Conditions for Lower Hybrid Current Drive in ITER

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Abstract
To control the plasma current profile represents one of the most important problems of the research of nuclear fusion energy based on the tokamak concept, as in the plasma column the necessary conditions of stability and confinement should be satisfied. This problem can be solved by using the lower hybrid current drive (LHCD) effect, which was demonstrated to occur also at reactor grade high plasma densities provided that a proper method should be utilised, as assessed on FTU (Frascati Tokamak Upgrade). This method, based on theoretical predictions confirmed by experiment, produces relatively high electron temperature at the plasma periphery and scrape-off layer (SOL), consequently reducing the broadening of the spectrum launched by the antenna produced by parasitic wave physics of the edge, namely parametric instability (PI). The new results presented here show that, for kinetic profiles now foreseen for the SOL of ITER, PI is expected to hugely broaden the antenna spectrum and prevent any penetration in the core of the coupled LH power. However, considering the FTU method and assuming higher electron temperature at the edge (which would be however reasonable for ITER) the PI-produced spectral broadening would be mitigated, and enable the penetration of the coupled LH power in the main plasma. By successful LHCD effect, the control of the plasma current profile at normalised minor radius of about 0.8 would be possible, with much higher efficiency than that obtainable by other tools. A very useful reinforce of bootstrap current effects would be thus possible by LHCD in ITER.

Introduction
Experiments of JET (Joint European Torus), utilising plasma configuration at high triangularity (d 0.4) and main heating power up to 30 MW applied at the end of the plasma current ramp-up ($q_{95}$ 5, $I_p=1.5MA$ $B_r=2.3T$), were performed for developing fully non-inductive steady-state regimes relevant for ITER [1]. High values of normalised b ($b_N$) and confinement were obtained ($\beta_N$ 2.8, $H_{98}$ 1.05) during an ELMy H-mode phase of discharges with radially broad transport barriers (TBs). By the relatively high main heating power applied in these experiments ( 30 MW), a radially broad and steep pressure gradient occurred, which consequently produced a relatively high bootstrap current density ($j_{BS}$) at the plasma periphery [2,3]. However, this current was insufficient for freezing significantly the current relaxation. As a consequence, the improved confinement lasted only several confinement times due to the onset of strong low-n MHD activity.
Thus, for a successful development of reactor-graded plasma operations, it would be important to have different and flexible tools capable of producing and controlling steady-
state profiles with a high fraction of non-inductive plasma current driven in the outer half of the plasma column. The solution of this problem could be simplified by means of the lower hybrid current drive (LHCD) effect [4]. By coupling radiofrequency power in the range of a few GHz to tokamak plasmas, non-inductive current was driven with high efficiency in many experiments [5–7]. Unfortunately, the LHCD effect was routinely observed only operating at plasma densities markedly lower that these required for ITER, and the extrapolation to reactor grade higher densities resulted to be problematic. Indeed, in LHCD experiments on FTU at high densities, operating in standard regime, LHCD signatures disappear for high line-averaged plasma densities \( n_{e_{av}} \sim 1.1 \times 10^{20} \text{ m}^{-3} \) [8]. In Alcator C-Mod, which operates at the frequency \( f_0 = 4.6 \text{ GHz} \) (the closest used frequency to that, 5 GHz, envisaged for ITER), the LHCD signatures disappear for high line-averaged plasma densities \( n_{e_{av}} \sim 1.5 \times 10^{20} \text{ m}^{-3} \) and decreased much more markedly than expected at medium densities, \( n_{e_{av}} \sim 0.8\text{–}1.0 \times 10^{20} \text{ m}^{-3} \), depending on the operating parameters [9]. The effect of collisional absorption [10] was invoked for interpreting the observed anomalous LH power damping at the edge. However, these plasmas have relatively low electron plasma temperature in the core, which prevents the full deposition of the coupled LH power at the first radial pass. The effect of collisional absorption was ruled out by analysis performed considering the available data of experiments of JET operating in condition of first-pass LH regime, and presenting the same effect of LH power damped at the very edge, unexpected by quasi-linear wave theory [13,9]. In the latter experiments, the lack of penetration of the coupled LH power in the core, was observed to occur at relatively high density even at the periphery \( n_e \sim n_{e_{0.8}} \sim 0.4 \times 10^{20} \times 10^{20} \text{ m}^{-3} \), where \( n_{e_{0.8}} \) represents the density at normalised minor radius \( r/r_{Sep} \approx 0.8 \), where \( r_{Sep} \) is the plasma minor radius.

Considering the available data of these experiments of JET, a modelling work showed that the anomalous LH damping at the plasma edge can be a consequence of the effect of a huge spectral broadening due to parametric instability (PI), which is expected to occur in the cold radial region of the plasma periphery [12,13].

The problem of how extrapolating the LHCD effect at high densities, which resulted unsuccessful for decades, was recently solved by experiments on FTU [9]. These experiments were performed following the guidelines of previously formulated theoretical prediction on the PI-produced spectral broadening effect [12,13]. This prediction consists in relatively high electron temperature of the plasma SOL and periphery, having the effect of diminishing the local parasitic LH power damping due to the PI-produced spectral broadening. Consequently, the LH power penetration in a high density plasma core is enabled.

The phenomenon of the LH spectral broadening was monitored in the experiments at high density on FTU. A simple tool was utilised consisting in a RF (radio-frequency) loop antenna probe located outside the machine and connected to a spectrum analyser, centred at the LH operating frequency [14,15]. This diagnostic gives indication of effects of wave physics of the edge that are decisive for determining the LH power propagation and damping in tokamaks.

The RF probe showed that, in standard operating conditions of FTU high density plasmas, in which no LHCD effect was observed to occur as in other experiments, the operating line frequency was hugely broadened by LH sideband waves (up to about 15 MHz) [8]. Considering the successful interpretation of the LH experiments performed at high plasma densities on FTU [8] and JET [11], we have extended the model approach to the case of a
possible LH current drive experiment on ITER. In the next section, some details of the model approach are shown, and in Sec. 3 preliminary results are presented.

The modelling approach

The LHstar code [16,12,13,8], developed at the ENEA Laboratory of Frascati, is a unique available tool for LH modelling in tokamak plasmas that considers the effect of non-linear physics of the edge produced by parametric instability. The code describes the wave propagation and damping and produces the radial density profiles of LH absorbed power and driven current. The initial $n_{\parallel}$ spectrum modified by the PI phenomenon at the plasma edge is first calculated and then is inputted in the ray-tracing and Fokker-Planck modules, together with the kinetic profiles and the magnetic reconstructed equilibrium data. As further special feature of the LHstar code, the ray-tracing and Fokker-Planck analyses are consistently coupled as shown hereafter. The ray trajectory is provided to the Fokker-Planck code that computes the absorption on the modified distribution function of electrons.

We consider here the case of a possible LHCD experiment on ITER, considering the magnetic equilibrium data and the kinetic profiles foreseen for steady-state scenario. An operating frequency of 5 GHz has been taken into account.

The kinetic profiles utilised for the modelling [17] are shown in Figure 1.

![Figure 1a](image1.png)  ![Figure 1b](image2.png)

Figure 1a. Electron plasma density radial profile foreseen for the steady-state scenario of ITER. Figure 1b. Electron (red curve) and ion (blue curve) plasma temperature radial profiles foreseen for the steady-state scenario of ITER [17].

The radial profile of LH-driven current density has been modelled considering the effects of LH wave propagation in toroidal geometry. These effects can broaden and up-shift the $n_{\parallel}$ initial spectrum inputted in the ray-tracing and Fokker-Planck modules of the LHstar code. In the code, the inputted LH $n_{\parallel}$ spectrum (initial spectrum) does not coincide with...
the nominal antenna spectrum, as usually done in other modelling tools, but is produced as output of a dedicated module (LHPI: lower hybrid parametric instability). This module calculates the spectral broadening of PI produced at the plasma edge, utilising a slab geometry as described in Refs. 12,13.

In summary the runs of the code are performed in the following steps.

i) The non-linear physics of plasma edge produced by the PI phenomenon is taken into account for calculating the broadening of the spectrum launched by the antenna. This result allows calculating the amplification factor that considers, for any LH sideband spectral $n_{//}$ component, the convective losses of PI that occur in the realistic conditions of experiment. These conditions consist in considering the plasma inhomogeneous, and the finite spatial extent of the region illuminated by the antenna. Significant convective losses are produced indeed by the plasma inhomogeneity and finite extent of the pump wave region imposed by antenna geometry. Consequently, considering the kinetic profiles of the SOL (scrape-off layer) and plasma periphery (typically for $r/r_{\text{Ant}} < 0.8$, where $r_{\text{Ant}}$ is the radial layer of the antenna mouth), the initial $n_{//}$ spectrum is obtained and inputted to the ray-tracing and Fokker-Planck modules.

The availability of such initial spectrum is essential for determining, via quasi-linear effects, the coupled LH power propagation and damping in the plasma. To neglect the effect of spectral broadening due to PI should be allowed only provided that PI effects are negligible. However, this circumstance does not ever occur for typical tokamak plasma edge parameters [13]. A more complete evaluation of the spectral broadening (not done in the LH$^{\text{star}}$ code) should be obtained by including also the effect of linear scattering by density fluctuations, as done in a recent work [18].

ii) The initial spectrum is inputted in ray-tracing Fokker-Planck modules, which calculate the radial profiles of LH deposition by retaining the effects of ray propagation in toroidal geometry [16]. The effect of toroidicity can produce a further change of the spectrum launched by the antenna, consisting in an $n_{//}$ broadening and up-shift. The ray-tracing and Fokker-Planck modules are properly coupled: in a code run, starting from the edge layer, the ray tracing and Fokker-Planck analyses are performed step by step together and consistently for each ray. Consequently, the spatial evolution of the LH power distributed in the $n_{//}$ spectrum is calculated consistently with the quasi-linear effects, and the LH deposition profile is accurately calculated.

In case a ray reaches a LH wave cut-off layer, located at the plasma edge, the geometric optic limit fails, since as the wavelength becomes locally too large. Consequently, the ray-tracing technique cannot be further used. Therefore, in these cases, the LH$^{\text{star}}$ code does not provide a complete output of LH deposition profiles.

In summary, the original features of the LH$^{\text{star}}$ code consist in considering the PI-produced spectral broadening and in producing consistent quasi-linear and ray-tracing analyses. The broadened initial spectrum provides an essential contribution for filling the gap in phase
velocities for LHCD, and for taking into account the parasitic LH power deposition at the edge at high densities. The calculations are performed only in the framework of validity of the WKB limit [12,13]. Consequently, the LH\textsuperscript{star} code is asked to not treat completely cases in which rays reach the LH cut-offs at the plasma edge. Conversely (and incidentally), other widely utilised LH modelling tools, e.g., in Refs. 21,22, are however enabled continuing the ray-tracing runs also in case LH cut-offs are reached. Moreover, differently from the LH\textsuperscript{star} code, these tools calculate the toroidicity effects by ray-tracing independently of Fokker-Planck analysis. In these tools, the ray tracing runs are generally performed before initiating the Fokker-Planck analysis of quasi-linear damping. In this way, the toroidicity effect should underestimate the effect of initial spectral broadening. This problem can be solved by coupling together the ray-tracing and Fokker-Planck analysis as done in the LH\textsuperscript{star} code.

**Results**

We show here preliminary results of the modelling producing the radial profiles of LH current density driven expected for ITER. A coupled power density of 10 MW/m\textsuperscript{2} at frequency of 5 GHz has been considered. The nominal antenna spectrum has a Gaussian distribution at around \( n_s = 1.95 \) and width of 0.5. The modelling has been performed taking into account the effect of spectral broadening produced at the edge by PI, which is expected to occur with the following two cases of different electron temperatures in the SOL. i) The same SOL profiles foreseen for ITER are considered (\( T_e \approx 20 \text{ eV for } r/a \approx 1.0 - 1.05 \)); ii) relatively higher electron temperature are assumed in most of the SOL, as further reasonable guess for ITER (\( T_e \approx 700 \text{ eV for } r/a \approx 1.0 - 1.01, T_e \approx 500 \text{ eV for } r/a \approx 1.01 - 1.04, T_e \approx 20 \text{ eV for } r/a \approx 1.04 - 1.05 \)).

Higher electron temperature might be obtainable with operations aimed at reducing the particle recycling from the vessel walls. A local heating produced by coupling radiofrequency power at the electron cyclotron frequency should be also considered.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{LH-driven current density profiles expected for ITER considering the same plasma parameters but different electron temperatures in the SOL. Consequently, a different broadening in the initial \( n_s \) spectrum is produced by parametric instability. Case a (blue lines): profile foreseen for ITER. Case b (red lines): higher electron temperature has been assumed, see the text.}
\end{figure}
As consequence of the modelling performed with the LH² code, the LH-driven current density profiles expected for ITER for the aforementioned cases are shown in Figure 2. For the case of electron temperature profile foreseen for ITER, a huge spectral broadening and a consequent LH power deposition at the very edge are expected to occur. Conversely, assuming a warmer edge, the coupled LH power is enabled to penetrate into the plasma bulk thanks to the consequently diminished PI-produced spectral broadening. Such result is supported by observation during the LH experiment on FTU performed in standard regime at ITER-relevant high plasma density. In these experiments, no effect of the coupled LH power occurred in the core when operating with an electron temperature profile in the periphery and SOL of FTU very similar to that of ITER [9]. Moreover, the FTU experiment result was optimistic for extrapolating LHCD scenarios to ITER, as weaker PI spectral broadening effect are expected to occur for an operating frequency (8 GHz) higher than the maximum foreseen for ITER (5 GHz).

**Conclusions**

The parametric instability is a phenomenon that broadens the LH spectrum launched by the antenna. Both a huge spectral broadening and the failure of the LH power penetration in the core occur in presence of plasma with SOL and periphery relatively cold, as typically occurs in LH experiments at high plasma densities. In this condition, also the collisional damping effect acts, preventing the LH power penetration in the core. However, this effect resulted small in experiments of JET at high density and in single pass LH regime, in which the same failure of LH power penetration was observed to occur, as in other LH experiments at high densities.

The PI is generally expected to occur at the antenna-plasma interface, where the relatively high densities necessary for coupling ($\omega_{pe} > \omega_0$) are generally accompanied by relatively low temperature of plasma edge. Low electron temperature favours indeed the spectral broadening, with consequent increase of the power deposition at the periphery. A case with higher temperature in the SOL has been considered (to account also for the strong uncertainty at this moment of the design), and inputted in the LH² code for modelling the LHCD in ITER.

Operations producing a relatively high electron temperature in the SOL are necessary in ITER for reducing the risk of interaction of the coupled LH power with parametric instability at the plasma edge, which is detrimental for LH power penetration in the core.

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