MW$ and the total radiated power $6-7MW$ (i.e. $\approx 1/3$ of the power). The adopted density was about a factor of 2 higher than that used in earlier L-mode experiments: core densities of $7\times10^{19}m^{-3}$ were reached; the line averaged density was typically $5\times10^{19}m^{-3}$. The (electron) temperature peaking is typically higher than that of the density: the difference between the core value and that at mid-radius was as high as 2.6 at low minority concentrations and was always larger than 2. Electron heating was very efficient. Core electron temperatures up to $T_{e,o}=5keV$ were reached but large amplitude sawteeth (ΔT_e of $1-2keV$) routinely occurred. The bulk ion temperature remained more modest, $T_{D,o}<3keV$.

The heating efficiency was evaluated both in L- and in H-mode using break-in-slope (BIS) analysis (see e.g. [11]) of the plasma and diamagnetic energy; see Fig.1. Four different BIS methods were adopted: two 'classical' versions determining the gradients before and after the RF power break and fitting the data to linear curves (one imposing a common hinge point, the other not requiring the fitted curves to connect), a BIS method that captures the saturation due to losses and the time delay between the power jump and the temperature break, and finally a method where a numerical rather than a simplified analytical equation is integrated to study the temperature response. The various slightly different BIS models used in the analysis yield slightly different results with a spread of 20% on the efficiency found, as was seen in earlier L-mode experiments [4]. At modest $X[H]$ ($6-8\%$), the heating efficiency is high both in L- and in H-mode: in L-mode the peak efficiency is about 70%; in H-mode virtually everything is absorbed. At high $X[H]$, the L-mode efficiency drops significantly to 30% while the H-mode figure remains as high as $\approx 70\%$. At very low $X[H]$, the heating customarily becomes less efficient. The present data show hints for such behavior in L-mode (optimal $X[H]\approx 6\%$). The density – a factor of 2 lower in the L-mode phase 'landing' at the end of the shot than in the H-mode phase – is believed to be responsible for that (see the section on modeling). For H-mode, however, low enough concentrations were clearly not reached for the experimental maximum to convincingly occur.

It is known that the indirect heating of the electrons by RF-created fast ions causes a time delay between abrupt changes in the launched power and the break this power drop or rise causes in the slope of e.g. the diamagnetic energy; recall that the fast particle energy is $W_{fast}=4/3(W_{dia}-W_{plasma})$. Models – such as the classical BIS method – *not* capturing this time delay tend to *underestimate* the absorbed power while models that *do* – such as more sophisticated BIS models – provide a more accurate estimate (for more info, see e.g. [11]). While the various BIS methods estimating W_{dia} agree better at high $X[H]$, it was found that the various predicted efficiencies differ up to a 50% at low $X[H]$. The hint provided by this difference that a fast particle population is formed at low $X[H]$ is confirmed by fast particle diagnostics: The TOFOR (time of flight) diagnostic sees a distinct D tail at low $X[H]$ in H-mode, a rather weak tail at high $X[H]$ in H-mode, and absence of a D tail in

L-mode. Qualitatively in line with this observation, the neutral particle analyzer sees a reduction of 2 orders of magnitude in the fast particle flux when the $X[H]$ concentrations rises from 2 to 20%.

2. WAVE AND FOKKER-PLANCK MODELLING

Theory corroborates the results found. Modelling has been done using 1 and 2D wave equation solvers [12, 13] and a 1D Fokker-Planck solver [14]. At the high densities and for the parameters adopted in the experiments, the absorption in a full transit is almost complete at modest concentrations (see the lines in Fig.1), and drops to 70% at $X[H] = 25\%$. The electron heating fraction is fairly constant while the sum of the ion heating fractions is as well. At very low H concentrations, D majority heating is significant, but it drops under the 10% level at $X[H] \approx 5\%$. In L- mode the drop of the overall absorption both at low and high concentrations is much more pronounced. Interestingly, *Be* absorption – although always low (< 15%) – is much more prominent in L- than in H-mode. Further more, Fokker- Planck analysis confirms that fast particle tails preferentially slowing down on electrons rather than bulk ions are easily formed at the applied power levels, even at the fairly high densities that were typical for the H-mode shots.

3. ICRH & IMPURITIES

The plasma energy, the diamagnetic energy and the temperature degrade when the hydrogen minority concentration $X[H]$ increases; see Fig.2. In contrast to the total radiation, the bulk radiation tends to decrease with $X[H]$ as well (not shown). There are various hints that a minimum is reached when $X[H] \approx 20\%$ but the statistical spread on the data and the fact that the minority concentration was not scanned well beyond 20% does not allow to draw this conclusion firmly.

Whereas a clear minimum of the bulk radiated power was observed at intermediate concentrations in earlier L-mode experiments at lower density – the radiation dropping by a factor of 1.7 when increasing $X[H]$ from 12 to 20% for $P_{ICRH} \approx 3.4MW$ – this effect was absent in higher density H-mode at similar ICRH power and only weakly observed at higher P_{ICRH}: a modest reduction of only 1.2-1.3 was observed at $P_{ICRH} \approx 4.7MW$ at very low $X[H] \approx 2\%$. Soft X-ray analysis reveals a *reduced* central W concentration at small minority concentrations ($X[W] = 0.8 \times 10^{-4}$ for operation at $X[H] = 2\%$ while $X[W] = 1.2 \times 10^{-4}$ at $X[H] = 10\%$) aside from $X[W]$ values insensitive to $X[H]$ well inside the plasma but away from the core. Spectroscopical data suggest that the core concentrations of impurities such as Ni vary little with X[H] while the edge concentrations do increase with larger minority content. At small concentrations, ICRH creates high energy H and D ions, both of which Coulomb collisionally slow down on electrons, giving rise to strong electron heating. Both the Ni and W findings thus hint at the fact that efficient core electron heating is a key asset for keeping high Z impurities out of the center, as was earlier found for the carbon wall. Increasing the RF power level (either on top or substituting part of the NBI power) results in lower core W concentrations. One mechanism proposed in the past is the RF induced change of the radial impurity density transport – or pinch – velocity associated with the high electron temperature gradient [7]. Consistent with the interpretation that RF sheaths favor impurity release from plasma facing components, higher levels of impurity concentrations were observed at the edge at higher power levels. In the adopted high density, high power operation range the removal of impurities from the core seems capable to overcome the increased influx at the edge provided sufficient RF power is available.

At low concentrations but high NBI+RF power, sawteeth were fully stabilized during 4s. On the other hand, high amplitude sawteeth routinely occurred when either or both these conditions were not fulfilled. Interestingly, abrupt and significant drops in the RF power ($\Delta P_{ICRH} \approx 3MW$) were observed to *trigger* sawteeth. This effect has often been seen in RF power modulation experiments in presence of high energy ion tails when sawteeth tend to 'lock' to the modulation frequency. Although further investigations are clearly needed for better understanding, this effect possibly opens perspectives for ICRH sawtooth pacing i.e. exploiting ICRH power modulation to control the core impurity level by imposing the rate at which sawteeth flush out particles from the plasma centre. This mechanism for avoiding W accumulation in the core might be a natural complement for the pinch velocity effect. In TCV, sawtooth pacing has proven to be possible using ECRH (see e.g. [15]) and the fact that the triggering effect is seen at modest ($X[H] \approx 3 - 4\%$) but not extremely low minority concentrations at which the RF power dominantly passes from the waves to the minority tail and then collisionally to the electrons, suggests that electron dynamics is crucial for the underlying physics. More generally, the notion grows that magnetic instabilities can be used at one's advantage to help flushing the impurities from the core through sawteeth [16] and from the edge through ELMs [17].

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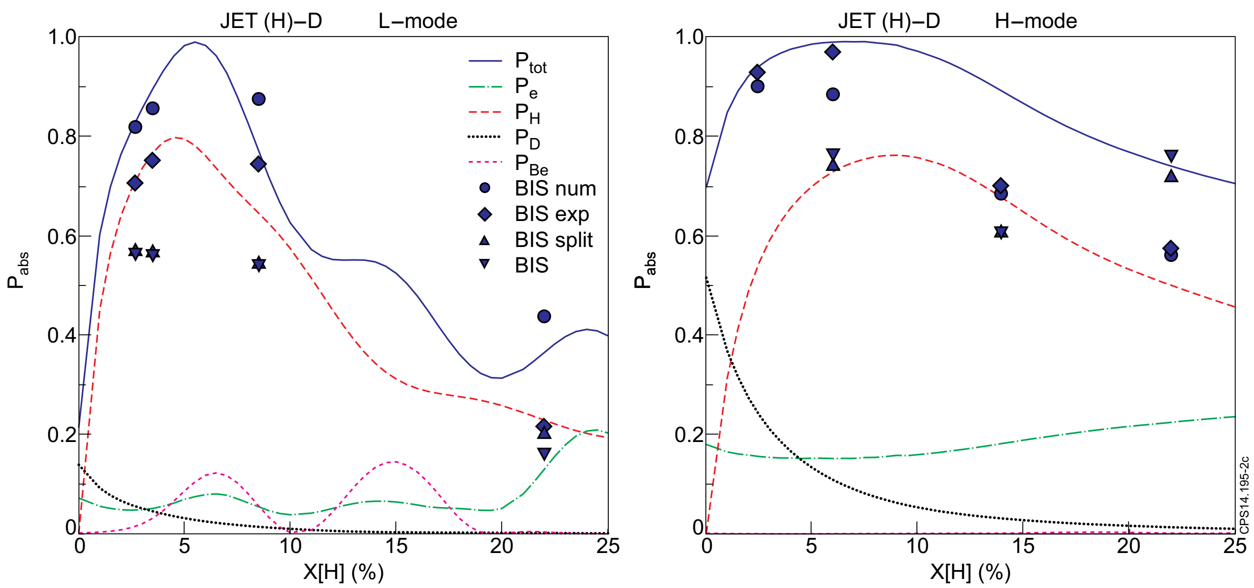

Figure 1: Heating efficiency in L-mode (left) and H-mode (right) as a function of the minority concentration. The symbols represent the experimental data inferred from BIS analysis; the lines are the corresponding theoretical predictions for the absorption in a full transit over the plasma.

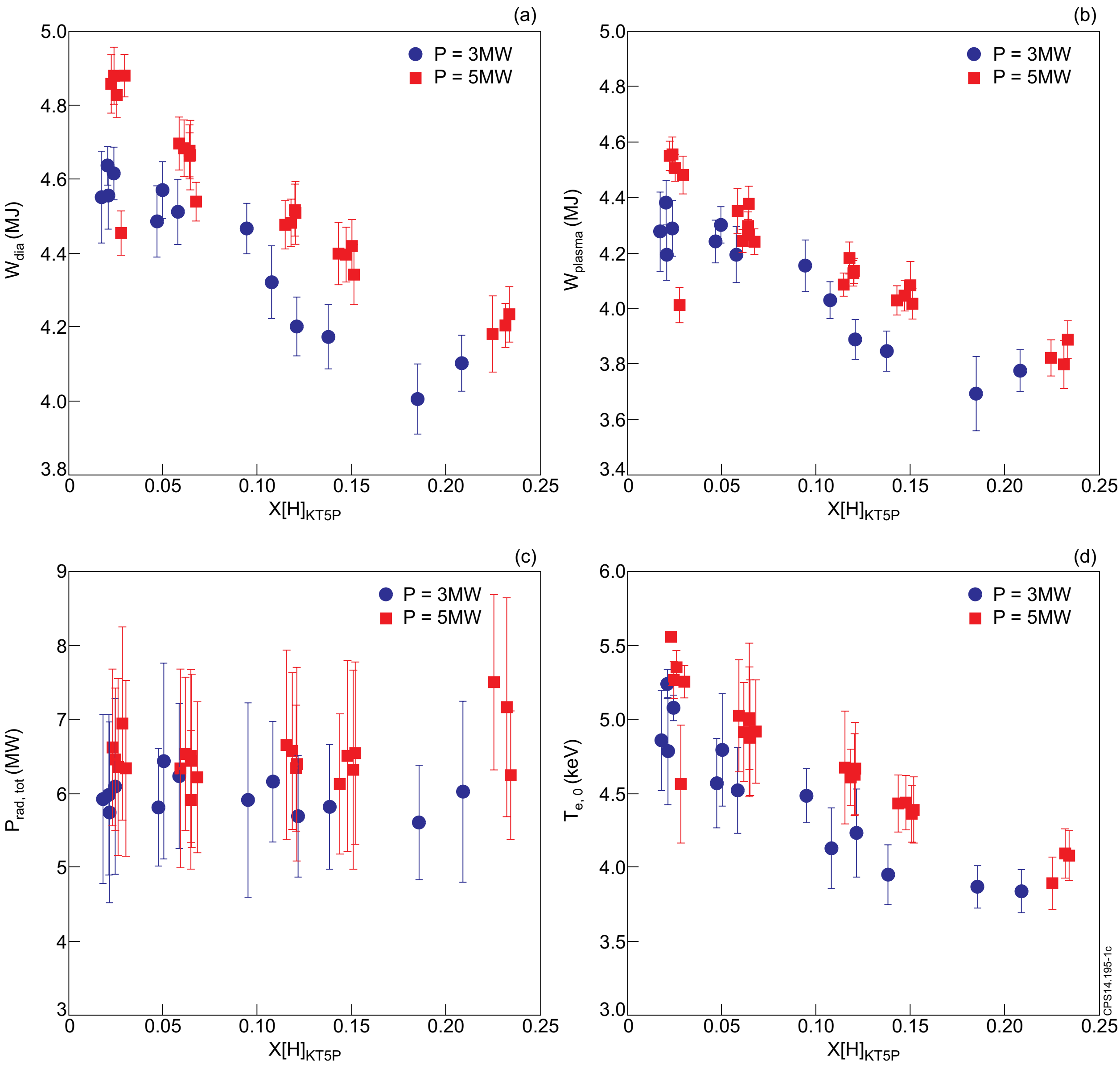

Figure 2: Diamagnetic energy (a), plasma stored energy (b), total radiated power, (c) and ECE central electron temperature (d) as a function of the minority concentration evaluated spectroscopically in the edge from the ratio of line intensities H_α/D_α (KT5P diagnostic).