EFDA–JET–PR(11)16

R. Cesario, L. Amicucci, C. Castaldo, M. Kempenaars, A. Krivska, S. Jachmich,
J. Mailloux, O. Tudisco and JET EFDA contributors

Plasma Edge Density and Lower Hybrid Current Drive in JET (Joint European Torus)

Plasma Edge Density and Lower Hybrid Current Drive in JET (Joint European Torus)

R. Cesario[1], L. Amicucci[2], C. Castaldo[1], M. Kempenaars[3], A. Krivska[1], S. Jachmich[4], J. Mailloux[3], O. Tudisco[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associazione EURATOM/ENEA sulla Fusione, Centro Ricerche Frascati, Italy
[2]ENEA fellow, Associazione EURATOM-ENEA sulla Fusione, Consorzio RFX Padova, Italy
[3]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]Association EURATOM-Belgian State, Koninklijke Militaire School - Ecole Royale Militaire, B-1000 Brussels Belgium
** See annex of F. Romanelli et al, "Overview of JET Results", (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).*

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

INTRODUCTION

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. More specifically, in ITER (International Thermonuclear Experiment Reactor), these regimes are predicted to have a relatively flat density profile with high density even at the periphery of the plasma column: $n_{e\_0.8} \sim 0.6\times10^{20}$–$0.7\times10^{20}$ 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. The flat profile and the high gradients in the far outer part of the plasma will contribute to self-generating at large radii non-inductive current by collisional transport, denoted as bootstrap current [1]. Because in the complex self-organised behaviour of fusion plasmas, 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]. 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 $n_{e\_av} \sim 0.8$–1.0×10^{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 [10], signatures of LH penetration in the core occurred up to line-averaged plasma density $n_{e\_av} \approx 1.0\times10^{20}$ m^{-3}, even though with density profiles more peaked and edge density lower than expected in AT scenarios in ITER ($n_{e\_0.8} \approx 0.4\times10^{20}$ m^{-3}).

For assessing the LHCD concept at reactor grade high plasma densities, the present paper considers the same research approach of FTU, which recently has found a new regime where LHCD signatures were still present at the maximum explored densities, corresponding to: $n_{e\_av} \approx 2.0\times10^{20}\,m^3$, $n_{e0} \approx 4\times10^{20}\,m^3$, and $n_{e\_0.8} \approx 0.85\times10^{20}\,m^3$ [11]. This experiment confirmed theoretical predictions that edge non-linear interactions, namely, the broadening of the launched LH $n_{//}$ spectrum caused by the parametric instability (PI) phenomenon [12,13,8], are diminished under relatively high electron temperatures at the plasma periphery, resulting wave penetration in high-density plasmas [7,8] (here $n_{//}$ is the LH wavenumber referring to the direction of the confinement magnetic field).

The relation between the lack of the LH power penetration into high density plasma core and strong PI-produced spectral broadening was observed for the first time in early experiments, which coupled LH power at high plasma densities (so that $\omega_{LH} \approx \omega_0$ in the core) with the aim of heating the core plasma ions. In these experiments the coupled LH power produced only edge physics effects, consisting in PI signatures in the frequency spectra of the signal received by RF (radio-frequency) probes located in the Scrape-Off Layer (SOL), or outside the machine. These spectra show a broadening in the LH operating line frequency (orders of magnitude higher than the line width of the RF power sources), more markedly for higher operating plasma densities, and sidebands shifted by harmonics of the ion-cyclotron frequency of the plasma edge, exhibiting a typical non monotonic envelop for relatively high operating plasma densities [14–16]. Strong PI signatures were also observed using CO_2 laser scattering on the Alcator C tokamak [17]. The LHCD experiments operated, instead, at relatively lower plasma densities and higher frequencies (so that $\omega_{LH} \approx \omega_0$ in the core. ω_{LH} is the cold resonant LH frequency). In this context of experiments, the spectral broadening results to be less marked, whilst the ion-cyclotron LH sidebands become very small, or disappear at all [8]. The phenomenology of the spectral broadening, interpreted by the PI phenomenon, was recognised to be important in LHCD experiments, as its consideration allowed producing LH power radial deposition more in periphery of the plasma column consistently with the available diagnostic's data [7,8]. For LHCD experiments of JET, the occurrence of the spectral broadening was documented by data from RF probe [18] and microwave reflectometry [8].

Incidentally, ion tail formation, occurring at the edge in the early LH experiments aimed at heating the core plasma ions, were not observed in LHCD regime, consistently with PI modelling expecting that for lower plasma densities and higher operating frequencies (as those utilised in the LHCD experiments), the $n_{//}$ spectral broadening would be insufficient for bridging the gap between LH wave phase velocities and thermal velocities of peripheral plasma ions, as necessary for ion acceleration by LH power [8].

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. The present paper considers the problematic LHCD operations with relatively high plasma density at the edge of JET, which represent a new context of experiments whose parameters are much closer to ITER requirements than in other experiments.

RESULTS

The main focus of the present paper is to show new results and modelling of JET experiments particularly relevant for assessing the role of the plasma edge in determining conditions for penetration of the LH power, coupled during an H-mode phase, into the plasma core and current drive. In experiments performed with high triangularity (δ~0.35) plasma configuration, the LH power does not penetrate into the core. The plasma density profile has a shape like that expected for ITER but lower densities in the centre ($n_{e0} \approx 0.5\times10^{20}$ m^{-3}) and at the periphery ($n_{e\_0.8} \approx 0.4\times10^{20}$ m^{-3}). Instead, clear LHCD signatures occur in the core in operations with low δ (~0.25), producing more peaked density profile ($n_{e0} \approx 0.4\times10^{20}$ m^{-3}) with lower plasma densities more markedly at the edge ($n_{e\_0.8} \approx 0.2\times10^{20}$ m^{-3}). The experimental results shown in the present paper should be considered as an important reference for modelling tools useful for assessing the LHCD concept for ITER and high density reactor grade plasmas. By numerical code, which takes into account the effect of the PI-produced spectral broadening, we have obtained results useful for a possible solution of the aforementioned LHCD problem for the case of JET.

In the following, since the launched LH waves resonate with relatively high tail electron velocities (≈ 2.5–$4\, v_{the}$), the occurrence of wave penetration is estimated by detection of supra-thermal 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 [19]. In the rest of the paper the supra-thermal emission due to fast electrons will be referred to as LH-ECE-edge signal.

EXPERIMENTS

Experiments with ITER-relevant density profile plasma shape have been obtained on JET with plasma configuration at high δ, toroidal magnetic field B_T= 2.7T and plasma current I_P =1.8MA [20]. Figure 1 shows the time traces of the main plasma parameters of the considered experiment at high δ. 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.1f). Figure 1b 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 = 3.78m, 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 $r/r_{Sep} \approx 1.02$). This layer is optically thin (the optical thickness is always less than 1 and, more specifically, $\tau \approx$ 0.14 at 44.1s, the time point in which the LH-ECE-edge signal drops reaching the NB background level). Supra-thermal 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 1d 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 ($n_{e\_0.9} \approx 0.25\times10^{20}$ m^{-3}, at $r/r_{Sep} \approx 0.9$) and in the core ($n_{e0} \approx 0.27\times10^{20}$ m^{-3}). During most of the H-mode phase, the plasma density is higher: $n_{e\_0.9} \approx 0.4\times10^{20}$ m^{-3} 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 [3] experiments with different combinations of antenna spectrum ($n_{//} = 2.30$ and $n_{//} = 1.84$) 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 occurs as in Fig. 1d, i.e., only at the start of the main heating phase, although the accessibility condition was not satisfied in some cases. Moreover, in plasmas with same configuration but higher values of toroidal magnetic field ($B_0 = 3.4$T, in place of 2.7T, JET Pulse No: 77616), so that the margin of accessibility was enhanced, the electron temperature in the plasma core resulted insensible to the LH power, also when coupled with pulsed waveform for enhancing the capability of revealing signatures [21]. These results allow making the conclusion that the LH power does not penetrate indeed into the core in plasmas with relatively high plasma density at the edge, independently of the fulfilment of the accessibility condition. Its role in determining the occurrence of LHCD effect in the core, is ruled out also by the occurrence of clear LHCD signatures in plasma discharges of JET (like Pulse No: 72595) despite that the LH accessibility condition was not satisfied, due to the low values of the magnetic field (= 2.4T) and $n_{//}$ (= 1.4) utilised in the experiment. In this case, the LH power was coupled during an L-mode phase with relatively low density mainly at the edge ($n_{e\_av} \sim 1\times10^{19}$ m^{-3} with peaked profile), which confirms the role of the plasma density profile in determining the occurrence of LHCD effect in the core. Therefore, the accessibility of the launched LH spectrum is not the dominant factor in the wave propagation and absorption in these conditions, and the physics occurring in the SOL and plasma edge should be considered.

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 [22–24,7].

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]. 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 δ, higher toroidal field and plasma current, $B_T = 3.4$ T and I_P

= 2.3MA, heated in the H-mode phase by a combination of ~ 17MW of NBI and ~ 4MW of ICRH. Lower plasma density, mainly at the periphery ($n_{e0.9} \sim 0.2\times10^{20}$ m^{-3}, $n_{e0} \approx 0.4\times10^{20}$ m^{-3}), characterize such experiments, due to reduced edge pedestal confinement in the low δ configuration. As in the high δ experiments, the layer is optically thin (τ ≈ 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.2d). This latter fully follows the LH power waveform (Fig.2f). 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.1d).

In the case of the experiment of Figure 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 Figure 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. 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], which provided a fair interpretation of the LH-sustained ITBs of JET experiments [22–24], by producing an LH deposition profile in agreement with the available diagnostics data. The recent results are interpreted, by PI modelling, in terms of strong $n_{//}$ LH 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 δ. 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.

Simulations.

Following Refs. 7,8, LH modelling has been carried out comparing the experiments of Figs 1 and 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 [25], 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 modelling approach consists in calculating the broadening of the $n_{//}$ spectrum launched by the antenna by solving the parametric dispersion relation [12,13]:

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

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 indicates 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) [13]. The condition: $A>1$ occurs over the plasma periphery layer for coupled LH power density $W_{\mathrm{LH}} \approx 10\mathrm{MW/m^2}$. 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 [7,8]. 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 [7,8].

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 $T_{\mathrm{e}} \approx 500\mathrm{eV}$ is indeed located at about 10 cm from the LH antenna in Pulse No: 72835, against 4cm in Pulse No: 53430. This condition favours 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$^{\mathrm{star}}$ modelling 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. Such assumption would take into account the effect of possible operations aimed at producing higher electron temperature of the plasma periphery, which were expected to be very useful for enabling the occurrence of LHCD effects at high plasma densities as confirmed by FTU results [11].

We have chosen a simple data interpolation in Fig.3 for giving more robustness to the analysis. For the case of warmer plasma of periphery, this choice underestimates indeed the temperature in the relevant radial region, with respect to a standard interpolation with two different functions (outside and inside the separatrix). This circumstance is due to the effect of the non-linear behaviour of the PI phenomenon, which amplifies the different spectral components of LH sideband waves when a certain threshold condition is exceeded. For the considered experiments, a significant difference in the threshold conditions actually occurs, mainly as consequence of the marked difference in the radial gap of the SOL and periphery plasma regions, in which relatively low electron temperatures occur (≲0.5keV). The extent of this radial gap is robust against experimental uncertainties.

PI modelling expects that the frequency spectral broadening due to LH sideband waves increases with the edge plasma density consistently with the RF probe phenomenology, which has been generally observed in LHCD experiments, including JET [18,8]. However, for determining the LH deposition (which is the main output of the model) the relevant parameter to be considered as input is the broadened $n_{//}$ spectrum, which has been calculated here on the basis of the experimental data, i.e. kinetic profiles, antenna parameters and other data of experiment.

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 [22–24] with $n_{//Max} \approx 3.7\pm0.5$ [7]. A more strongly broadened spectrum, $n_{//Max} \approx 18\pm6$, 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 0.4keV – 0.5keV does not significantly affect the broadening result.
The small difference of spectrum is sufficient for producing significant differences in the quasi-linear effect and, consequently, in the LHCD deposition profile. As shown in classical literature, indeed, quasi-linear effect results to be strongly sensitive also to little LH power carried by spectral contributions at high $n_{//}$, provided that they form a tail, i.e., a spectral broadening continuously produced up the nominal $n_{//}$ peak [26]. For these reasons, the side lobes of the antenna spectrum (however considered in the calculation) do not give significant contribution to the LH deposition profile.

The initial spectra and the experimental temperature and density profiles are then used for calculating the LH deposition profiles shown in Fig.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} [27]).

Modelling indicates that electron would be accelerated to tail energies in the range 50keV –70keV. This implies that, assuming similar behaviour 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. On the other hand, considering the initial LH spectrum obtained by modelling 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.1d).

For the aforementioned case of experiments in which the LH accessibility is not satisfied, the modelling shows that the coupled LH power suffers the occurrence of mode conversion to fast waves, in the outer half of plasma radial region. After being reflected to the edge, the fast waves might be converted back to LH waves, but the calculations have been stopped there, as the geometric optic for LH waves fails at the LH wave cut-off (a full wave model approach would be necessary for properly continuing the analysis). Instead, in case of satisfied accessibility condition, most of the coupled LH power reaches the plasma core, and a significant fraction is reflected back to the edge, where, again, the calculations have been stopped due to the failure of the geometric optic limit.

On the other hand, considering the PI-produced $n_{//}$ spectral broadening effect, most of the coupled LH power results to be deposited in the core at the first radial pass, fully respecting the geometric optic limit. This model approach was shown for the first time in Refs. 7, 8 (where the LH^{star} code has been described in detail).

DISCUSSION

The experimental and modelling 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 cm – 7 cm, the deposition of the coupled LH power would only occur at the very plasma periphery.

The LH modelling 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 [22–24] in good agreement with the available diagnostics data [7,8]. Modelling 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 privileging fuelling by pellets, and electron cyclotron resonant heating. Available data of recent LH experiments on FTU give strong support to this model-based extrapolation [11].

In conclusion, the results presented here indicate a potential route for testing experimentally the LHCD concept 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 SOL and prevent the coupled LH power to penetrate into the plasma core. The conditions in the plasma edge and SOL should be properly optmised to favour low LH spectrum broadening and, thus, to achieve LHCD conditions relevant for ITER.

ACKNOWLEDGEMENT

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors thank X. Litaudon who coordinated some of the considered experiments and F Rimini for the very useful discussions.

REFERENCES

[1]. Freidberg, J. Plasma Physics and Fusion Energy, Cambridge Univ. Press, 2007

[2]. A. Fasoli et al, Nuclear Fusion, **47**, S264 (2007)

[3]. M Brambilla, Kinetic Theory of Plasma Waves, Oxford, 2003

[4]. N.J. Fisch, Physical Review Letters, **41** (1978) 873

[5]. N.J. Fisch, Rev. Mod. Phys, **59**, (1987) 175

[6]. S. Bernabei, et al., Physical Review Letters, **49**, 2 (1982) 1255

[7]. R. Cesario, et al., Physical Review Letters, **92** 17 (2004) 175002

[8]. R. Cesario, et al., Nuclear Fusion, **46** (2006) 462-476

[9]. G. Wallace et al. RF Conf, Gent, Belgium 2009

[10]. V. Pericoli et al. Physical Review Letters, **82**, 93 - 96 (1999)

[11]. R Cesario et al., Nature comm., **1**(5) 55, 2010

[12]. M. Porkolab, Physics of Fluids **17**, 1432 (1974)

[13]. C.S. Liu and V. K. Tripathi Phys. Fluids Report **24**,1709 (1984)

[14]. Y. Takase, et al. Physics of Fluids **26**, 2992 (1985)

[15]. R. Cesario and V. Pericoli-Ridolfini, Nuclear Fusion, **27**, 435 (1987)

[16]. R. Cesario and A. Cardinali, Nuclear Fusion, **29**, 1709 (1989)].

[17]. Y. Takase, et. al., Physics of Fluids, **28**, 983 (1985)].

[18]. V. Pericoli-Ridolfini, A. Ekedahl et al, Plasma Physics and Controlled Fusion, **39** (1997) 1115

[19]. M. Bornatici, R. Cano, O. De Barbieri and F. Engelmann, Nuclear Fusion, **23** (1983) 1153

[20]. X. Litaudon et al 2007 Nuclear Fusion, **47** 1285

[21]. K.K. Kirov, et al., 36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.33E, P-5.162 (2009)].

[22]. J. Mailloux, B Alper, Y Baranov, A Becoulet, et al., Physics of Plasmas, **9**,5, (2002) 2156

[23]. F. Crisanti, X. Litaudon, J. Mailloux, D. Mazon, et al., Physical Review Letters, **88** (2002) 145004

[24]. C. Castaldo, R Cesario, A Cardinali, et al., Physics of Plasmas, **9** 8 (2002) 3205

[24]. A. Cardinali, 2000 Recent Research Developments in Plasmas, Vol. **1**, 185

[26]. S. Succi, et al., Plasma Physics and Controlled Fusion, **27** (1985) 863-871)].

[27]. R. Cesario, C. Castaldo, A. Fonseca, R. De Angelis, et al RF Power in Plasma Conf USA, Clearwater, 2007

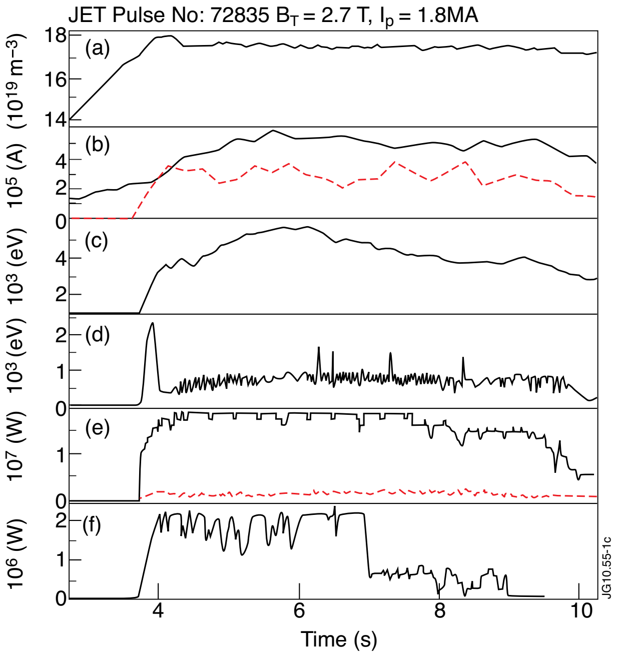

Figure 1. Time traces of the JET plasma Pulse No: 72835. B_T = 2.7 T. The LH spectrum ($n_{//peak}$ = 2.30) satisfies the LH accessibility condition. a) plasma current, b) central LIDAR density, R = 3m (black), and at the periphery (R = 3.84m, red), c) central temperature (ECE radiometer), d) ECE emission from periphery (R = 3.82m), e) NB power (black), ICRH power (red), f) coupled LH power.

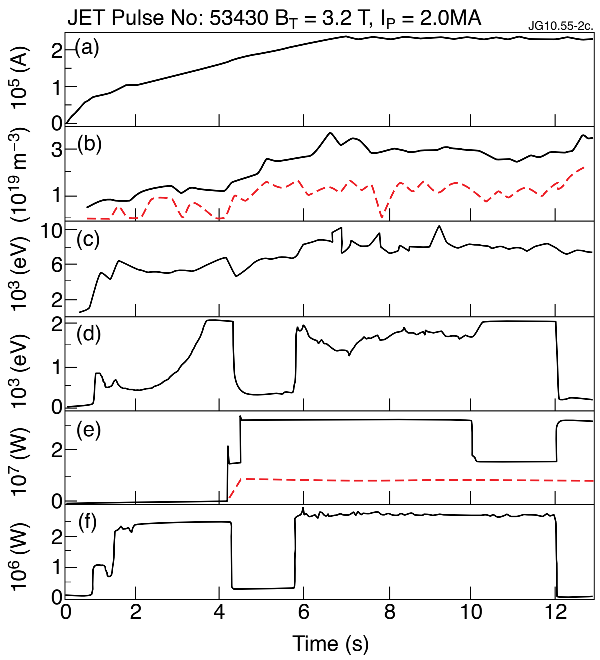

Figure 2: Time traces of the JET plasma Pulse No: 53430. B_T = 3.4T. The LH spectrum ($n_{//peak}$ = 1.840) satisfies the LH accessibility condition. a) plasma current, b) central LIDAR density, R = 3m (black), and at the periphery (R = 3.84m, red), c) central temperature (ECE radiometer), d) ECE emission from periphery (R = 3.82m), e) NB power (black), ICRH power (red), f) coupled LH power.

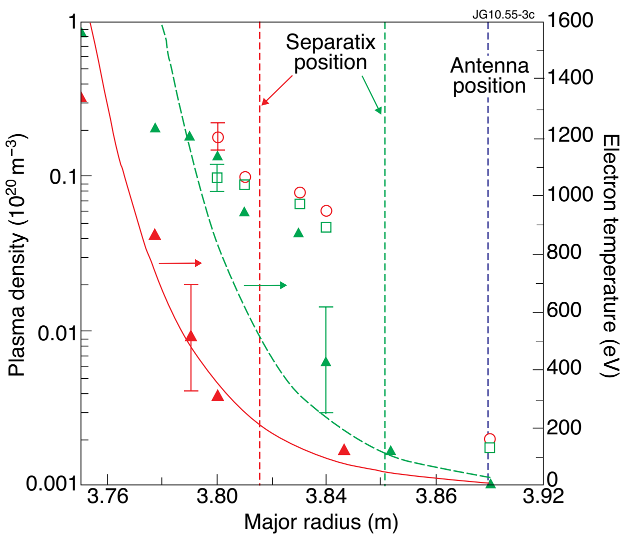

Figure 3: Plasma edge kinetic profiles obtained by the edge LIDAR and the Langmuir probe diagnostics. Plasma density: high δ case (same Pulse No: 72835 of Fig.1), red circles; low δ case (same Pulse No: 53430 of Fig.2), green squares. Error bar: one standard deviation. Electron temperature: high δ case, red triangles (red curve: exponential fit); low δ case, green triangles (green curve: exponential fit). Error bar: one standard deviation. 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 uncertainty in the radial locations is about ±1cm. Langmuir probes provide the Scrape-Off Layer (SOL) data for the low δ discharge. The same SOL profiles have been assumed also for the high δ case, which would imply to underestimate density and overestimate temperatures at the very edge and, consequently, underestimate the spectral broadening.

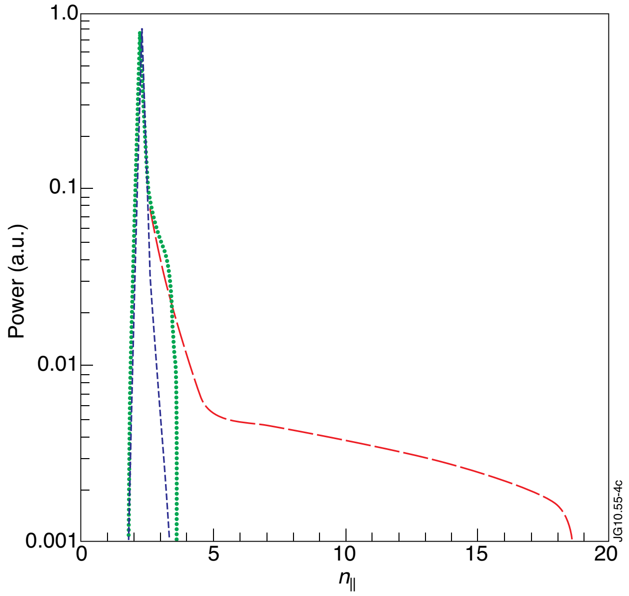

Figure 4: LH $n_{//}$ spectra. Nominal LH antenna spectrum utilized for the high δ discharge of Fig.3 (Pulse No:72835, $n_{//peak}$=2.304), blue curve. The side lobes do not have been shown in the figure (see the text). Initial spectrum calculated by the kinetic profiles of the high δ discharge of Fig. 3, red curve, and by artificially considering the same T_e profile of the low δ discharge of Fig. 3, green curve.

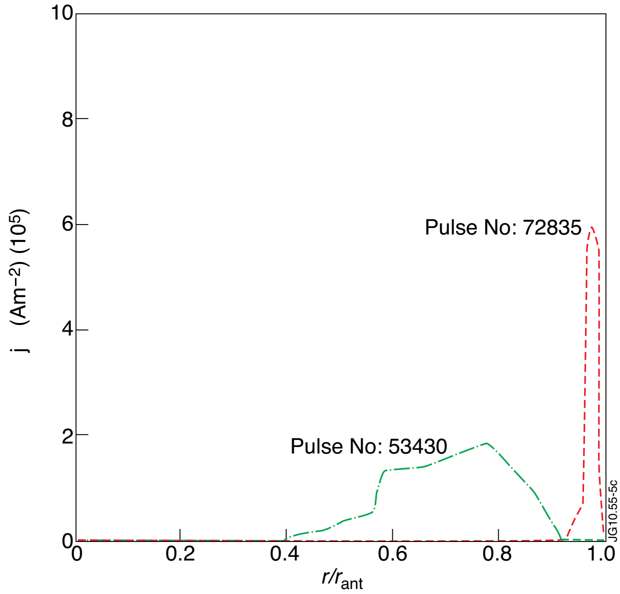

Figure 5: LH-driven radial current density profile obtained by the LH^{star} code with the two different initial spectra of Fig.4a. r_{ant} is the radial antenna position. Red curve: calculated considering the kinetic profiles of the high δ discharge of Fig.3 (and Fig.1: Pulse No: 72835). Green curve: calculated by artificially considering the same T_e profile of the low δ discharge of Fig.3 (and Fig.2: Pulse No: 53430).