LOWER HYBRID WAVE PROPAGATION IN TOKAMAK PLASMAS

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Lower Hybrid (LH) waves, first proposed for the purpose of ion heating in magnetic Fusion devices [1], are widely used at present for current drive in tokamaks. In spite of the fact that the current drive efficiency experimentally achieved in large machines is close to theoretical estimations, the physical picture of LH wave propagation and absorption in toroidal plasma systems is still far from been completed. In particular it is true in respect to the problem of LH wave number spectrum formation, which in the case of modest size tokamaks had got the name of "spectral gap" problem.

The present paper is devoted to experimental study of excitation and propagation of slowed down component of LH wave in tokamak plasma. A special Enhanced Scattering (ES) technique, sensitive to small-scale waves is used for this purpose [2]. The effect of microwave back scattering cross section enhancement in the Upper Hybrid Resonance (UHR) is utilised in this diagnostic. The spatial localisation of measurements is determined in ES diagnostic by position of backscattering point r_s, given by the relation $k_i(r_s) + k_s(r_s) \approx 2k_i(r_s) = q$, where k_i, k_s and q are wave numbers of incident, scattered waves and fluctuation under investigation, correspondingly. The spatial scan is performed in this technique by variation of incident frequency ω_i or magnetic field, where as the wave number resolution is achieved by application of time-of-flight measurement scheme [3], based on the effect of the scattering signal time delay in the UHR. The relation between the ES signal time delay and the density perturbation wave number q, reading as $t_d = 2\int_{r_0}^{r_s(q)} dr/V_g$, where r_0 is the position of diagnostic horns and V_g is the radial component of incident wave group velocity, was checked in numerous experiments in laboratory plasmas [4]. Unlike [3], where the ES diagnostics was used for investigation of LH wave linear and non-linear conversion in the LH resonance, under conditions when the wave – ion interaction is dominant, in the present paper propagation of a higher frequency wave, interacting with electrons is studied.

The experimental set up.

The experiment was carried out at FT-1 tokamak [5] (R = 62.5 cm, a = 15 cm, B_T = 1 T, I_p = 30 kA, $n_e(0) = 1.1\cdot 10^{13}$ cm^{-3}, $T_e(0)$ = 400 eV). The LH wave at frequency 935 MHz and power up to 30 kW was launched into the plasma by capacitively coupled loop antenna. The conditions of the LH experiment were usual for LH Current Drive (CD). Super thermal soft X-ray emission and increase of 1st harmonic ECE accompanied the RF pulse, which lasted from 2 to 5 ms. The microwave probing at frequency 28 GHz and power 15 W was performed both in the cross-section of LH antenna and opposite to it. (These cross-sections are mentioned below as LH and ES.) The X-mode emitting and receiving horn antennae were positioned at high magnetic field side of the torus. The emitting antenna in ES cross-section was up shifted in poloidal direction by 45°, where as all other antennae were situated in the equatorial plane. The amplitude modulation of the incident wave at frequency 10 MHz was utilised providing the possibility for measurements of both the scattered signal power and its time delay averaged in the 60 MHz frequency band. The phase delay measurement scheme with amplitude modulation was discussed in detail in [3]. The mean time delay of the scattered signal was determined using the value of the phase shift of its modulation in respect to the incident wave modulation. Dependencies of the frequency spectrum, power and time delay of the ES signal in the 60 MHz band on the toroidal magnetic field were studied in the experiment for both the down and up shifted spectrum components, corresponding to LH waves propagating correspondingly into and outside the plasma.

The experimental results and discussion.

The backscattered microwaves, both downshifted and upshifted by the LH wave frequency were observed in both diagnostics cross sections, however the maximal signal was measured at high toroidal magnetic field in LH cross section, when the scattering point is in the loop antenna vicinity. The downshifted scattering spectral component observed there is shown in Fig.1a. The typical feature of this spectrum is a narrow line, corresponding to the LH generator frequency. This line was observed only in the LH antenna vicinity. It was more pronounced in the downshifted component than in the upshifted. The line was not observable at lower magnetic field values, when the distance of 2 – 3 cm separated the UHR from the LH antenna. It was also not typical for the ES cross section, where the scattering spectrum was much broader (see Fig. 1b). The dependencies of downshifted scattering power and corresponding LH wave number q on the scattering radius, measured in the LH cross section are shown in Fig. 2a and 2b. As it is seen there, the signal was increasing towards the LH antenna, which is quite natural and was already observed in [3] for LH frequency 360 MHz. However, unlike [3], the growth was very steep, so that the maximal values of the signal and LH radial wave number were observed there. The values 200 – 400 cm^{-1}, measured near LH antenna, corresponding to radial wavelengths 0.015 – 0.03 cm, are only possible for Ion Bernstein waves directly excited at the LH antenna. Similar values were measured recently in [3] in the vicinity of LH

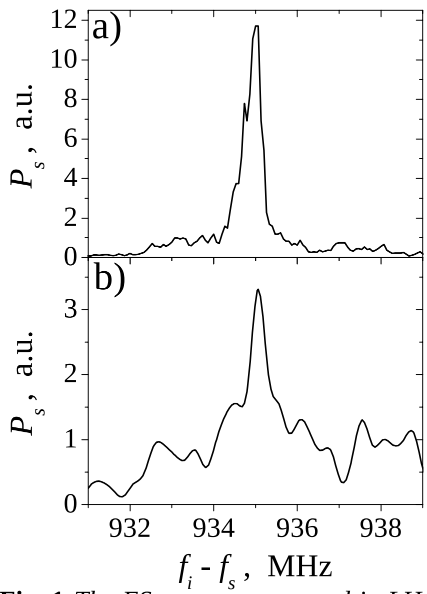

Fig. 1 *The ES spectra measured in LH (a) and ES (b) cross sections.*

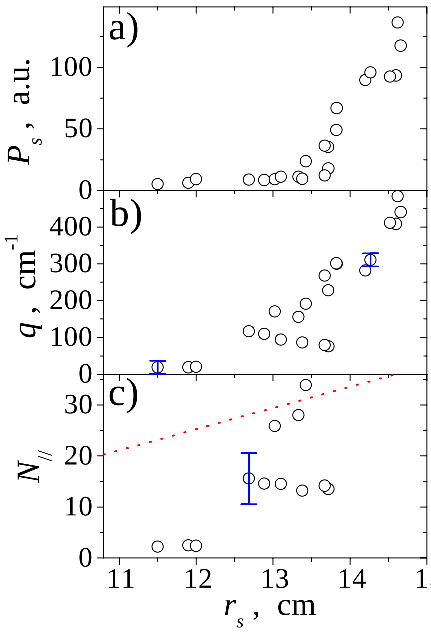

Fig. 2 *Dependence of ES signal power (a), wave number (b) and LH wave parallel refractive index (c) on scattering radius in the LH cross section.*

resonance, where linear conversion of LH wave into Ion Bernstein mode takes place. The wave number quickly decreases for UHR moving into the plasma. At distance 2 cm from limiter the typical radial wave number is smaller than 150 cm^{-1}. The parallel refractive index $N_{||}$ of these waves was estimated from experimental data using the LH wave dispersion relation $N_{||} \approx c/\omega_{pe}(r_s)$. Its dependence on the scattering point position is shown in Fig.2c. The dotted line there give the maximal possible value of $N_{||}$ at the Landau damping boarder $N_{||} = c/(3v_{Te})$, determined using T_e(r) profile [6]. As it is seen $N_{||}$ values in the edge plasma are high, close to the damping boundary. The supposition that such a high values of $N_{||}$ are caused by overestimation of radial wave number due to the input of the Ion Bernstein waves is not confirmed by observations in the ES cross section. When moving inward the plasma the $N_{||}$ value decreases, reaching the level $N_{||} = 2.5 \div 4.5$ at $r_s = 12$ cm. It should be mentioned that the relative procedural error of $N_{||}$ estimation from experimental data is rather high $\delta N_{||} \approx 5$. The scattering signal and radial wave number, measured far from the antenna in the LH cross section, are growing with the central plasma density (see Fig.3a, b), probably due to decrease of the distance between the UHR and the antenna. Because of the same reason the signal and wave number in the beginning of the RF pulse, accompanied by the density growth, were higher than in the end. (Squares and circles in Fig.3 correspond to beginning and end of RF pulse.) The amplitude of upshifted spectrum component is lower than that of the downshifted, corresponding to the inward energy flow. Its typical wave numbers are smaller.

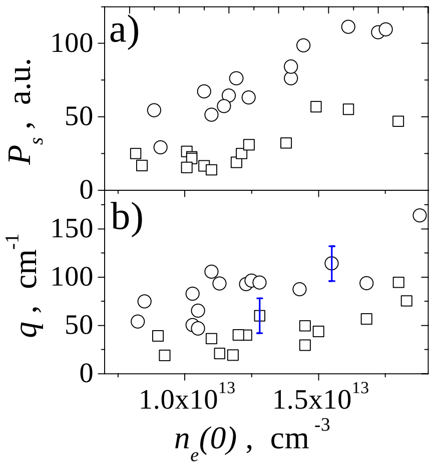

Fig. 3 *Dependence of ES signal power (a) and wave number (b) on central density in the LH cross section.*

The dependencies of ES signal amplitude and time delay on the scattering radius are different in the ES cross section. Neither growth of the signal was observed at small densities, nor any small-scale Ion Bernstein waves were seen there (Fig.4a, b). The broader spectra were measured there at intensity a factor of 5 lower, than that at the LH antenna. The radial wave number q variation from 150 cm^{-1} to 20 cm^{-1}, observed for decreasing r_s, (see

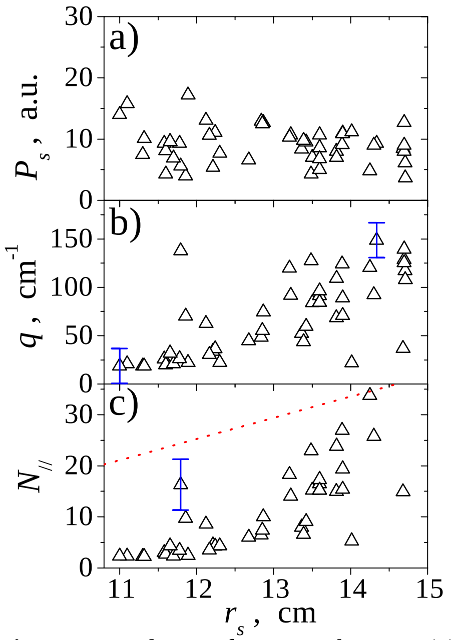

Fig. 4 *Dependence of ES signal power (a), wave number (b) and LH wave parallel refractive index (c) on scattering radius in the ES cross section.*

Fig.4b) is opposite to the standard behaviour one can foresee using the LH dispersion relation at constant $N_{||}$. It can be explained supposing that high $N_{||}$ LH waves are generated in the edge plasma and then absorbed, when propagating inward, due to increase of Landau damping with growing electron temperature. The reason for high $N_{||}$ production is probably associated with LH wave scattering off the tokamak density turbulence and toroidal ripple of magnetic surface, strong in the plasma edge. These mechanisms were discussed as candidates for the "spectral gap" filling in [7, 8]. The $N_{||}$ dependence on r_s calculated from the experimental data and the damping boundary $c/(3v_{Te})$, are shown in Fig. 4c. It should be mentioned that the values of LH wave parallel phase velocity, estimated in the present experiment, are low in the edge plasma, providing possibility of strong coupling of LH waves to the electron component.

Conclusions.

The ES measurements at the FT-1 tokamak have shown that small-scale LH waves, possessing high parallel refractive index $10 < N_{||} < 20$, are produced at the plasma edge in the RF heating experiment performed in the LH CD regime. These waves have been observed at a distance less than 2 cm from the limiter both near the RF antenna and in the poloidal cross section shifted from it by 180°. In the inner part of the discharge the faster LH wave component, possessing $N_{||} < 10$ was measured. Simultaneously excitation of fine scale Ion Bernstein waves was observed in the RF antenna vicinity.

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