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Investigation of slowed down Lower Hybrid waves in RF Heating and Current Drive experiments at FT-2 tokamak

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1. Introduction.

In spite of the fact that the current drive by lower hybrid (LH) waves is widely used in different size tokamaks, 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 localization of LH driven current and related 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 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 [1]. 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 $k_i(r_s) + k_s(r_s) = q$, 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 [2,3], based on the effect of the scattering signal time delay in the UHR. The relation between the ES signal time delay and the fluctuation 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 [3]. The time-of-flight ES measurement scheme was used at FT-1 tokamak for investigation of LH wave linear and non-linear conversion in the LH resonance, under conditions when the wave – ion interaction is

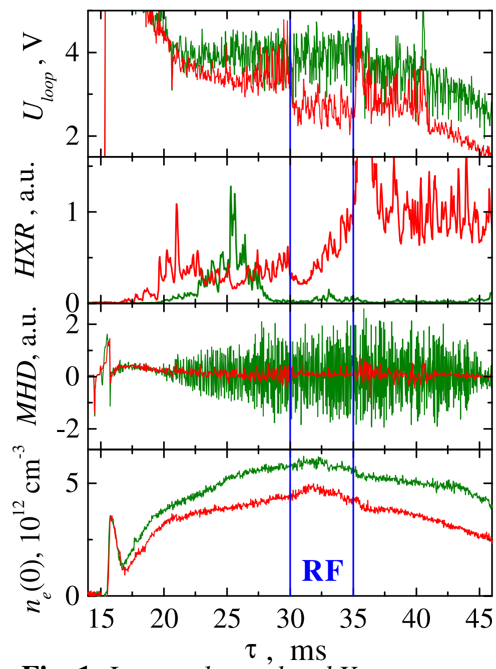

Fig. 1. *Loop voltage, hard X-ray signal, MHD signal and density.*

dominant [2,4]. Recently it was also utilized at FT-1 for study of excitation and propagation of a higher frequency wave, interacting with electrons [5]. These investigations are continued now at the FT-2 tokamak possessing a wider set of standard tokamak diagnostics and a grill LH launching system.

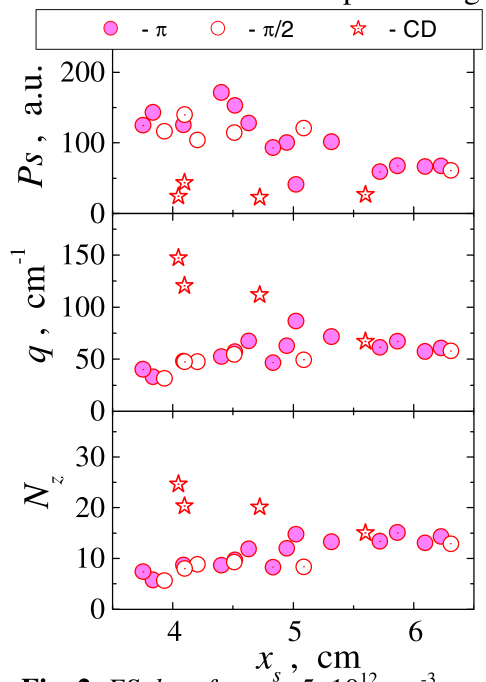

Fig. 2. *ES data for* $n_e \approx 5 \cdot 10^{12}$ cm^{-3}.

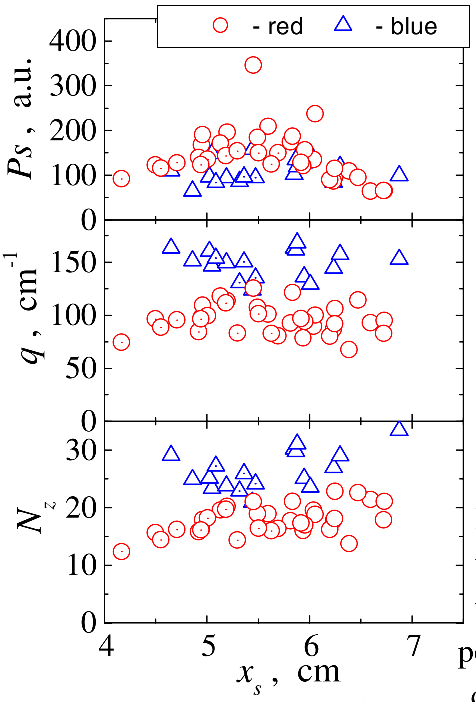

Fig. 3. *ES data for* $n_e < 10^{13}$ cm^{-3}.

2. Experimental situation.

The time-of-flight enhanced scattering diagnostics scheme [2] is assembled at the FT-2 tokamak possessing major radius R = 55 cm, minor radius a = 8 cm. The experiment was performed in low magnetic field discharges $B_T \approx (0.9 \div 1.1$ T) and at plasma current, $I_p \approx (13 \div 20)$ kA. The electron density was varied in the range $n_e(0) \approx (0.5 \div 2.2) \cdot 10^{13}$ cm^{-3} and central temperature was $T_e(0) \approx 300$ eV. LH power in the range 30-100 kW at frequency 918 MHz was launched into plasma by two-waveguide grill, allowing the phasing variation.

The microwave probing at frequency 28 GHz and power 20 W was performed in the cross-section shifted by 90° from the LH grill in toroidal direction. The X-mode emitting and receiving horn antennae were positioned at high magnetic field side of the torus 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 [2,4]. The mean time delay of the scattered signal was determined using 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 and thus on the scattering point position were studied in the experiment for both the down-shifted (red) and up-shifted (blue) spectrum components, corresponding to LH waves propagating correspondingly into and outside the plasma. Measurements were taken at different LH power level, grill phasing and plasma density.

3. Experimental results and discussion.

Wave forms of loop voltage, hard X-ray signal, MHD signal and line average density are shown in fig.1 for two typical discharges possessing central density $n_e(0) \approx 5 \cdot 10^{12}$ cm^{-3}.

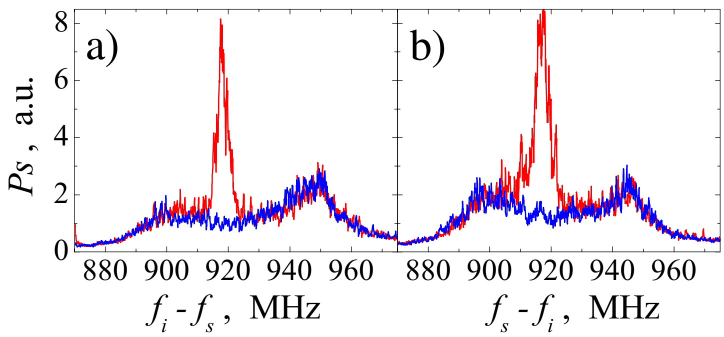

Fig. 4. *ES spectra for down- and up-shifted satellites.*

In the first of them shown by green lines the density was slightly higher, HXR emission before and during RF pulse was low and no influence of LH power on the loop voltage was observed. The ES data versus scattering point radius for this discharge is shown in fig.2 for down-shifted satellite and grill phasing π and $\pi/2$. As it is seen in fig.2, the scattering signal P_s , measured at 30 kW LH power incidence, is growing in the inward direction by a factor of 3, whereas the radial wave number q and calculated parallel refractive index N_z are decreasing from 75 cm^{-1} to 25 cm^{-1} and from 15 to 5 correspondingly, when the scattering point is shifted from r_s=6 cm to r_s=4 cm. This behavior is explained by approaching of the scattering point the LH resonance cone which should be situated according to ray tracing at r_s=4 cm. In the vicinity of the resonance cone the amplitude of LH wave grows and the role of the long scale LH waves originally excited by grill increases, thus leading to decrease of the wavenumber q. Another possible reason for average refractive index decrease is Landau damping of small scale LH wave component, which increases with growing electron temperature. It should be mentioned that variation of the grill phasing make no pronounced influence on the radial wave number and parallel refractive index. In the case of discharges possessing slightly lower density, shown in fig.1 by red wave forms, from the early stage the HXR radiation was higher and the loop voltage was lower than in the case discussed above that indicate the role of run away electrons. In these discharges evident decrease of loop voltage was observed during RF pulse, which was accompanied by suppression of MHD signal thus giving indication of LH wave interaction with electrons and LHCD. It is worth to point out that ES signal in these type of discharges was suppressed by an order of magnitude, whereas the radial wave number in the inner plasma region was up to 3 times higher. Possible explanation of these effects is related to enhanced absorption of fast LH waves in the region N_z<10, due to electron plateau formation. After suppression of these waves, which made the dominant contribution to the signal amplitude and average wave number in the first type of discharge, the relative input of minor RF wave component associated with small scale ion Bernstein waves or non-resonant oscillations at LH frequency, underlined by ES technique cross section maximum, increases leading to the wave number growth. The important feature of low density discharges $n_e(0)$ <10^{13} cm^{-3} is higher amplitude of down shifted ES signal component corresponding to inward propagating LH wave, observed in the vicinity of the resonant cone, compared to the up-shifted one (see

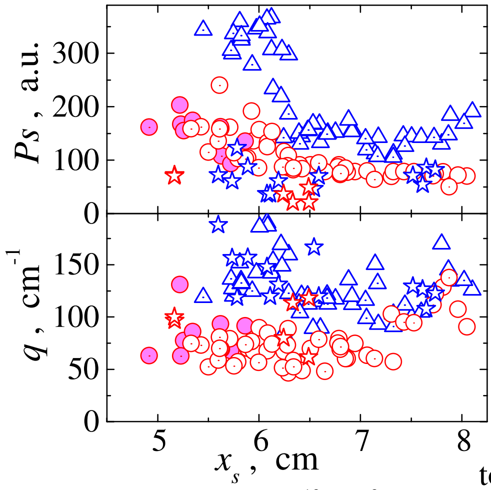

Fig. 5. *ES data for n_e* > 10^{13} cm^{-3}.

fig.3). The average wave number obtained for up-shifted component, propagating from the resonance cone region to the edge, q=150 cm^{-1} is a factor of 1.5 higher. It is not possible to attribute this value to LH wave because of its strong damping, it is rather related to small-scale ion Bernstein waves radiated from the cone or non-resonant oscillations at LH frequency. The spectrum width of up-shifted component shown in fig.4b is larger than that of down shifted in fig.4a probably due to more complicated propagation in plasma. As it is seen in fig.5, at higher plasma density $n_e(0)$ >10^{13} cm^{-3} the amplitude of both components is growing in the LH cone direction. However not only the wave number of up-shifted ES spectrum component but also its amplitude becomes larger than that of down shifted. The spectra of both components become more complicated. In addition to the line corresponding to LH frequency, lines shifted by the ion cyclotron harmonics appear in the spectrum in fig.6a indicating excitation of parametric decay instability. Simultaneously these additional lines appear in the spectrum measured by RF probe at the limiter. At growing RF power the onset of parametric decay became even more pronounced both in ES and RF probe measurements. However it was observable only at the low field side of plasma (green curve on fig.6b), whereas at the high magnetic field side only the LH line was seen by RF probe (blue curve on fig.6b). The typical wave number of the decay satellite, estimated by ES technique at RF power 100 kW appeared to be comparable to that measured for LH wave.

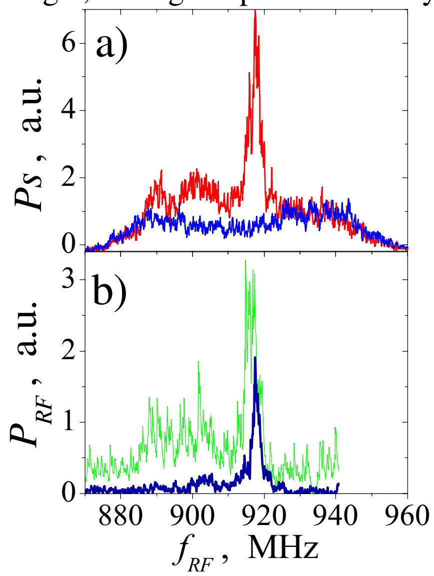

Fig. 6. *ES (a) (noise level – blue curve) and RF (b) probe spectra.*

4. Conclusions.

In conclusions we would like to stress that expectations of linear theory concerning propagation of LH waves in tokamak plasma were confirmed in our experiment only in the case of low density and low RF power P_{RF}<30 kW. However even at these modest experimental parameters no influence of the grill phasing on the LH wave number spectrum was observed. At high heating power and plasma density the LH wave pattern in tokamak plasma was very different from that predicted by theory.

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