ENHANCED DOPPLER EFFECT IN THE UPPER HYBRID RESONANCE FOR MICROWAVE BACKSCATTERING EXPERIMENT

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The new microwave back scattering diagnostic based on enhancement of Doppler frequency shift in the upper hybrid resonance applied to detailed local study of plasma poloidal rotation and micro turbulence in ohmic discharges and during lower hybrid heating and current drive.

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].

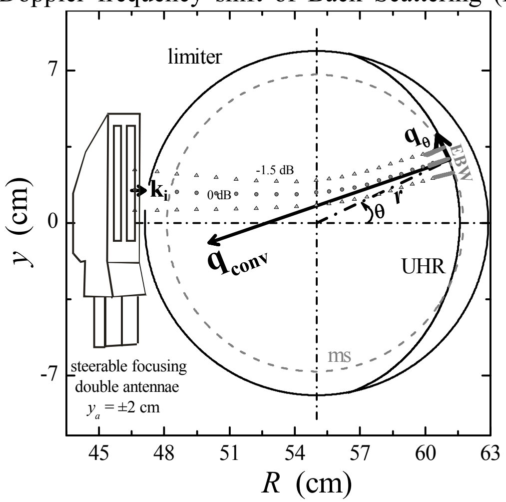

Fig. 1. Poloidal FT-2 section. ($\mathbf{k_i}$ – incident wave vector; $\mathbf{q_{conv}}$, $\mathbf{q_\theta}$ – fluctuation wave vector at BS efficiency maximum and its poloidal projection; circles – central ray of the probing beam, triangles –beam at 1.5 dB power suppression level)

The microwave BS experiment was performed at FT-2 tokamak with a new steerable focusing double antennae set, allowing off equatorial plane plasma X-mode probing from high

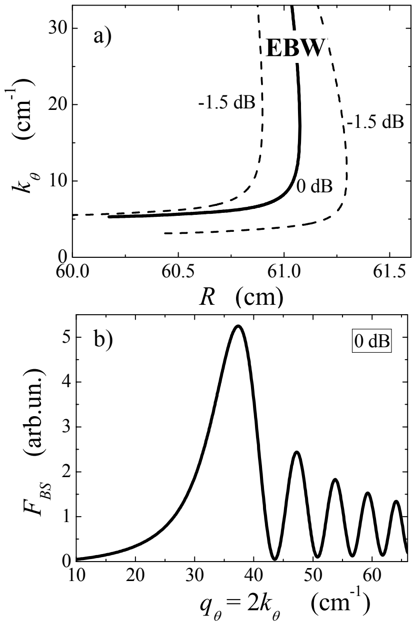

Fig. 2. (a) k_θ near UHR; (b) F_{BS} for central ray.

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 centre is ±2 cm, whereas the diameter of the wave beam near 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 k_θ 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 $F_{BS}(q_\theta)$ maximum is given by expression:

$$f_D = 2\left[k_{\theta 0} + \frac{q_{conv}}{2} \left. \frac{\mathbf{e_\theta e_R} f_{ce}^2}{R\left|\nabla(f_{pe}^2 + f_{ce}^2)\right|} \right|_{UHR} \right] V_\theta ,$$

where V_θ is the fluctuation poloidal velocity; $q_{conv} \equiv 2\left(2\pi f_i / c\right)\sqrt{c/V_{Te}}$ 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, $\mathbf{e_\theta}$ and $\mathbf{e_R}$ 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

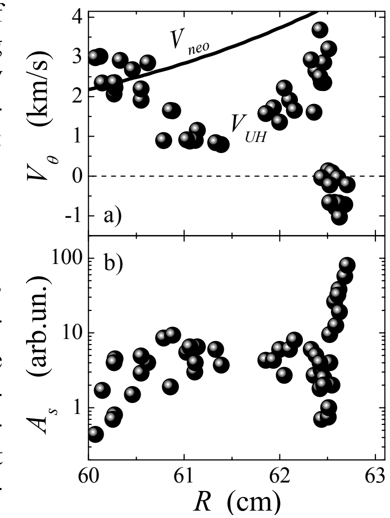

Fig. 3. High current profiles.

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 experiment was performed at research FT-2 tokamak (R = 55 cm, $a \approx 8$ cm, $B_T \approx (1.7 \div 2.2)$ T, $n_e(0) \approx (0.5 \div 5)\times10^{19}$ m^{-3}, $T_e(0) \approx 500$ eV), where very different poloidal rotation profiles were measured in ohmic discharges for plasma current values of 19 kA and 35 kA. The velocity profile $V_\theta(R)$ in the high current case is given in Fig. 3a by circles combining three moments in the shot: 27, 30, 33 ms. The important feature of this dependence is complicated behaviour resulting in minimum at R = 61.5 cm and very steep variation at 62 cm. As it is seen, the poloidal plasma velocity increases towards last closed field surface (LCFS), where it possesses discontinuity in agreement with expectations of neoclassical theory (the corresponding estimation is shown in Fig. 3a by solid curve). 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. The amplitude of the BS spectrum $A_s(R)$ in logarithmic scale is shown on Fig. 3b. There is a strong correlation between the velocity shear and turbulence level: in narrow 3 mm wide region in the vicinity of the LCFS the amplitude of the signal is suppressed by a factor of 12.

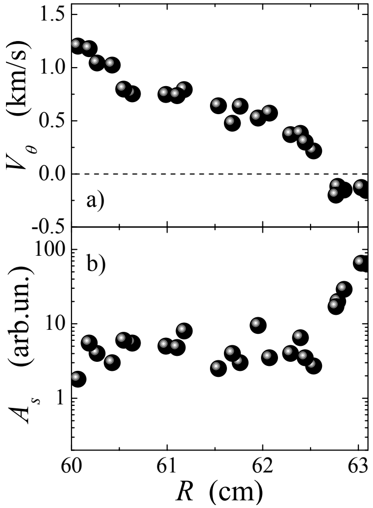

Fig. 4. Low current profiles.

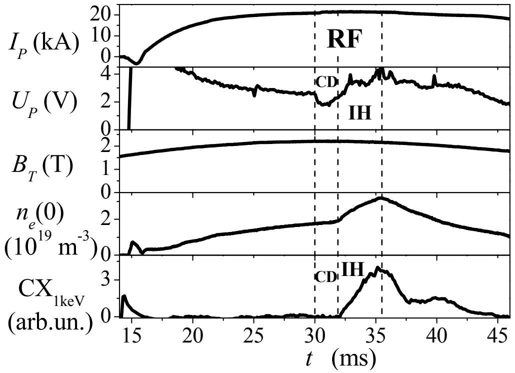

Fig. 5. Wave forms of the LH CD-IH discharge.

In the lower current regime no poloidal rotation discontinuity at the LCFS was observed. As it is shown in Fig. 4a (for 30 ms), 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 mechanism in formation of plasma potential in this region. The absence of velocity discontinuity is accompanied by flat profile of the BS spectrum amplitude (Fig. 4b). Out of the LCFS the turbulence level increases independently of the current value.

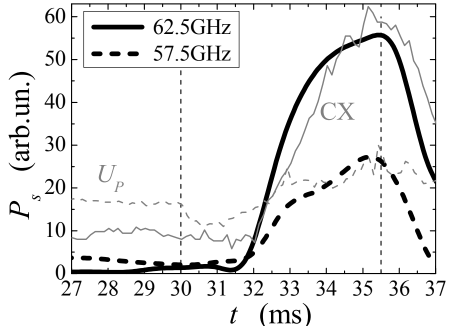

Fig. 6. Scattered power evolution.

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.

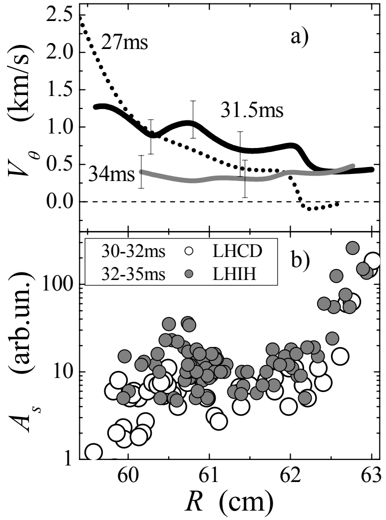

Fig. 7. LH CD-IH profiles.

The temporal variation of the poloidal plasma rotation and small-scale turbulence were also studied in low current regime under the incidence of RF heating power in Lower Hybrid (LH) frequency range. The RF power up to $P_{RF} \approx 120$ kW at frequency $f_{RF} = 918$ MHz was launched into the plasma by a two-waveguide grill. In the present paper a specific regime of LH heating at densities $2\cdot10^{19} < n_e(0) < 3\cdot10^{19}$ m^{-3}, at which the LH current drive (LHCD) and electron heating terminates and wave–ion interaction and ion heating starts, was investigated. Wave forms of the discharge are shown in Fig. 5. As it is seen there, just at the onset of RF pulse at t = 30 ms an evident decrease is observable in the loop voltage signal indicating the LHCD effect. This effect is accompanied by the plasma density growth, leading to the LHCD termination at $t \approx 32$ ms. After that the steep increase of fast ion population at energy in 1 keV range is observed in the discharge by the charge exchange diagnostic, indicating transition to the LH Ion Heating (LHIH) regime. Under these conditions excitation of small scale component of plasma turbulence was observed earlier at FT-2 tokamak by CO_2 [4] and UHR

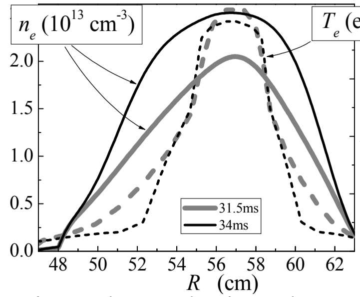

Fig. 8. Electron density and temperature profiles in CD and IH phases.

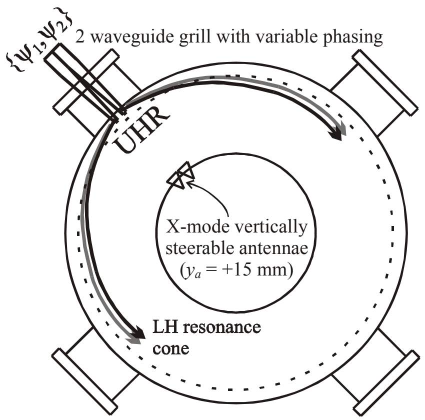

Fig. 9. LH and X-mode antennae positions.

scattering diagnostics [5]. Here we study the reasons and consequences of this effect.

The power level P_s of the UHR BS signal in the $f_D \pm 400$ kHz frequency band experienced substantial growth at the transition from the LHCD regime to the LHIH, as it is shown in Fig. 6 for probing frequency 62.5 GHz (black solid curve) and 57.5 GHz (black dashed curve). This growth is only partly associated with the outer shift of the UHR layer (from 4.3 to 5.5 cm for 62.5 GHz and from 5.3 to 6.6 cm for 57.5 GHz) and indicates the local growth of small scale component of tokamak micro turbulence. At 30 ms < t < 32 ms, the BS spectrum remains similar to that observed in ohmic heating. The fast reduction of the Doppler frequency shift and the spectrum narrowing, accompanied by steep increase of its amplitude, starts simultaneously with the fast neutral flux growth. The relaxation of the BS spectrum to that, observed in the ohmic discharge, starts just after the RF power switch off. The poloidal velocity profiles, determined from the Doppler frequency shift of the UHR BS spectra are shown in Fig. 7a for three typical moments: 27, 31.5, 34 ms. Before the RF pulse the velocity profile is typical for the low current regime, as measured by this technique. The velocity monotonically decreases when approaching the plasma edge and change sign in the vicinity of LCFS (dashed curve in Fig. 7a). At the LHCD phase the velocity increases slightly, however its shear remains unchanged during the first millisecond after RF power onset (black solid curve). The dramatic variation of the velocity profile is observed only after transition to the LHIH regime at t > 32 ms. As the result, at t = 34 ms poloidal velocity is substantially reduced and its profile in the edge region becomes flat (grey solid curve). It is important to note that the flattening of the rotation profile and related decrease of the poloidal velocity shear results in strong growth of the BS signal, proportional to the level of small scale density fluctuations, as it is shown by dependences of BS spectrum amplitude on the UHR position, plotted by open and solid circles in Fig. 7b for the LHCD and LHIH phases of RF pulse correspondingly. The drastic increase of the turbulence level initiated by the rotation shear suppression is accompanied by substantial cooling of the electron component (dashed lines in Fig. 8) at the plasma periphery, which occurs at the background of growing density (solid curves).

The typical feature of the plasma rotation at the very edge (out of the LCFS), observed by the UHR BS technique at RF power onset, was quick change of velocity direction. This effect well pronounced in all regimes of interaction and at different grill antenna phasing $\{\psi_1, \psi_2\}$ is clearly seen on Fig. 7a, in which the velocity is positive during the RF pulse for R > 62.1 cm in contrary to ohmic phase. The possible explanation of this robust effect taking place in the vicinity of the LH grill (Fig. 9), which is situated in the UHR BS diagnostics cross section, is based on the improvement of electron confinement along magnetic field due to their trapping by the ponderomotive potential $\Phi_{RF} = E_z^2 f_{pe}^2 / 16\pi f_{RF}^2$ produced by two LH wave resonance cones (where E_z is the toroidal component of RF field). The calculated distribution of this potential along the field line is shown in Fig. 10a for grill phasing $\{0,\pi/2\}$ and in Fig. 10b for $\{0,\pi\}$ at two minor radii $x = R\text{-}R_0 = 7.6$ and 7.2 cm, demonstrating gradual deepening of LH cones. At $P_{RF} \approx 88$ kW and $T_e \approx 10$ eV it appears to be comparable to plasma pressure.

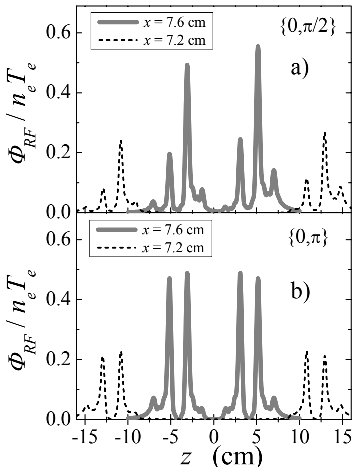

Fig. 10. Ponderomotive potential.

Conclusions

Based upon the robust Enhanced Doppler effect, observed in the off equatorial plane microwave UHR BS experiment, 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 ohmic regime with poloidal velocity and turbulence level profiles, showing features of edge transport barrier at high current discharge and without them in low current one, were found at FT-2 tokamak. An excitation of plasma micro turbulence accompanied by suppression of poloidal velocity shear was observed after transition from LHCD to LHIH in one RF pulse. The influence of ponderomotive potential produced by LH wave resonance cones on poloidal rotation was founded out of the LCFS.

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