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

Carbon is not compatible with the long term use required for plasma facing components in future fusion reactors of the tokamak type e.g. from the point of view of erosion and tritium retention.W and Be were chosen as plasma facing materials for ITER. JET was equipped with beryllium (as opposed to C or C-coated) walls in the shutdown of 2010-2011. To sustain the very high heat loads inevitably falling on it and thus excluding the use of metals with a low melting point such as Be and in spite of the fact that its radiation is significant because of its large Z, a Tungsten (W) orW coated divertor was simultaneously installed. The recent JET campaign has focused on characterizing high density high temperature operation with this "ITER-Like" Wall (ILW). One of the questions that needed to be answered is whether the auxiliary heating methods do not lead to unacceptable high levels of impurity influx preventing fusion-relevant operation. This paper briefly reports on two aspects of the present understanding of Ion Cyclotron Resonance Heating (ICRH) or Radio Frequency (RF) heating in presence of the ILW: ICRH-specific impurity influx and heating performance. They are complementing related discussions on heat loads [1], and on plasmaWcontent and possible sources [2]. A much more extensive study will be published elsewhere.

1. COMPARISON OF ICRH AND NEUTRAL BEAM HEATING

The adopted ICRH scheme was minority hydrogen (H) fundamental cyclotron heating in a deuterium (D) majority plasma, a heating scenario typically guaranteeing good single-pass absorption. By operating at 42MHz and $\vec{B}_0 = 2.7$T while keeping the concentration low ($X[H] = N_H / N_e \approx 5\%$), efficient core heating with on-axis absorption was ensured. High field side off-axis heating was done at 2.4T. A central temperature increase of 0.5keV/MW was characteristic for on-axis, and 0.3keV = MW for off-axis heating. These numbers are lower than what was realized with the C wall (ΔT up to 1keV/MW) but the change in energy content ($\approx$ 0.2MJ/MW) is similar; the density at which the recent experiments were done was typically higher (line integrated density around $6-7\times10^{19}m^{-2}$ as opposed to $\approx 4-5\times10^{19}m^{-2}$). Dipole phasing (exhibiting a spectrum that is symmetrical w.r.t. the wave vector component parallel to B_0, $k_{||}$, and that peaks at $|k_{||}| \approx 6.6m^{-1}$) was preferred for most experiments but heat load studies and specific W and Be sputtering characterization adopted both dipole and $-\pi/2$ phasing (the latter exhibiting a spectrum that is asymmetrical in $k_{||}$ and peaking at $k_{||} \approx -3.3m^{-1}$, hence a phasing option that is more suitable for driving current than for heating). The experimentally found instantaneous heating efficiencies for the two phasings agree with what is theoretically expected. For a variety of power levels, densities and plasma-antenna distances chosen, they were in the 60−90% range for dipole, while those of $-\pi/2$ phasing were in the 30−60% range. Heat loads on vulnerable Be parts where melting could occur did not pose any problem up to the highest tested ICRH power levels (P_{ICRH} = 4.5MW and up to 2MW per antenna; see [1]), allowing to move the plasma closer to the antenna while keeping the scrape-off-layer density profile constant.

As can be seen in figure 1, equal amounts of auxiliary heating power (3.5MW; Figure 1(a)) either applied to the plasma by ICRH waves or by NBI (neutral beam injection) while ensuring the density is the same (central line integrated density $\approx 6-7\times10^{19}m^{-2}$), have a profoundly different impact on the plasma. The radiation level (Figure 1(d)) differs by a factor of 3, ICRH having the higher radiation values and most radiation coming from the bulk while the radiation for beam heating is mainly concentrated in the divertor region. The W concentration in the plasma was evaluated from VUV spectroscopy [3]. Significantly more W is detected inside the plasma (Figure 1(c)) when applying ICRH compared to NBI although the W emission level in the divertor (together with the baffles potentially the main source of W) shows the opposite tendency; the top line in Figure 1 (c) is the concentration at $\rho \approx 0.65$m while the bottom line is the more central value at $\rho \approx 0.2$m. The seeming inconsistency between W levels at the source and inside the plasma stresses the need for a continued careful assessment of the impurity content of the plasma and the impurity source. Since the central electron temperature (Figure 1(b)) reached is very different (about 4keV for ICRH while only 2.5keV for NBI) although the plasma energy is similar (Figure 1(e)), one may speculate that the different behavior is at least partly an effect of the highly efficient minority RF heating scheme chosen rather than a general characteristic of wave heating: at low concentration, minority heating creates highly energetic minority tails and predominantly heats the electrons, either directly via Cerenkov damping or indirectly via the Coulomb collisional relaxation of the tail on the electrons; at higher X[H] fast H tails disappear and a different regime is reached (see next section). A similar experiment was then made unbalancing the auxiliary heating powers in an attempt to make the electron temperatures similar (not shown). Although the differences are less pronounced (the radiation level is now comparable) it is clear that the two heating mechanisms lead to a different behavior of the impurities: Also at equal Te the Be emission is stronger and more W is detected during the ICRH phase. The statistical analysis plots Figs.1-e&f show that while the radiation level is typically higher for ICRH than for NBI heated shots, the reached plasma energy level is similar.

Dipole heating phasing yields lower radiation ($\approx 60-70\%$ of the ICRH power) levels than does $-\pi/2$ current drive phasing ($\approx 90-100\%$), supporting the hypothesis that sheath rectification effects (which are stronger when using the less absorbing $-\pi/2$ phasing) are at least partially responsible for the enhanced impurity content in the plasma during ICRH. Although this radiation level is significant and can become an issue at higher power levels for $-\pi/2$ phasing, one should bear in mind that for ITER, steady state operation is envisaged at 80–90% radiation level to avoid excessive sputtering in the divertor through hot particle exhaust and that radiation itself is not seen as problematic as long as it does not degrade the particle nor energy confinement. For the available ICRH power levels, radiation does not compromise the plasma operation as high electron temperatures were achieved and the plasma energy is similar to that observed with a C wall. No (charge exchange) ion temperature profile measurement was available at the time of the experiments, but fast particle diagnostics suggest that at the relatively high densities the experiments were performed, the thermal part of the bulk ion population had a temperature in the same ballpark as that of the electrons.

2. HYDROGEN CONCENTRATION SCAN

The minority concentration is one of the most critical parameters that influences the heating efficiency in a minority heating scheme. Dedicated experiments aimed at changing the concentration X[H] and studying its impact were done; see Figure 2. Scanning the H concentration from modest values up to 30% reveals that e.g. the bulk radiation decreases steadily as a function of X[H] and reaches a minimum around 20% (see Figure 2 (b). The radiation increases again when proceeding to higher X[H] values. Scanning X[H] from 10 to 20%, the W concentration from W quasi-continuum emission (see Figure 2 (c) [3] drops from 1.8×10^{-4} to 0.4×10^{-4}; the W concentration deduced from W_{line} emission – which yields concentrations closer to the core - follows the same trend, be it less pronounced. In view of the strong correlation between the source W concentration and the edge density [2], the latter was equally monitored. Relatively high, fairly constant line integrated edge densities ($N_{e;line} \approx 3\times10^{19}m^{-2}$) were observed when making the X[H] scan. The Be-II emission - which characterizes the Be influx - drops by a factor 2 in the X[H] range considered. The increase of the radiation at very high X[H] is thought to be a consequence of the fact that the heating efficiency then has dropped significantly so that the electric field needs to grow large - giving rise to more efficient (usually non-resonant) particle acceleration in the edge – to ensure the launched power is damped inside the all-metal (Faraday cage) vessel. As can be seen in Figure 2 (a) depicting the plasma energy, the reduction in net heating efficiency is modest when keeping X[H] around 15% compared to the more commonly used X[H] ≈ 5%.

CONCLUSION AND DISCUSSION

The recent JET experimental campaign showed that for all currently attained ICRH power levels (P_{ICRH} 4.5MW), phasings and plasma configurations tested, the ILW and ICRH heating are compatible as heat loads and impurity levels stay within acceptable limits without compromising the heating performance; for more details, see [1, 2]. A higher radiation level - comparable to that envisaged for ITER for safeguarding the divertor - is observed when using ICRH as compared to NBI heating, but the same energy is reached. Along with a strong reduction in W level observed when the edge density is increased [2], it is found that it is beneficial to work at somewhat higher X[H] than the usual 3–5% to reduce the W concentration and bulk radiation although the reason for the high W concentration at the low X[H] commonly adopted for minority heating is not yet well understood, nor is it fully clear where the W originates from. Aside from the question if higher power levels would not pose a compatibility problem, an issue that has not at all been addressed yet is whether ICRH power is capable of ensuring impurity pump-out, in particular in H-mode. More detailed analysis is ongoing and will be reported in a more extensive survey of the experimental findings.

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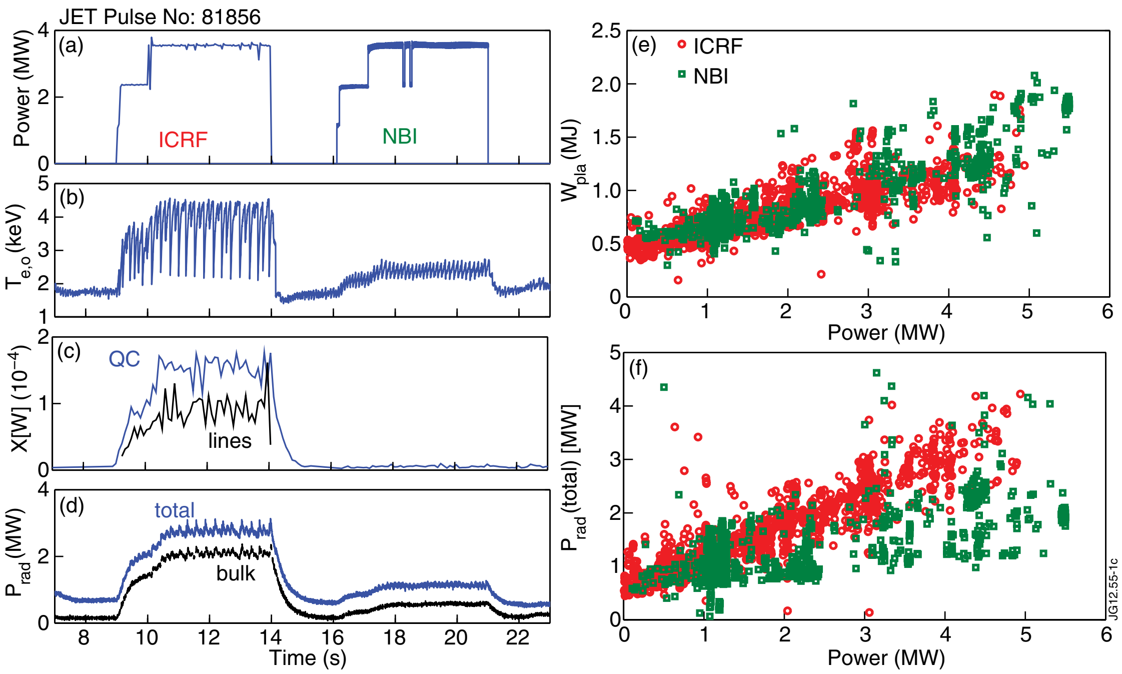

Figure 1: (a-d) Time traces of some key quantities during ICRH-NBI comparison for JET Pulse No: 81856 (P = 3.5MW) and (e-f) statistical analysis for L-mode dipole Pulse No's: 80661 to 82240.

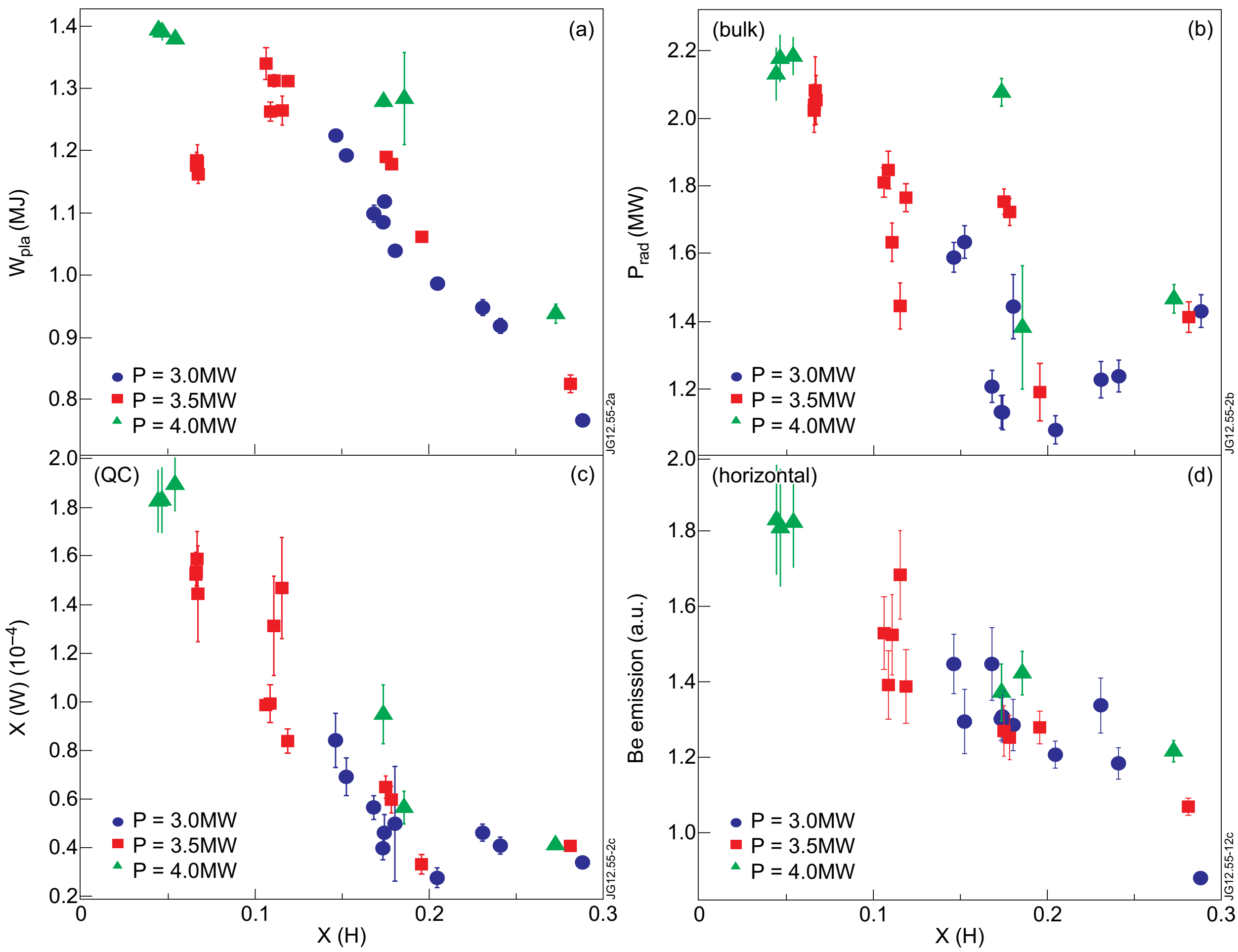

Figure 2: Plasma energy, radiated power, W concentration and Be emission as a function of the H concentration.