Observation of Enhanced Doppler Effect in the Upper Hybrid Resonance Backscattering Experiment at the FT-2 Tokamak

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Introduction.
The Doppler frequency shift of Back Scattering (BS) signal at oblique microwave plasma probing is often used for diagnosing of poloidal plasma velocity in magnetic fusion devices. The typical value of frequency shift of BS microwave of several hundred kHz in these diagnostics is usually substantially smaller than its broadening [1-3], which complicates interpretation and reduce the accuracy of measurements.

In the present paper an alternative approach to microwave diagnostics of plasma poloidal rotation in toroidal devices, based on the Upper Hybrid Resonance (UHR) BS is introduced. The UHR BS or enhanced scattering [4] utilizes for local diagnostics of small-scale plasma fluctuations the growth of wave vector and electric field of the probing extraordinary wave in the UHR, where condition $\omega^2 = \omega_{pe}^2 + \omega_{ce}^2$ is fulfilled for the probing frequency. This technique is only sensitive to the fluctuations possessing wavelength smaller than half probing wavelength. The scattering cross section of the UHR BS experiences very sharp maximum at the fluctuation wave number

$$q = 2k_{conv} \equiv 2\left(\frac{\omega_{ce}}{c}\right)\sqrt{c/v_{te}},$$

which corresponds to BS in the linear conversion point [4]. According to [5], in toroidal devices, where the UHR and magnetic surfaces do not coincide due to dependence of magnetic field on the major radius $R$, the large probing wave vector $k_y$ perpendicular to the UHR surface, has a finite projection onto the poloidal direction, given by relation

$$k_0 \approx k_y \frac{y}{r} \left(\frac{2\omega_{ce}^2 L_n}{\omega_{pe}^2 R_{UHR}}\right),$$

where $y$ and $r$ are a vertical displacement from the equatorial plane and minor radius of BS point at the UHR surface, correspondingly, $L_n$ is the density scale length. This projection, which can be much bigger than the poloidal component of wave vector at the antenna, can lead to substantial enhancement of the Doppler frequency shift of the microwave BS off fluctuations moving with poloidal plasma flow. The frequency shift corresponding to the BS cross section maximum, according to (1) and (2), is given by:
Experimental results and discussion.

In this paper the first observations of this giant Doppler frequency shift effect of the highly localized microwave BS in the UHR are reported. The experiment is performed at the FT-2 tokamak ($R = 55 \text{ cm}$, $a = 8 \text{ cm}$, $B_t \approx 2.2 \text{ T}$, $I_p \approx 23 \text{ kA}$, $T_e(0) \approx 500 \text{ eV}$, $n_e(0) < 4 \times 10^{13} \text{ cm}^{-3}$), where a new stirrable focusing double antennae set, shown in fig. 1, allowing off equatorial plane plasma X-mode probing from high magnetic field side, was installed. The maximal vertical displacement of antennae is $\pm 2 \text{ cm}$, whereas the diameter of the wave beam at the position of UHR, as measured in vacuum is $1.5 - 1.7 \text{ cm}$, depending on the probing frequency. The probing is performed in the frequency range 53 - 69 GHz at power level of 20 mW. The coupling of emitting and receiving antennae is less than 40 dB. The UHR position is scanned from 4 cm to 8 cm by the probing frequency variation. The BS signal is analyzed with quadrature scheme, shown in fig. 2, which allows measurements of BS spectra, as well as determination of BS signal phase and amplitude. Just after the new antennae set installation a separate line less than 1.5 MHz wide and shifted by up to 2 MHz became routinely observable in the BS spectrum under condition of accessible UHR. The BS spectrum possessing the highest (2 MHz) shift, observed at $2 \text{ cm}$...
antenna vertical displacement, is shown in fig.3a. The amplitude of BS line there is higher than for the probing line because of enhancement of scattering cross section and small coupling of antennae horns. The ratio of the line frequency shift and broadening is larger than unity, which allows reliable determination of shift with high accuracy. The BS spectrum observed in equatorial plane and possessing no shift is shown in fig.3b. For comparison the BS spectra observed with the same antenna set, shifted by 2 cm from equatorial plane, under conditions when the UHR is not accessible is shown in fig.3c. This spectrum, which in fact corresponds to Doppler reflectometry with tilting angle of 15°, is only slightly shifted. The shift can be estimated with poor accuracy at the level of 100 kHz. The line frequency shift proportionality to the vertical displacement of BS point is confirmed in a special experiment in which the antennae shift from the equatorial plane was varied from discharge to discharge (see fig.4a). As it is seen the frequency shift of the BS satellite changes sign, when the antennae set crosses the equatorial plane. It appears also in fig.4b that the BS line broadening, which is approximately constant at small vertical displacement, grows at extreme values. Different symbols in fig.4 correspond to different moments of the discharge and thus to slightly different UHR position. The UHR BS satellite frequency shift is shown to be strongly dependent on the probing frequency and thus on the UHR position. The corresponding dependence of poloidal rotation velocity on radius determined using formula (4) is shown

\[ f_s - f_p, \text{ MHz} \]

**Fig.3.** UHR (a, b) and X-mode Doppler reflectometry (c) BS spectra.

**Fig.4.** Spectra Doppler shift and broadening.
in fig.5. As it is seen, the poloidal velocity is negative in the edge region, which is probably associated with plasma drift in positive radial electric field. The velocity changes sign in the vicinity of LCFS. In the inner plasma region the poloidal velocity is positive, whereas the corresponding radial electric field should be negative. This sign, as well as the velocity value of 4 km/s is in agreement with expectations of neoclassical theory and do not disagree with the poloidal velocity, measured recently by spectroscopic method at the FT-2 tokamak.

Conclusions.
The giant Doppler frequency shift is routinely observed in the off equatorial plane UHR BS experiment at FT-2 tokamak in agreement with theoretical predictions. The enhancement of the BS signal frequency shift is explained by growth of poloidal wave number of probing wave in the UHR, which should occur in toroidal devises, where the UHR and magnetic surfaces do not coincide and thus giant UHR wave vector, which is perpendicular to the UHR surface, have a big projection onto poloidal direction. The poloidal plasma velocity estimated from the frequency shift agrees with the neoclassical theory expectations. The found robust effect has a potential for development of a high resolution scheme for local diagnostics of poloidal rotation in tokamaks and stellarators.

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