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Poloidal Plasma Rotation Diagnostic at FT-2 Tokamak by the Upper Hybrid Resonance Backscattering

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The Doppler frequency shift of backscattering (BS) signal at oblique microwave plasma probing in the cutoff vicinity is often used for diagnosing of poloidal plasma velocity in magnetic fusion devices [1, 2]. The data interpretation in this “Doppler reflectometry” (DR) diagnostics is however complicated by the contribution of the eigen frequency of fluctuations contributing to BS which is often comparable to the shift caused by their E×B rotation. According to theoretical expectations [3], the frequency of drift waves responsible for BS is given by the following expression:

$$\Omega_{LF} = q_\theta \left(V_{E\times B} + V_{dr} \left[1 + \left(q_\theta^2 + q_r^2 \right) \rho_s^2 \right]^{-1} \right) , \tag{1}$$

where $V_{E\times B} = cE_r / B$ is the plasma poloidal rotation velocity, $\rho_s = \omega_{ci}^{-1} \sqrt{T_e/m_i}$, q_θ and q_r are poloidal and radial fluctuation wave numbers and V_{dr} is the drift wave phase velocity at $\left(q_\theta^2 + q_r^2 \right) \rho_s^2 \ll 1$, which is proportional to gradients of plasma parameters and depends on the drift mode type. According to (1), the phase velocity quickly decreases at wave numbers satisfying condition $\left(q_\theta^2 + q_r^2 \right) \rho_s^2 \gg 1$. Thus it can be beneficial for the plasma poloidal velocity diagnostics to measure BS off small-scale turbulence component, possessing wave number in the range $\left(q_\theta^2 + q_r^2 \right) \rho_s^2 \gg 1$. The upper hybrid resonance (UHR) backscattering (BS) technique which utilizes the effect of probing wave number and electric field growth in the UHR resulting in enhancement of scattering signal and measurement localization [4] is suitable for this purpose. The important effect which should be taken into account when planning and interpreting the UHR BS experiment in tokamak is the growth of poloidal component of the probing wave vector [5, 6] at off equatorial plane probing, which is described by relation

$$k_\theta = k_{\theta 0} + k_r \left. \frac{\vec{e}_\theta \vec{e}_R f_{ce}^2}{R \left| \vec{\nabla} (f_{pe}^2 + f_{ce}^2) \right|} \right|_{UHR} , \tag{2}$$

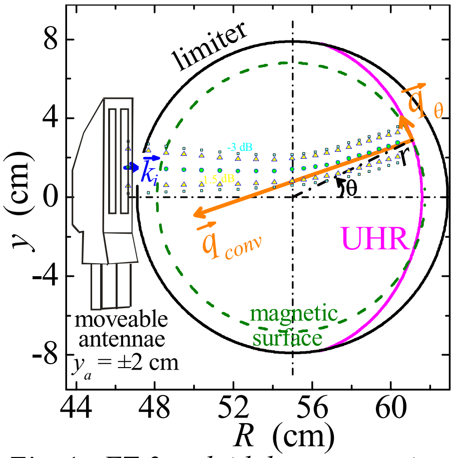

Fig. 1. *FT-2 poloidal cross section ($\vec{k}_i$ – incident wave vector, $\vec{q}_{conv}$ and $\vec{q}_\theta$ – fluctuation wave vector at BS efficiency maximum and it's poloidal projection, circles – central ray of the probing beam, triangles and squares – probing beam at 1.5 and 3 dB power suppression levels).*

where $k_{\theta 0}$ 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. This growth is associated with a finite projection of the large probing wave vector, perpendicular to the UHR surface, onto the poloidal direction. It is typical for toroidal devices, where the UHR and magnetic surfaces do not coincide due to dependence of magnetic field on the major radius R. This effect can lead to substantial increase of poloidal wave number of the fluctuations contributing to the UHR BS signal $q_\theta = 2k_\theta$ and, in accordance with (1), to enhancement the Doppler frequency shift f_D of the microwave BS off fluctuations moving with poloidal plasma flow. In the present paper the new scheme for local diagnostics of plasma poloidal rotation is benchmarked against DR and impurity spectroscopy diagnostics data and applied to detailed local study of plasma rotation in tokamak.

The experiment is performed at research FT-2 tokamak, ($R = 55$ cm, $a \approx 8$ cm, $B_T \approx 2.2$ T, $I_p \approx$ (19-37) kA, $n_e(0) \approx (0.5\text{-}5)\times 10^{19}$ m^{-3}, $T_e(0) \approx 500$ eV), where a moveable focusing double antenna set, allowing off equatorial plane plasma X-mode probing from high magnetic field side, is installed (fig. 1). As it was shown in [6], a separate line less than 1.5 MHz wide and shifted by up to 2 MHz is routinely observed in the BS spectrum under condition of accessible UHR. The line frequency shift depends on the probing frequency (fig. 2) and changes sign at the frequencies lower than 55 GHz, when the UHR layer is situated at the plasma edge. The line frequency shift appears to be proportional to the antennae vertical displacement. This dependence is explained in [6] using the X-mode ray tracing and the drift wave dispersion relation (1), which is used for the poloidal velocity determination from the line frequency

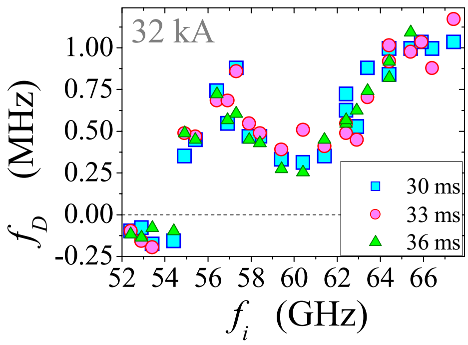

Fig. 2. *The UHR BS Doppler frequency shift versus probing frequency.*

shift. The radial wave number of fluctuations $q_r = 2k_r$ contributing to the BS signal also needed, according to (2), for this purpose is obtained using the correlation analysis of simultaneously measured BS signals at different probing frequencies f_i and $f_i + \Delta f_i$ [7].

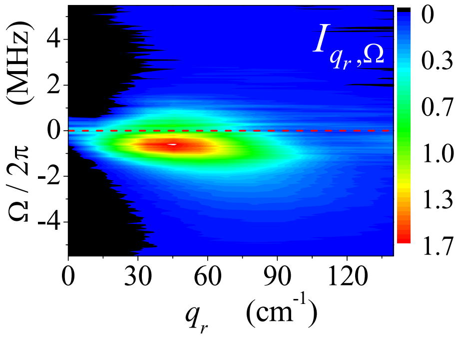

Fig. 3. *The UHR BS spectrum at* f_i = 60.6 *GHz in* 32 *kA discharge.*

The normalized CCF dependence on Δf_i proportional to the UHR spatial separation ($\Delta R_{\mathrm{UH}} = \Delta f_i\, \partial R_{\mathrm{UH}} / \partial f_{\mathrm{i}}$) was Fourier transformed. The obtained cross-correlation spectrum was transformed into the UHR BS spectrum $I_{q_r,\Omega}$ (fig. 3) via multiplication by the UHR BS homodyne spectrum $P_s(\Omega)$. Using this type of spectrum we determine the frequency and radial wave number of fluctuations providing the largest contribution to the signal. (In the case of UHR BS spectrum shown in fig. 3 we get f_D = 0.6 MHz and q_r = 45 cm^{-1}). The fluctuations poloidal wave number $q_\theta = 2k_\theta$ entering the relation (1) is determined using expression (2), in which parameter $k_{\theta 0}$, as well as the position of BS, are determined using the ray tracing computation. The poloidal velocity profile obtained in the 32 kA FT-2 discharge using the above procedure is shown in fig. 4a by circles. As it is seen, in the inner discharge zone plasma rotates in the electron diamagnetic drift direction at typical value 3 km/s, which is close to the value provided by the neoclassical formula [8] $V_{neo} \approx c\dfrac{T_i}{eB}\left[\dfrac{\partial(\ln n_e)}{\partial r} + (1-k)\dfrac{\partial(\ln T_i)}{\partial r}\right]$. At $R \approx 62$ cm the rotation velocity increases and than in the nearest vicinity of LCFS, at $R \approx 62.4$ cm the rotation velocity quickly decreases and changes sign in the edge region, where it is natural to expect positive plasma electric field, caused by electron losses along open magnetic field lines. The rotation velocity measured by DR in the same discharge is shown in fig. 4a by triangles. The typical value given by this technique is 1.5 km/s which is substantially smaller than that provided by the UHR BS technique. The difference, according to expression (1), may be attributed to the

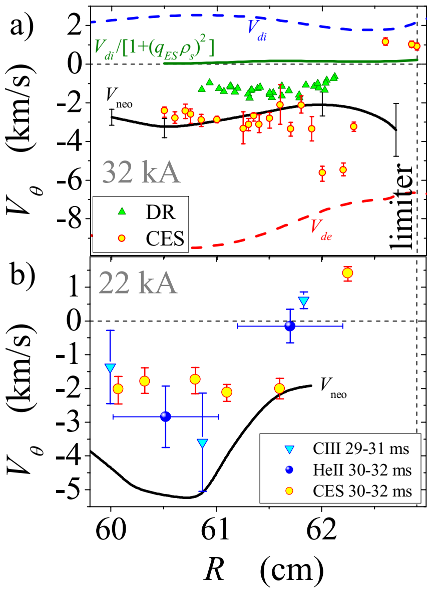

Fig. 4. *Poloidal velocity profiles.*

contribution of negative ion diamagnetic drift velocity to the long-scale fluctuation velocity shown by the blue dashed line in the fig. 4a. The plasma rotation profile provided by the UHR BS technique was also benchmarked against the visible light impurity spectroscopy data. For this purpose measurements were performed during He-puffing into the optical diagnostic cross section, which resulted in the spectral lines emission growth. The comparison of rotation profiles obtained by two techniques in the 22 kA discharge is shown in fig. 4b. As it is seen, within large error bars of spectroscopy points profiles look similar. It should be stressed that both techniques indicate the change of rotation direction at the very edge of tokamak discharge.

Finally, the UHR BS diagnostics was applied to investigation of plasma rotation dynamics during the current ramp up in the FT-2 tokamak. At the 30th ms of discharge the plasma current was ramped up from 22 to 32 kA. This perturbation was accompanied by variation of plasma density and temperature both at the edge and in the central region. The variation of rotation profile is shown in fig. 5. As it is seen both from UHR BS and DR profiles, the region of tokamak-like confinement, for which negative electron diamagnetic drift rotation direction is typical, became broader after the current ramp up. The velocity values provided by DR are again substantially smaller here (as in fig. 4a, the velocity difference is close to ion diamagnetic drift velocity), whereas the profile is smoother than that measured by the UHR BS, which is explained by the UHR BS better spatial localization. The profile provided by the CIII-spectroscopy (blue triangles) lie closer to the DR profile, whereas the neoclassical black curve is closer to the UHR BS data. Unfortunately due to large error bars both are not sufficient to make a definite choice in favor of DR or UHR BS technique.

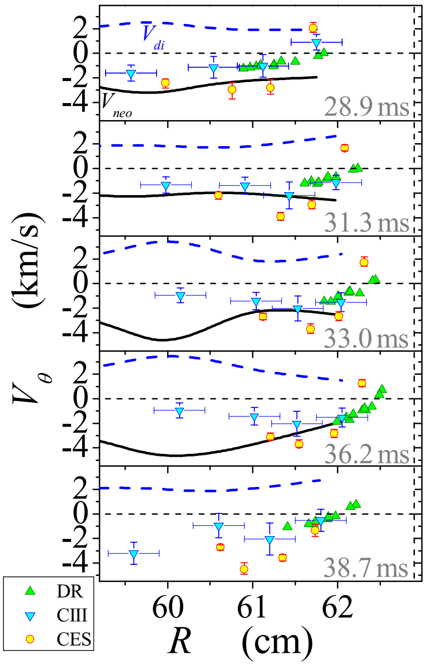

Fig. 5. *Poloidal velocity profiles in current ramp up experiment.*

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