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# Application of the Upper Hybrid Resonance Back Scattering Enhanced Doppler Effect for Plasma Rotation Diagnostic at FT-2 Tokamak

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Inhomogeneous plasma rotation, according to the present day understanding, can play a substantial role in energy confinement in toroidal plasmas, suppressing drift micro turbulence and thus reducing anomalous heat and particle fluxes. 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 the "Doppler reflectometry" diagnostics based upon this effect is usually substantially smaller than its broadening, which complicates interpretation and reduce the accuracy of measurements. Recently a possibility of a drastic increase of the Doppler frequency shift of microwave BS signal in toroidal devices, based on the Upper Hybrid Resonance (UHR) BS was demonstrated experimentally [1]. The microwave BS experiment

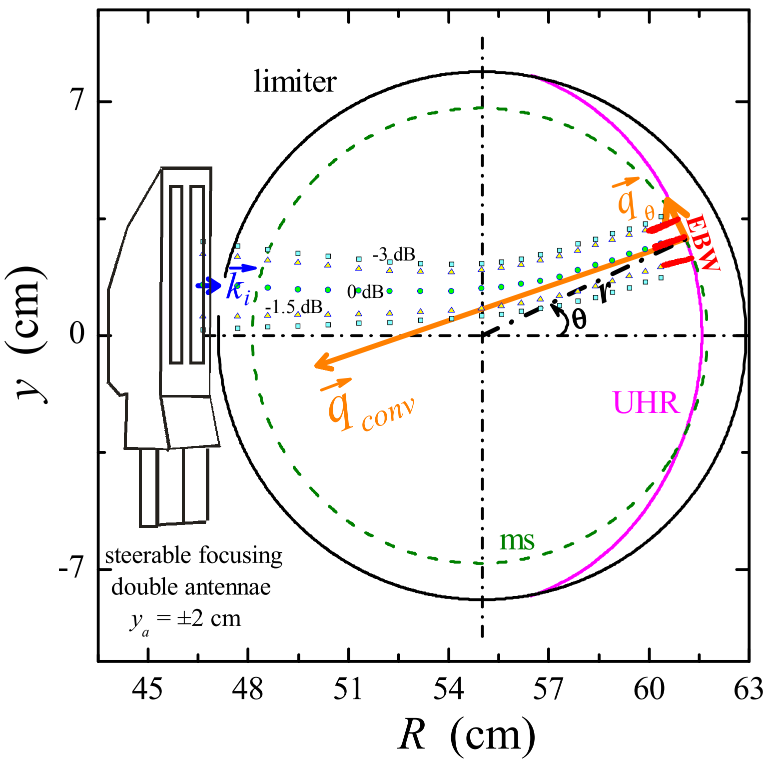


**Fig.1.** *Poloidal FT-2 tokamak cross section with antennae set. $\vec{k}_i$ – incident wave vector (blue), $\vec{q}_{conv}$ and $\vec{q}_\theta$ – fluctuation wave vector at BS efficiency maximum and it's poloidal projection (both orange), circles – central ray of the probing beam, triangles and squares – probing beam at 1.5 dB and 3 dB power suppression levels, ms – magnetic surface (green), red curves – Electron Berstein Waves (EBW) at 0 dB and 1.5 dB power suppression levels.*

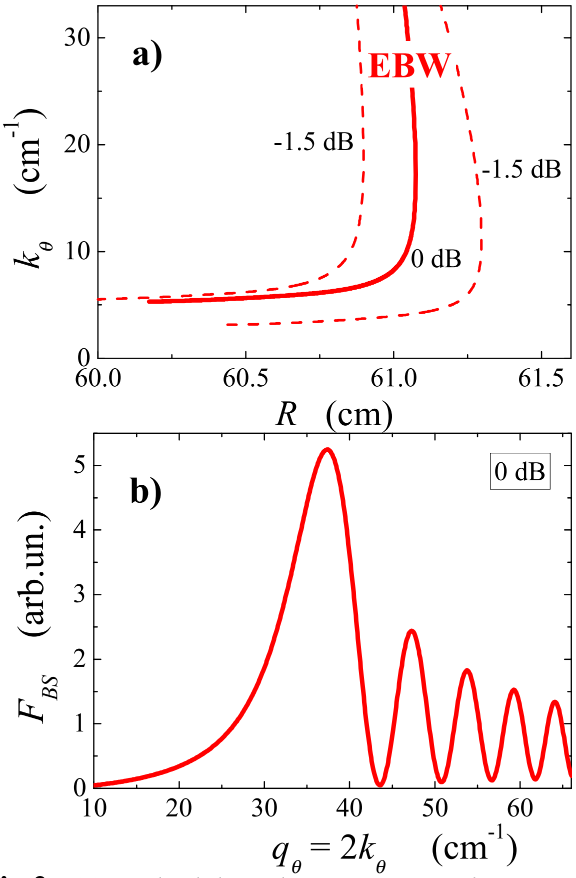


**Fig.2. (a)** *Poloidal probing wave number near UHR,* **(b)** *BS efficiency for central probing ray.*

was performed at FT-2 tokamak with a new steerable focusing double antennae set, allowing off equatorial plane plasma X-mode probing from high magnetic field side. The spatial distribution of the focused probing beam, computed using the beam tracing code [2], is shown in Fig. 1. The maximal vertical displacement of antennae center is $y_a = \pm 2$ cm, whereas the diameter of the wave beam at the position of UHR, where the probing frequency satisfies condition $f_i^2 = f_{ce}^2(R) + f_{pe}^2(r)$, as computed by the code, was close to the values measured in vacuum (1.5 – 1.7 cm, depending on the probing frequency in the range 52 – 69 GHz). According to theoretical predictions [1, 3] and computations shown in Fig. 2a, the probing poloidal wave number grows rapidly in the vicinity of the UHR linear conversion point, where the BS cross section $F_{BS}(q_\theta)$ possesses sharp maximum, as demonstrated in Fig. 2b. This projection, which can be much larger than the poloidal component of wave vector at the antenna, can lead to substantial enhancement of the Doppler frequency shift of the microwave BS by fluctuations moving with poloidal plasma flow. The frequency shift corresponding to the BS efficiency maximum is given by

$$f_D = 2\left[ k_{\theta 0} + \frac{q_{conv}}{2} \frac{\vec{e}_\theta \vec{e}_R f_{ce}^2}{R\left|\vec{\nabla}(f_{pe}^2 + f_{ce}^2)\right|}\Bigg|_{UHR} \right] V_\theta \ , \tag{1}$$

where $V_\theta$ is the fluctuation poloidal velocity; $q_{conv} \equiv 2(2\pi f_i/c)\sqrt{c/V_{Te}}$ is the wave number value of fluctuation leading to BS in the linear conversion point; $k_{\theta 0}$ gives the probing extraordinary mode poloidal wave number out of the UHR zone, $\vec{e}_\theta$ and $\vec{e}_R$ are unit vectors in poloidal and major radius directions; $R$ gives the major radius in the UHR. In agreement with theoretical predictions a separate line less than 1.5 MHz wide and shifted by up to 2 MHz, was reliably observable in the BS spectrum under condition of accessible UHR [1].

In this paper, the recently observed giant Doppler frequency shift effect of the highly localized microwave BS in the Upper Hybrid Resonance (UHR) [1] is applied to tokamak plasma rotation diagnostics. The obtained profiles of plasma poloidal velocity are benchmarked against the Doppler reflectometry data. The experiment is performed at research FT-2 tokamak ($R$ = 55 cm, $a \approx$ 8 cm, $B_T \approx$ (1.7 ÷ 2.2) T, $I_p \approx$ (19 ÷ 37) kA, $n_e(0) \approx$ (0.5 ÷ 5)$\times 10^{13}$ cm$^{-3}$, $T_e(0) \approx$ 500 eV), where very different poloidal rotation profiles are measured in ohmic discharges for plasma current values of 19 kA and 35 kA.

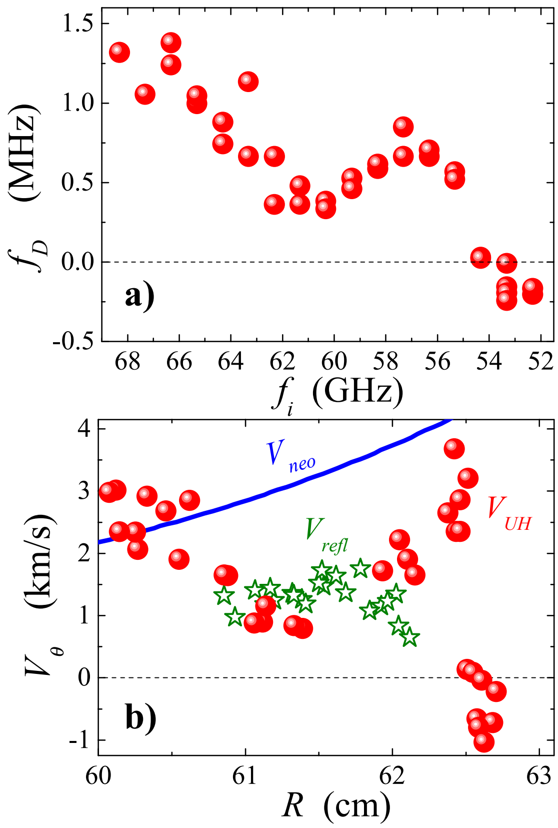


**Fig.3.** **(a)** *Doppler frequency shift versus incident frequency (* $y_a$ *= +15 mm).*
**(b)** *Poloidal velocity profiles for* $I_p$ = 35 kA. *Red circles – UHR BS, green stars – O-mode Doppler reflectometry, blue curve - neoclassical dependens.*

The dependence of BS frequency shift on the probing frequency in the high current case is shown in Fig. 3a. The important feature of this dependence is complicated behavior resulting in minimum at $f_i$ = 60.3 GHz and very steep variation at $f_i$ = 57.3 GHz. The corresponding poloidal rotation profile, determined using (1), is given in Fig. 3b by red circles. As it is seen, the poloidal plasma velocity increases towards LCFS, where it possesses discontinuity in agreement with expectations of neoclassical theory (the corresponding estimation is shown in Fig. 3b by blue curve). The corresponding velocity values determined using the UHR BS technique fit well those obtained by the O-mode Doppler reflectometry, which are shown by green stars in Fig. 3b. Out of the LCFS the rotation velocity changes sign, which indicate the dominant role of electron losses to the limiter along the magnetic field lines.

In the lower current regime no poloidal rotation discontinuity at the LCFS was observed. As it is shown in Fig. 4, at current less than 30 kA the rotation velocity decreases continuously towards the LCFS, where it changes sign, which is not consistent with the neoclassical theory expectations and indicates important role of anomalous electron losses

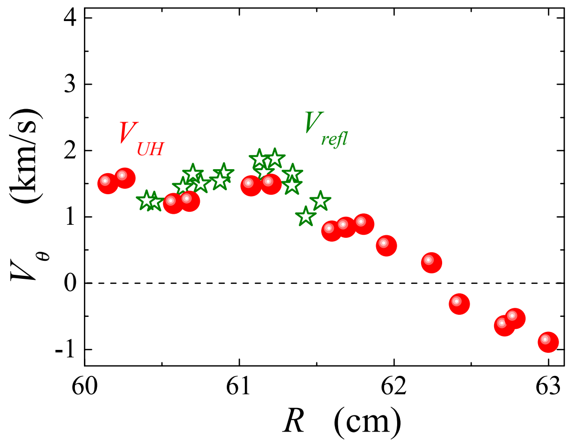


**Fig.4.** *Poloidal velocity profiles for $I_p$ = 19* kA. *Red circles – UHR BS, green stars – O-mode Doppler reflectometry.*

mechanism in formation of plasma potential in this region. It should be stressed that in this regime as well the poloidal rotation velocity obtained by Doppler reflectometry and UHR BS diagnostics are in nice agreement. It should be underlined that in spite of the fact both microwave BS techniques provide information on fluctuation rotation, the wave length of those fluctuations differs by two orders of magnitude. It is very unlikely that the phase velocities for such a different fluctuations coincide, which gives an argument in favor of plasma rotation origin of the frequency shift measured by both diagnostics. It is important to note that the calculated electron diamagnetic drift velocity all over the measurement region exceeds the experimental values of poloidal rotation velocity by a factor of 3 – 5. This result provides additional confirmation to our assumption that the Doppler frequency shift is rather associated with the plasma flow than with fluctuation phase velocity, which is quite natural because the fluctuations producing BS in the UHR possess radial wave number much higher than the poloidal one and thus are not similar to the drift wave eigen-modes.

**Conclusions.**

Based upon the robust Enhanced Doppler effect observed in the off equatorial plane microwave UHR BS experiment at FT-2 tokamak a new scheme for precise diagnostics of plasma poloidal rotation in tokamaks and stellarators possessing high spatial and temporal resolution has been developed. Two types of poloidal plasma rotation profiles are observed at FT-2 tokamak. The new diagnostic has been successfully benchmarked against the Doppler reflectometry technique data.

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