Effect of Gas Injection during LHCD Experiments in ITER-Relevant Coupling Conditions

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Abstract. LHCD experiments were carried out on the JET tokamak in ITER-relevant conditions which include: low (δ~0.22) and high (δ~0.45) triangularity ELMy plasmas, high safety factor (q_{95}=4.0-6.8) and gaps between the separatrix and the antenna varying between 0.08m and 0.16m.

Good coupling conditions, throughout the entire antenna, are found when the power injection is assisted by local D_2 gas feed. The beneficial modification of the SOL in the flux tubes passing in front of the antenna is documented by measurements of a reciprocating Langmuir probe. This allowed to couple up to 3.1MW, with a gap of 0.15m, corresponding to a power density of 15MW/m^2, but 22 MW/m^2 on half of the antenna which is close to the power density required at 3.7GHz for ITER.

Modeling of the modification of the SOL by LH power absorption was performed with the EDGE2D fluid code. Flat j_{sat}/density profiles similar to experimental ones are obtained when a small fraction of the LH power is supposed to be absorbed in a ~20mm thick layer in front of the antenna.

The parallel heat flux ($F_{//}$) on a plasma-facing component due to LH power dissipation in th SOL is computed from infra-red data. The strong dependence of $F_{//}$ with the injected LH power gives further evidence of the LH-induced density modification. It is concluded that with optimized gas injection $F_{//}$ in H mode should not exceed 5MW/m^2 at maximum power density (25MW/m^2).

The effect of large gap and gas injection on LH current drive efficiency was studied in L-mode discharges for which the real-time control was used in order to keep the loop voltage constant (0.2V) and leave the plasma current floating. The plasma current of the large gap/gas injection case is lower than that the small gap/no injection case by 5%. At the same time a significant increase of density fluctuations measured by reflectometry at the plasma periphery is measured for the large gap/gas injection case.

The effect of the gas injection on the energy confinement is investigated. No effect on the global confinement or on the neutron rate was observed in the advanced tokamak scenario, Only a slight modification of the type-I ELMs amplitude and frequency was observed when the connected pipe puffed gas. The confinement degrades with the line-averaged density normalized to the Greenwald density, identically for pulses for which the connected gas injection is used or not.

1. Introduction

Lower Hybrid (LH) waves constitute a unique tool to provide current drive in the outer part of the plasma (i.e. at a normalized plasma radius between 0.6-0.8) with high current drive (CD) efficiency [1, 2]. On ITER, non-inductive scenarios with reversed q-profiles (q being the safety factor) require a significant fraction of the plasma current to be driven by LH waves. Moreover, LHCD could be necessary from the early phase of ITER operation to ramp-up the current and to save magnetic flux for 400s pulses.

On the JET tokamak, LHCD experiments have been performed in ITER-relevant conditions which include high triangularity plasmas and a large distance between the separatrix and the wall (~0.15m). This was achieved by injecting Deuterium gas from a pipe located ~1m away from the antenna, referred as the GIM (Gas Injector Module) 6. The JET LH launcher is made of 2 toroidal by 3 poloidal modules (each module corresponds to 48 waveguides and 4 klystrons) also referred as top, middle and bottom row (a row corresponding to 2 toroidal modules).The 8 holes of the GIM6 pipe are magnetically connected to the launcher middle and bottom rows but not to the upper row for the range of edge safety factor used in these reported experiments. Beneficial effects of the gas injection on the density profile in the scrape-off layer (SOL) and on the LH coupling is presented. Possible drawbacks of the wide SOL and the gas injection on power dissipation in the SOL, CD efficiency and energy confinement are also examined.

2. LH Coupling with a large gap between the separatrix and the antenna

In order to ensure that LH waves can launch the appropriate parallel index spectrum with maximized CD efficiency and propagate to the plasma core with a weak power reflection to the generator, the electron density at the LH antenna aperture must exceed the cut-off density which is $n_{co}=1.7\times10^{17}m^{-3}$ at 3.7GHz. On ITER, the separatrix could be up to 0.16m from the wall and with the expected SOL density profiles, this condition could be not fulfilled. Nevertheless it has been shown on several tokamaks (Asdex [3], Tore Supra [4], JT60-U [5]) that the density in front a LH launcher can be significantly increased when the antenna is powered. This is generally attributed to enhanced ionization by a small fraction of the LH power which is dissipated in the SOL although modification of the particle transport could contribute to this effect. Early experiments on JET have shown that the gap between the antenna and the separatrix (D_{sa}) could be extended to 0.11m with gas injection [6]. During the 2006 and 2007 campaigns, further experiments were carried out with low (δ~0.21) and high triangularity (δ~0.45) H-mode plasmas and Radial Outer Gap (ROG), defined as the distance between the separatrix and the limiter in the equatorial plane, varying between 0.08 and 0.15m. The plasma current (I_p=1.5-1.9MA) and toroidal field (B_0=3-3.1T) were adjusted to obtain a high edge safety factor (q_{95}=4.0-6.8).

The LH antenna is positioned 20mm behind the poloidal limiters (PL) and the resulting connection length in front of the antenna is much shorter ($L_{//}$=2.5m) than further away in front of the PL ($L_{//}$>20m). The modification of the SOL density in the flux tubes passing in front of the antenna is documented by the measurements of a reciprocating Langmuir probe (RCP) located at the top of the machine. For the range of q_{95} of these experiments, the field line connected to the RCP can either be passing slightly below the LH launcher or being connected to the lower rows of the launcher. The LH power was applied during the H-mode phase with Edge Localised Modes (ELMs) frequencies varying between ~20Hz and ~200Hz. The RCP saturation current (J_{sat}) was measured between the ELMs when the D_α signal does not exceed the base line by more than 30%. When the LH power is increased the density rises in a layer which extends in front of the PL by several centimetres and a plateau is formed when the LH power is sufficiently high (figure 1). The low power pulse of figure 1 was performed with no gas injection (open circles) and beneficial effect of GIM6 is clear when the J_{sat} profile is compared to those with gas injection (closed symbols). Such a plateau is obtained experimentally in most of the cases when the applied LH power is sufficiently large. In order to clarify the respective role of gas injection and LH power, the current density on the magnetic surface grazing the leading edge of the poloidal limiters (labelled J_{sat}@wall) is plotted as a function of the LH power (figure 2) for $R-R_{sep}$=0.10m and low triangularity plasmas. The beneficial effect of the LH power for increasing the density at the plateau is clearly seen from figure 2. When the LH power is varied between 0 and 3MW, J_{sat}@wall increases by a factor ~6 with no indication of saturation. With the same data, when J_{sat} is plotted as a function of gas flux, one obtains a wider scattering of the points at high gas puffing values. Similar results are obtained for the high triangularity plasmas but the efficiency of LH power to raise the density, estimated from the slope of the plot of J_{sat}@wall as a function of P_{LH}, is lower by a factor ~2.

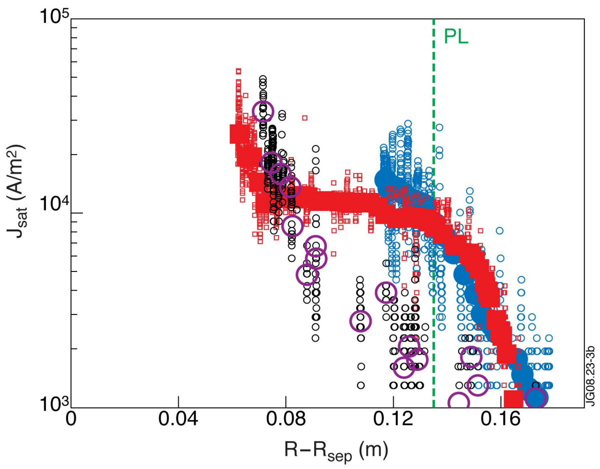

Fig.1. J_{sat} profiles: F_{GIM6}= 0, P_{LH}=0.6MW (open circles), F_{GIM6}=4×10^{21}el./s, P_{LH}=0 (closed red circles) and F_{GIM6}=2×10^{21}el./s, P_{LH}=3.2MW (closed blue squares). All data (small symbols) and time-averaged data (large symbols) are shown. High triangularity plasmas, D_{sa}=0.15m.

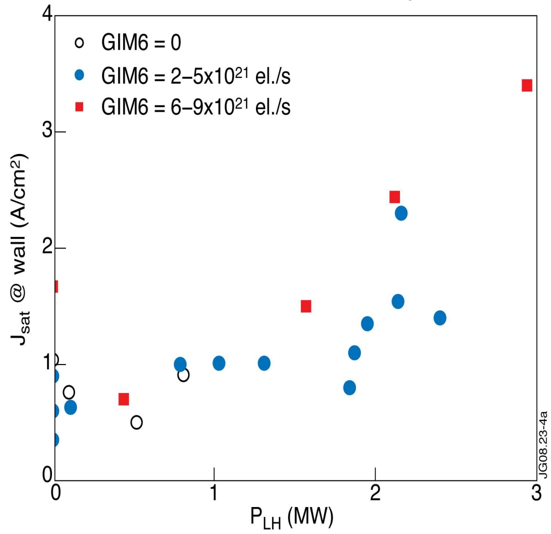

Fig.2. J_{sat} at the wall as a function of coupled LH power. Low triangularity plasmas, D_{sa}=0.10m.

The power reflection coefficient (RC), measured for the 6 rows of modules, is in agreement with the RCP density measurements. When J_{sat}@wall is lower than 10^4A/m^2, weak coupling with RC exceeding 20% is observed, indicating a density below the cut-off in front of the antenna. This occurs at low power/low gas injection. Optimal coupling conditions, with RC<5%, are obtained for J_{sat}@wall =1-2×10^4A/m^2. For higher values, RC slightly increases, indicating that the density at the plasma-antenna interface exceeds ~10 times the cut-off density provided that non-linear effects do not affect the coupling significantly. This sharp transition can be explained if we assume that at low power, the density behind the PL falls off with an e-fold decay length λ_n~10mm and, when high LH power is coupled, the density plateau, measured in front of the PL, actually starts from the plasma-antenna interface. This transition is more pronounced for the bottom rows, although these rows are more recessed from the plasma, suggesting that the density is larger in front of the bottom than in front of the top one. This is coherent with the fact the upper row is marginally connected with the GIM6 pipe. During ELMs, the fast acquisition of the RCP gives evidence that the ion flux (J_{sat}) measured 0.10m behind the separatrix can be increased by almost two orders of magnitude. This increase of density is generally beneficial to the LH coupling and an RC decrease can be observed when the D_α signal grows. However, when gas is puffed from GIM6, during an ELM decay, the RC of the lower row starts slightly decreasing to a minimum and increases later whereas the RC of the upper row monotonically increases. According to LH coupling code predictions, this suggests again that the density is larger in the lower part of the antenna than in the upper part.

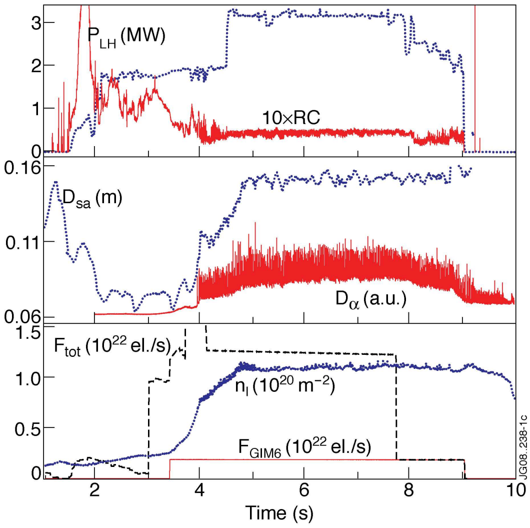

Figure 3. Time traces of JET pulse 67883 (high δ case): LH power and global RC (upper part), Dand D_a signal (middle part), line-integrated density, total gas injection and GIM6 gas injection (lower part)

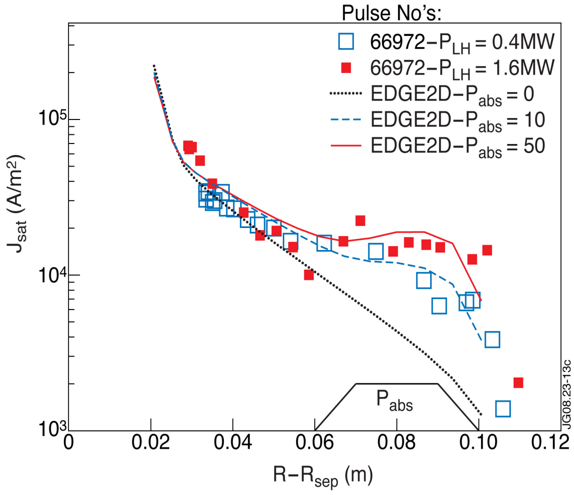

Figure 4. Modelling of J_{sat} (pulse 66972) with P_{abs}=0 (dotted line) and P_{abs}=10 (dashed line) and P_{abs}=50 (solid line). D_{LW}=0.02m. Experimental data (after time-averaging) are shown for P_{LH}=0.4MW (□) and P_{LH}=1.6 MW (■). Values for P_{abs} in normalized units as used in the code.

With such scenarios up to 3.1MW was coupled with D_{sa}=0.15m and a global RC of 5% (figure 3), corresponding to an averaged power density of 15MW/m^2. Note that 22 MW/m^2 were reached on half of the antenna which is close to the power density required at 3.7GHz for ITER.

Modeling of the density modification in the SOL by LH power absorption was performed with the two dimensional fluid code EDGE2D-NIMBUS which was modified in order to account for possible enhanced ionization in the SOL. The PL acting as sinks for the particles are also included in the model [7]. The enhanced ionization is obtained by assuming that a fraction of the LH power P_{abs}, is absorbed by the electrons in a layer extending in the radial direction from the launcher position to a radius located at a distance D_{LW} ~ 0.02m from the launcher. J_{sat} profiles are well modeled in various cases: steep profile (P_{LH}=0), broad profile (P_{LH}=0.4MW) and flat profile (P_{LH}=1.7MW) when P_{abs} is set to 0, 10 and 50 respectively, in the code units (figure 4). The ratio of P_{abs} is the same as for the experimentally used LH powers. This result indicates that the dissipated power in the edge is a constant fraction of the launched power. Effect of the diffusion coefficient in the SOL was also tested with the code. The main result is that with no additional power source dissipated in the SOL, no reasonable value of the diffusion coefficient can be found to explain the experimentally observed very flat J_{sat} profile in the far SOL.

3. Power dissipation in the SOL

LH power absorption in the flux tubes passing in front of the antenna may lead to enhanced ionization of the gas but can also produce in the SOL, a fast electron tail in the velocity distribution function in a way very similar to the acceleration of fast electrons in the plasma core by Landau damping. On JET, heat power deposition on the upper part of the divertor has been observed with a CCD camera during LHCD experiments [8]. The infra-red camera recently installed on JET now allows quantifying the heat flux. This was performed for two shots using surface temperature measurements of the left-hand side limiter (referred as MTL3) of the new ITER-like ICRH antenna (ILA), located toroidally ~45° clockwise (in the ion drift direction) from the LH antenna ($L_{//}$~3m). From field line tracing it can be concluded that the hot spots on MTL3 are connected to the lower part of the LH antenna. Depending on the actual radial position of the LH antenna (for which an uncertainty of 25mm toward the plasma is assumed), the radial extension of the field lines passing in front of the LH antenna and connected to the ILA side limiter, can vary between d_0=7.5 and d_0=15mm. Two power deposition profiles were assumed: constant parallel flux on the limiter tile (peaking factor PF=1) and linear increase of the flux with radial distance from the antenna (peaking factor PF=1.5). Two discharges with various phases in H and L mode, have been analysed (see 66970 on Figure 5). The parallel heat flux ($F_{//}$) was computed from the thermo-hydraulic code CAST3M using the infra-red camera data as input. The good agreement between experiment and modelling (Figure 5) of the temperature in particular in the decay phases with no LH power (for t > 12s) leaves an uncertainty on the peaking factor but indicates that effects due to thin carbon layers often observed on plasma facing components, are in this case, weak and probably negligible. When the radial extension of the fast electron beam is reduced from d_0=15mm to d_0=7.5mm on the side limiter tile, $F_{//}$ is increased by a factor ~1.8. As the LH power is varied between 0.5MW and 3MW, $F_{//}$ on MTL3 varies from 0 to 5MW/m^2 in H-mode, with the flux scaling roughly as the square of the LH power (Figure 6). This non-linear dependence has been also observed on Tore Supra [9] and is the consequence of the density increase near the antenna with LH power giving further evidence of the LH-induced density modification. The highest flux in L-mode is also a consequence of the higher density in the SOL than that in H-mode. It is concluded that with optimized gas injection maintaining a constant density while the LH power is raised, $F_{//}$ should scale linearly with the LH power and should not exceed, in H mode, 5MW/m^2 at maximum LH power density (25MW/m^2).

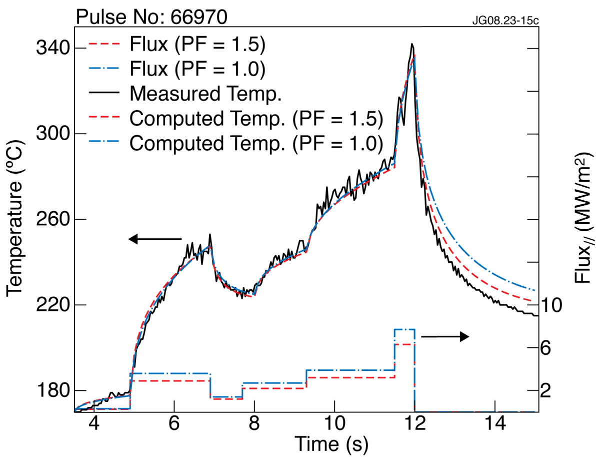

Figure 5. Time evolution of the temperature of tile 8 of the ILA side limiter (MTL3): measured (solid line) and calculated with two peaking factors for the power deposition, PF=1 (dot-dashed line) and PF=1.5 (dashed line). The corresponding parallel heat flux for these two computations are also shown. Pulse 66970, d_0=7.5mm. H mode for t < 7.8s, L mode later

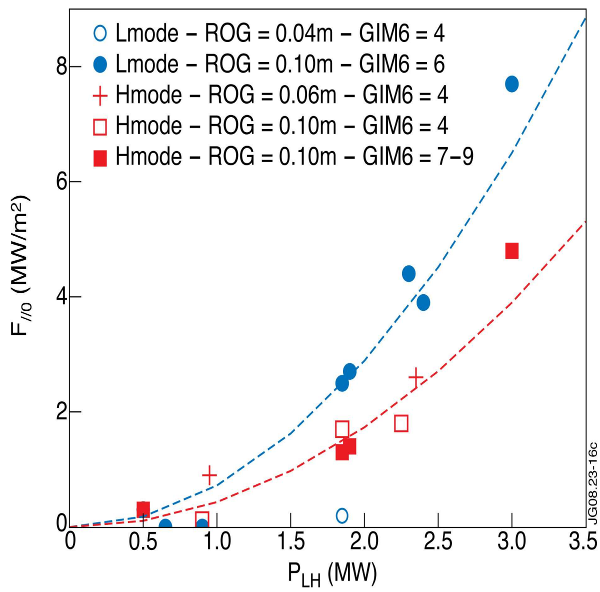

Figure 6. Parallel heat flux on MTL3 as a function of LH power

4. Current drive efficiency.

The possible drawback of density rise in the SOL is a loss of coupled power to the plasma core by the already discussed increase of Landau damping on thermal electrons or a modification of the power deposition due to spectral broadening induced by parametric decay instabilities [10]. This effect was investigated recently in a set a experiments carried out in L-mode plasmas with the following parameters: B_t=2.7T, I_p=1.5MA, P_{LH}=3.2-3.7MW (2.6MW for one pulse) for 10s, line-averaged density $\overline{n_e}$=1.4-1.9×10^{19}m^{-3}. Two parameters were varied: the ROG between 34 and 88mm and the gas rate from GIM6 F_{GIM6}=0.6-4.5×10^{21}el./s. Stationary conditions are obtained after 2-3s for these low temperature plasmas (volume-averaged temperature $\langle T_e \rangle$=0.9-1.1keV) and the signals discussed are averaged on the last 7s of the LH pulse. For this range of parameters the loop voltage V_{LH} varied between 0.21V and 0.26V (0.32V for the lower power pulse) with a typical standard deviation of 0.015V.

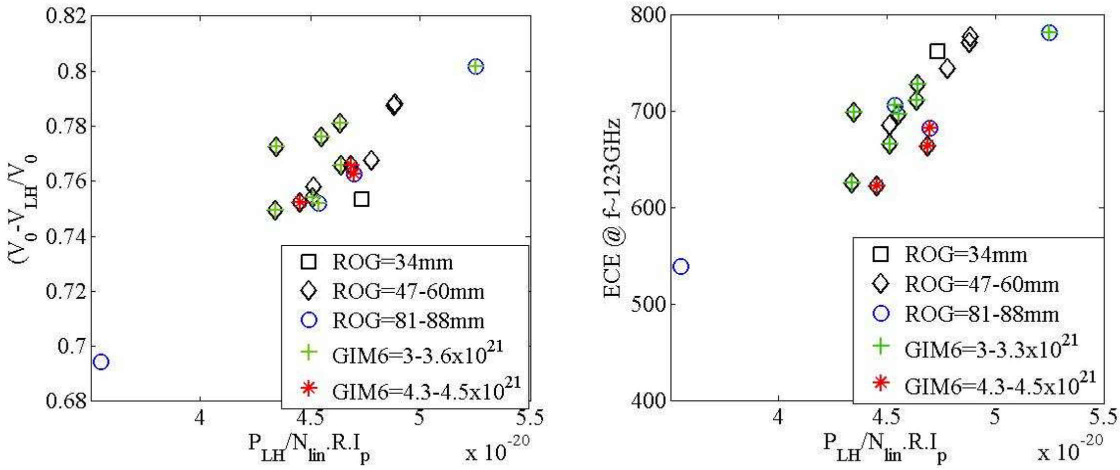

Figure 7 a) Relative loop voltage drop b) Non thermal second harmonic ECE amplitude as a function of the normalized LH power. Open symbols indicate low gas injection from GIM6 (F_{GIM6}= 0.6-2×10^{21}el./s).V_0 is the loop voltage in the ohmic phase

Figure 7a shows the relative loop voltage drop $(V_0-V_{LH})/V_0$ as a function of the normalized LH power $P_{LH}/\overline{n_e}RI_p$ (in W.A^{-1}.m^{-2}) where R the major plasma radius. For the same normalized power, the relative loop voltage varies by less than 4% and no clear correlation can be found between ROG / F_{GIM6} and $(V_0-V_{LH})/V_0$. For the same pulse list, the amplitude of the non-thermal part coming from the downshifted second harmonic electron cyclotron emission (f ~123GHz) is also plotted as a function of the normalized power (figure 7b). In the three pulses performed at the highest gas rate (F_{GIM6}=4.3-4.5×10^{21}el./s), this amplitude is lower by ~10% whereas no significant effect of the antenna-plasma gap can be inferred. It should be noticed that this smaller CD efficiency reduction which is likely to be inferred for high gas rate from GIM6 is not due to higher plasma core density as similar trend was observed in pulses with higher $\overline{n_e}$. Similar effect of high level of near-grill gas injection was reported in earlier JET experiments [11]. It should be noted that the frequency of the second harmonic ECE increases from f=122GHz to f=123.5GHz when the ROG is increased from 34mm to 85mm indicating that the current deposition profile is shifted by ~45mm. It suggests that the normalized radius of the profile and the energy of the fast electrons are marginally changed when the ROG is increased. A possible drawback of gas puffing near the launcher is an increase of the fluctuations leading to enhanced wave scattering [12]. Density fluctuations measured by reflectometry at the plasma periphery (r/a ~0.xx??) do not indicate any change for the whole series. A significant increase of the fluctuations rate was found in earlier experiments for the large injection case (+50%±30%). This difference could be due to either the higher density of these pulses ($\overline{n_e}$~2.3×10^{19}m^{-3}) or the lower accuracy of the low density pulses.

5. Energy confinement

Gas injection may lead to a degradation of the energy confinement in H-mode via a reduction of the height of the pressure pedestal [13]. In order to quantify the specific effect of deuterium gas injection from GIM6 on confinement, the H factor H98(y,2) was computed for various discharges performed at high q (q_{95}~ 5) with gas injected from GIM6 or/and from the divertor region. Two series, with different H factors, were analyzed. The two series differ mainly from the equilibrium: high (δ~0.4) and low (δ~0.25) triangularity, large (75-130mm) and low (65mm) ROG. LH power varied from 0 to 3.1MW in the first series and 0 to 2.5MW in the second one. Ion cyclotron frequency power was added from 0 to 2.6MW and 0 to 5.7MW, respectively. The magnetic field (3-3.1T and 2.65T) and plasma current (15-1.9MA and 1.75MA) had close values for both series. H factor was corrected from fast ions due to neutral beam injection (~10% of the diamagnetic energy) but not from the fast protons heated by the ion cyclotron minority heating scheme whose contribution is negligible for these pulses (~1% of the diamagnetic energy).

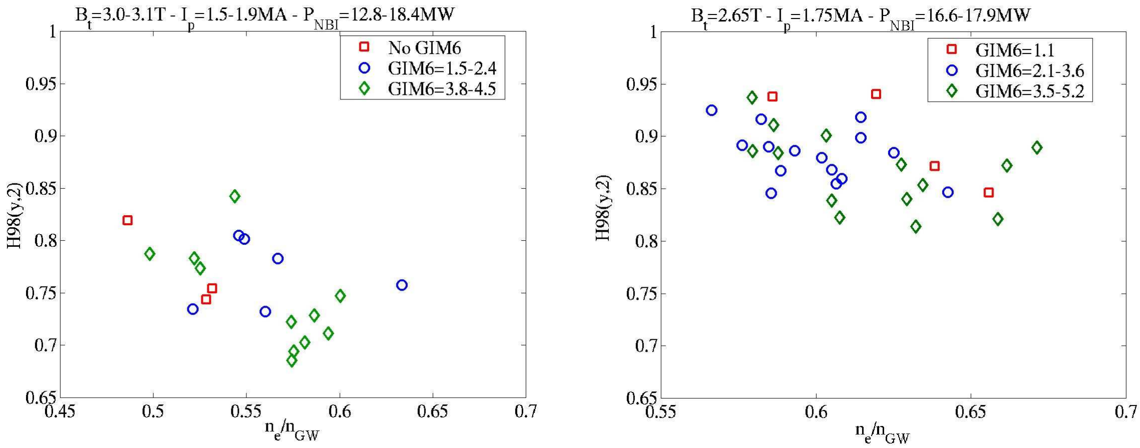

Figure 8: H98(y,2) versus n_e/n_G for a) high triangularity plasmas/large ROG b) low triangularity/low ROG. The data is averaged over a 1s for a) and 2s for b) time period. GIM6 denotes the gas rate from GIM6 in units of 10^{21} el/s.

Figure 8 shows H98(y,2) versus the electron density normalised to the Greenwald density limit n_e/n_G ($n_G=\overline{n_e}/I_p/\pi a^2$). The various GIM6 levels can be distinguished. The points corresponding to zero flow (red square on fig.6a) or low flow (red square on fig.6b) from GIM6 have gas injection from the divertor region only. No difference in confinement can be seen, whether GIM6 is used or not: the confinement degrades with the density identically for pulses for which GIM6 is used (with a rate in the 2-5×10^{21}el./s range) or not.

No specific effect of gas injection from GIM6 on type-I ELMs frequency and amplitudes were noticed, in particular pulses performed with the same high gas rate from GIM6 (4×10^{21}el./s) have low frequency ELMs or high frequency ELMs depending only on the total gas flow (Figure 9). Similar results are obtained in the hybrid scenario (with H98(y,2)=0.75-0.9) performed at low magnetic field (1.7T) and also a large ROG. Specific effects on confinement linked to the interaction of the wave with the SOL seem to be discarded. However, this results requires confirmation from discharges with H98(y,2)~1 when $n_e/n_G \geq 0.7$.

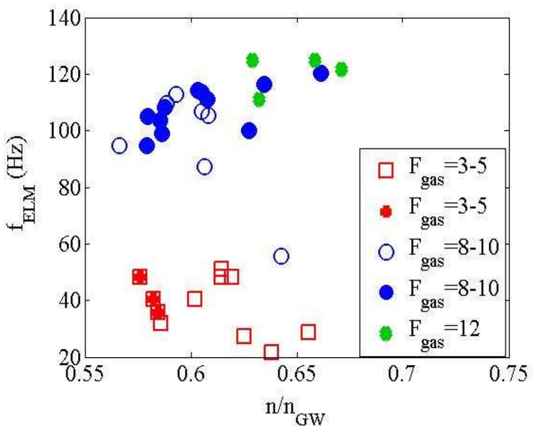

Figure 9: ELM frequency versus n_e/n_G for different gas injection rates. Open and closed symbols are for low (F_{GIM6}=1-3.5×10^{21}el./s) and high gas rate from GIM6 (F_{GIM6}=4-5×10^{21}el./s), respectively. Total gas rate F_{gas} is in units of 10^{21} el/s.

6. Conclusion

High power LH pulses with low RC were performed on JET in ITER-relevant coupling conditions, i.e. with a distance between the separatrix and the wall (the PL on JET) as large as 0.13m, the LH antenna being located ~0.01m behind the wall. This was achieved with the assistance of gas injection from a pipe magnetically connected to the plasma in front of the antenna, in the high q_{95} advanced scenarios characterized by rather high recycling. RCP measurements show clearly a beneficial effect of the LH power. The enhanced ionization of the gas which scales roughly linearly with LH power, could allow a lower gas rate after the power ramp up. In optimized conditions of gas feed, heat fluxes from accelerated electrons are tolerable for a tilted first wall and current drive efficiency as plasma performance are marginally affected by gas injection and the resulting power loss in the SOL. Before extrapolating these results to ITER, the effect of a metallic wall has to be documented on JET when the ITER-like wall is installed.

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