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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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1. INTRODUCTION

The coupling of the Lower Hybrid (LH) waves to the plasma is a critical issue which is still difficult to extrapolate from present tokamaks to the next generation. In particular the distance between the separatrix and the antenna front-end can be as large as ~0.15m on ITER whereas most of the present antennas operate with a 'gap' (i.e. separatrix-antenna distance) of 0.03-0.06m.

2. EXPERIMENTAL SET-UP

Since 2003 [1], LHCD experiments have been carried out on JET with a gap varying between 0.09 and 0.16m and LH power in the range of 0-3.2MW [2]. Two plasma shapes have been tested: low (δ_{up}/δ_{low} = 0.16/0.27) and high (δ_{up}/δ_{low} 0.38/050) triangularity. Plasma was mainly heated by NBI and the LH power was applied during the H-mode phase with either type III or type I ELMs. The plasma current (I_p = 1.5−1.9MA) and toroidal field (B_0 = 3−3.1T) were adjusted to meet the requirements of the advanced scenarios (q_{95} = 4−5). With this magnetic configuration the Reciprocating Langmuir Probe (RCP) is magnetically connected to the flux tubes passing in front of the LH antenna. This probe was systematically reciprocated during these experiments and a profile of the saturation current (J_{sat}) in the 'far' Scrape-Off Layer (SOL) (i.e. at least 3cm behind the separatrix) was obtained with a sufficient time resolution to distinguish 'between ELMs' and during the rise and decay of the ELMs. It should be noted that the LH antenna is positioned 2cm (5mm for the early experiments) behind the Poloidal Limiters (PL) with a short connection length ($L_{//}$~2m). The profile in this LH private zone can not be measured. During LH power injection, the Gas Introduction Module located near the LH antenna (GIM6) was systematically used aiming at raising the electron density in the flux tubes connected to the antenna. A database of 70 time slices including RCP and LH coupling measurements has been established.

3. RCP MEASUREMENTS

In order to ensure good coupling of the LH waves to the plasma (i.e. an averaged power Reflection Coefficients RC <5%), the density at the antenna-plasma interface must be above the cut-off density, in particular between ELMs. The Jsat profile during these phases is established by processing only the data when the D_α signal is below a set value (chosen to be ~1.5 times the baseline value). Jsat profiles with relatively low scattering are then obtained. These measurements indicate clearly the effect of local ionisation by the wave. When the LH power is increased from 0.4MW to 1.6MW, the density rises in a layer which extends in front of the PL by several cm (Figure 1) and a J_{sat} (ne) plateau is formed when the LH power is large enough. Closer to the separatrix, the profile is marginally modified. Such a plateau formation can be numerically obtained with the EDGE2D code when an additional power source term is added to model the LH power absorbed near the antenna [3]. When the LH power is varied between 0 and 3MW, Jsat measured just in front of the PL (labelled Jsat@wall) raises continuously with no indication of saturation (figure 2).

Effect of gas injection level F_{GIM6} is noticeable but not dominant: The plot of J_{sat}@wall versus

F_{GIM6} indicates also an beneficial effect of F_{GIM6} but with a very large scattering. Note that the EFIT equilibrium indicates that the field lines with $R\text{-}R_0 \geq 30.06$m hit the inner wall and the resulting recycling is likely to contribute to the plateau formation. Similar result were obtained for the high δ pulses, performed with a larger gap between the separatrix and the PL (0.14m). For this configuration the ionisation efficiency (i.e. the slope of figure 2) is weaker by a factor ~2.

4. LH COUPLING MEASUREMENTS

LH coupling is measured from the RCs averaged for each of the 6 rows of modules (each containing two rows of waveguides). Unfortunately, not all the klystrons were powered and different RF feedings were used which makes proper comparison difficult because of the strong cross-coupling between waveguides. For the pulses of figure 2, the RC of row 2 (upper row) and row 6 (bottom row) are plotted as a function of J_{sat}@wall in figure 3.

For J_{sat}@wall <1A/cm^2, the coupling is very weak and RC exceeds 20%, indicating that the density in front of the antenna is below the cut-off ($n_{cut\text{-}off} \sim 2 \times 10^{17}$ m^{-3}). The measured electron temperature at the PL radius is about 15eV, so the density, corresponding to J_{sat}@wall =1A/cm^2, is $n_e = 4 \times 10^{18}$ m^{-3} (assuming no flow in the SOL). We conclude that the density falls off by one order of magnitude in the shadow of the PL. This is consistent with an e-fold decay length ln~1cm. Optimal coupling conditions are obtained for J_{sat}@wall =1-2 A/cm^2. For higher values, RC slightly increases indicating that the density at the plasmaantenna interface exceeds at least 5 times the cut-off density, according to coupling code prediction. This transition is more pronounced for the lower rows (5 and 6), suggesting that the density is larger at the bottom than at the top. It should be noted that the 2003 pulses (open symbols) were achieved with a smaller distance between the PL and antenna (5mm) and consistently RC reaches larger values up to 5-6%. We found the same threshold of ~1A/cm^2 for the plasmas with high triangularity and a gap of 0.14m. Note that because of the high recycling associated with this configuration, low RC (<5 %) was achieved for 5 rows out of 6 with no gas injection from GIM6. Moderate injection (4×10^{21} el/s) allowed to improve the coupling of row 6 (RC<2%) with a record distance between the waveguides and the separatrix of 0.16m.

5. RCP AND LH MEASUREMENTS DURING ELMS

During ELMs, the particle flux (J_{sat}) measured by the RCP may increase transiently by more than one order of magnitude, even 0.1-0.14m behind the separatrix. RC measurements indicate clearly that, at least in the low d configuration with a gap of 0.10m, the ELM perturbation does not vanish completely, 2cm behind the PL. During an ELM the RC generally starts decreasing then increases. The optimal density is obtained earlier for the bottom rows than for the upper rows, confirming the assumption that the ‘base plasma’ (between ELMs) is more dense below the equatorial plane. However the distance to the plasma is slightly larger for the bottom rows due to the mismatch of the field lines with the antenna poloidal shape. For high triangularity plasmas, the coupling is found more insensitive to the ELM amplitude.

CONCLUSIONS

RCP measurements show that ionisation of the SOL by the LH wave occurs very efficiently and proportionally to the LH power in the flux tubes passing in front of the LH antenna on a radial distance which is typically 5cm. Gas injection from a magnetically connected valve may be necessary at least in the initial phase to allow the power to be coupled and to initiate the ionisation. RC measurements suggest that electron density is higher in the bottom part of the antenna and 'over-dense' regime ($n_e >> n_{cut\text{-}off}$) is achieved in case of high power and high gas injection. Although the density increased significantly during ELMs bursts, 2cm behind the PL, no deleterious effects with respect of the power transmission were observed.

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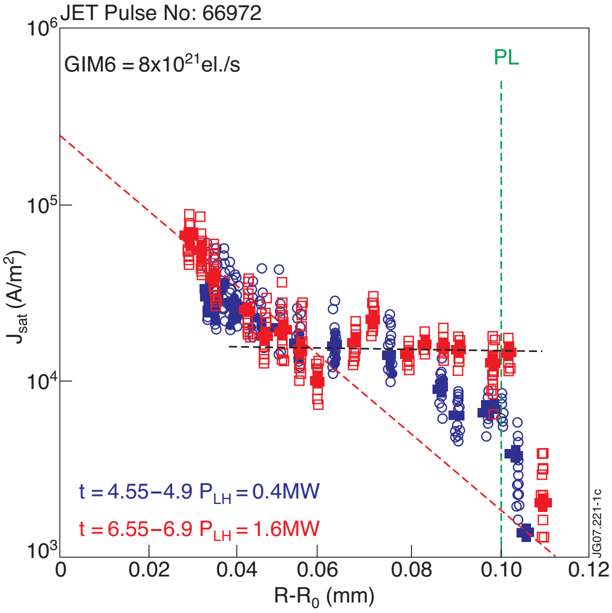

Figure 1. J_{sat} profile in the equatorial plane measured during LH power injection between ELMs.

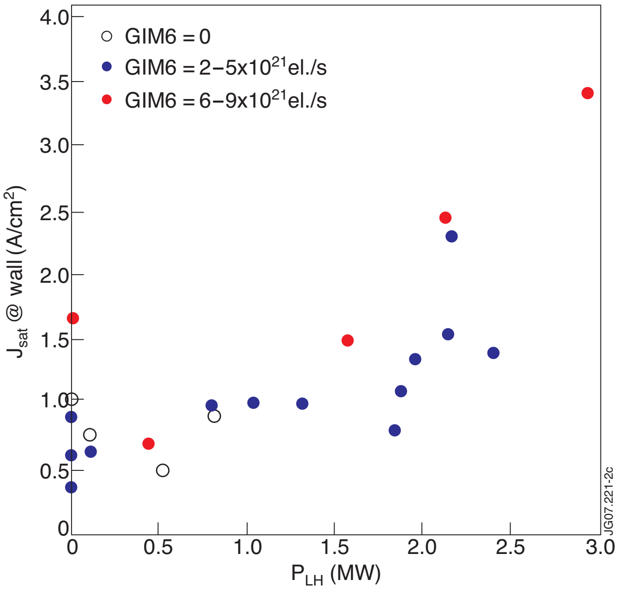

Figure 2. J_{sat} at the wall as a function of coupled LH power (Low d plasmas, separatrix at 0.10m from the wall).

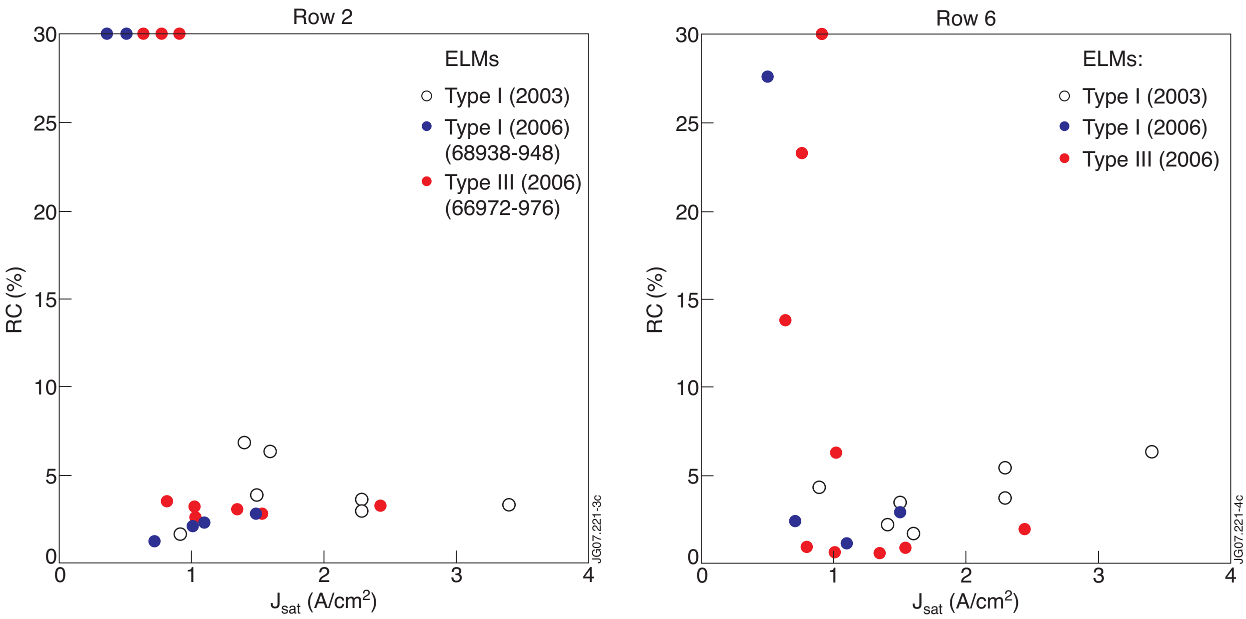

Figure 3. RC of upper row (left) and bottom row (right) as a function of J_{sat}@wall (low d case, gap of 0.10m)