Reverse of Tokamak Plasma Rotation under Tearing-Mode Locking by External Resonant Magnetic Perturbation

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Introduction. Rotation of tokamak plasma attracts considerable attention in the fusion research because this rotation, particularly shear of rotation velocity, affects plasma stability and confinement. The plasma rotation velocity in the vicinity of a rational magnetic surface can be influenced by the development of the tearing mode. According to experiments and numerical modelling, the tearing-mode locking by externally applied non-rotating Resonant Magnetic Perturbation (RMP) with the same helicity can be followed by a rotation reversal of the Resonant Plasma Layer (RPL) occupied by magnetic island structure (see [1, 2]). Results of calculations and analysis of the plasma rotation reversal subject to the tearing mode locking are presented in this paper. The main attention is paid to conditions providing the rotation reversals separately in toroidal and poloidal directions, as well as the concurrent changes of both rotation directions.

Computational model. The TEAR code [3, 4] used for the calculations is based on the visco-resistive MHD approximation that gives coupled diffusion-type equations for the magnetic flux perturbation and for the plasma rotation velocities in toroidal and poloidal directions. The axisymmetric velocities of the poloidal and toroidal plasma rotation $\mathbf{V} = V_\theta(r,t)\mathbf{e}_\theta + V_\varphi(r,t)\mathbf{e}_\varphi$ are obtained from the equation of motion poloidal and toroidal components:

$$\rho\frac{\partial(V_\theta - V_{\theta 0})}{\partial t} = f_{\mathrm{EM}\,\theta} + \mu_\theta\left\{\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial(V_\theta - V_{\theta 0})}{\partial r}\right] - \frac{V_\theta - V_{\theta 0}}{r^2}\right\}, \tag{1}$$

$$\rho\frac{\partial(V_\varphi - V_{\varphi 0})}{\partial t} = f_{\mathrm{EM}\,\varphi} + \frac{\mu_\varphi}{r}\frac{\partial}{\partial r}\left[r\frac{\partial(V_\varphi - V_{\varphi 0})}{\partial r}\right], \tag{2}$$

where ρ is the ion mass density, μ_θ and μ_φ are the poloidal and toroidal coefficients of plasma viscosity. In (1) and (2), $f_{\mathrm{EM}\theta}$ and $f_{\mathrm{EM}\varphi}$ are the poloidal and toroidal components of the electromagnetic force applied to the RPL, $\mathbf{V}_0 = V_{\theta 0}(r)\,\mathbf{e}_\theta + V_{\varphi 0}(r)\,\mathbf{e}_\varphi$ is the intrinsic plasma rotation velocity in the absence of magnetic islands and RMP that is an input parameter in the calculations as well as the RMP waveform. Integration of the equation of motion over the RPL under the assumption that the plasma angular velocity components are uniform inside this layer gives equations for the plasma poloidal and toroidal rotation velocities at the radius of the rational magnetic surface, r_S, where the safety factor $q = m/n$:

$$\frac{I_\theta}{r_S}\frac{\partial\left(V_\theta - V_{\theta 0}\right)}{\partial t} = T_{EM\,\theta} + T_{V\theta} \ , \tag{3}$$

$$\frac{I_\varphi}{R}\frac{\partial\left(V_\varphi - V_{\varphi 0}\right)}{\partial t} = T_{EM\,\varphi} + T_{V\varphi} \ . \tag{4}$$

Here, m and n are the poloidal and toroidal wave numbers, I_θ and I_φ are the poloidal and toroidal moments of inertia of the RPL, $T_{EM\theta}$ and $T_{EM\varphi}$ are electromagnetic torques, $T_{V\theta}$ and $T_{V\varphi}$ are viscous torques. The electromagnetic torques are calculated as the reaction to the total torque applied to the conductors with the external helical currents from the magnetic field perturbation caused by the tearing mode. The viscous torques are calculated under assumptions that the Prandtl number is of the order of unity and that poloidal viscosity coefficient is about two-three orders of magnitude higher than the toroidal one.

The instantaneous value of the mode angular frequency is:

$$\Omega(t) = \frac{d\Phi_\psi}{dt} = \Omega_{nat} + \frac{\pi a^2 \omega_R}{W}\Delta_i' \sin\left(\Phi_i - \Phi_\psi\right), \tag{5}$$

where

$$\Omega_{nat} = \left(mV_\theta / r_S - nV_\varphi / R - \omega^*\right)\Big|_{r_S} \tag{6}$$

is the natural frequency depending on the components of plasma velocity and generally speaking on the electron diamagnetic drift, ω^*. In the equation (5), Δ_i' is the part of the tearing mode stability index arising under the externally applied RMP and the magnetic field of helical current induced in the vacuum vessel, Φ_i and Φ_ψ are the angular phases of the total resonant magnetic perturbation and perturbation caused by the tearing mode respectively, $\omega_R = \eta/\mu_0 a^2$ is the inverse resistive time.

In the case of sufficiently large magnetic islands and hot plasma (see [5]) under investigation in this paper, the instantaneous value of the mode angular frequency, Ω, is approximately equal to Ω_{nat}. The mode locking occurs due to the effect of the RMP-produced electromagnetic torque applied to the RPL. The toroidal and poloidal electromagnetic torque components are balanced by corresponding components of the viscous torque depending on the plasma rotation profiles outside the RPL.

Results of calculations. To begin with, the results of the tearing mode m=2, n=1 simulation for the T-10 tokamak parameters (see [4]) under an assumption that the electron diamagnetic drift, ω^*, in (6) can be omitted are presented in FIG.1 – FIG.4. The waveforms of the RMP, the magnetic island width, toroidal and poloidal components of plasma rotation velocity at $r = r_S$ and the natural frequency after the RMP switch-on at $t = 0$ are presented in FIG.1 for $\mu_\varphi/\rho = 1\,\mathrm{m^2/s}$ and $\mu_\theta/\rho = 500\,\mathrm{m^2/s}$.

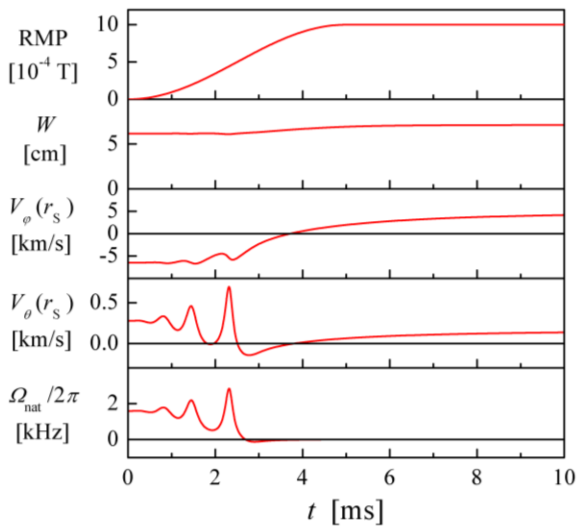

FIG.1. Dynamics of RMP effect on the magnetic island width, plasma rotation velocities and natural frequency

In this example, the RMP application does not result in a significant rise of the magnetic island width. After a transient velocity-oscillation stage when RMP is not sufficient for locking, the velocity components finally achieve some saturation levels. The natural frequency reduces to zero that corresponds to the mode locking. In FIG.1, the direction of ultimate poloidal velocity coincides with the direction of poloidal velocity before RMP application while the toroidal velocity changes its sign.

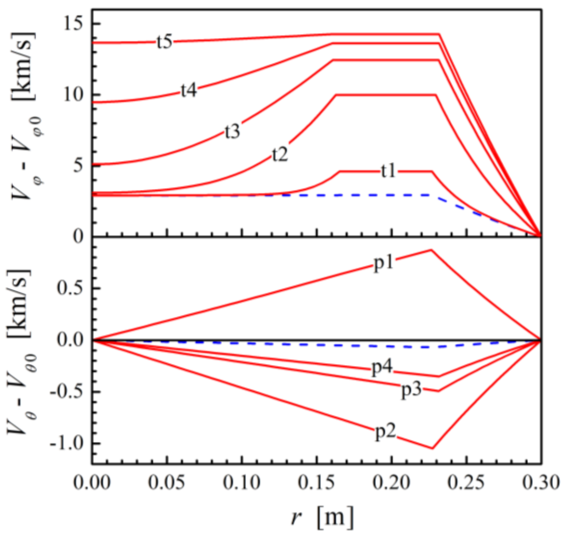

FIG.2. Profiles of plasma toroidal velocity at $t = 2$ ms (t1), $t = 4$ ms (t2), $t = 6$ ms (t3), $t = 10$ ms (t4), $t = 20$ ms (t5) and plasma poloidal velocity at $t = 2.3$ ms (p1), $t = 2.8$ ms (p2), $t = 10$ ms (p3), $t = 20$ ms (p4) after RMP switch-on. The dashed curves correspond to the velocity profiles before the RMP application

For the simulation conditions of FIG.1, the time variations of the plasma velocity profiles with respect to intrinsic profiles are presented in the FIG.2. In this figure, the poloidal-velocity profiles p1 and p2 are given for the time moments when $V_\theta(r_S)$ reaches the maximum and minimum values during the oscillation stage. The toroidal velocity oscillations are less because the toroidal moment of inertia is higher than the poloidal one. After the oscillation stage, the time for the toroidal velocity profile saturation is longer than for the poloidal one due to lower value of the toroidal viscosity.

The results of parametric analysis of the toroidal and poloidal viscosity effects on the ultimate values of the plasma velocity components at $r = r_S$ are illustrated in FIG.3 and FIG.4. In these figures, one can see that the reversal of the toroidal or poloidal velocity occurs when the corresponding plasma viscosity is sufficiently small.

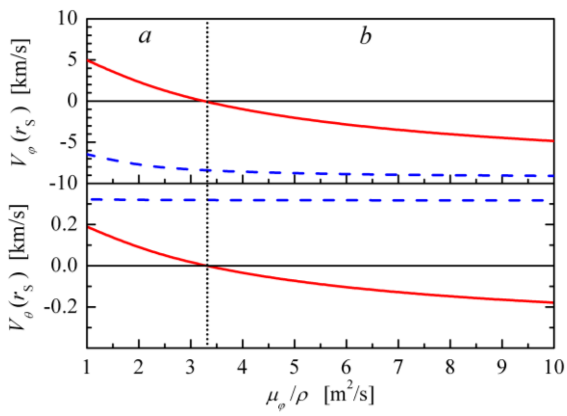

FIG.3. Reversals of the toroidal (a) and the poloidal (b) components of plasma velocity vs the toroidal viscosity at $\mu_\theta/\rho = 500\,\mathrm{m}^2/\mathrm{s}$. The dashed curves represent velocities before RMP application

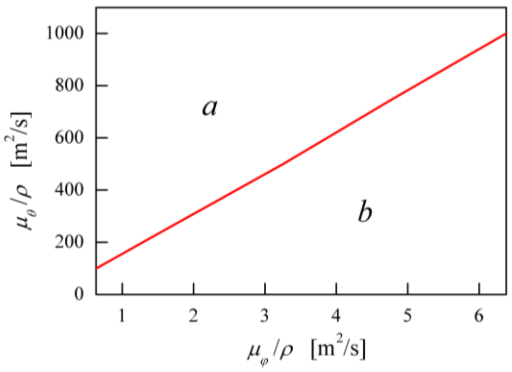

FIG.4. Areas of toroidal (a) and poloidal (b) plasma-velocity reversals under mode locking by RMP. The solid line represents termination of both rotation components: $V_\varphi(r_S) = V_\theta(r_S) = 0$

The simulation result of the mode locking effect on the plasma rotation with account of the electron diamagnetic drift in the equation (6) is shown in FIG.5. According to calculations, concurrent reversals of the RPL toroidal and poloidal rotation velocities at the mode locking can occur under this assumption.

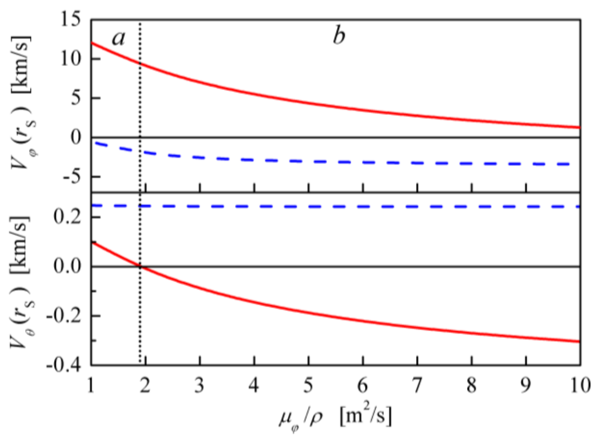

FIG.5. Reversals of the toroidal (a) and both the toroidal and poloidal (b) components of plasma velocity vs the toroidal viscosity at $\mu_\theta/\rho = 500\,\mathrm{m}^2/\mathrm{s}$ with account of $\omega^*/2\pi = -1\mathrm{kHz}$. The dashed curves represent velocities before the RMP application

Discussion and summary. At the mode locking, the superposition of plasma toroidal and poloidal velocity projections at $r = r_S$ on the direction of the mode phase velocity (the $\mathbf{r}\times\mathbf{B}$ direction) is inhibited till the full stop of the mode rotation. Therefore, if the initial directions of these velocity projections coincide, at least one of the RPL velocity components can change its sign. These alternative possibilities depend on interrelation between toroidal and poloidal viscosity coefficients. Concurrent reversals of the RPL toroidal and poloidal rotation velocities can occur at the mode locking if the electron diamagnetic drift is significant for the tearing mode natural frequency. The RPL velocity reversal extends due to plasma viscosity to some area surrounding the RPL.

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