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1. INTRODUCTION

The advantage of the Lower Hybrid (LH) waves to generate efficiently Current Drive (CD) in fusion plasma has been highlighted in many theoretical works [1]. Early experimental studies reported [2], however, decrease of the CD effects above a certain density.

The study presented here uses modulated power to assess the LH power deposition and CD efficiency. The response of the electron temperature, T_e, provided by the Electron Cyclotron Emission (ECE) diagnostic, is investigated by means of FFT analysis.

1. EXPERIMENTAL SETUP AND DIAGNOSTICS

Details on the LH system at JET can be found in [3]. The launched Radio Frequency (RF) power has a narrow spectrum, peaked at parallel refractive index, $N_{||}$, of about 1.8. For the experiments reported here square wave modulations at $f = 41.67$Hz were used. This helped investigating the higher harmonics and fitted best the measurements of CD efficiency.

ECE radiometer at JET consists of 96 channels, which covered the outboard plane and were used in 2X mode. The optical thickness of the plasma in most of the experiments was sufficiently large in the region of interest [4]. Only very low-density plasmas were found to have smaller optical thickness, which affected mainly channels near the edge. In the study this region was excluded from the analysis. The error bars of ECE measurements were assessed to be around 5%. All the profiles are mapped on the outboard midplane radius, R.

The LH power, P_{LH}, and electron temperature profile were processed by means of FFT analysis as the quantities of interest are the amplitudes, δT_{e1} and δT_{e3}, of the oscillations at the 1st and 3rd harmonics, respectively, and the phase, ϕ, of T_e perturbations. The latter is a difference between T_e and PLH phases at the 1st harmonic and is always negative as T_e changes follow the LH power. The ratio $\delta T_{e3}/\delta T_{e1}$ and ϕ can be used to assess the CD efficiency, whilst δT_{e1} and ϕ profiles are closely related to the LH power deposition profile.

3. THEORETICAL BACKGROUND AND MODELLING

When LH wave is launched in the plasma the applied RF power is not immediately absorbed by the thermal bulk electrons; instead it takes many collisional times for the fast electrons, on which LH wave damps via Landau damping, to transmit their energy to the thermal ones. The absorbed wave power, p_W, and the power, which is lost to the bulk electrons, p_C, evolve in a different way when transient events are considered. A Fokker-Plank (FP) code which accounts for the transient effects related to the modulations was used to calculate p_W and p_C.

The LH wave absorption was modelled by means of RF induced quasi-linear flux. The quasi-linear diffusion coefficient was approximated by a step function with non-zero values of D_0 between w_1 and $w_2 = w_1 + \Delta$, where w is the parallel velocity normalised to the thermal one, $v_{te} = (T_e/m_e)^{1/2}$. D0 is normalised to v_{te}^2/τ_{te} with τ_{te} being the collisional time. The resulting distribution function forms a plateau with origin and width of about w_1 and Δ, whilst the LH CD efficiency scales as

$\Delta(w_1+w_2)$ [1]. The shape of p_C is strongly affected by the plateau width, Fig. 1a, as for large Δ the rise and the fall time of p_C increase. Full scan of the plateau parameters and D_0 was done by modelling the modulation sequence. The ratio, $\delta p_{C3}/\delta p_{C1}$, of the 3rd to the 1st harmonic amplitudes of p_C and the phase, j, of p_C fluctuations at the fundamental frequency were investigated. It was found that j and $\delta p_{C3}/\delta p_{C1}$ are most sensitive to the plateau width; e.g. an increase of D from 2 to 6 reduces $\delta p_{C3}/\delta p_{C1}$ by about 20%, Fig.1b. The plateau origin was found to have small impact in the range from 2.8 to 3.5, so $w_1 = 3$ was adopted in the numerical analysis, while $D_{\neq 0}$ was assessed between 0.1 and 0.3.

The relation between modulated source, p_C, and T_e response is not trivial as the transport effects have a significant impact on the latter. Electron heat transport was accounted for by implementing the Critical Gradient Model (CGM) [5] in JETTO transport code. The simulations showed that $\delta T_{e3}/\delta T_{e1}$ minimum and ϕ maximum are located near the maximum of the LH deposition. The phase f decreases strongly in the deposition free region, and this feature was used to identify the region where LH is not absorbed. These observations facilitated the deduction of important information about the LH power deposition profile, $p_{LH} \equiv p_C$, based on the analysis of the T_e perturbations. It was also found that near the deposition centre $\delta p_{C3}/\delta p_{C1} = C\, \delta T_{e3}/\delta T_{e1}$, where C is between 2.4 and 3.

4. EXPERIMENTAL RESULTS

The experiments presented here were performed at magnetic field of 3.4T and plasma current of 1.5MA and 1.8MA. Pulses with central density, n_{e0}, from $1.5\times10^{19}m^{-3}$ to about $5\times10^{19}m^{-3}$ were investigated, Fig.2a. It was observed that δT_{e1} has 'U'-like shape with increasing values for R<3.2m and R>3.7m and generally decreases when density increases as most notable change occurs in the transition from L to H-mode plasma. For example, increase of $n_{\neq e0}$ from $4.2\times10^{19}m^{-3}$ (Pulse No: 77612) to $4.8\times10^{19}m^{-3}$ (Pulse No: 77616) resulted in significant decrease of δT_{e1}, Fig.2b. In the latter case the temperature perturbations were localised between 3.3m and 3.6m. The decrease of δT_{e1} in Pulse No: 77616 can be related to LH power losses in the plasma periphery. LH wave accessibility condition also indicates that LH wave with $N_{||} \leq 1.8$ will not propagate inside R<3.7m, so that only the large $N_{||}$ fraction of the launched LH power propagates and is eventually absorbed in the core. Furthermore it was found that f always decreases with the electron density. Its maximum is in the plasma core, $R \approx 3.5$m-3.6m, for $n_{e0} < 2\times10^{19}m^{-3}$ and always moves outward when density increases [6].

The steady-state and perturbed electron temperature were modelled by means of CGM. The results for δT_{e1} and f are compared to the experimental data, Fig.3a, 3b. At moderate and low density, $n_{e0} < 4\times10^{19}m^{-3}$, good agreement for δT_{e1} between 3.1m and 3.6m was observed for broad off-axis peaked p_{LH} with maximum shifting towards the edge when density increases.

The experimental T_e phase is always lower than the transport predictions, by 0.9rad for the lowest density pulse Pulse No: 77607 and by 0.3rad for Pulse No: 77609. The large offset between the model and the experiment is an indication of large CD efficiency in accordance to the FP modelling results, which predict phase delay of p_C larger than 0.5rad for $\Delta > 7$ and about 0.3rad for $\Delta \approx 6$. Indeed, the time needed for the fast electrons to heat the thermal ones is proportional to their energy, hence the broader the plateau, the larger the phase delay between p_C and p_w is.

The plateau width Δ is assessed via comparison of the experimental data for $C\ \delta T_{e3}/\delta T_{e1}$ and FP results for $\delta p_{C3}/\delta p_{C1}$, Fig.3c. The results were taken in a region between 3.56m and 3.65m and indicate large plateau, $\Delta \geq 6$, hence significant CD efficiency for Pulse No: 77609 with $n_e(3.6\text{m}) \approx 2\times10^{19}\text{m}^{-3}$. At higher density, $n_e(3.6\text{m}) \approx 3\times10^{19}\text{m}^{-3}$ in Pulse No: 77612, the value of $C\ \delta T_{e3}/\ \delta T_{e1}$ was found consistent with FP results for $\Delta \approx 2$, which implies reduction of CD efficiency.

Ray-tracing results do not match the experimental data at high density. A possible explanation of the CD efficiency decrease for $n_e > 3\times10^{19}\text{m}^{-3}$ is that $N_{||}$ increases immediately – just after few bounces of the rays at the plasma periphery – to a sufficiently high value for an efficient absorption in the plasma core by electrons with lower energy.

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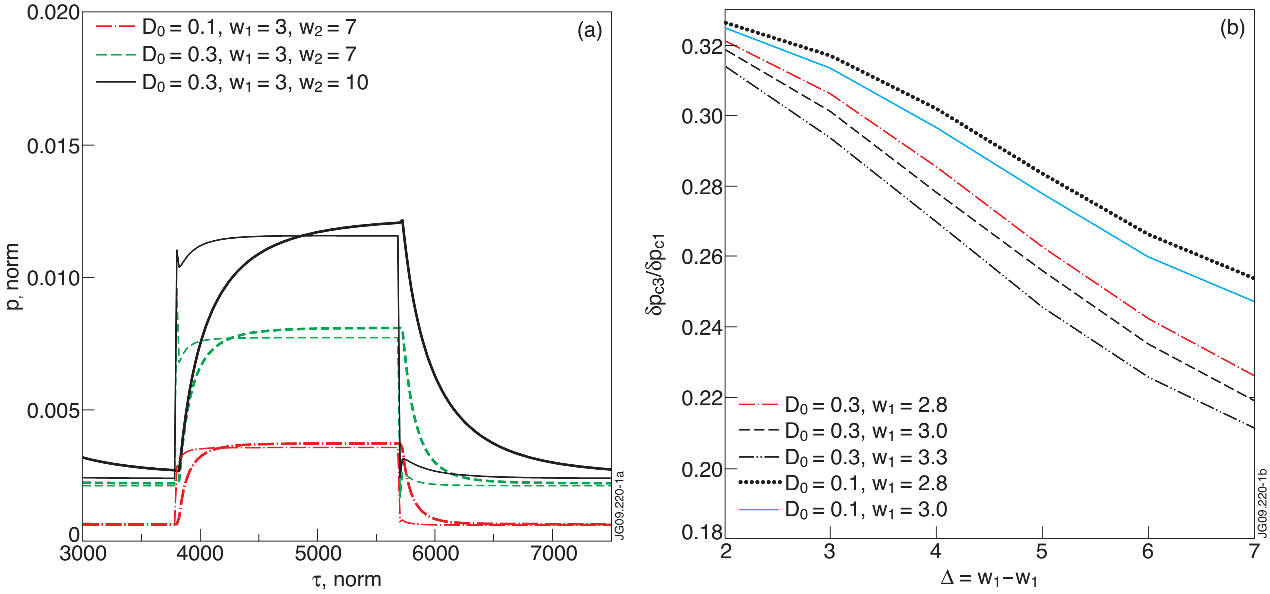

Figure 1: Power waveforms p_W (thin lines) and p_C (thick lines) normalised to $n_e m_e v_{te}^2/\tau_{te}$ from FP modelling (a) with $w_1=3$, D_0 and w_2 as shown in the legend and RF power switched on at normalised time $\tau=t/\tau_{te}=3800$ and off at $\tau=5700$. Dependence of the ratio δ_{pC3}/ dp_{C1} on Δ for w_1 between 2.8 and 3.3 and D_0 values of 0.1 and 0.3 (b).

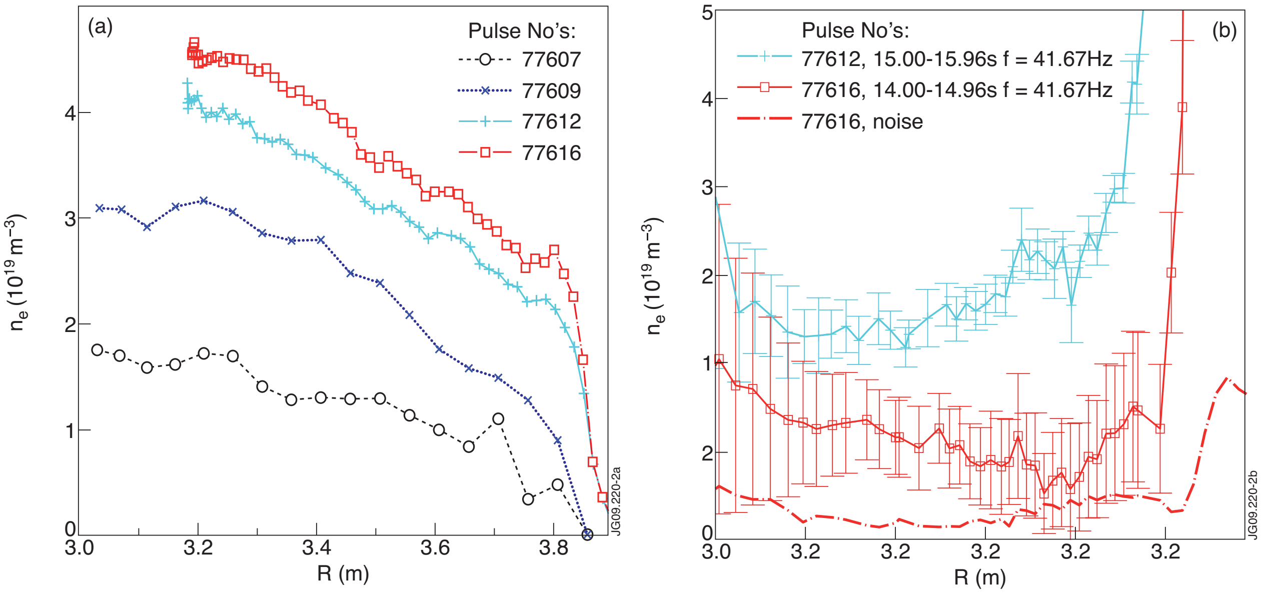

Figure 2: Density scan at 3.7T (a) and δT_{e1} profiles for the high density cases (b). Pulse No: 77616 was in H-mode.

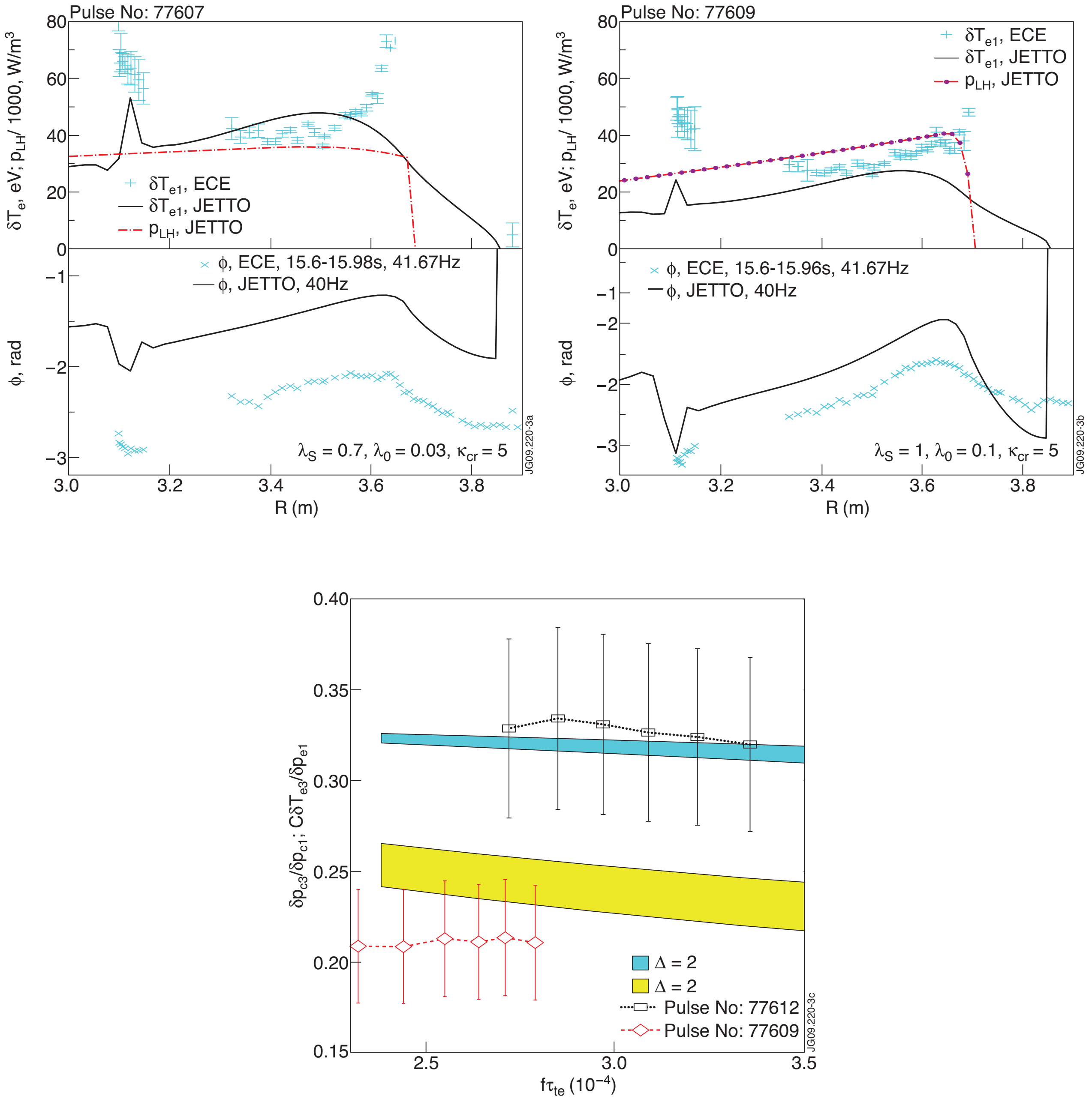

Figure 3: Modelled and experimental T_e amplitude and phase for Pulse No's: 77607(a) and 77609(b). The parameters of CGM, l_S, l_0 and k_{cr} are indicated at the bottom, for more details on GCM see Ref. [5]. FP results (c) for dp_{C3}/dp_{C1} (shaded area) vs. normalised modulation frequency $f\ \tau_{te}$ for f=41.67Hz, Δ=2 and 6, D_0=0.1-0.3 and w_1=3 compared to the ratio C $\delta T_{e3}/\delta T_{e1}$ from experimental measurements (square and diamond points).