Rotation Coupling of Magnetic Islands with Different Toroidal Wave Numbers due to Plasma Viscosity in Tokamak

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Introduction. The well-known electromagnetic coupling of the tearing-modes (see [1]) with different poloidal, *m*, and equal toroidal, *n*, numbers occurs because in toroidal geometry each mode has side-band components that differ by the *m* numbers. On the contrary, the tearing-mode does not have side-band *n*-harmonics because of the axisymmetric tokamak geometry with respect to the main vertical toroidal axis. Therefore, the electromagnetic coupling of tearing-modes with different toroidal, *n*, numbers seems impossible. However, rotation of these different-*n* modes can be coupled via viscous radial transfer of angular momentum in plasma. This sort of coupling has been observed earlier in the T-10 tokamak [2].

The experimental data on the rotation coupling between $m = 2$, $n = 1$ and $m = 3$, $n = 2$ modes in the T-10 tokamak and simulation of these data are presented in this paper.

Experimental observations. T-10 is a tokamak with a circular plasma cross-section. The major and minor radii of the vacuum vessel are $R = 1.5$ m and $r_{VV} = 0.4$ m. The plasma minor radius determined by the position of the rail limiter is $a = 0.3$ m. The presented experiments were carried out at the discharge parameters: toroidal magnetic field was 2.12-2.42 T, discharge current was 210-246 kA, line-average density of deuterium plasma was about $1\times10^{19}\,\mathrm{m}^{-3}$. The $m = 2$, $n = 1$ and $m = 3$, $n = 2$ harmonics of the Error Field at the plasma boundary were 1.5×10^{-4} T and 0.25×10^{-4} T respectively.

In the T-10 tokamak, the space structure of MHD modes is measured with a set of poloidal magnetic field sensors located at the inner side of the vacuum vessel wall. The poloidal magnetic field perturbation can be represented by a superposition of several modes with certain *m* and *n* numbers. For each mode, the magnetic perturbation at the radial position of the magnetic sensors is $B(\theta,\varphi,t) = B_C(t)\cos(m\theta - n\varphi) + B_S(t)\sin(m\theta - n\varphi)$, where φ and θ are the toroidal and poloidal angles respectively, $B_C(t)$ and $B_S(t)$ are the cosine and sine components of the magnetic perturbation. The spatial phase of each mode is defined as $\Phi(t) = \arctan\left[B_S(t)/B_C(t)\right]$. The Instantaneous Angular Velocity (IAV) of the mode is $\Omega(t) = d\Phi/dt$.

In the specially chosen T-10 regime, the $m = 2, n = 1$ mode with (1.5-2.5) kHz intrinsic frequency and the $m = 3, n = 2$ mode with (3-5) kHz intrinsic frequency are observed. The behavior in time of these two modes differs in detail from pulse to pulse in the chosen tokamak regime. We compare the mode rotation peculiarities for cases of single mode (the other mode is not present) and double mode (both modes are present simultaneously) at certain time periods. The case of single modes is shown in Fig.1 and Fig.2 while the case of double modes is shown in Fig.3 and Fig.4.

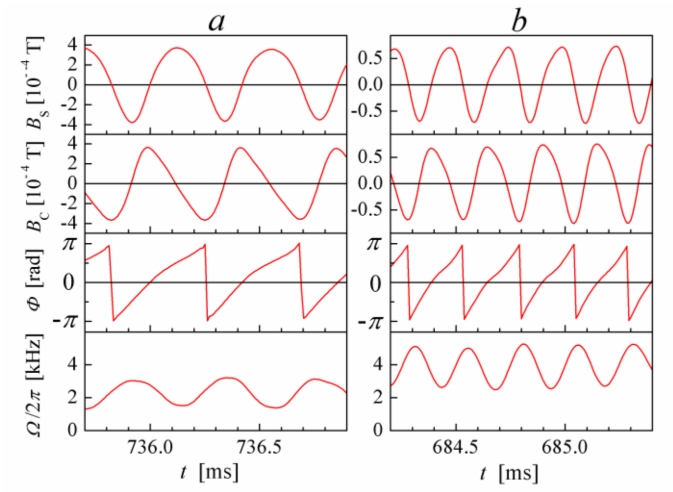

Fig.1. Experimental waveforms of single $m = 2$, $n = 1$ (a) and single $m = 3$, $n = 2$ (b) modes: sine and cosine components of magnetic perturbations; spatial phases; Instantaneous Angular Velocities

In the case of single modes, the periods of observed IAV variations in time are equal to the periods of each mode oscillations. This sort of rotation irregularity is attributed to oscillations of the electromagnetic torque, applied to the Resonant Plasma Layer (RPL) from the Resonant Magnetic Perturbation (RMP), along with the island rotation. The Fourier spectra of the IAV oscillations, $\tilde{\Omega}$, are shown in Fig.2 for the case of the single mode presence. Each of these spectra for the $m = 2, n = 1$ and $m = 3, n = 2$ modes contains only one spike denoted by number "1" and number "2" respectively.

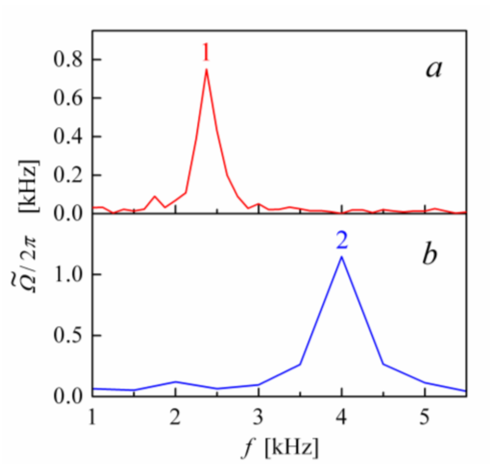

Fig.2. Fourier spectra of experimental IAV oscillations, $\tilde{\Omega}$: for single $m = 2$, $n = 1$ (a) and single $m = 3$, $n = 2$ (b) modes

If the $m = 2$, $n = 1$ and $m = 3$, $n = 2$ modes are present at the same time (see Fig.3 and Fig.4), the rotation irregularity (IAV oscillations) of each mode due to the Error Field is used as a marker to distinguish this mode effect on the IAV oscillations of the other mode. The Fourier spectra of the IAV oscillations are shown in Fig.4 for the case of the double mode presence.

Each of the spectra in Fig.4 for the $m = 2$, $n = 1$ (a) and $m = 3$, $n = 2$ (b) modes contains two spikes indicating the both IAV-oscillation frequencies. The primary spikes denoted similarly to spikes in Fig.2 by number "1" for $m = 2$, $n = 1$ mode and by number "2" for $m = 3$, $n = 2$ mode correspond to the mode rotation irregularity originated at $q = 2$ and $q = 1.5$ magnetic surfaces due to the rotating tearing-mode interaction with permanent

Error Field. The secondary spikes denoted by number "3" for $m = 3$, $n = 2$ mode and number "4" for $m = 2$, $n = 1$ mode correspond to the reciprocal IAV-oscillation admixtures produced by coupling with the other modes in question.

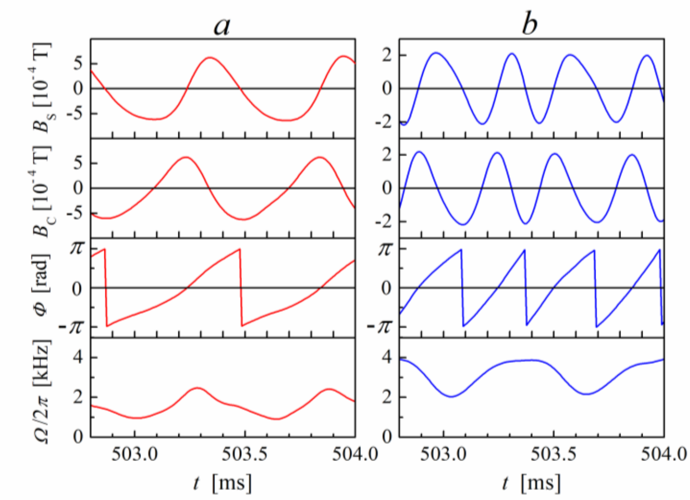

Fig.3. Experimental waveforms of double $m = 2$, $n = 1$ (a) and $m = 3$, $n = 2$ (b) modes: sine and cosine components of magnetic perturbations; spatial phases; Instantaneous Angular Velocities

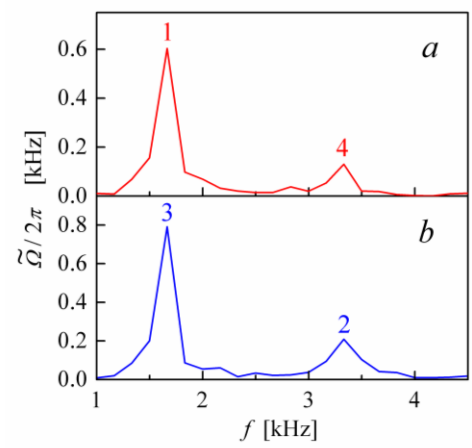

Fig.4. Fourier spectra of experimental IAV oscillations, $\tilde{\Omega}$, for double $m = 2$, $n = 1$ (a) and $m = 3$, $n = 2$ (b) modes observed simultaneously

Simulation results. The visco-resistive TEAR-code [3, 4] is used for simulation. In this code, coupled diffusion-type equations for the magnetic flux perturbation and for the plasma rotation velocities in toroidal and poloidal directions are used. The components of plasma angular velocity are supposed to be uniform inside each RPL in the vicinity of rational magnetic surfaces where the safety factor is $q = m/n$. The width of RPL is assumed to match the width of the corresponding magnetic island. In this paper, we consider two RPL areas for $m = 2$, $n = 1$ and $m = 3$, $n = 2$ modes. The time-dependent profiles of the plasma toroidal and poloidal velocity components outside the RPL areas are obtained from the plasma equations of motion with account of its inertia and viscosity. The electromagnetic torques affecting motion of each RPL are calculated as the reaction to the total torque applied from the magnetic field perturbation caused by the tearing mode to the conductors with the external helical currents producing RMP. The RMP consists of the permanent Error Field and the magnetic perturbation of eddy current induced by rotating tearing-mode in the vacuum vessel wall. The viscous torques are calculated under assumptions that the Prandtl number is of the order of unity and that poloidal viscosity coefficient, μ_θ, is two-three orders of magnitude higher than the toroidal one, μ_φ.

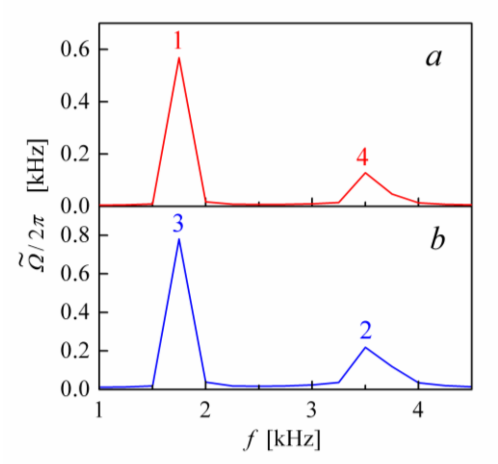

Fig.5. Fourier spectra of calculated IAV oscillations, $\tilde{\Omega}$, for double m = 2, n = 1 (*a*) and m = 3, n = 2 (*b*) modes

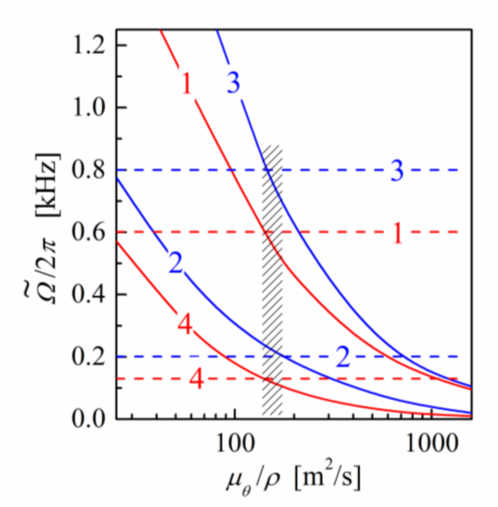

Fig.6. Results of the parametric analysis for plasma poloidal viscosity

The calculations of the two-mode coupling have been performed for the conditions of the experiment shown in Fig.3 and Fig.4. The calculated Fourier spectra presented in Fig.5 are consistent with the experimental spectra in Fig.4. The specific values of the toroidal, $\mu_\varphi/\rho = 1\,\mathrm{m}^2/\mathrm{s}$, and poloidal, $\mu_\theta/\rho = 150\,\mathrm{m}^2/\mathrm{s}$, momenta radial diffusivity used for these calculations, where ρ is the plasma mass density, have been obtained by parametric analysis.

The result of the parametric analysis for finding the poloidal viscosity is shown in Fig.6. In this figure, the solid curves with the denoting numbers corresponding to numbers in Fig.5 represent the heights of calculated spectra spikes. The levels indicated by dashed lines with denoting numbers represent the experimental-spike heights of Fig.4. The shaded area in Fig.6, where the solid curves intersect the corresponding dashed lines, indicates the result of the parametric analysis $\mu_\theta/\rho \approx 150\,\mathrm{m}^2/\mathrm{s}$. According to the parametric analysis for toroidal viscosity, the calculation results do not significantly depend on the toroidal viscosity in the range of $0.1\,\mathrm{m}^2/\mathrm{s} \le \mu_\varphi/\rho \le 10\,\mathrm{m}^2/\mathrm{s}$.

Summary. A rotation coupling between $m = 2$, $n = 1$ and $m = 3$, $n = 2$ tearing-modes has been observed in the T-10 tokamak. The comparison of simulation results with the experimental data confirms the assumption that the observed rotation coupling is attributed to plasma viscosity.

References

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