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Investigation of plasma poloidal rotation in the presence of a magnetic island in the FT-2 tokamak by Doppler enhanced scattering

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Received November 3, 2023
Revised January 29, 2024
Accepted February 17, 2024

Plasma poloidal rotation velocity in the presence of a magnetic island with poloidal and toroidal mode numbers $m/n = 2/1$ was measured using Doppler enhanced scattering technique. Inside the island, the magnitude of the perturbation of plasma poloidal rotation velocity was estimated; its value reached 250 m/s. Magnetic island's contribution to the perturbation of the average plasma poloidal rotation velocity appeared to be maximum near its boundaries, where it reached 8−17%.

Keywords: Perturbation of plasma velocity in a tokamak, magnetic island, Doppler enhanced scattering.

DOI: 10.61011/TPL.2024.06.58467.19792

Magnetohydrodynamic (MHD) instabilities in a tokamak are of scientific interest, since their development affects the quality of plasma confinement. Specifically, the tearing mode (TM) instability alters the plasma equilibrium, which becomes asymmetrical. This regime is characterized by the emergence of a chain of magnetic islands near rational magnetic surfaces. Magnetic field lines connect inner and outer sides of an island, inducing an enhancement of radial heat and particle fluxes and a corresponding degradation of confinement.

The emergence of oscillations of Doppler frequency shift f_D of the scattering spectrum, which is used to estimate the plasma rotation velocity, was detected in the vicinity of TMs via Doppler backscattering in experiments at the Globus-M2 tokamak [1]. The oscillation frequency matched the rotation frequency of the TM with mode numbers $m/n = 2/1$. The influence of an island on plasma rotation has also been noted in experiments at the TUMAN-3M tokamak [2]. When radial profiles of the calculated neoclassical poloidal plasma rotation velocity were compared with velocity V_θ determined from Doppler backscattering measurements, the data obtained at the W-7X stellarator [3] with a stationary magnetic island with $m/n = 5/5$ revealed differences between the velocity values within an island. This difference, which was the greatest at the boundaries of an island and reached its minimum in the center of it, at the so-called O-point was interpreted as the contribution of a magnetic island to plasma rotation.

In the present study, oscillations of the Doppler frequency shift of the enhanced scattering (ES) diagnostic spectrum [4], which is sensitive to V_θ oscillations, are examined in detail and compared with magnetic field oscillations detected with the use of MHD probes. Experiments were carried out at the FT-2 tokamak (major radius, 55 cm; limiter radius, 7.9 cm) in hydrogen plasma in a series of repeated discharges with a duration up to 50 ms and the following maximum parameter values: plasma current, 33 kA; toroidal magnetic field, 2.3 T; central density, $2.1 \cdot 10^{19}\,\mathrm{m}^{-3}$; and central electron temperature, 600 eV. The ASTRA code [5] was used to reconstruct the profile of safety factor q; a magnetic island with $m/n = 2/1$, which rotated in the electron diamagnetic direction, was investigated by a set of MHD probes near the magnetic surface with $q = 2$ located at radius $r = 4.8$ cm. A spectral line at frequency $f_{\mathrm{MHD}} = 35$ kHz is apparent in the signal power spectrum of one of the MHD probes (curve *1* in Fig. 1, *a*). The transceiving ES diagnostic antenna was shifted upward by 15 mm relative to the equator, and the 59−69 GHz frequency range was used for probing. This allowed us to shift the radial position of the scattering region within the range of $r = 3{-}6.5$ cm. The analysis of time-varying ES spectra provided an opportunity to reconstruct the evolution of their Doppler frequency shifts $f_D(t)$ with a time resolution of 2.6 μs. Within a certain interval of r, one or two spectral lines emerged in the power spectrum of measured signal $f_D(t)$. Specifically, lines at frequency f_{MHD} are present at $r = 4.7$ cm in the spectra of signal $f_D(t)$ (curve *2* in Fig. 1, *a*) and the MHD probe (curve *1*). The coherence between two signals at this frequency (see curve *3* in Fig. 1, *b*) was as high as 90% and exceeded the noise level (line *4*). A second line at higher frequency f_{GAM}, which corresponds to the geodesic acoustic mode (GAM) that has been examined earlier in different operating regimes of the FT-2 tokamak [4], is present in the spectrum of signal $f_D(t)$.

In order to determine the amplitude of oscillations of $f_D(t)$, test signal

$$f_{D\,test}(t) = \delta f_{\mathrm{MHD}} \cos(2\pi f_{\mathrm{MHD}} t) + \delta f_{\mathrm{GAM}} \cos(2\pi f_{\mathrm{GAM}} t) + n(t) \qquad (1)$$

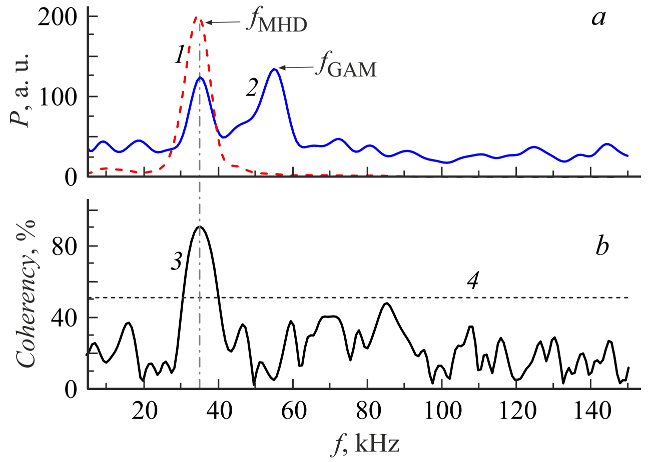

Figure 1. *a* — Power spectra for signals of the MHD probe (*1*) and $f_D(t)$ (*2*); *b* — coherence spectrum for these signals (*3*) and noise coherence level (*4*).

was formed for each line in the measured signal spectrum. This test signal included two harmonics at MHD and GAM frequencies with amplitudes δf_{MHD} and δf_{GAM} and random noise n. The parameters in expression (1) were set in such a way as to reproduce the experimentally observed spectrum. Following adjustment performed for different ES positions, profiles of amplitudes of $f_D(t)$ oscillations at the corresponding frequencies (shaded regions *1* and *2* in Fig. 2, *a*) and the profile of Doppler frequency shift $\langle f_D \rangle$ averaged over 2.3 ms (circles connected by curve *3*) were plotted. The amplitudes of oscillations at MHD and GAM frequencies are as high as 0.2 MHz and occupy different (but partially overlapping) radial regions. The region of localization of oscillations at the MHD perturbation frequency is located near the magnetic surface with $q = 2$, and its width is 1.5 cm. Note that the amplitudes of MHD and GAM lines are hard to determine without spectral analysis, since signal $f_D(t)$ has a considerable dispersion (colored region *4* in Fig. 2, *a*) due to the presence of broadband noise.

Doppler frequency shift $f_D = q_\theta V_\theta/(2\pi)$ allows one to estimate velocity V_θ at constant q_θ. The component of the wavevector of a probing extraordinary wave ($k_{i\,\mathrm{UHR}}$) normal to the upper hybrid resonance (UHR) surface grows near this surface. In view of this, scattering off fluctuations proceeds within a wide range of wavenumbers $q_{\mathrm{UHR}} = 2k_{i\,\mathrm{UHR}}$, which produce contributions to the signal with different weights. Direct measurements were performed with the use of the correlative ES modification [4,6] to obtain the radial profile of wavenumbers of fluctuations q_{UHR} providing the maximum contribution to the ES signal at frequency f_D. The measured q_{UHR} value was used to calculate the corresponding poloidal projection q_θ. The velocities of plasma rotating in the electron diamagnetic direction, which were determined based on Doppler frequency shifts, are presented in Fig. 2, *b*. Open (*1*) and filled (*2*) circles denote the amplitudes of velocity oscillations δV_{MHD} and δV_{GAM} at MHD and GAM frequencies relative to the mean value of velocity $\langle V_\theta \rangle$, which is represented by squares *3*. The interpretation of periodic velocity perturbation at the GAM frequency is trivial, since it is related to the local symmetric oscillation of the radial electric field [4]. The case of oscillations at the MHD frequency is not that straightforward. At first glance, it follows from the shape of velocity profile *1* in Fig. 2, *b* that perturbation δV_{MHD} increases to 0.4 km/s in the vicinity of a magnetic island at a mean velocity as high as 2 km/s. The magnitudes of periodic velocity perturbation are determined from f_D oscillation magnitudes, but these oscillations may be unrelated to the velocity perturbation within an island. In the process of rotation of an island with a density perturbed relative to the background level [7], the UHR surface shifts periodically in r. With a radial V_θ gradient present, this leads to modulation of the amplitude of the experimentally observed Doppler shift of the ES spectrum. Another effect triggered by the rotation of an island is periodic distortion of the UHR surface shape, which induces oscillations of the poloidal projection of the fluctuation wavevector (q_θ). Thus, the asymmetry of magnetic surfaces, which is introduced by a magnetic island, needs to be taken into account when one interprets the measured f_D oscillations. The shape of magnetic surfaces of an island with width w located on the resonance surface with radius r_{res} was characterized using the model developed in [8]. Our analysis of experimental data rests on the assumption of smallness of perturbation of the magnetic field associated with a magnetic island. This makes it possible to use the perturbation method and consider the influence of various factors in an additive fashion. Modeling was performed to examine the influence of density $\delta n/n$ perturbed in an island on the modulation of both the position of scattering and the q_θ value. Velocity perturbation δV_{mod} was calculated in this modeling for an island rotating with frequency f_{MHD} in background plasma with the experimentally measured profile of mean velocity $\langle V_\theta \rangle$. Having swept through the values of modeling parameters r_{res}, w, and $\delta n/n$, we minimized the differences between the „experimental“ profile of velocity oscillations at the MHD frequency (δV_{MHD}), which was estimated based on the measured f_D values without regard to the influence of an island on the position of scattering and the value of poloidal wavenumber q_θ, and the „model“ profile (δV_{mod}), where the indicated features were taken into account. The $\delta n/n$ values in an island were varied within the interval from 0 to 25%. Laser Thomson scattering [9] was used to perform comparative measurements of temporal dynamics of the electron density in the examined regime both on resonance surface $q = 2$ and outside of an island. It was found that the maximum relative density perturbation $\delta n/n$ in the interior of an island did not exceed 10%.

It turned out to be impossible to characterize the observed δV_{MHD} velocity profile (circles connected by curve *1* in Fig. 3, *a*) using only the mechanisms from the examined model. The procedure of parameter variation allowed us

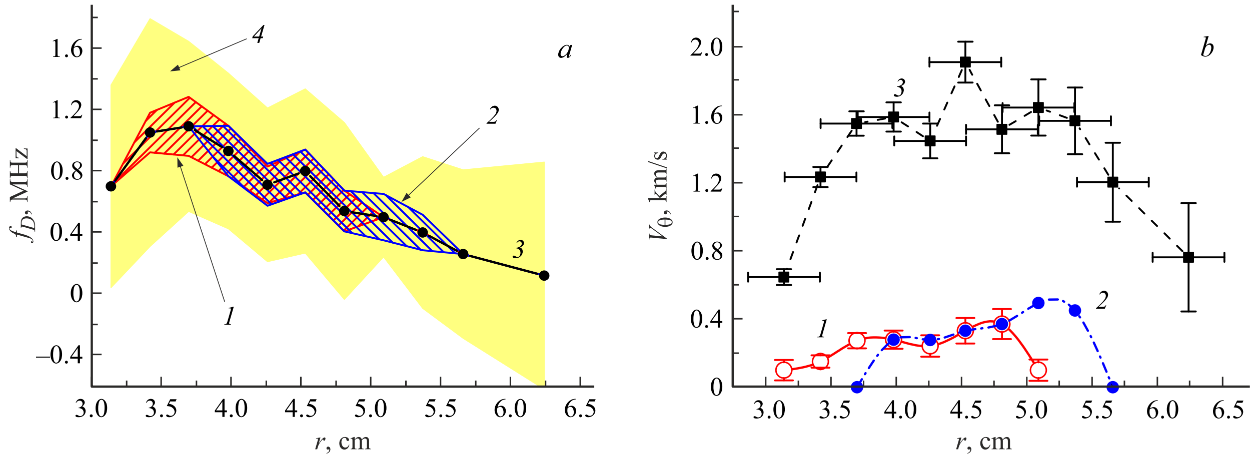

Figure 2. *a* — Radial profiles of parameters characterizing Doppler frequency shift $f_D(t)$: amplitudes of its oscillations at MHD (*1*) and GAM (*2*) frequencies relative to the mean level (*3*) against the background of its dispersion (*4*); *b* — radial profiles of parameters characterizing velocity V_θ: amplitudes of its oscillations at MHD (*1*) and GAM (*2*) frequencies and the mean value (*3*).

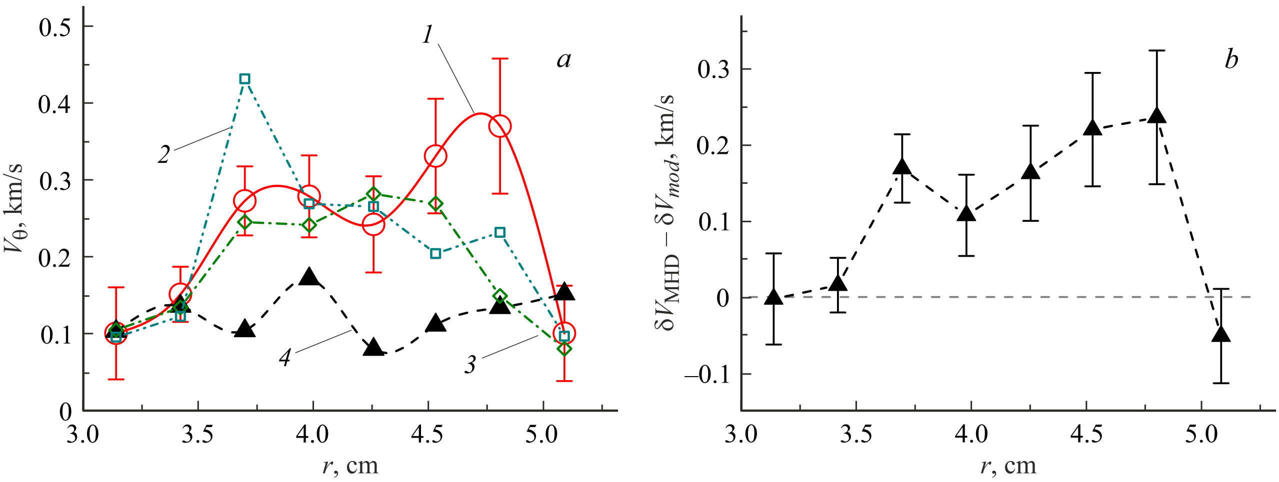

Figure 3. *a* — Radial profiles of velocity oscillations at the MHD frequency: „experimental“ δV_{MHD} profile (*1*), „model“ profiles for MAPE = 20% with a large density perturbation $\delta n/n = 25\%$ (*2*) and a short resonance radius $r_{res} = 3.6$ cm (*3*), and „model“ δV_{mod} profile for realistic parameters (*4*); *b* — difference between profiles *1* and *4*.

to reduce the mean absolute percentage error (MAPE) between the model and experimental velocity perturbation profiles only to 20%. Examples of calculated profiles are shown in Fig. 3, *a* with symbols of two types (squares and diamonds connected by lines *2* and *3*). Parameters $r_{res} = 4.3$ cm, $w = 1.1$ cm, and $\delta n/n = 25\%$ were determined for the first of these calculations (curve *2*), while the second one (curve *3*) had $r_{res} = 3.6$ cm, $w = 1.4$ cm, and $\delta n/n = 10\%$. Parameters $\delta n/n$ (in the first case) and r_{res} (in the second case) were nowhere near the estimates and the results of measurements by other methods. Model velocity profile δV_{mod} obtained with realistic parameter values is represented by triangles connected by curve *4*; the MAPE value in this case was reduced just to 50% at the following parameter values: $r_{res} = 4.5$ cm, $w = 1.2$ cm, and $\delta n/n = 10\%$. Although the δV_{mod} velocity perturbation amplitudes were lower than δV_{MHD}, their contribution cannot be neglected, since it is comparable to the measurement error level or exceeds it. The obtained result may be regarded as an illustration of the presence of both a finite „modulation“ contribution to velocity perturbation δV_{mod} and a real rotation velocity perturbation in a magnetic island. Difference $\delta V_{\mathrm{MHD}} - \delta V_{mod}$, which is presented in Fig. 3, *b*, may serve as the lower estimate of this real perturbation. The $\delta V_{\mathrm{MHD}} - \delta V_{mod}$ profile values (with errors taken into account) at its boundaries, which are located outside of an island, were near-zero. The velocity increases to 0.15–0.25 km/s near the boundaries of an island and drops to 0.1 km/s as one gest closer to its center.

The key result of the present study, which was focused on interpreting the experimentally observed oscillations of the Doppler frequency shift of the ES spectrum at the rotation frequency of a magnetic island, is the estimate of the amplitude of oscillations of the poloidal plasma rotation velocity in an island. This amplitude turned out to be as high as 0.25 km/s. The estimate was obtained with account for the probable diminishing influence of the effects of modulation of the ES position and the poloidal wavenumber of fluctuations. Viewed against the background of a mean plasma rotation velocity of 1.5−2 km/s, the velocity perturbation did not exceed 8−17% at the boundaries of an island and decreased further in its interior.

Funding

This study was supported financially under state assignment No. 0034-2021-0002 of the Ioffe Institute; the operation of the FT-2 tokamak and basic diagnostics was supported partially under state assignment No. 0040-2024-0028 of the Ioffe Institute.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin