Observation of Spectral Broadening of Lower Hybrid Waves in Alcator C-Mod*)

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Observations of the spectral broadening of lower hybrid (LH) waves in Alcator C-Mod are presented. We report the dependence of the pump broadening on two plasma parameters: plasma density and magnetic topology. As the plasma density was raised, we observed a significant increase of the pump broadening at 10 dB below the maximum peak. However, at the constant plasma density, when the magnetic topology was changed from the diverted plasma to the inner wall limited plasma, the spectral broadening was reduced. In an attempt to understand the causes of this variation, we report the change of density profiles in front of the LH launcher in two different magnetic topologies. The model analyses indicate that both the scattering process and parametric decay instability can contribute to the spectral broadening. Further experimental investigations are necessary to identify the causality between spectral broadening and the degradation of lower hybrid current drive efficiency at high density plasmas.

Keywords: spectral broadening, lower hybrid wave, scattering, parametric decay instability

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1. Introduction

Lower hybrid current drive (LHCD) has been proposed as a way to generate non-inductive toroidal currents in tokamaks. One of the unsettled issues in LHCD stems from an observation of spectral broadening of LH waves [1–5]. While a number of papers link the spectral broadening to the degradation of current drive efficiency [6–9], there has been no general agreement on the mechanism how the spectral broadening affects LHCD. Thus, it is necessary to understand the cause of spectral broadening to clarify whether it is related or not to the degradation of LHCD efficiency, especially at high density ($n_e \geq 1 \times 10^{20}\,\mathrm{m}^{-3}$) plasmas.

There are two known mechanisms responsible for this pump broadening. The first mechanism is the scattering of LH waves by low frequency density fluctuations [10–12]. The second is ion sound quasi-modes induced by parametric decay instability (PDI) [9, 13, 14]. Both [8, 9] can affect the current drive efficiency in terms of LH power transmission and the modification of the parallel refractive index ($N_\parallel$) spectrum of LH waves.

In this paper, we report observations of the spectral broadening of LH waves measured by the probe in Alcator C-Mod. In addition, we calculate the spectral broadening using the scattering model, and we perform a preliminary numerical analysis to study PDI.

2. Measurement of Spectral Width of LH Waves

In Alcator C-Mod, LH waves are launched by a grill antenna at a frequency of 4.6 GHz. In this grill, there are 4 rows of 16 waveguides (7 × 60 mm), delivering a maximum power up to 1.0 MW. There are two Langmuir probes mounted between each of the four waveguide rows. By adding a tee adapter and a DC block at the signal output of the probe, we measured the microwave frequency spectrum at 4.6 GHz picked up by the probe [1], while preserving its conventional capabilities. In the top panel of Fig. 1, we show typical frequency spectra at 4.6 GHz for two different line-averaged plasma densities. The dependence of the pump broadening on the density has been observed in other tokamaks [2, 8] as well. At $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$, in addition to larger pump broadening, we observed the harmonics of ion cyclotron peaks separated by approximately 30 MHz, implying that they were generated at the plasma periphery. The integrated spectral power ratio of the sidebands to the main lobe was about 20 % when we numerically integrated the power spectrum for each spectral lobe.

In the bottom panel of Fig. 1, we show the zoomed-on spectra of the same discharges near the frequency of the pump wave. The spectrum at $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$ is slightly down-shifted starting from 10 dB below the peak, persisting until the ion cyclotron side-bands dominate the spectrum, whereas the pump broadening of LH waves is symmetrical at $n_e = 0.84 \times 10^{20}\,\mathrm{m}^{-3}$. We attribute the down-shifted asymmetric spectrum at $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$

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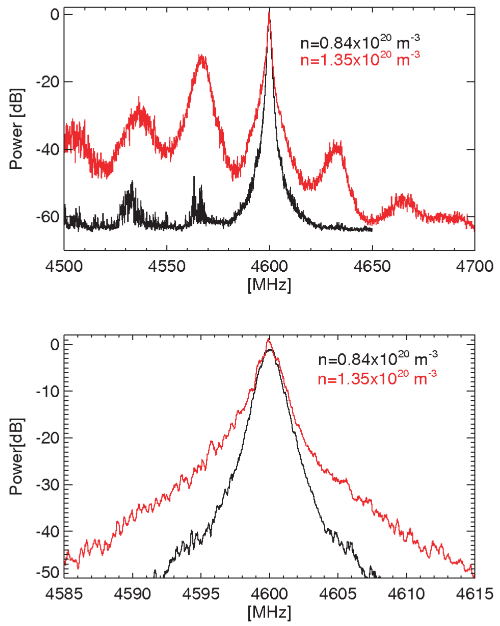

Fig. 1 LH spectra measured by the probe for two different densities at $n_e = 0.84 \times 10^{20}\,\mathrm{m}^{-3}$ and $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$. Lower single null plasmas, $B_0 = 5.4\,\mathrm{T}$, $I_p = 800\,\mathrm{kA}$, $P_{LH} = 600\,\mathrm{kA}$, $N_\parallel = 1.9$. Broad-band (Top), and narrow-band (Bottom) spectra near the pump frequency.

to ion sound quasi-modes induced by PDI, rather than to the scattering effect. Although we observed that the peak power was higher by about 2 dB compared to that at $n_e = 0.84 \times 10^{20}\,\mathrm{m}^{-3}$, a question remains which components of LH waves are measured by the probe.

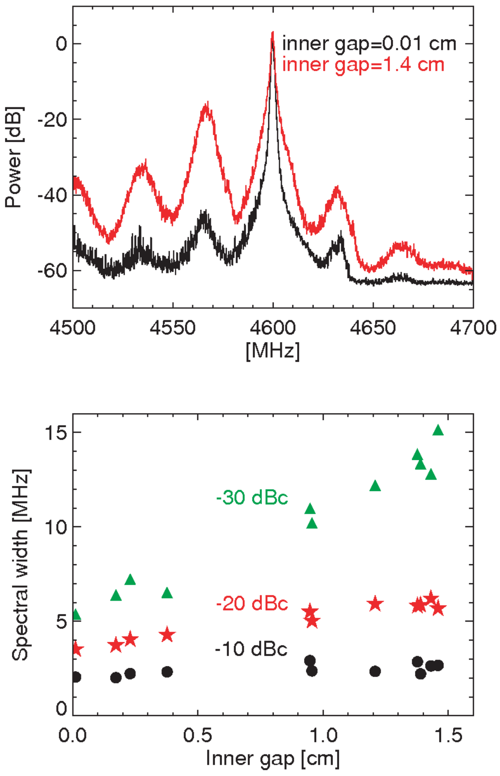

Fig. 2 LH spectrum measured by LH probe for two different inner gap at $n_e = 1.4 \times 10^{20}\,\mathrm{m}^{-3}$. Upper single null plasma, $B_0 = 5.4\,\mathrm{T}$, $I_p = 800\,\mathrm{kA}$, $P_{LH} = 550\,\mathrm{kA}$, $N_\parallel = 1.9$ (Top) Broad band spectrum (Bottom) Spectral width at 10, 20 and 30 dB down to the maximum peak.

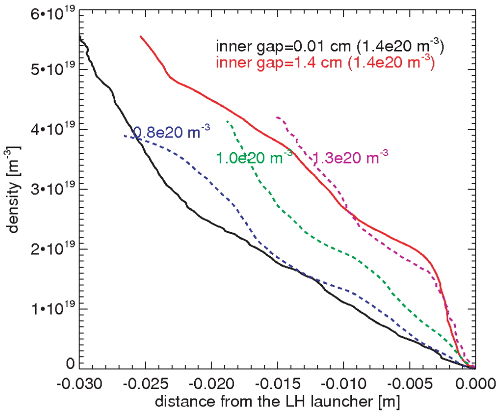

Fig. 3 Density profiles in front of the LH launcher of the large gap plasma (red) and the small gap plasma (black) in the upper null configuration. Over-plotted are density profiles at three different plasma densities in the upper null configuration with the inner gap ≈ 1.2 cm.

The dependence of the pump broadening on the magnetic topology has been observed at the fixed plasma density. The inner gap, the distance between the inner wall and the separatix, was scanned from 0.01 cm to 1.4 cm at the density $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$ in the upper null configuration. Interestingly, hard X-rays increased as the inner gap decreased, and the number of photons from hard X-rays increased to the number that was predicted by the ray-tracing/Fokker-Planck simulation [15]. The top panel of Fig. 2 shows the LH spectrum for both the large gap (1.4 cm) and the small gap (0.01 cm) cases. A slightly down-shifted (1 MHz) spectrum was observed in the large gap plasma. The LH spectrum in the small gap plasma showed a similarity to that of the low density plasma ($n_e = 0.84 \times 10^{20}\,\mathrm{m}^{-3}$) with the large gap (1.2 cm) in the upper null configuration. In the bottom panel of Fig. 2, the pump broadening as a function of the inner gap is shown. There is a linear dependence of the spectral width on the inner gap distance, suggesting that there might be more relevant parameters, other than the line-averaged plasma density, that best represent the plasma conditions that favor the spectral broadening. For example, the X-mode reflectometry system [16] indicates that the magnitude of density in front of the LH launcher may be a important parameter. As shown in Fig. 3, the density profile of the small gap (0.01 cm) plasma at the density, $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$ is similar to that of the large gap (1.2 cm) plasma at the lower density, $n_e = 0.8 \times 10^{20}\,\mathrm{m}^{-3}$. In general, the lower density in front of the LH launcher reduces the effect of both the scattering and PDI.

3. Scattering Analysis

Most of the scattering process is expected to occur when LH waves traverse the SOL, where a large level (≈ 50%) of density fluctuations exists. Using the 2-D scattering model [10, 11], we calculate the spectral broadening to be on the order of 1 MHz by the scattering process in the SOL at the high density plasma ($n_e \approx 1.5 \times 10^{20}\,\mathrm{m}^{-3}$), based on the density profiles in front of the LH launcher and the typical spectrum of low frequency density fluctuations. This width approximately corresponds to the full-width at 5 dB below the maximum peak of the spectra shown in the top panel of Fig. 2. Based on this model, it is difficult to explain the pump broadening of more than 5 MHz by the scattering effect, unless the probe measures LH waves that are trapped in the SOL and affected by intensive scattering processes. In addition, the scattering process cannot easily explain the asymmetrical pump broadening.

4. PDI analysis

The purpose of PDI analysis is to look for decay channels via ion sound quasi-modes that could be responsible for spectral broadening. In Fig. 4, we show the solution of the real frequency (ω_R) and the growth rate (γ) of the ion sound quasi-mode normalized by ω_0 for the given wavenumber (k) of the low-frequency mode by solving the parametric dispersion relation based on the dipole approximation [13, 17]. We use typical plasma parameters in front of the LH launcher to find the most unstable mode. The relative angle (δ) between the perpendicular wave-vector of the lower side-band ($k_\perp^-$) and the perpendicular wave-vector of the pump wave ($k_{0\perp}$) is assumed to be 90°. We note that the frequency of the ion sound quasi-mode is on the order of 4.6 MHz ($\omega_R/\omega_0 \approx 1 \times 10^{-3}$) and $\gamma/\omega_0 \geq \omega_R/\omega_0$ in this range. In this particular case with $\delta = 90°$, the numerical results show that only the lower side-band is resonant, that can result in the asymmetrical broadening. To test whether PDI can cause the symmetrical pump broadening, we vary δ from 0° to 90° and calculate the real term of the dielectric function of the lower and upper side-band, as shown in Fig. 5. The lower side-band stays to be resonant regardless of δ, but the upper side-band becomes closer to the resonant condition only when $\delta \leq 20°$. The numerical calculation shows that the maximum growth rate and the corresponding real frequency of the ion sound quasi-mode is not sensitive to δ. As δ becomes smaller, the parallel motion of the electrons by parallel electric field of the pump wave becomes important [2] in determining the strength of the PDI. This type of coupling has the lower convective loss compared to the other type of the coupling driven by the $\vec{E} \times \vec{B}$ drift motion of electrons. Thus, if these modes can be sufficiently amplified, it may lead to large spectral broadening.

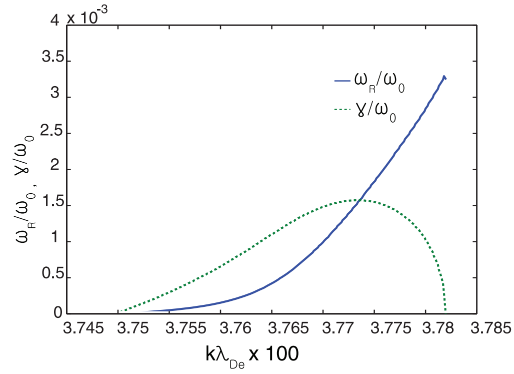

Fig. 4 Numerical solution of the parametric dispersion relation for ω_R/ω_0 and γ/ω_0. Parameters used are $n_e = 1 \times 10^{18}\,\mathrm{m}^{-3}$ (deuterium plasma), $T_e = T_i = 30\,\mathrm{eV}$, B = 4 T, $n_{e,WG} = 0.5 \times 10^{18}\,\mathrm{m}^{-3}$, $\omega_0/2\pi = 4.6\,\mathrm{GHz}$, and $P_{rf} = 100\,\mathrm{kW}$.

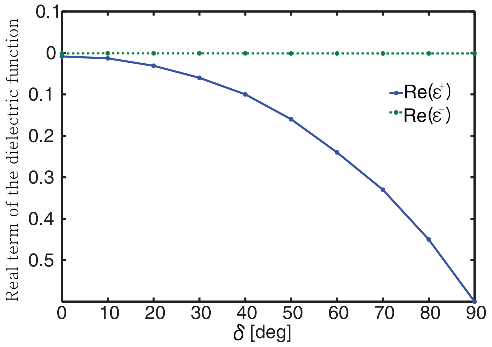

Fig. 5 The variation of the real term of the dielectric function for the lower side-band (ϵ^-) and upper side-band (ϵ^+) with respect to δ (the angle between $k_\perp^-$ and $k_{0\perp}$). Other plasma parameters are same as in the case of Fig. 4.

5. Discussion

Our observation shows that spectral broadening is minimized when the density in front of the LH launcher is lowered. In addition, we observed spectral broadening became severe when we observed the degradation of LHCD efficiency. It is difficult to link the degradation of the current drive efficiency to the power depletion of pump waves to the ion cyclotron bands, because the LH power available in the main lobe at $n_e = 1.35 \times 10^{20}\,\mathrm{m}^{-3}$ remains to be about 80 %, which should result in higher count rates of hard X-rays than observed. The other possibility is the change of the launched $N_\parallel$ spectrum by ion sound quasi-modes. It is reported [18] that the PDI driven by ion sound quasi-mode can redistribute the launched $N_\parallel$ spectrum, which can modify the driven current density profiles especially at higher densities, resulting in the degradation of the current drive efficiency. To obtain the modified $N_\parallel$ spectrum numerically, one needs to calculate the amplification factor that determines how much side-bands can grow. However, this step is not straightforward unless the structure of the pump wave field and the type of the coupling are known in advance. In the presence of the scattering effect in the SOL, this analysis can be further complicated because the propagation path can be perturbed. To address these issues, we plan to measure LH spectrum at different radial and toroidal locations.

Acknowledgements

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[1] G. Wallace, R. Parker, P. Bonoli, A. Hubbard, J. Hughes, B. LaBombard, O. Meneghini, A. Schmidt, S. Shiraiwa, D. Whyte, J. Wright, S. Wukitch, R. Harvey, A. Smirnov and J. Wilson, Phys. Plasmas **17**, 082508 (2010).
[2] Y. Takase, M. Porkolab, J. Schuss, R. Watterson, C. Fiore, R. Slusher and C. Surko, Phys. Fluids **28**, 983 (1985).
[3] R. Cesario and V. Pericoli-Ridolfini, Nucl. Fusion **27**, 435 (1987).
[4] R. Cesario and A. Cardinali, Nucl. Fusion **29**, 1709 (1989).
[5] R. Cesario, R. Bartiromo, A. Cardinali, F. Paoletti, V. Pericoli-Ridolfini and R. Schubert, Nucl. Fusion **32**, 2127 (1992).
[6] V. Pericoli-Ridolfini, R. Bartiromo, A. Tuccillo, F. Leuterer, F. Soldner, K. Steuer and S. Bernabei, Nucl. Fusion **32**, 286 (1992).
[7] V. Pericoli-Ridolfini, L. Giannone and R. Bartiromo, Nucl. Fusion **34**, 469 (1994).
[8] V. Pericoli-Ridolfini, G. Calabro, E. Giovannozzi, L. Panaccione and A. Tuccillo, 37th EPS Conf. on Plasma Physics **34A**, P5.176 (2010).
[9] R. Cesario, L. Amicucci, A. Cardinali, C. Castaldo, M. Marinucci, L. Panaccione, F. Santini, O. Tudisco, M. Apicella, G. Calabro *et al.*, Nature Communications **1**, 1 (2010).
[10] P. Andrews and F. Perkins, Phys. Fluids **26**, 2537 (1983).
[11] P. Andrews and F. Perkins, Phys. Fluids **26**, 2546 (1983).
[12] P. Bonoli and E. Ott, Phys. Fluids **25**, 359 (1982).
[13] M. Porkolab, Phys. Fluids **20**, 2058 (1977).
[14] R. Cesario, A. Cardinali, C. Castaldo, F. Paoletti, W. Fundamenski, S. Hacquin *et al.*, Nucl. Fusion **46**, 462 (2006).
[15] G. Wallace, A. Hubbard, P. Bonoli, R. Harvey, J. Hughes, B. LaBombard, O. Meneghini, R. Parker, A. Schmidt, S. Shiraiwa *et al.*, Nucl. Fusion **51**, 083032 (2011).
[16] C. Lau, G. Hanson, J. Wilgen, Y. Lin and S. Wukitch, Rev. Sci. Instrum. **81**, 10D918 (2010).
[17] Y. Takase and M. Porkoklab, Phys. Fluids **26**, 2992 (1983).
[18] R. Cesario, L. Amicucci, C. Castaldo, M. Kempernaars, S. Jachmich, J. Mailloux, O. Tudisco, A. Galli, A. Krivska and JET-EFDA contributors, Plasma Phy. Control. Fusion **53**, 085011 (2011).