OBSERVATIONS OF THE TIME DELAY OF THE SIGNAL BACKSCATTERED IN THE UPPER HYBRID RESONANCE IN THE FT-1 TOKAMAK

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The microwave backscattering effect in the vicinity of the Upper Hybrid Resonance (UHR), so called Enhanced Scattering (ES), was widely used during the last decade for diagnostics of small scale waves and fluctuations in magnetized plasmas [1]. Enhancement of scattering cross-section caused by the probing and scattering wave electric field increases in the vicinity of the UHR, as well as good measurement localization and possibility to measure simultaneously scattering signals produced by fluctuations with different spatial scales are among the merits of this diagnostics. The poor wavenumber resolution related to the wide variation of the incident wavenumber in the UHR for a long time was its main drawback. The time of flight modification of ES diagnostics, based on the linear dependence of the backscattered signal time delay on the fluctuation wavenumber, was proposed recently [2] to deal with this drawback.

According to theory [2], the time delay of the signal backscattered in the UHR is given by

$$t_d = \frac{2\omega_i q}{\left| \frac{\partial \omega_{pe}^2}{\partial x} + \frac{\partial \omega_{ce}^2}{\partial x} \right|} \qquad (1)$$

where ω_i is the incident wave frequency and q is the fluctuation wavenumber component in the inhomogeniety direction.

The first observations of ES signal time delay in the tokamak plasma are reported in the present paper. The experiments were carried out on the FT-1 tokamak in two regimes with typical parameters B = 1 T, I_p = 5 kA, $n_e(0)$ = 4*10^{12} cm^{-3} and B = 1 T, I_p = 30 kA, $n_e(0)$ = 9* 10^{12} cm^{-3}, which are mentioned below as 5 kA and 30 kA discharges. In the first one plasma is not completely ionized, where as the second one is usual tokamak ohmic discharge with central electron temperature T_e = 400 eV [3]. The geometrical parameters of the tokamak are R = 62 cm, a = 15 cm. A set of electromagnetic diagnostics and 4-channel interferometer was used in the experiment. The lower hybrid (LH) wave launched into the plasma at frequency f_{LH} = 360 MHz and power up to 35 kW was used as a test wave providing backscattering in the UHR. The LH antenna was situated on the low magnetic field side of the torus in the limiter shadow. Two couples of X-mode microwave antennae, emitting and receiving, were situated in the equatorial plane of the torus at the high magnetic field side. The first couple possessing angular width of the pattern ± 20° was positioned in the LH antenna poloidal cross-section, where as the second one was shifted by 180° in toroidal direction. The angular width of these antennae pattern was ± 10°. The probing was performed by X-mode at frequency 27.6 GHz and power 50 W, produced by TWA with amplification width ~1GHz. The amplitude modulation of the incident wave at frequency 10 MHz was used. The time delay of the scattered signal was determined from the value of the phase shift of its modulation in respect to the incident wave. The superheterodyne scheme was used for analysis of the scattered signal, down shifted by 360 MHz from the probing frequency. Both the spectrum and AM phase delay of the signal in the 60 MHz band was studied. For the last purpose the quadratic detection of the signal was performed and the phase of 10 MHz oscillations of the scattered signal was measured using the phase detection scheme. The 1 kHz phase inverter of the 10 MHz signal used for control of AM microwave modulator was utilized to make the phase detector measurements easier. The tunable phase output of the 10 MHz oscillator provided a reference signal, used for calibration of the scheme during which the signal in the "sin" channel-S was put equal to zero. The calibration was performed at low magnetic field $B \leq 0.75$ T, in the reflectometer mode of operation, when the UHR was inaccessible for the X-mode.

In the case of 5 kA discharge the spectrum of scattering signal measured in the LH antenna cross-section consisted of several equidistant lines which correspond to the LH wave and satellites at smaller frequencies excited in plasma by parametric instability (Fig.1*a*). The line down shifted by 360 MHz from the probing one produced by LH pump wave was moved out of the filter and is observed as a small pike in the left part of the Fig.1*a*. The phase traces corresponding to Fig. 1*a* are shown in Fig.1*b*, where one can easily see the 1 kHz modulation in both channels. The phase delay determined from this modulation is higher than $\pi / 4$, that corresponds to $t_d \geq 10$ ns. The pronounced variation of both the scattered signal and its phase delay are due to density and magnetic field changes during the RF pulse, which resulted in a spatial scan of the UHR in accordance with condition $\omega_{pe}^2 + \omega_{ce}^2 = \omega_i^2$. The dependencies of scattering signal power and time delay on the density in the UHR is shown in Fig. 1*c* and 1*d*. The density scan there was performed via toroidal magnetic field variation from discharge to discharge. The maximum in the $P_S\,(n_{UH}\,)$ distribution is situated close to the LH resonance position for frequency 300 MHz, central for the filter characteristics - $n_{LH} \cong 3.2 \cdot 10^{12}$ cm^{-3}. A factor of 3 increase of time delay from $t_d = 6$ ns to $t_d = 18$ ns observed for density changing from $1 \cdot 10^{12}$ cm^{-3} to $4 \cdot 10^{12}$ cm^{-3} could be partly explained by diminishing of density gradient in the central part of the discharge and probably also related to the approaching of the LH resonance by parametric decay satellites. The LH wavenumber obtained from Fig.1*d* with the aid of Eq. (1), where *dn/dr* was taken from the experimental density profile, is $K_{\perp max} = 50 \div 70$ cm^{-1}. The LH wavelength parallel to the magnetic field determined from Fig. 1*d* with the help of dispersion relation $\lambda_{II} = \sqrt{\frac{\varepsilon}{\eta}}\lambda_{\perp}$ is estimated as 10 cm.

In the 30 kA discharge unlike the previous case the backscattering spectrum consists of a single broad satellite, 2 ÷ 5 MHz width, downshifted from the probing wave frequency by 360 MHz (see Fig.2*a*). The phase traces for this scattering signal are shown in Fig. 2*b*. The robust variation of the signal amplitude and phase delay during the RF pulse is typical for this signal. It is explained by a factor of 1.5 increase of the electron density accompanied by a shift of the UHR position. The phase delays up to $\varphi_d = \pi$ are observed in the experiment. Dependencies $P_S\ (n_{UH})$ and $t_d\ (n_{UH})$ are shown in Fig. 2*c*,*d*, where open circles correspond to the beginning of RF pulse and solid - to the end. Both curves demonstrate a very steep increase for densities $2{*}10^{12} < n_e < 3.5{*}10^{12}$ cm^{-3}. The growth of $P_S\ (n_{UH})$ saturates after a factor of 4.5 increase where as the time delay than decreases from 35 ÷ 45 ns to the level of 15 ÷ 20 ns for $n_{UH} = 5.5{*}10^{12}$ cm^{-3}. The maximum time delay $t_d \approx 30$ ns, observed in the beginning of RF pulse, when the density profile was measured, corresponds to $K_{\perp} \approx 3.3{*}10^2$ cm^{-1} , which is only possible for ion Bernstein waves. In the density region $3{*}10^{12} \div 3.5{*}10^{12}$ cm^{-3} they could be converted from LH waves possessing high parallel refractive index $N_{//} \geq 10$. This waves should be heavily damped when propagate into the warm plasma column, thus in the higher density region the scattered signal should be produced by LH waves possessing much smaller $N_{//}$ and smaller $K_{\perp}$.

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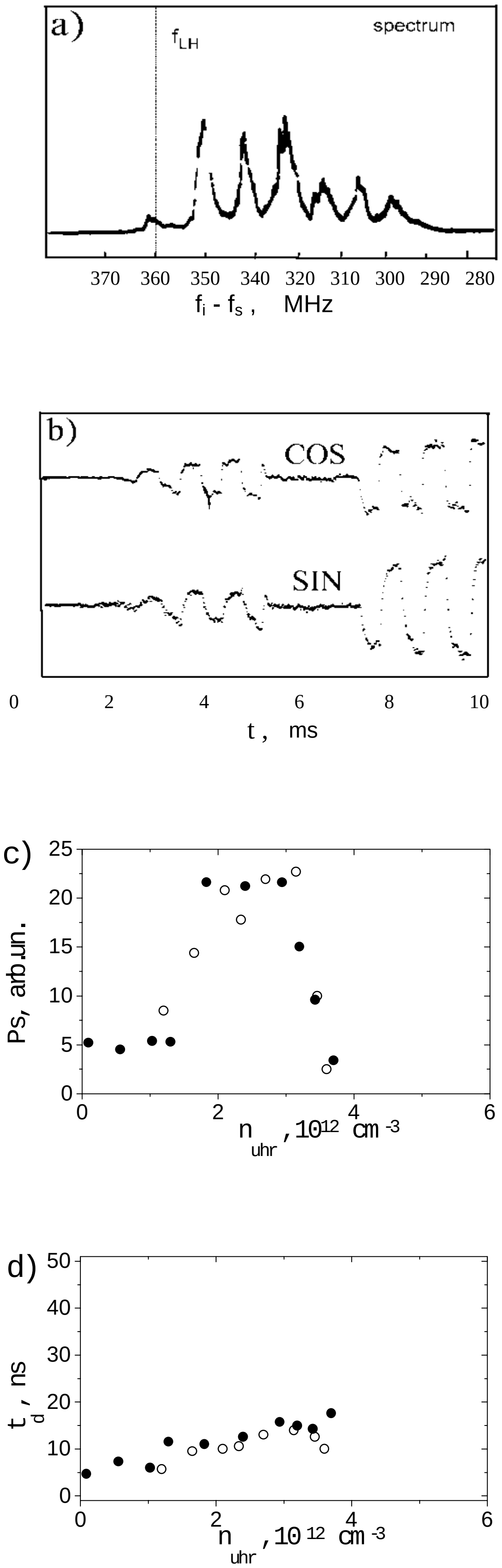

Fig. 1. ES in the low current discharge: a) scattering spectrum for B = 0.91 T; b) phase detector traces; c) dependence of ES power on density in the UHR; d) dependence of ES signal time delay on density in the UHR.

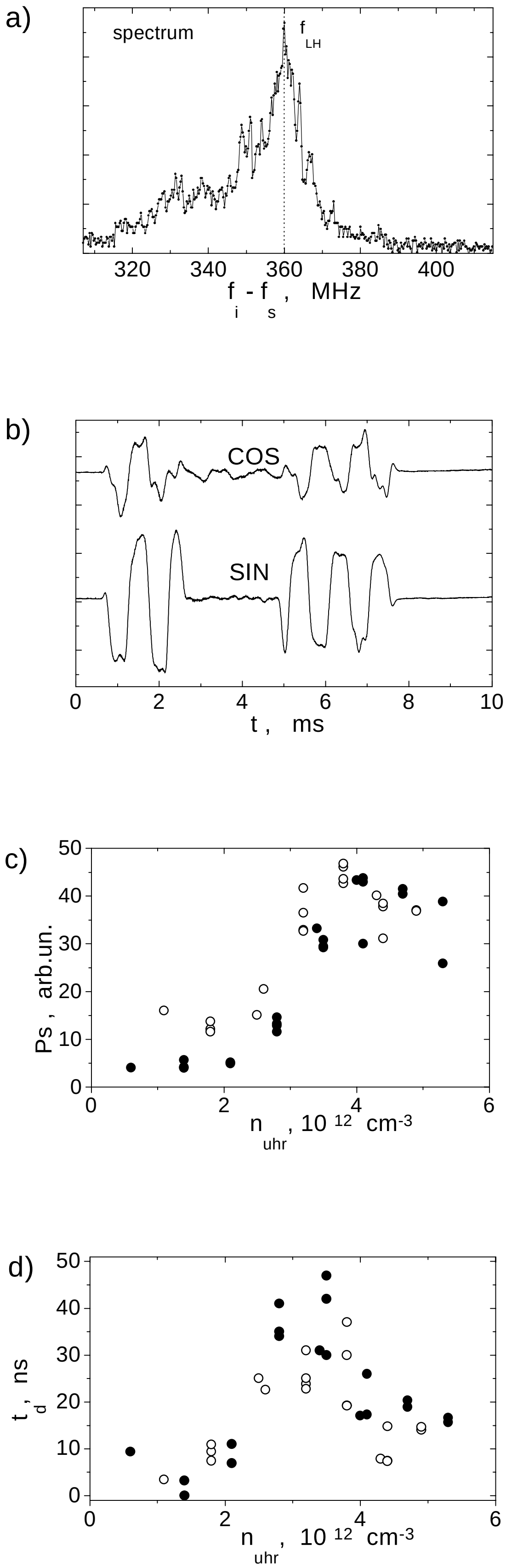

Fig. 2. ES in the high current discharge: a) scattering spectrum for B = 0.96 T; b) phase detector traces; c) dependence of ES power on density in the UHR; d) dependence of ES signal time delay on density in the UHR.