OBSERVATION OF NONLINEAR COUPLING OF WAVES EXCITED AT DISTINCT REGIONS OF OVERLAPPING DUAL LOWER HYBRID AND ION CYCLOTRON RESONANCES

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This study shows the evidence of the non-linear coupling between waves in the lower hybrid (LH) and its harmonic frequency range excited spontaneously at spatially separated regions in a magnetically confined fusion-oriented (MCF) plasma with existence of energetic ions. (i) Semi periodic burst-like emissions of waves in LH frequency (f_0) and their harmonic frequency ranges accompanied by sidebands with two distinct ion cyclotron (IC) frequency range intervals f_1, and f_2 were observed. (ii) Bicoherence analysis revealed that LH and its harmonic range waves (lf_0) nonlinearly coupled with the sidebands ($mf_0 \pm nf_1$, $mf_0 \pm nf_2$) characterized by f_1 and f_2. (iii) Two spatially separated "dual resonances", namely DR1 and DR2 were identified in the main confinement region. The LH resonance (LHR) of f_0 overlaps with the ion cyclotron resonance (ICR) of f_1 at DR1 and the LHR of f_0 overlaps with the ICR of f_2 at DR2. This fact that waves, which can potentially contribute to the resonant heating of bulk ions, spontaneously grow nonlinearly due to the presence of high-energy ions and distinct spatially separated dual resonances, has a significant impact on exploring scenarios for sustaining fusion burning plasmas.

Understanding of the energy cascade process of energetic ions is an important issue for fusion plasma research. If we can find a scenario where fusion born α particles excite waves that resonantly heat bulk ions, efficient sustainment of the burning plasma can be expected. Nonlinear first-principles simulations demonstrated that stimulated fast Alfvén wave emission whose frequency is $18\omega_{c\alpha}$ caused by population inversion in the velocity space of fusion-born α particles enhance the externally applied weak fast Alfvén wave of $18\omega_{c\alpha}$ and increase the energy density of the thermal majority deuterons [1]. In large MCF plasmas, an analogous energetic ions population can be realized by neutral beam (NB) injection and suprathermal ion cyclotron emissions (ICEs) are detected up to higher harmonic bands. In addition to IC waves and their harmonics, waves in the LH frequency range have also been observed during the NB injection without injection of external radiofrequency waves [2] in the Large Helical Device (LHD). Since the α channeling with using the IC wave and the LH wave have been discussed, it is worth to study mechanisms how to interact these waves with energetic ions analogous to α particles.

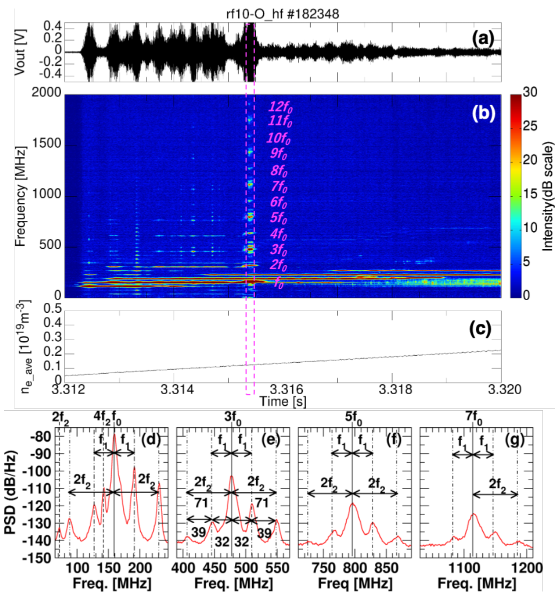

Figure 1. (a) The time evolution of the signal detected by dipole antenna, (b) The frequency spectrogram obtained by FFT analysis, (c) The time evolution of line averaged electron density, (d)-(g) The frequency spectra averaged during 3.31535 s ≦ t ≦ 3.31545 s

During the plasma start-up in the LHD with simultaneous injections of tangential NB and electron cyclotron (EC) waves, semi periodic burst-like emissions of waves in the LH frequency (100-200 MHz) and their harmonic frequency ranges accompanied with sidebands with frequency intervals of IC frequency range (30~40MHz) were observed as shown in Fig.1-(b). From t=3.300 s, the hydrogen NB was injected tangentially from the beam line 3 (BL3) with 164 keV/ 3.86MW and EC waves of 154 GHz were injected simultaneously with 2.0 MW in total. As the background plasma density increases, higher hydrogen IC harmonic frequency appears in order. In a previous simulation study [2], it was derived that the IC harmonic wave with $\omega \simeq l\omega_{ci}$, is excited when the lower hybrid wave with ω_{LH} approaches $l\omega_{ci}$ in the presence of energetic ions. However, the excitation of waves in the harmonic range of the LH frequency was not discussed there. The emissions in the harmonic range of the LH frequency only appeared during the periods when the detected electric field signal intensity burst. Here we focus on bursty emissions around t=3.3154 s. Panels (d)-(g) in Fig. 1 show that intense frequency peaks appear at multiples of f_0 = 159.167 MHz and intervals of the sidebands from lf_0 are 32 MHz, and 35.5*2=71 MHz. As shown in Fig.2, the auto-bicoherence analysis indicates that waves of lf_0 interact with $mf_0 \pm nf_1$, and $mf_0 \pm nf_2$, where f_1=32 MHz and f_2=35.5 MHz. The locations of LHR of f_0 = 159.17 MHz and ICRs of f_1=32 MHz, and f_2=35.5 MHz were examined with assuming a hollow density profile where the electron density is $0.028\times10^{19}\mathrm{m}^{-3}$ at the magnetic axis. We found that the LHR of f_0 = 159.17 MHz overlaps with the ICR of f_1=32 MHz at a poloidal cross-section 8 degrees away from the longitudinal cross-section namely dual resonance 1 (DR1). And the LHR of f_0 = 159.17 MHz also overlaps with the ICR of f_2=35.5 MHz at the longitudinal cross section, DR2. Note that $2f_2$ and $4f_2$ are detected as shown in Fig.1-(d). Considering that f_0 =159.17 MHz is nearly five times f_1=32 MHz, high-energy ions originating from the tangential beam can exist from the core to the peripheral region and are confined almost on the same magnetic surfaces under these experimental conditions. Based on simulation results in Ref. [3], the excitation of intense lower hybrid and cyclotron harmonic emissions can be expected in DR1.

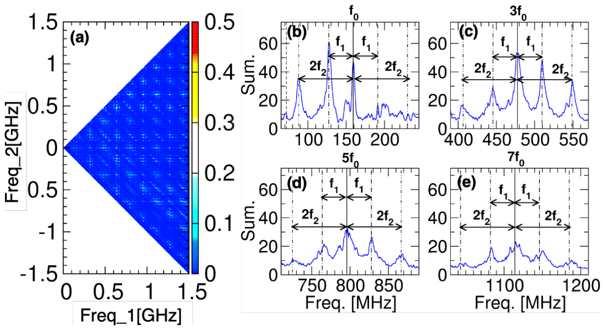

Figure 2.: (a)The auto bicoherence and (b)-(e) summed auto bicoherence.

The frequencies of the ICR that overlap with the LHR of 159.17 MHz can exist continuously in the torus. However, the condition where multiple regions of ICR with the same frequency overlap with the LHR at 159.17 MHz within the same poloidal cross-section occurs discretely as described in Fig. 3 (DR1/2 upper and lower). At this stage, this remains a hypothesis, but we consider that waves traveling between these DRs interfere with each other as summarized in Fig.4, leading to parametric oscillations described by equations such as the Mathieu equation or Hill equation, resulting in the nonlinear growth of the resonance frequency and its higher harmonics. To verify this hypothesis, both wave propagation analysis and analysis using a mathematical model of parametric excitation and are required.

This study demonstrated the potential to enhance the growth of waves at the LH frequency and its harmonics, as well as waves at the IC frequency and its harmonic frequencies, by establishing multiple dual resonances at distinct locations in the presence of energetic ions. This opens the possibility of exploring scenarios for bulk ion heating in fusion MCF plasmas through resonant heating induced by these spontaneously excited waves.

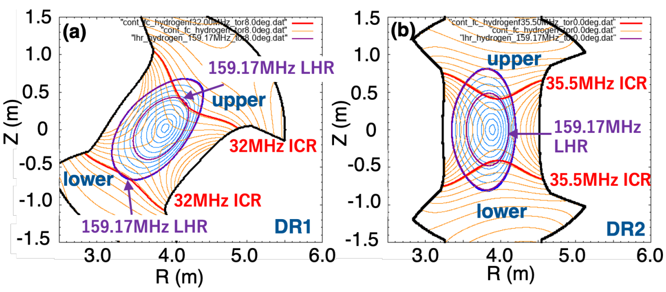

Figure 3.: Locations of the LHR of f_0 = 159.17 MHz overlapping with (a) the ICR of f_1=32 MHz, namely DR1 upper and lower, (b) the ion cyclotron resonance of f_2=35.5 MHz, namely DR2 upper and lower. The blue lines represent magnetic flux surfaces, while the orange lines represent magnetic field strength contours.

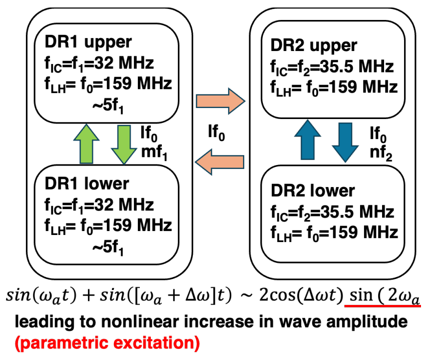

Figure 4: Possibility of periodic amplitude modulation at twice the resonant frequencies at each DR

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