Local measurements of the radial plasma velocity fluctuations in the FT-2 tokamak core plasmas by equatorial enhanced scattering

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Considerable interest in radial fluctuations of plasma velocity is associated with their significant role in the formation of radial turbulent flows. Since these flows determine the transport of energy and particles, the problems of their characterization are directly related to solving the fundamental problem of high-temperature plasma physics and controlled thermonuclear fusion with magnetic confinement – anomalous plasma transport in a tokamak. At present diagnostics that allow local measurements of fluctuations of radial velocities simultaneously with density fluctuations in the plasma core is Heavy Ion Beam Probe with multi-slits energy analysers or multiple cell array detectors [1]. It should be noted that HIBP diagnostics is technically complicated and expensive due to the use of high-voltage devices, high-energy ions, special ports for the injection of fast ions and analysis of the secondary ionized beam in one section of the tokamak or stellarator. A technically simple and cheap method used in this work is not intended to fully replace the HIBP method, but is designed to perform more local measurements of radial velocity fluctuations in a wider wavelength range in research tokamak plasma with an electron temperature in the centre up to 1 keV. For these purposes, we implement the special microwave technique – the equatorial enhanced scattering (EES) [2], possessing a sub-millimetre spatial radial resolution, and demonstrate its feasibility for diagnosing temporal and spatial characteristics of the radial plasma velocity fluctuations.

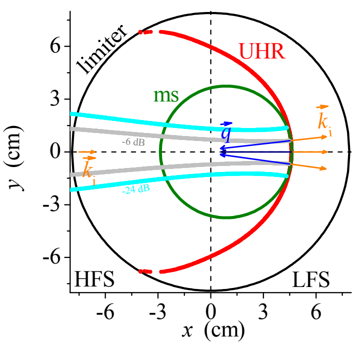

Fig. 1. Experimental geometry. Grey and cyan lines - levels of antennae patterns convolution corresponding to the signal's level drop by 6 and 24 dB.

The diagnostics developed at the FT-2 tokamak (major radius $R = 55$ cm and a radius of limiter $a = 7.9$ cm) utilizes the equatorial microwave X-mode probing by a narrow beam (with wave vector $\vec{k}_i$) from the high field side and measurements of backscattering off small-scale density fluctuations with wave vector $\vec{q} = -2\vec{k}_i$ in the upper hybrid resonance (UHR) vicinity (fig. 1). The radial propagation of the density fluctuations associated with the plasma motion leads to the Doppler frequency shift in the EES spectrum. Correspondingly, the turbulent, random nature of the plasma radial motion results at long-term measurements in the broadening of the frequency spectrum of the backscattering signal $2\pi\delta f = \delta v_r q_r$, where δv_r is the root-mean-square (rms) value of plasma radial velocity fluctuations. Accordingly, δv_r can be expressed in terms of the standard deviation σ of the time derivative of the signal phase $\delta v_r = 2\pi\sigma(\partial\psi/\partial t)/q_r$. The velocity mean value $<v_r>$, which, according to gyrokinetic (GK) global simulations by ELMFIRE code [3], possesses the level $0.03\delta v_r$, provides the small Doppler spectral shift less than 50 kHz.

A pair of well-reproducible ohmic discharges (with a current $I_p = 19$ kA and a toroidal magnetic field $B_0 = 2.2$ T) with different working gases (hydrogen or deuterium) and as close as possible density and electron temperature profiles were specially selected (fig. 2) for validating of the EES method against pre-made GK ELMFIRE simulations [3].

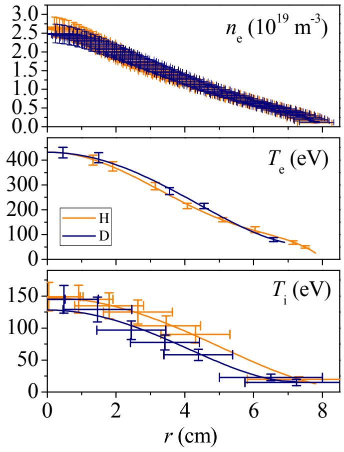

Fig. 2. Profiles in H- and D-regimes.

The frequency spectrum of a backscattering signal and its phase were measured by a quadrature detection scheme. A technically more sophisticated diagnostics of correlation enhanced scattering [4, 5] was used to measure the radial wave numbers q_r of density fluctuations contributing to the EES signal. The q_r value corresponding to the maximum of the signal spectrum $P_{EES}(f, q_r)$ was used for estimating the level of δv_r, in accordance with the above expressions.

Profiles of δv_r values estimated from $\sigma(\partial\psi/\partial t)$ are shown in fig. 3 by triangles for H-case (top) and by rhombuses for deuterium (bottom). The solid curve in the figure demonstrates the rms-level of the radial velocity oscillations obtained in the GK modeling along the entire poloidal angle θ. It should be noted that δv_r in the numerical simulation are non-uniform in the poloidal direction. The range of oscillations varies with θ and the corresponding extreme values are shown by dashed curves, with a maximal level near the equatorial plane at the LFS.

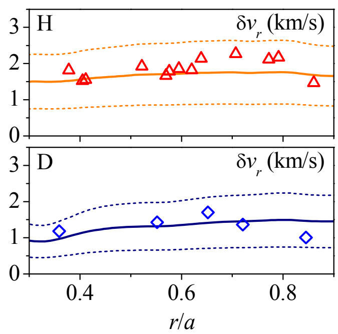

Fig. 3. The level of the radial velocity fluctuations.

Additionally, two other mechanisms [6] of producing the EES signal spectrum broadening not related to fluctuations of the radial plasma motion were considered.

The first is associated with the Doppler broadening of the backscattering signal frequency spectrum, which is the result of non-zero poloidal wavenumbers q_θ of partial waves also

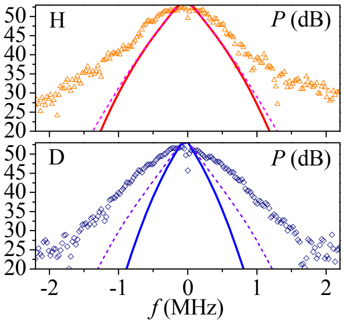

Fig. 4. EES spectra at $r/a = 0.63$.

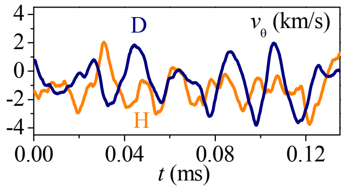

Fig. 5. GAMs at $r/a = 0.63$.

contributing to the EES signal. These wavenumbers increase in the UHR region with a vertical displacement y from the equatorial plane of the illuminated point as $q_\theta = 2k_{i\theta 0}(y) + q_r\cos(\alpha(y)) \equiv (a_1 + a_2 q_r)y$ [7]. Both, the poloidal wavenumber $k_{i\theta 0}$ of the probing ray near the UHR and the angle α between the normal to the UHR surface and the tangent to the magnetic surface can be easily computed by ray tracing. A comparison of the experimental spectra in H and D with the expression $P(f) \propto \exp\left\{-a_3\left(\frac{2\pi f}{v_\theta(a_1 + a_2 q_r)}\right)^2\right\}$ obtained from the square of the antenna pattern $P_{\text{ant}}{}^2 = \exp\left\{-a_3 y^2\right\}$ by expressing the vertical displacement in terms of q_θ and using its relation to the frequency $v_\theta = 2\pi f/q_\theta$, is shown in fig. 4. The radial profile of the mean poloidal velocity was studied in detail by the Doppler correlation ES technique [3]. The approximation of the experimental spectra using the above expression (solid curves in fig. 4) demonstrates that relatively broad experimental spectra (shown by symbols) cannot be described using the available narrow antennae patterns with measured values of the mean v_θ. An important feature of the poloidal plasma rotation in the considered cases is the presence of the region ($0.4 < r/a < 0.8$) with intense GAMs with amplitudes exceeding $\langle v_\theta \rangle$ (fig. 5). The existence of GAMs was taken into account by substituting the time evolution of the poloidal velocity values $v_\theta(t)$ into the formula written above and carrying out its integration over the time: $\int P\left(f, v_\theta(t)\right)dt$. Spectra obtained in this way are shown in fig. 4 by dashed curves. The influence of the variable $v_\theta(t)$ leads to the rise of the wings of the spectrum after several periods of GAMs. However, quantitative analysis shows that the contribution of GAMs, even at the point of their maximum intensity, is also insufficient to describe the experimental spectrum.

The second mechanism leading to the broadening of the signal spectrum is the multiple small-angle scattering of the probing and scattered waves on the way to the UHR and back. According to the theory [8], the width of the spectrum at the level of max$\{P(f)\}$/e is $\Delta f = q_r^2\left(\delta n/n\right)\sqrt{L_n l_{\delta n}\left\langle f_0^2\right\rangle}\Big/\left(8\omega_{\text{ce}}/c\right)$, where $\delta n/n$ is fluctuation's relative level, L_n is the density scale length, f_0 and $l_{\delta n} \approx 5$ mm are the width of the density fluctuations frequency spectrum and their correlation length [9]; ω_{ce} is the electron cyclotron frequency in the UHR.

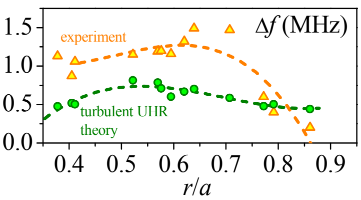

Fig. 6. Spectral width at 1/e level in H-case.

A comparison of the experimental spectra width with the theoretical prediction is shown in fig. 6. At the plasma periphery ($r/a > 0.75$), where $\delta n/n > 0.08$, the considered mechanism of multiple small-angle scattering is sufficiently strong to be responsible for the entire spectrum broadening. In the internal regions, its influence is smaller so that the dominant mechanism of spectrum formation is related to oscillations of the radial velocity of the plasma, which are swinging small-scale density fluctuations. It is worth noting that we do not consider the simultaneous manifestation of several mechanisms for broadening the spectra, trying only to reveal the conditions where one or another mechanism turns out to be dominant.

The high radial locality of the EES method allowed us to implement a correlation technique with dual-frequency probing (f_1= 62.4 GHz; f_2 = 62.45 - 63.95 GHz with 150 MHz step from shot to shot) to measure the $\partial\psi_{1/2}/\partial t$ coherence of two signals. Examples of power spectra $P_{\delta v}(f)$ for $\delta v_r(t)$ obtained experimentally and numerically by GK simulation and the coherence as a function of the radial separation Δr (for f = 50 and 190 kHz) are shown in fig. 7. Both approaches demonstrate that the radial correlation length of the radial velocity fluctuations is close to $l_{\delta v} \approx 3.5$ mm. As expected, it is less than the previously measured [9] radial correlation length of the density fluctuations $l_{\delta n}$.

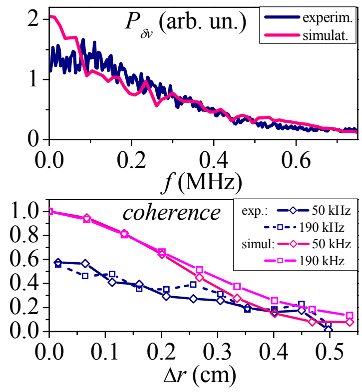

Fig. 7. δv_r spectra and radial coherence (D-case; r/a = 0.62).

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