Lower hybrid current drive efficiency at high density on Tore Supra

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1) Introduction

High lower hybrid current drive efficiency ($\eta = \overline{n_e} RI_{LH}/P_{LH} \sim 0.3\times10^{20} A.W^{-1}m^{-2}$) has been obtained at rather low plasma densities ($\overline{n_e} < 3\times10^{19}m^{-3}$) on JET and JT-60 when the steady state scenario of ITER requires a density $\overline{n_e} = 7\times10^{19}m^{-3}$. Recent results on FTU [1] ,C-Mod [2], and JET [3] indicate that the current drive efficiency strongly decays for density exceeding 5-7×$10^{19}m^{-3}$. Interaction of the wave with the edge plasma has been evoked as the cause for reduction of CD efficiency. LHCD experiments (P_{LH}=2MW) have been carried out on Tore Supra with the density varying between 3.2 and 5.2×$10^{19}m^{-3}$. Plasma edge and scrape-off layer (SOL) were modified by various means: change of particle fuelling method (pellets injection), change of the limiter on which the plasma is leaning, reduction of the plasma size, variation of the distance between the antenna and the confined plasma. Fast electron population is monitored from the measurement of the fast electron bremsstrahlung in the hard X-ray (HXR) range and the down-shifted non-thermal electron cyclotron emission. Probes embedded in the LH antenna provide a measurement of the ion saturation (j_{sat}) fluctuations (10-500kHz).

2) Bremsstrahlung and ECE measurements

When the volume-average density $\langle n_e \rangle$ is varied from 1.5 to ~4.0×$10^{19}m^{-3}$, the HXR emission decays according to $\langle ne \rangle^{-2.5}$ for the lowest range of X-rays (40-80keV) and to $\langle ne \rangle^{-3.5}$ for the highest range (100-140keV). This decay is very likely to be consistent with the modelled LH-driven (from ray tracing and Fokker-Planck codes) which is found to also decay strongly with the density [3]. The central and volume-averaged electron temperatures, which decay as

$1/\langle n_e \rangle$ in these experiments performed at constant LH power, contributes to this decrease of CD efficiency with density. The effective charge Z_{eff} also decreases as $1/\langle n_e \rangle$ and, as HXR emission is sensitive to the charge Z of the ions, it decreases with decreasing Z_{eff}. For density exceeding $\langle n_e \rangle = 4.0 \times 10^{19} m^{-3}$, a stronger decay of the HXR signal is observed for the standard Tore Supra plasma (a=0.72m). This strong decay occurs for the lower energy photons (E<80keV) whereas the higher energy ones keep on following the same density scaling (Fig.1, left). This indicates a higher photon temperature, which increases from 33keV to ~60keV. A similar decay of the down-shifted non thermal ECE is measured (Figure 1, right). When the plasma minor radius is reduced from a=0.72m to a=0.66m, the anomalous decay of the fast electron bremsstrahlung and non-thermal ECE is much weaker and starts at higher density (Fig.1, left). Accordingly, the photon energy remains constant (T_{ph}=34keV). At $\langle n_e \rangle = 5.0 \times 10^{19} m^{-3}$, for the standard plasma, the HXR is reduced by a factor of 3 with respect to the $1/\langle n_e \rangle^{2.5}$ scaling whereas this reduction factor is only 1.4 for the smaller plasma. Exactly the same phenomenology was observed when fuelling a standard plasma with pellets [4]. Electron density at the last closed flux surface (LCFS) is found to be identical at low plasma density ($3.5 \times 10^{19} m^{-3}$) and lower by 15% at high density ($5.3 \times 10^{19} m^{-3}$) for the smaller plasma which has also a larger e-fold decay length (4cm vs. 3cm). Edge temperature is not measured very accurately but is likely to be quite similar for the standard and small plasmas.

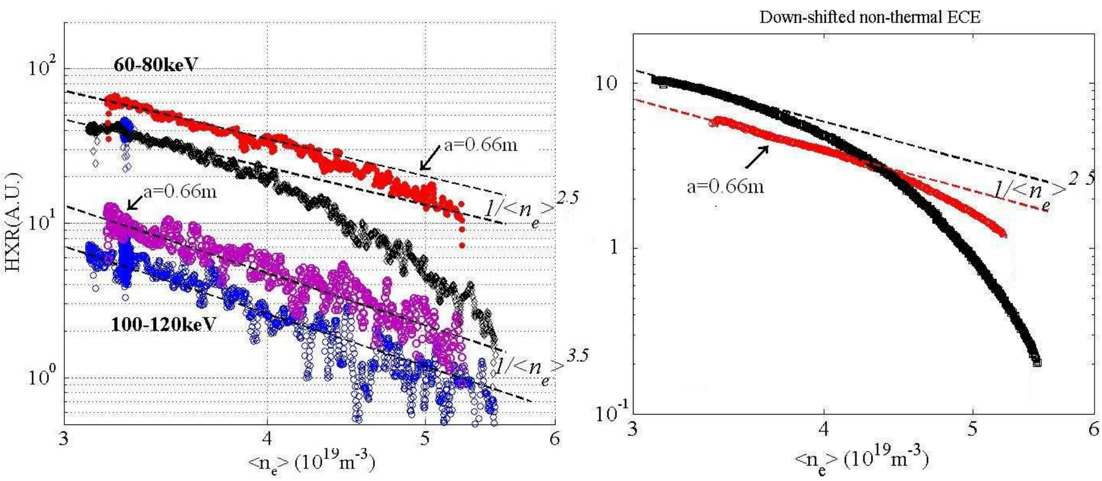

Figure 1. HXR (left) and non-thermal ECE (right) as a function of the volume-averaged density for two plasma sizes (a=0.72m and a=0.66m)

In order to change strongly the particle recycling, the plasma was pushed against an unpumped outboard limiter, a configuration which reduces the wetted surface by a factor ~20 with respect to the standard configuration where the plasma is leaning on the toroidal pumped limiter located at the bottom of the machine. This comparison was done with the small plasma in order to leave a 6cm clearance with other limiters. Gas injected for building a high density plasma was 3 times lower than in the reference case and density at the LCFS increased by ~50%. Electron temperature measured near the LCFS (r/a=0.96) is also likely to be higher for this high recycling case by ~50%. With such edge plasma conditions, (hotter and more dense), the HXR emission and non-thermal ECE do not fall off at high density. The fast electron signatures were also found independent of the gap between the LH launcher which was changed from 8cm to 4 cm away from the LCFS in the case of a small plasma leaning on the toroidal limiter.

3) Density Fluctuation measurements

For the standard plasma (a=0.72m), the fluctuation rate estimated from $RMS(j_{sat})/\langle j_{sat}\rangle$ is strongly enhanced for high density plasmas whereas the fluctuation rate is almost unchanged for the smaller plasma (Figure 2). The density threshold for enhanced fluctuation rate is very close to that of decay of HXR emission ($\langle n_e\rangle \approx 4\times10^{19}m^{-3}$). It should be noted that the standard plasma required a larger gas injection rate, leading to a higher density (from j_{sat}) in the SOL, for achieving a high density plasma. The same result is obtained when a standard plasma is fuelled with pellets with also constant fluctuation rate when the density is varied between $3\times10^{19}m^{-3}$ and $5\times10^{19}m^{-3}$[4]. In this case, the fluctuation frequency spectrum was measured and compared to the gas-fuelled plasma. The spectrum of the gas-fuelled pulse has a much larger high-frequency component (Figure 3).

For the small plasma configuration, when the plasma is leaning on the outboard small limiter or when the LHCD antenna is approached at 4cm from the LCFS, the edge density increases by a factor ~ 2 (small limiter) and ~3 (reduced gap between antenna and LCFS) but the fluctuation rate is unchanged with respect of the reference case (plasma leaning on the toroidal pumped limiter).

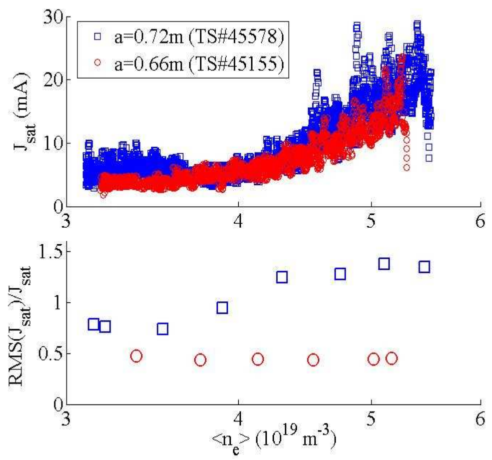

Figure.2 J_{sat} and fluctuation rate versus plasma density for 2 plasma sizes.

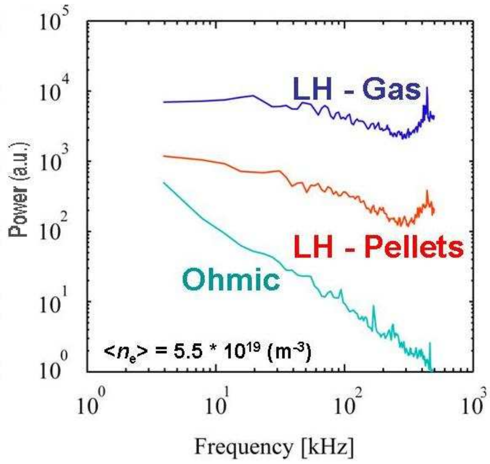

Figure 3 Fluctuation spectrum for pulses fuelled with gas and pellets

4) Discussion and conclusions

For line-averaged density $\overline{n_e}$ in the range of $3.5\text{-}4.5\times10^{19}m^{-3}$, the scaling of the HXR (and non-thermal ECE) with density ($n_e^{-2.5}$) is apparently consistent with standard LHCD theory. It was verified that this parametric dependency is still valid for plasma density as low as $\langle n_e\rangle=1.5\times10^{19}m^{-3}$. A full reconstruction of the HXR signal from the fast electron distribution and plasma equilibrium is currently under way. At higher density $\overline{n_e}=4.5\text{-}6\times10^{19}m^{-3}$, the HXR emission (and ECE) decreases more rapidly for the standard configuration (large gas-fuelled plasma). We found three configurations for which this effect is strongly mitigated: reduced size of the plasma, fuelling with pellets and plasma leaning on the small outboard limiter. This indicates that the particle recycling is very likely to be an important point and is in the line of results on FTU [2].. In addition, the degraded LHCD efficiency is strongly correlated to enhanced density fluctuation rate in the SOL near the antenna.

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