Symmetry breaking driving spontaneous plasma rotation in tokamak fusion devices

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Abstract
Plasma rotation plays a critical role in improving plasma confinement in a magnetically confined fusion device. Spontaneous plasma rotation and its reversal of orientation without external momentum input have been observed in some tokamak fusion devices, while the underlying physics is not well understood. A new mechanism based on neoclassical toroidal plasma viscosity induced by symmetry breaking is proposed and well reproduces both spontaneous toroidal rotation and its reversals in tokamaks by considering a small non-axisymmetric displacement in the plasma center, since internal instabilities are often observed in those experiments. The nonlinear hysteresis process of plasma rotation reversals is also well reproduced in the modeling. The mechanism for driving spontaneous plasma rotation proposed in this paper may be utilized for achieving more economical operation of future tokamak fusion reactors.

Keywords: intrinsic rotation, neoclassical toroidal plasma viscosity, rotation reversals

Plasmas usually rotate in nature, such as in stellar interiors, accretion disks, and laboratory plasmas. Because particle, energy and momentum confinement are all linked to each other, understanding the physics of plasma rotation is imperative to comprehend plasma dynamics in general and momentum confinement in particular. As often happens in plasmas, more than one mechanism can cause plasma rotation. It is best to test the supposed theoretical mechanism in a laboratory setting to resolve several competing processes.

Intrinsic or spontaneous plasma rotation without external momentum input has been widely observed in tokamaks [1–3]. Furthermore, it is interesting to observe that the intrinsic plasma rotation spontaneously changes its orientation when plasma density exceeds a threshold [4–10]. This phenomenon still puzzles us, although some efforts have been made in the last ten years [11]. A previous study has shown that the rotation reversal can be induced by the change of turbulence flux based on Non-Maxwellian equilibria effect [12]. Spontaneous rotation and its reversals are often observed in plasmas with sawteeth caused by internal kink magnetohydrodynamics (MHD) instability [11], and the reversal normally occurs inside the sawtooth inversion radius, i.e. \( q = 1 \) magnetic flux surface. Here, \( q \) is the safety factor. Sawtooth crash and its precursor mode induce non-axisymmetric displacement of
magnetic flux surface, \( \tilde{\zeta} \), which causes helical magnetic field ripple \( \delta B = \frac{\nu}{eB} \tilde{\zeta} \cdot \nabla B \), where \( B \) is equilibrium magnetic field strength and \( B_0 \) is the magnetic field strength on the magnetic axis. The additional radial drift caused by helical magnetic field ripple results in a non-ambipolar transport flux known as neo-classical toroidal plasma viscosity (NTV) [13–16]. Therefore, a novel mechanism based on NTV physics [13] is proposed to explain spontaneous toroidal rotation reversals in tokamaks in this paper. The experimentally observed rotation reversals during plasma density ramps can be well reproduced by the modeling using the NTV-TOK code [17, 18].

There are solutions of steady state toroidal plasma rotation, \( \omega_{\|} \), in both co-current (\( \omega_\| > 0 \)), electron root) and counter-current (\( \omega_\| < 0 \), ion root) directions determined by NTV in low collisionality regime because of symmetry breaking [17, 19]. In stellarator, H-mode is achieved by using electron root to improve plasma confinement performance [20]. This mechanism can be used to drive flow and improve confinement in tokamaks. Toroidal rotation reversal is possible when the steady state flow jumps between ion root and electron root that determined by NTV torque depending on plasma collisionality [19].

From the NTV theory, the general form of the induced NTV torque density can be written as [17–19, 21, 22],

\[
T_{NTV} = -\frac{d\psi_e}{dV} \sum_{j=1,e} \rho_j \Gamma_j \left( \omega_\| - \omega_{\|,n} \right)
\]

\[
\omega_{\|,n} = q \left( \omega_\| + \omega_{s,i,j} - \omega_{s,j} + \frac{\lambda_{s,j}}{\lambda_{1,n}} \omega_{T,j} \right),
\]

where \( 2\pi \psi_e \) is the poloidal magnetic flux and \( 4\pi V \) is the volume enclosed by each surface, \( \rho_j \) is the ion mass density, \( \mathcal{R} \) is the major radius, \( \langle \cdot \rangle_{\tilde{\zeta}} \) denotes the flux surface average, \( \omega_\| \) and \( \omega_{\|,n} \) are the toroidal and poloidal angular frequencies, \( \omega_{s,i,j} \) and \( \omega_{s,j} \) are diamagnetic frequencies for the \( j \) \((i \equiv \text{ions, and } e \equiv \text{electrons}) \) species and the energy integrals \( \lambda_{s,j} \propto |\delta B|^2 \) driving by helical ripples, has been defined in equation (23) in [18]. Equation (2) is the general form of the steady-state flow for each species, if the contribution of this species dominates. The total NTV torque on the plasma induced by internal kink mode is in fact coming from an exchange of torque between plasma and the wall or surrounding structures [23].

It is known that the direction of the steady state flow depends on normalized plasma collisionality [21], \( \nu_{se} \propto n_e / T_e \), where \( \nu_{se} \) is the ratio of the electron collisionality to bounce frequency, \( n_e \) is electron density and \( T_e \) is electron temperature. The NTV torque has different asymmetric limit regimes depending on collisionality, such as the \( 1 / \nu \) regime, the \( \nu / \sqrt{\nu} \) regime, and the superbanana plateau regime, etc. This has been summarized in a recent review paper [24]. In low collisionality plasmas, the ion is often in the \( \nu / \sqrt{\nu} \) regime or the superbanana plateau regime, but the electron may be still in the \( 1 / \nu \) regime [21, 22], because the electron collisionality is normally much larger than the \( E \times B \) drift frequency. Therefore, electron NTV is comparable to ion NTV, and hence, there are multiple solutions of steady-state flow, i.e. electron root and ion root [13], which is well known in ELMO Bumpy Torus [25] and stellarators [26]. In high collisionality plasmas, the ion NTV is normally dominant and there is an ion root only, which was reported previously in DIII-D during the application of non-axisymmetric magnetic field [27]. In the low density case with low collisionality, the steady state flow is possible at the electron root, i.e. in the co-current direction, if there is a helical ripple. The threshold collisionality for this transition is of the order \( \nu_{se} \sim 0.01 \) [21].

During the ramping up of plasma density, the direction of toroidal rotation might jump from the co-current (electron root) into the counter-current (ion root) direction at a certain critical density, because there is only ion root at high density with high collisionality. This explains the observed rotation reversals in the experiments during density ramp. To verify this hypothesis, a modeling of the intrinsic rotation driven by NTV torque is given in the following based on one example case with plasma conditions similar to the experimental ones on C-Mod [4].

Figure 1 shows the magnetic configuration constructed by using the CHEASE code [28] and radial profiles of \( n_e \), electron (ion) temperature \( T_e(T_i) \), \( m/n = 1/1 \) radial displacement \( \xi \) and \( q \) used in the NTV torque simulation using the NTV-TOK code [17, 18, 21]. For simplicity, \( n_i = n_e \) has been used. Since sawtooth crash and its precursor mode usually induce a 1/1 displacement of the order of centimeters, an internal kink mode eigen function like displacement with an amplitude \( \xi \) = 1 cm is used. This displacement results in a helical ripple \( \delta B \) of the order \( 10^{-3} \) in this simulation. The temporal evolution of the toroidal angular momentum is simulated by solving the momentum transport equation (17) without input torque in [22]. In the present study, only the diffusion term in the momentum transport flux is considered for simplicity. The NTV torque and all required inputs to evaluate it are updated at each step. The steady state flow is obtained until the toroidal flow saturates to a fixed profile state, i.e. the NTV torque is balanced by the momentum diffusive term. The momentum diffusivity is estimated from \( \chi = \alpha^2 / T_E \), in which \( T_E \) is the energy confinement time and \( \alpha = 0.21 \) m is the plasma minor radius on C-Mod [7]. In this simulation, the dependence of \( T_E \) on plasma density is fitted by using first order polynomials functions from the profiles shown in figure 28 in [7]. Here, the value of \( T_E \) are in the range from 15 ms to 35 ms and the value of \( \chi \) are in the range from 1 m\(^2\) s\(^{-1}\) to 3 m\(^2\) s\(^{-1}\). The pinch velocity is assumed to be zero and no input torque is considered in calculation.

The simulation results well reproduce the main features of experimentally observed rotation reversals during plasma density ramp [7], as shown in figure 2. Two cases are considered in the simulation. In figure 2(a), the red solid line with triangles shows the dependence of the steady-state toroidal rotation on the core electron density \( n_{e0} \) at the normaliztion minor radius \( \rho = 0.2 \) during density ramping up. The toroidal rotation reverses from the co-current to the counter-current direction suddenly when the plasma density exceeds a critical value at \( n_{e0} \sim 6 \times 10^{20} \) m\(^3\). The corresponding critical \( \nu_{se} \) is around 0.035. In figure 2(b), the red line for another case
Figure 1. (a) The $(\rho, \theta)$ grids in Hamada coordinates, and (b) the radial profiles of $n_e$ (red solid line), $T_e$ (pink dashed dotted line), $T_i$ (green dotted line), $\xi$ (black dashed line) and $q$ (black solid line).

Figure 2. (a) The red line with triangles is the dependence of steady state toroidal rotation $\omega_\phi$ on the electron density $n_{e0}$ during density ramping up and the green dashed line is the dependence of $\nu^*_{e}$ on $n_{e0}$ near the plasma core at $\rho = 0.2$; (b) the red line with asterisks is the dependence of $\omega_\phi$ on $n_{e0}$ at $T_{e0} = 2.0$ keV when the density ramping down at the beginning and then ramping up later and the blue dashed line with triangles is the dependence of $\omega_\phi$ on $n_{e0}$ at $T_{e0} = 2.5$ keV. shows the trajectory of $\omega_\phi$ during density ramping down at the beginning and then ramping up later, which is done using the rotation profile obtained from the solution in the previous density case as the initial rotation profile and using zeros rotation profile as an initial condition for first one in the simulation. Here, the diffusion coefficient $\chi$ is 1.5 times larger than that used in the first case just to reproduce the hysteresis in experiment. The hysteresis shown in the red line is a typical nonlinear bifurcation process. The toroidal rotation reversal and hysteresis shown in the modeling in these two cases agree well with the experimental observations (figures 2 and 4 in [7]). Furthermore, the blue dashed line of figure 2(b) shows that the critical density for rotation reversal increases with increasing electron temperature (or decreasing collisionality), which might explain the observed plasma current $I_p$ dependence of critical density (figure 10 in [7]) since the ohmic heating power increases with increasing $I_p$.

More details about the simulations are shown in the following. The magnitude of the NTV torque density at two different plasma densities respectively above and below the threshold in figure 2(a) with zero plasma rotation is shown in figure 3(a). The red solid line indicates that NTV torque profile at the lower density is positive in the core, while the blue dot-dashed line indicates that the NTV torque profile at the higher density is negative. The magnitude of NTV torque density can be up to $0.1$ N m$^{-2}$ with $\xi = 1$ cm and scales with $\xi^2$. It is the same order of magnitude as high as the NBI torque density in present tokamaks.

The intrinsic rotations determined by zeroing NTV torque density (b) and the final steady state flows determined by the
The final steady state rotation is reversed at these two densities case (blue dashed line) as shown in figure 3 (red solid line), while there is only one ion root in the higher density case. The unstable root and the counter-current roots in the intrinsic rotation determined by NTV, i.e. the core non-axisymmetric displacement caused by internal kink mode. The magnitude of NTV torque is big enough to change the steady state rotation jumps between ion root and electron root determined by the NTV theory can explain toroidal rotation of plasma collisionality, i.e. increasing of machine size and performance [19], it may play a critical role in driving flows in future tokamak fusion reactors. The mechanism for driving spontaneous plasma rotation proposed in this paper may be utilized for achieving more economical operation of future fusion reactors.

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