35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.32D, P-2.106 (2008)

Lower hybrid current drive at high densities of ITER

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Abstract

As widely documented by available experimental and modelling data [1,2], a broadening in the lower hybrid (LH) wave frequency and $n_{//}$ (parallel wavenumber) spectrum is produced by parametric instability (PI) that can affect the propagation and deposition of the LH power launched in tokamak plasmas. The electronic dynamics at the plasma edge mainly determines the occurrence of the ion-sound quasimode-driven PI, whose growth rate is intrinsically high at the radial layers close to the antenna-plasma interface, as its maximum occurs in the same conditions necessary for performing the antenna coupling (i.e.: $\omega_{pe}/\omega_0 \gtrsim 1$ at the plasma edge). The radial extent in the plasma of the region with high growth rate determines the spectral broadening size. Radially deeper is this region, smaller are the convective losses and consequently bigger is the spectral broadening. The present work shows that considering a case of relatively high densities (n_e) and low electron temperatures (T_e) of the scrape-off layer (SOL), the LH spectral broadening should be strong enough to produce the radiofrequency (RF) power deposition at the very plasma periphery of ITER (International Thermonuclear Experiment Reactor). Conversely, operating with slightly low n_e and high T_e in the SOL, the radial extent of the PI region results reduced and, consequently, a useful LHCD can be performed in the plasma bulk.

The problem of LHCD in tokamaks at high plasma densities

To achieve the performances of confinement and stability of ITER, a large amount of non-inductive plasma current is necessary. This goal could be enormously simplified by using lower hybrid current drive (LHCD), provided that its effectiveness should be demonstrated when operating at the high plasma densities with broad radial profile, as requested for ITER. The Figure 1 shows the kinetic profiles of the ITB scenario today modelled for ITER: just inside the last closed flux surface (LCFS), i.e., for normalised flux radii: $\rho \lesssim 0.9$, $n_e \gtrsim 0.8\ 10^{20}\ m^{-3}$ (although this value is supposed to be slightly overestimated. An assessment of the ITER ITB scenario is ongoing and new guidelines are expected shortly). The extensive search performed by the experiments which operated at high densities ($\frac{\omega_{\mathrm{LH}}}{\omega_0} \approx 1$ in the bulk) for producing ion heating by LH waves, did not observed signs of LH power penetration in the bulk. E.g., Alcator C operating at the frequency f_0=4.6 GHz (that is the closest used frequency to the expected 5 GHz envisaged for ITER), observed only strong spectral broadening and other phenomena of physics of the edge. The relevant parameters for deuterium plasma edge of this experiment are $\left[\frac{\omega_{\mathrm{LH}}}{\omega_0}\right]_{LCFS} \approx 0.3$ and $T_e \approx$20 eV in layers close to the LCFS, $\left[\frac{\omega_{\mathrm{LH}}}{\omega_0}\right]_{Ant} \approx 0.07$ and $T_e \approx$5 eV close to the antenna-plasma interface. In the recent experiments of JET relevant for the ITB configuration of ITER in which high n_e occurred at the periphery during the main heating phase, the not fulfilled LH accessibility condition might have produced the absence of LHCD effects [R Cesario et al RF Conf USA 2007]. The running attempts now performed in condition of LH accessibility will address the solution of this problem.

Modelling of the LH physics of the edge for ITER

The References 1,2 have been considered. The parametric dispersion relation (rdd) relevant for identifying the mode coupling of LH waves and ion-sound quasimodes at the edge that determines the spectral broadening is:

$$\varepsilon(\omega,\mathbf{k}) - \frac{\mu_1(\omega_1,\mathbf{k}_1,\mathbf{k}_0,E_0)}{\varepsilon(\omega_1,\mathbf{k}_1)} - \frac{\mu_2(\omega_2,\mathbf{k}_2,\mathbf{k}_0,E_0)}{\varepsilon(\omega_2,\mathbf{k}_2)} = 0 \qquad 1$$

Retaining the ions as magnetised, the rdd is expressed in terms of the low frequency driving mode: $Re(\omega)+i\gamma$, where γ is the growth rate of the PI and the frequency of the sidebands are given by $\omega_{2,1}=\omega\pm\omega_0$. ε is the dielectric function and μ_1 and μ_2 are the coupling coefficients referring to the lower and the upper sidebands respectively:

$$\mu_{1,2} = \frac{\chi_e(\omega)-\varepsilon(\omega)}{\chi_e(\omega)} \frac{\omega_{pi}^2}{\omega_0^2} \frac{\omega_{pi}^2}{4k^2c_s^2}\left(1+\frac{\omega}{k_z v_{the}}Z\right)^2 \sin^2\delta_{1,2} \frac{u^2}{c_s^2} \qquad 2$$

The Eq. 1 solutions together with the convective effects and the pump depletion modelling determine the effective LH spectrum, which is utilised as input of a proper Fokker-Planck ray-tracing tool. The solutions: $Re(\omega)$ and γ are shown in Figure 2 for ITER considering respectively the operating frequency f_0 = 5 GHz (Fig 2 a) or the alternative f_0 =3.7 GHz (Fig 2 b). In the case of f_0 = 5 GHz, a value of γ lower by a factor two is obtained. For estimating the spectral broadening in ITER, the following guesses of the SOL parameters are assumed: Case 1: n_{e_LCFS} = 8 10^{19} m^{-3}, T_{e_LCFS} = 500 eV, and

$n_{e\_Ant} = 1\ 10^{18}$ m^{-3}, $T_{e\_Ant} = 10$ eV. Case 2: $n_{e\_LCFS} = 2\ 10^{19}$ m^{-3}, $T_{e\_LCFS} = 3$ keV, and $n_{e\_Ant} = 5\ 10^{17}$ m^{-3}, $T_{e\_Ant} = 20$ eV. For $f_0 = 5$ GHz it gives: $\left[\frac{\omega_{LH}}{\omega_0}\right]_{LCFS} \approx 0.2$ and $\left[\frac{\omega_{LH}}{\omega_0}\right]_{Ana} \approx 0.08$, values not very different from the aforementioned Alcator C conditions, but the higher T_e in case 2. With P_{LHCD} =10 MW, about 10% of the power spectrum results broadened with markedly different values of the maximum $n_{//}$: respectively $n_{//Max} \approx 12$ for the case 1, and $n_{//Max} \approx 3.5$ for the case 2. From the whole of the simulations, the electron temperature in the SOL results to be the most relevant parameter in defining the role of the PI-induced spectral broadening. Consequently, the LH power should be deposited, respectively, at the very periphery ($\rho \approx 0.9$), and usefully more inside (at $\rho \approx 0.7$-0.8, with $I_{LHCD} \approx 0.55$MA), see Figure 3. This latter case is documented by the result of the ray tracing tool including the physics of the edge (LH^{star} code) shown in Figure 4.

Conclusions

The parametric instability, potentially relevant for LH spectral broadening, is generally expected to occur at the antenna-plasma interface, where, at the density necessary for coupling, low T_e could occur. Low electron temperatures, and consistent high densities in the SOL, favour the spectral broadening with consequent increase of the power deposition at the periphery. The cases with guessed SOL parameters (to account for the strong uncertainty at this moment of the design) considered by means of the LH^{star} code for modelling the LHCD in ITER (at 5 GHz) show that to operate at higher frequency and relatively high T_e in the SOL are useful options for reducing the risk of detrimental interaction with parametric instability.

References

1. R. Cesario, et al., Phys. Rev. Letters, **92** 17 (2004) 175002
2. R. Cesario, et al., Nucl. Fusion 46 (2006) 462-476 and References therein

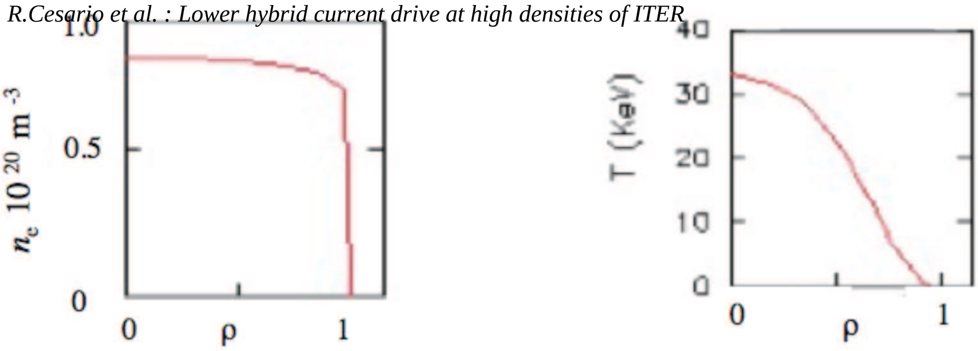


Fig 1. Plasma electron temperature (a) and (b) density profile for the ITB scenario of ITER

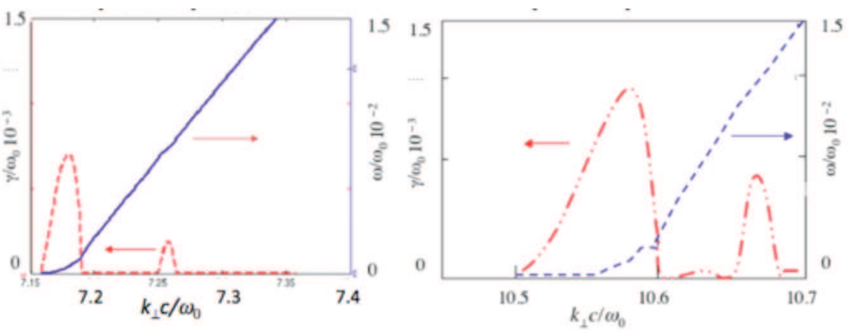
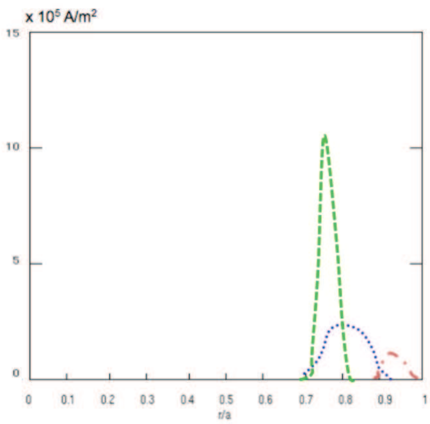


Fig. 2. Growth rate (in red) and frequency (in blue) of the quasimode driving PI relevant for the spectral broadening for the two different operating frequencies proposed for LHCD in ITER: f_0 = 5 GHz (fig a), and f_0= 3.7 GHz. Operating parameters: $n_e=10^{18}$ m^{-3}, T_e=25 eV $n_{//0}$=1.8 (pump wave), $n_{//}$=3 (ion-sound quasimode), B_T =4 T.



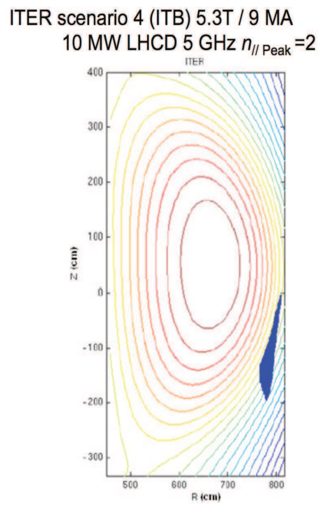


Fig. 3. LHCD deposition profile obtained the in the Case 1 (see the text, dotted-dashed line), Case 2 (dotted), and no spectral broadening (dashed).

Fig. 4. Ray tracing relevant for Case 2 of Fig. 3, (by the LH^{star} Code).