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M. Goniche et al.

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Edge plasma – lower hybrid wave interaction and current drive efficiency

M.Goniche[1], K.Kirov[2], J.Mailloux[2], G.Antar[3], B.J.Ding[4], A.Ekedahl[1], M.H.Li[4], Y.Peysson[1] and JET Contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.*

[2] *CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*

[3] *American University of Beirut, Riad el-Solh, Beirut 1107-2020, Lebanon*

[4] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, P. R. China*

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Introduction

Lower Hybrid Current Drive (LHCD) has the unique capability to drive current with high efficiency in the outer part of the plasma (r/a>0.5) and to shape the current profile required for the fully non-inductive steady state scenario. So far, fully or quasi-fully non inductive discharges have been carried out at low or medium plasma density ($\bar{n}_e$ <5x10^{19}m^{-3}) whereas the ITER steady state scenario assumes $\bar{n}_e$ ~7×10^{19}m^{-3}.

Experiments have been performed on JET [1], Alcator C-Mod [2], FTU [3] and Tore Supra [4] at ITER-relevant plasma densities. The fast electron tail and the LHCD efficiency were estimated from the bremsstrahlung emission by the Hard X-ray (HXR) diagnostic (40-200keV) for the last 3 facilities and from the Electron Cyclotron Emission of the fast electron population ($ECE_{non\ th.}$) for JET and Tore Supra. When the density is ramped up at constant LHCD power, the HXR or ECE signal decays very fast typically like $\bar{n}_e^{\ -k}$ with k~3 on Tore Supra, k~4.5 on C-Mod. The HXR signal is satisfactory reconstructed when ad-hoc broadening of the wave index spectrum is included in the C3PO/LUKE ray-tracing/Fokker Planck code [5, 6]. The fast electron tail can be increased by more than on order of magnitude by additional heating provided by ICRH (C-Mod [7]) or by changing the particle recycling wall obtained by lithium layer deposition (FTU [3], EAST [8]). Whereas the first technique can both increase the core and edge electron temperature, the second one can be assumed to mostly affect the edge temperature. Low edge temperature may lead to parasitic wave absorption (collisional absorption) or wave spectrum modification (wave scattering, parametric decay). We here investigate the link between the frequency spectrum broadening, related to the coherent quasi-mode at the ion sound frequency (~MHz), and the fast electron tail.

Experimental results

The effect of LHCD power on spectrum broadening was investigated on JET. The frequency spectrum was measured outside the vacuum vessel by a magnetic loop or from the reflected RF power. When the LH power is increased from 0.1MW to 3.2MW, the pump broadening, measured 30dB below the maximum, increases linearly and doubles without observed threshold.

$ECE_{non\ th.}$ and HXR measurements were performed, on JET and EAST respectively, during L-mode discharges whose line-averaged density $\bar{n}_e$ was ramped-up from 1.5 (EAST)-1.9 (JET)×$10^{19}m^{-3}$ to 2.8 (JET)-3.5 (EAST) ×$10^{19}m^{-3}$ by gas injection. The toroidal field was 1.95-2.43T on JET and 2.24T on EAST. Following the Stix-Golant accessibility condition (no propagation effect), the wave can penetrate to the very edge only where the density gradient is large: typically for a density of $\bar{n}_e$=2.5x$10^{19}m^{-3}$ the wave penetrates up to r/a~0.99 at 2.1T and r/a~0.90 at 2.4T on JETwith a parallel wave index was used $N_{//}$=1.8. On EAST ($N_{//}$=2.1), the wave can penetrate much further in, up to r/a~0.6.

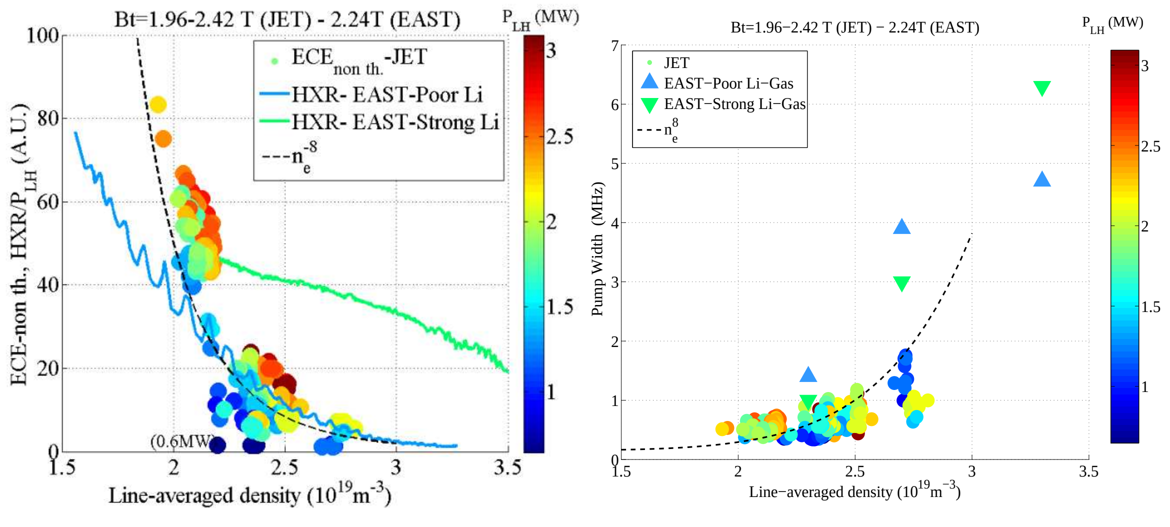

Figure 1. a) $ECE_{non\ th.}$(JET) and HXR (EAST) b) Pump width at -30dB (JET) , -20dB (EAST) as a function of $\bar{n}_e$. Bt=2.22-2.43T, $N_{//}$=1.8 (JET), Bt=2.24T, $N_{//}$=2.1 (EAST).

For this range of magnetic fields, a very strong decrease of the signal (k=-8) is observed on both machines when $\bar{n}_e$ exceeds ~2.2x$10^{19}m^{-3}$ (figure 1-a). Although the $ECE_{non\ th.}$ and HXR signals are normalized to LHCD power, the fast electron emission still increases with power, consistent with a beneficial effect on the generation of the fast electron tail of higher electron temperature from the higher injected power. After lithium deposition on the vessel walls in EAST, $1/\bar{n}_e$ scaling is found up to $\bar{n}_e = 2.6 \times 10^{19} m^{-3}$. For the same discharges, a weak increase of the pump width Δf_{-30dB} (from ~0.5MHz to ~1MHz) is observed on JET with increasing density whereas Δf_{30dB} increases from 3.8MHz to 8.7MHz on EAST (1.4MHz to 4.7MHz when measured at -20dB, figure 1-b). After lithium deposition, a strong increase of ΔF is observed with even a larger value for the highest density case when compared to the high recycling case.

From the same database, the $ECE_{non\ th.}$ signal is now plotted as a function of the density normalized to the accessible density at r/a=0.9 (figure 2.a). The scattering of the fit is significantly reduced (RMS goes from 7 to 4) and the k exponent is reduced from 8 to 5. It should be noted that for an edge density exceeding the accessible density by ~70%, there is still a fast electron tail. The EAST data, performed with a higher wave index ($N_{//}$=2.1), have a much lower range of normalized density (0.4-0.75) and do not scale the same way as the JET data, keeping the normalizing factor of the ECE data with the HXR data of figure 1. Parametric decay is expected to affect strongly the LHCD efficiency when the ratio of the lower hybrid frequency ω_{LH} to the operating frequency ω approaches ~0.5 [9]. Here ω_{LH}/ω lies between 0.13 and 0.16 for the JET data and between 0.18 and 0.21 for the EAST data (Figure 2.b). The EAST Δf data are now more in the line of the JET ones although there is still a difference when considering that the Δf_{30dB} is about twice Δf_{20dB}.

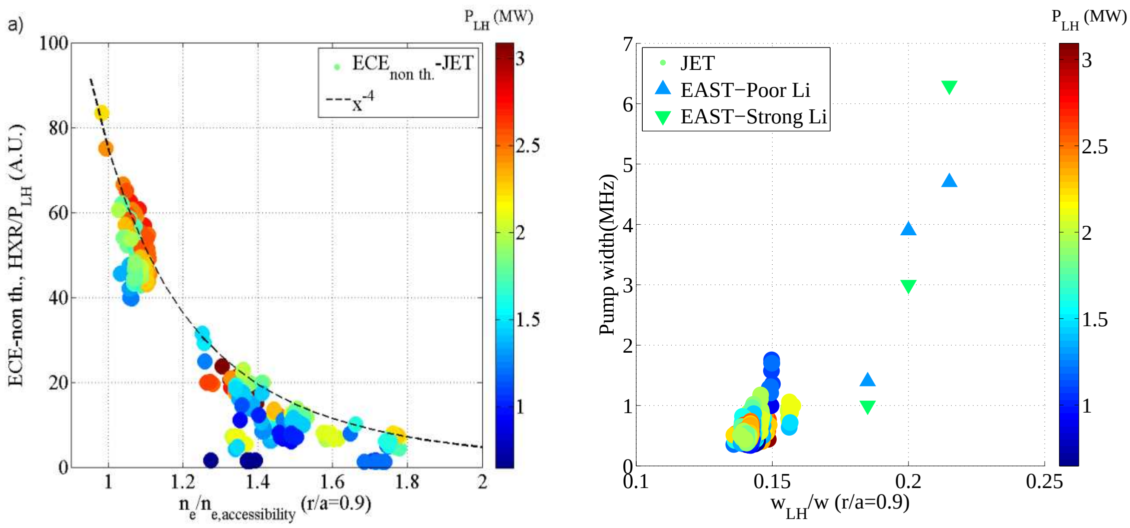

Figure 2. a) $ECE_{non\ th.}$(JET) as a function of $n_e/n_{e,\ acess}$. b) Pump width at -30dB (JET) , -20dB (EAST) as a function of ω_{LH}/ω. Bt=1.96-2.43T, $N_{//}$=1.8 (JET), Bt=2.24T, $N_{//}$=2.1 (EAST).

Discussion and conclusions

The link between parametric instabilities triggered at the plasma edge and LHCD efficiency have been studied on a data base of 56 JET discharges and 2 EAST discharges with a density ramp. On JET, for these weakly accessible conditions, the fast electron tail decays, as it does on C-Mod or Tore Supra (k=3-5) when the density is normalized to $n_{e,accessibility.}$ However the amplitude of the ion-sound quasi-mode, derived from Δf_{30dB}, increases quite modestly with density and is poorly related to the fast electron tail decay. The HXR data of EAST ('poor lithium' case) indicates a similar decay of the fast electron tail for $\overline{n}_e > 2\times10^{19} m^{-3}$ although the wave can penetrate deeper in the plasma. The pump width is much larger than for the JET discharges for similar density and the ω_{LH}/ω scaling is more relevant when comparing the results of the two machines. However when comparing the results before (high n_e, low T_e at the edge) and after (low n_e, highT_e) Li deposition on the walls , there is clearly a discrepancy between the frequency broadening at high density (Δf is wider after Li deposition) and fast electron tail (larger by more than one order of magnitude after Li deposition).

For this range of densities, JET and EAST data do not show evidence that parametric decay in ion-sound wave is the dominant mechanism to explain the decay of the fast electron tail with density. On JET the very poor accessibility of the wave could be the main cause of the strong decay of the fast electron tail with density.

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