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ABSTRACT.

One of the most promising lines of research into a viable thermonuclear fusion reactor relies on the development of the so-called Advanced Tokamak (AT) scenarios, thermally well insulated, robust to plasma micro-instabilities and approaching steady-state conditions [1]. The current driven inductively, peaking close to the plasma magnetic axis, is not well adapted to create and sustain AT scenarios and a significant fraction of non-inductive current should be driven at locations further off-axis. The capability to drive such non-inductive current in the high density conditions typical of fusion reactors is, therefore, one of the crucial issues to be studied starting from present day devices.

INTRODUCTION

More specifically, in ITER (International Tokamak Experiment Reactor), these regimes are predicted to have a relatively flat density profile with high density even at the periphery of the plasma column : $n_{e0.8} \sim 0.6\times10^{20}$–$0.7\times10^{20}\,m^{-3}$ at normalised minor radius r/r_{Sep} ~0.8, where r_{Sep} is the plasma minor radius at the Last Closed Magnetic field Surface (LCMS). The flat profile and the high gradients in the far outer part of the plasma will contribute to self-generating non-inductive current by collisional transport, denoted as bootstrap current, at large radii [1]. Because in the complex self-organised behaviour of a fusion plasma, dominated by the self-generated heating due to slowing-down of alpha particles, heating and turbulent transport are intimately related and it is presently unknown whether bootstrap current alone can support reactor relevant AT plasma operations. It will be, therefore, essential for a successful development of AT scenarios to have different tools capable of driving non-inductive current in the outer half of the plasma column and controlling profiles in steady-state conditions [2].

Lower Hybrid (LH) waves, externally launched in tokamak plasmas by means of a phased waveguide grill antenna, are theoretically capable to propagate into high density and temperature fusion relevant plasmas and be absorbed via Landau damping on the high velocity tail of the electron distribution function, around 2.5−4 times the thermal velocity v_{the} [3]. The Landau Damping mechanism is at the basis of the Lower Hybrid Current Drive (LHCD) concept [4,5], , which was successfully tested in tokamaks as early as the 1980s [6]. LHCD efficiency in driving current was experimentally found to be much larger than those typical of tools based on launching waves in the ion-cyclotron or electron-cyclotron frequency range [5], especially in the outer half of fusion relevant plasmas [7, 8]. Unfortunately, most of the experiments carried out so far in tokamaks have demonstrated the validity of the LHCD tool only at operating densities in the outer plasma lower than the ITER requirements. In cases where LHCD operation was extended to high-density regimes, less positive results were obtained. Indeed, in C-Mod, the effects of LHCD were observed to decrease more markedly than expected for $n_{e,av} \sim 0.8$–$1.0\times10^{20}\,m^{-3}$, depending on the operating parameters [9].

In addition, in dedicated experiments on FTU aimed at demonstrating the maximum operating densities for LHCD, signatures of LH penetration in the core occurred up to line-averaged plasma density $n_{e,av} \approx 1.3\times10^{20}\,m^{3}$, even though with density profiles more peaked and edge density lower than expected in AT scenarios in ITER ($n_{e\_0.8} \approx 0.5\times10^{20}$ m^3) [10]. Recently a regime has been found on FTU where LHCD signatures were still present at the maximum explored densities, corresponding to: $n_{e,av} \approx 2.0\times10^{20}$ m^3, central density: $n_{e0} \approx 4.5\times10^{20}$ m^3, and $n_{e\_0.8} \approx 0.85\times10^{20}$ m^3 [11]. This improvement has been attributed to a minimization of LH spectral broadening caused by parametric instability phenomena at the plasma periphery. In order to fully assess the usefulness of the LHCD tool in given experimental conditions is, therefore, important to take into account potential edge physics effect likely to influence the LH wave propagation in the high density confined plasma. As discussed in previous works, the observed lack of penetration of LH waves in the core of high density plasmas could be explained by the effect of spectral broadening produced by Parametric Instability (PI) at the plasma edge [7,8]. Numerical modeling of PI identified in the relatively low electron temperature at the plasma periphery and Scrape-Off Layer (SOL), consequence of the high density conditions, the main cause of the broadening of the launched $n_{//}$ spectrum and, as consequence, of the reduced wave penetration into the core (here $n_{//}$ is the LH wavenumber referring to the direction of the confinement magnetic field) [7,8]. The strong PI is consequence of the RF energy density which is higher than the local thermal energy density for the standard operations of LHCD experiments: this circumstance corresponds to satisfy the strong turbulence condition which is necessary for activating the non-linear mode-coupling of the PI mechanism [12].

The main focus of the present letter is to show new results and modeling of JET experiments particularly relevant for assessing the role of the plasma edge in determining conditions for LH power penetration into the plasma core and current drive. In the following, since the launched LH waves resonate with relatively high tail electron velocities ($\approx$2.5-4 v_{the}), the occurrence of wave penetration is estimated by detection of suprathermal electron emission (typically in the range 20 keV–80 keV) and its correspondence with the coupled LH power waveform. Radiometer channels tuned for receiving electron-cyclotron emission from optically thin layers, typically located in the scrape-off plasma, provide at JET a powerful tool for assessing the LH propagation in the plasma core with very high sensitivity also in cases of little LH coupled power [13]. In the rest of the paper the suprathermal emission due to fast electrons will be referred to as LH-ECE-edge signal. ITER-relevant AT experiments of JET with plasma configuration at high triangularity ($\delta = 0.35$) are considered here, with toroidal magnetic field $B_T = 2.7$T and plasma current $I_P = 1.8$MA [14].
Figure 1 shows the time traces of the main plasma parameters of the considered experiment at high ´. The main heating power, provided by ~ 18MW of Neutral Beams (NB) combined with ~ 2MW of Ion Cyclotron Resonant Heating (ICRH), is applied at the end of the plasma current ramp-up, in combination with ~ 2MW of LH power (Fig.1(f)). Fig.(b) shows the trend of the plasma density detected by LIDAR Thomson Scattering in the core (major radius on the axis: R_0= 3.0 m) and at the periphery ($R = 3.78$m, corresponding to $r/r_{Sep} \approx 0.9$). Fig.1(d) shows the trend of the LH-ECE-edge signal (the radiometer channel tuned for receiving the emission from layers located at $r/r_{Sep} \approx 1.02$). At this layer, the optical thickness is always less than 1 and, more specifically, $f \approx 0.14$ at 4.1s, the time point in which the LH-ECE-edge signal drops reaching the NB background level. Suprathermal

electrons produced in the plasma can be thus properly detected. It is worth noting that fast electrons generated by the NB power and linked to the ELM activity are also detected during the whole of the H-mode phase, producing a background level of about 700eV in Fig.1(d) between $t = 4.0-9.5$s. Calculations indicated that ECE cut-off, potentially causing the ECE signal drop, never occurs during the considered experiment. The short emission peak (occurring between $t = 3.75-4.0$s) can only be due to LH-generated fast electrons. The subsequent sharp decrease of this signal is taken to indicate that the LH power no longer penetrates into the core plasma. The LH-ECE-edge signal decreases at the beginning of the ELMy H-mode phase, during the building-up of the pressure profile, when the density exceeds a certain values at the periphery ($\approx 0.25\times10^{20}\,m^{-3}$, at $r/r_{Sep} \approx 0.9$) and in the core ($n_{e0} \approx 0.27\times10^{20}$). During most of the H-mode phase, the plasma density is higher: $\approx 0.4\times10^{20}\,m^{-3}$ at $r/r_{Sep} \approx 0.9$ and, in the core, $n_{e0} \approx 0.5\times10^{20}\,m^{-3}$. Note that no changes in T_{e0} or in the LH-ECE-edge signal are observed at the LH-power switch-off (at 7s). It is, therefore, reasonable to assume that, after the short transient at the beginning of the main heating phase, the coupled LH-power does no longer penetrate into the plasma core and it is likely to be deposited at the very periphery. In order to verify the possible dependence of the lack of the penetration in the core of the coupled LH power on the accessibility condition [15] experiments with different combinations of antenna spectrum ($n_{//} = 2.303$ and $n_{//} = 1.840$) and toroidal magnetic field (2.7T and 2.3T) have been performed in the same plasma configuration. In all the comparable cases, the same short transient LH effect of Fig1.(d) has been found. This additional observation indicates that accessibility of the launched LH spectrum is not the dominant factor in the wave propagation and absorption in these conditions and suggests that physics occurring in the SOL and plasma edge should be considered, as will be done in the present letter.

On the contrary, clear LHCD effects were observed in previous AT experiments in JET, in which long lasting Internal Transport Barriers (ITBs) were produced and sustained by LHCD [16,17]. In these earlier experiments, the coupled LH power produced a local reduction of the magnetic shear in the layer close to the ITB radial foot with a LH driven current fraction: $I_{LH}/I_P \approx 25\%$ [7,8]. The time traces of the main plasma parameters for a typical plasma discharge are shown in Figure 2. The experiment is carried out at low $\delta \sim 0.25$, higher toroidal field and plasma current, $B_T = 3.4$T and $I_P = 2.3$MA, heated in the H-mode phase by a combination of ~ 17MW of NBI and ~ 4MW of ICRH. Lower plasma density, mainly at the periphery ($\approx 0.2\times10^{20}\,m^{-3}$, at $r/r_{Sep} \approx 0.9$, $n_{e0} \approx 0.4\times10^{20}\,m^{-3}$), characterize such experiments, due to reduced edge pedestal confinement in the low δ configuration. As in the high δ experiments, the optical thickness is less than 1 ($f \approx 0.25$). As further evidence of the effect of the coupled LH power in the plasma core, the central electron temperature (Fig.2(c)) rises in concomitance with the LH-ECE-edge signal (Fig.(d)). This latter fully follows the LH power waveform (Fig.2(f)). During the main H-mode phase, this signal is systematically higher by about a factor 3−4 than the NB-induced background level, as observed only transiently in the case of the high-δ experiment (Fig.1(d).

In the case of the experiment of Fig.1, the LH-ECE-edge signal begins to drop at a time point in which the core density is ($n_{e0} \approx 0.25\times10^{20}$ m^{-3}) still well below that occurring in the experiment in Fig.2 (up to $n_{e0} \approx 0.38\times10^{20}$ m^{-3}). Subsequently, the LH-ECE-edge signal disappears when the operating density at the plasma periphery ($r/r_{Sep} \approx 0.8$) exceeds by a factor two the corresponding values occurring in previous experiments at lower δ (δ = 0.25). This circumstance is a further indication that the wave physics of the SOL and edge may be important in LHCD experiments, as assessed in previous works [7,8]. The modeling approach utilized in these References provided a fair interpretation of the LH-sustained ITB s of JET experiments, producing an LH deposition profile in agreement with the available diagnostics data.

By PI modeling, the recent results are interpreted in terms of strong $n_{//}$ LH wave spectral broadening occurring at the edge. This spectral broadening is mainly produced by the low edge electron temperatures, occurring in the SOL radial layer between antenna and main plasma, which characterize the configuration at high-´. Consequently, the deposition of the LH power occurs at the very plasma edge, and the electron acceleration is expected to be lower than the minimum energies generally produced in LHCD experiments.

Following Refs. [7,8] LH modeling has been carried out comparing the experiments of Figs 1,2 by utilizing the LH^{star} code. This code has the following options: i) to consider the spectrum launched by the antenna as input of the ray-tracing + 2D Fokker-Planck module [18], and calculate the effect of $n_{//}$ up-shift due to propagation in the toroidal geometry; ii) to include the relevant non-linear wave physics of the plasma periphery, which provides a source of broadening of the $n_{//}$ spectrum coupled by the antenna.

In summary, the modeling approach consists in calculating the broadening of the $n_{//}$ spectrum launched by the antenna by solving the parametric dispersion relation:

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

which gives frequencies and growth rates $\gamma\,(\boldsymbol{k}_i, E_0, \omega_0, \omega_i)$ of the relevant instability channels which in the LHCD experiments in tokamaks are generally provided by ion-sound quasimodes. In the equation, ε is the dielectric function, ω the complex frequency, $\boldsymbol{k}$ the wave-vector of the low frequency perturbation, the suffix $i = 0,1,2$, refers to the coupled LH wave, the lower and the upper sideband waves, respectively. $\mu_{1,2}$, are the coupling coefficients of the lower and upper sidebands, respectively. The instability spatial amplification factor is:

$$A = \gamma\,(\boldsymbol{k}_i, E_0, \omega_0, \omega_i)L/\mathrm{v}_{gi\xi}$$

where L is the width of the pump region in the x, z plane, $\mathrm{v}_{gi\xi}$ is the group velocity component of the sideband $i = 1,2$ in the direction perpendicular to that of the pump). The condition: $A>1$ occurs over the plasma periphery layer for coupled LH power density $W_{LH} \approx 10\mathrm{MW/m^2}$. As consequence, a redistribution (of the order of 10%) of some coupled power is expected to occur over an $n_{//}$ spectrum broader than that coupled by the antenna. Convective loss due to plasma inhomogeneity limits the broadening, but it results enhanced, for given plasma density profile, when lower T_e occurs over a broader SOL radial region located between the antenna mouth and the main plasma.

The edge LIDAR and the Langmuir probe diagnostics provide the kinetic profiles, shown in Fig.3, used in the code. In the plasma of Fig.1 (Pulse No: 72835), the higher plasma densities together with the inner radial position of the separatrix produce a markedly larger radial layer between antenna and main plasma in which the electron temperature is lower.

The layer with $T_e \approx 500$eV is indeed located at about 10 cm from the LH antenna in Pulse No: 72835, against 4cm in Pulse No: 53430.

This condition favors the occurrence of stronger spectral broadening and, consequently, of an LH deposition at the very edge of the confined plasma. In order to test the effect of the edge temperature on LH spectral broadening and deposition, LH^{star} modeling has been carried out both for the edge T_e profile of the high-δ Pulse No: 72835 in Fig. 3 and by artificially replacing it with the higher T_e profile of Pulse No: 53430. The calculated broadened $n_{//}$ spectra, to be used in the ray-tracing and Fokker-Planck modules for calculating the LH deposition profile, will be referred to as *initial spectra* (Fig. 4). For the test case of assumed higher edge T_e, the resulting spectrum is similar to that found considering the parameters of the experiment of Fig 2, relevant to LHCD-sustained ITBs [7,8] with $n_{//Max} \approx 3.7 \pm 0.5$. A more strongly broadened spectrum, $n_{//Max} \approx 18 \pm 6$, is obtained instead, with the actual parameters of the experiment of Fig.1. The uncertainty in estimating $n_{//Max}$ has been determined by assuming changes of ~20% in temperature. However, the uncertainty of the shape of the radial profile for temperatures greater than 0.4 keV−0.5 keV does not significantly affect the broadening result.

The initial spectra and the experimental temperature and density profiles are then used for calculating the LH deposition profiles shown in Figure 5. With the moderately broadened initial spectrum (green curve in Fig 4), the LH power is fully deposited in the outer half of plasma, at the first half radial pass (green curve). The LH-driven current ($I_{LH}/I_P \approx 10\%$) has a density peak j_{LH_Maz} ($\approx 1.8\ 10^5\ Am^{-2}$) of about half of the bootstrap peak ($j_{BS\_Max} \approx 3.5\ 10^5\ Am^{-2}$). Both peaks are localized at large radii ($r/r_{Sep} \approx 0.78$ for j_{LH_Maz} , and $r/r_{Sep} \approx 0.85$ for j_{BS_Max} [19]

Modeling indicates that electron would be accelerated to tail energies in the range 50−70keV. This implies that, assuming similar behavior of wave physics of the edge for the experiments of Fig.1 and Fig.2, clear effects of supra-thermal electrons should occur, which is in contrast with the experimental observations. Conversely, considering the initial LH spectrum obtained by modeling with the actual available data of experiment of Fig.1, the large LH spectral broadening results in LH deposition only at the very plasma periphery and negligible LH acceleration of plasma electrons (<10keV). Generation of such a low energy tail is consistent with the fact no LH-ECE-edge signal is observed in most of the main heating phase of the high edge density experiment (Fig.1(d)).

The experimental and modeling results discussed in this paper show that the operating parameters at the plasma periphery could be crucial for ensuring effective penetration of the launched LH spectrum into the bulk plasma and, consequently, allowing LHCD to be used as tool for non-inductive current generation in the region of interest for AT scenarios. When operating with an edge plasma too cold, electron temperatures lower than a few hundred eV, within a radial antenna-plasma distance too big, roughly >5−7cm, the deposition of the coupled LH power would only occur at the very plasma periphery.

The LH modeling approach considered in this paper, stressing the importance of the edge and SOL physics, is the same which produced an interpretation of the LHCD-sustained ITBs of JET in good agreement with the available diagnostics data. Modeling was here successfully applied to interpret the lack of penetration in the plasma core observed in the recent AT experiments of JET at high δ. These results suggests that, both in present and future devices, the LH spectral broadening due to PIs could be substantially reduced by optimizing the in ITER-relevant AT experimental scenarios so as to obtain higher electron temperatures at the plasma edge and further into the SOL. This could be achieved, for example, by means of low recycling, low gas fuelling or privileging fuelling by pellets and edge electron cyclotron resonant heating. Available data of very recent LH experiments on FTU give strong support to this model-based extrapolation [20, 21].

The conditions in the plasma edge and SOL should be properly optmized to favor low LH spectrum broadening and, thus, to achieve LHCD conditions relevant for ITER. By data available relevant to the ITER project, a quite large plasma-wall radial layer with relatively low temperature would occur (namely, T_e 100eV in the range r/a = 1.007−1.1, see [22,23]. In this condition, by operating with an antenna-plasma radial gap of about 0.2m (the minor radius of ITER is of about 2.0m) a strong spectral broadening is expected to occur and, consequently, the LH power would be deposited at the very periphery of plasma. For a more useful operation, the layer between antenna and plasma in which relatively low temperatures occur (T_e 0.5keV) should not exceed an extension of only a few centimeters. In this way, the PI-produced spectral broadening should be diminished and the LH power should helped penetrating in the plasma core. This conclusion has been supported by modeling results carried out considering the ITER parameters for steady-state scenario, as shown in [24, 25, 26].

CONCLUSIONS

The results presented here indicate a potential route for testing experimentally the LHCD effect in the full range of plasma densities relevant for a thermonuclear reactor experiment. The LH waves that, in principle are intrinsically suitable for propagating and driving non-inductive current at the high density plasmas necessary for ITER, do not produce effect of propagation into the plasma core in operations of JET, with high plasma density profiles approaching those necessary for ITER. In these conditions, the parametric instability is expected to occur in the scrape-off layer and prevent the coupled LH power to penetrate into the plasma core. These results are fully consistent with those recently obtained in FTU, in which a new method, based on high edge temperature operation, has been developed for enabling the LH power penetration to high plasma, and extending the range of LHCD usefulness to regimes of critical relevance for fusion reactors [20, 21].

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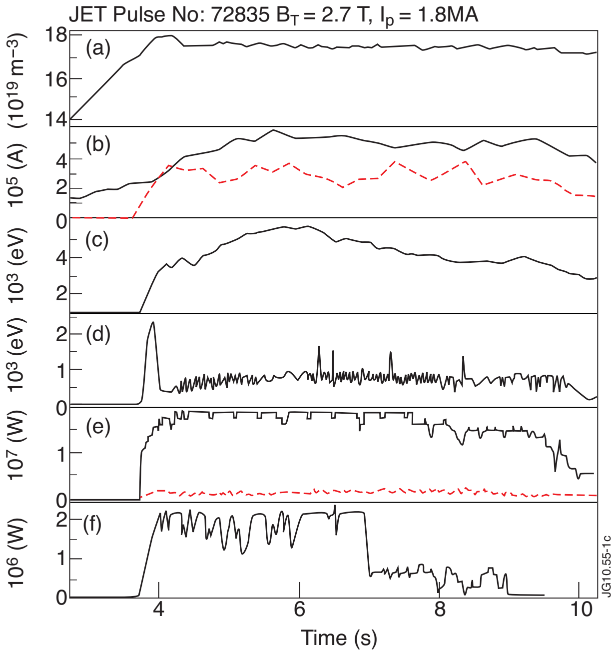

Figure 1: Time traces of the JET plasma Pulse No: 72835. B_T = 2.7T, I_P = 1.8MA, LH antenna spectrum peaked at $n_{//}$=2.3. (a) plasma current, (b) Central LIDAR density, R = 3m (red), and at R = 3.84m (black), (c) central temperature (ECE radiometer), (d) ECE emission from periphery (R = 3.82m), (e) NB power (red), ICRH power (blue), (f) LH power.

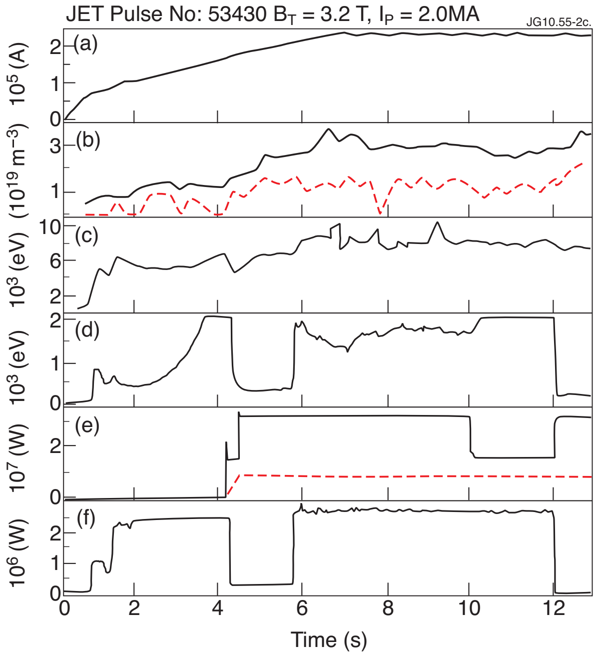

Figure 2: Time traces of the JET plasma Pulse No: 53430. B_T = 3.2 T, I_P = 2MA, LH antenna spectrum peaked at $n_{//}$=1.8. (a) plasma current, (b) Central LIDAR density, R=3m (red), and at R=3.84m (black), (c) central temperature (ECE radiometer), (d) ECE emission from periphery (R=3.82 m), (e) NB power (red), ICRH power (blue), (f) LH power.

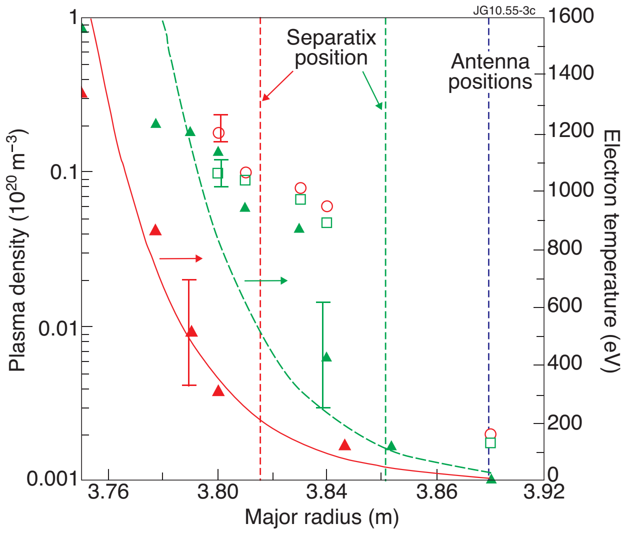

Figure 3: Kinetic profiles utilized in performing the modeling obtained by the edge LIDAR and the Langmuir probe diagnostics. Plasma density: red circles refer to Pulse No: 72835, green squares to Pulse No: 32430. Electron temperature: red triangles refer to Pulse No: 72835, green triangles to Pulse No: 32430. The profiles are kept during the LH power coupling phase: t = 5.1s for Pulse No: 72835, t = 6.1s for Pulse No: 53430. The available SOL data provided by Langmuir probes for the low triangularity plasma configuration (Pulse No: 53430) have been utilized. The same SOL profiles have been assumed also for the high-δ plasma case (Pulse No: 78835, which would imply to underestimate density and overestimate temperatures at the very edge, resulting in spectral broadening slightly smaller than that estimated for this case).

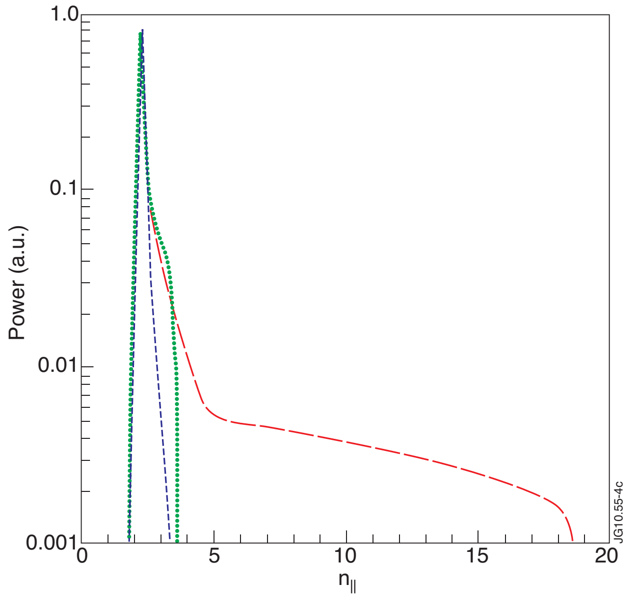

Figure 4: Power $n_{//}$ spectra considered modeled by considering the LH wave physics of the edge. Blue curve: nominal LH antenna spectrum (peak centered at $n_{//}$ =2.304. Initial spectrum calculated considering the PI-produced broadening at the edge: red curve, for the experiment data of Pulse No: 72835 (see Figs.1 and 3) and, green curve, by artificially considering the same T_e profile of Pulse No: 53430 in Fig.3.

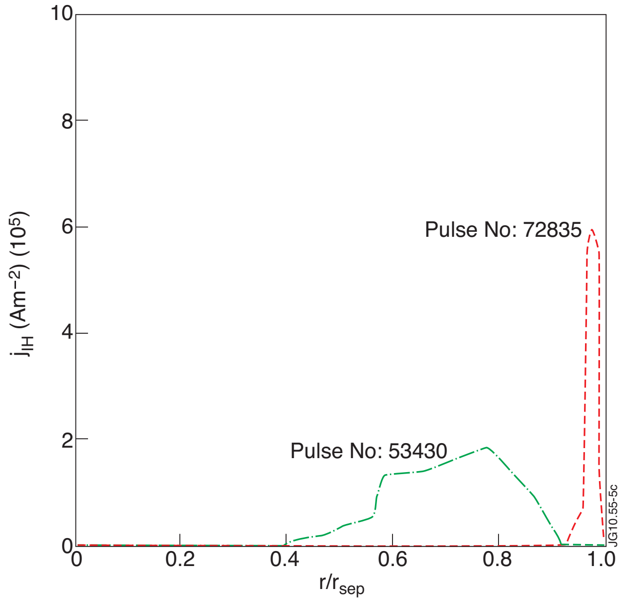

Figure 5: LH-driven current density profile obtained by the LH^{star} code by considering: the initial spectrum relevant to the experiment of Fig.1 (Pulse No: 72835, red curve); by artificially considering the T_e edge profile of experiment of Figure 2 (Pulse No: 53430, green curve).