Toroidal rotation braking by ELM-induced NTV on EAST

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Abstract:
Spontaneous rotation has been observed in LHCD H-mode plasmas with type III ELMs (edge localized modes) on EAST, and it revealed that type III ELMs can induce the loss of both core and edge toroidal rotation. Here we work on the breaking mechanism during the ELMs. Several large tokamaks have discovered ELMs filamentary structures. It revealed that the ELMs are filamentary perturbations of positive density formed along the local field lines close to the LCFS. Currents flowing in the filaments induce magnetic perturbations, which break symmetry of magnetic field strength and lead to deformation of magnetic surface, thus generate NTV (neoclassical toroidal viscosity) torque that affects toroidal rotation. We adopt 1cm maximum edge magnetic surface displacement from experimental observation and our calculation shows that the edge torque is about 0.35 N/m\textsuperscript{2}, and the core very small. The expected angular momentum density change is about 3.8N/m\textsuperscript{2}, nearly 10 times larger than the calculation. Previous work on EAST has suggested that there is a mechanism at the edge that breaks the rotation, while the core rotation change is mostly likely related with momentum transport to the edge. In other words, NTV torque should have less impact on the core but great on edge, which corresponds with the calculation as well. In our calculation, we found that the core has little dependence on the magnetic surface displacement, while the edge relies on it heavily. The exact profile of the edge torque has uncertain that comes from the exact edge displacement profile and the accurate mode number. However, the magnitude of the edge NTV torque is still nearly 0.1-1N/m\textsuperscript{2}, indicating it should been emphasized while considering rotation change. Further work including transport code is planned.

1 Introduction

Plasma rotation has been observed on large tokamaks and attracts considerable attention for years, but there are still many mysterious problems not answered in many respects. It plays an important role in the control of the magnetohydrodynamics (MHD) instabilities in tokamaks because of its stabilizing effects on resistive wall modes (RWMs) and neoclassical tearing modes (NTMs). It also improves the error field tolerance through increasing field penetration threshold. In future reactor-grade devices, rotation provided by the external momentum input may not be available due to the large machine sizes,
high densities and the limitations of beam current. However, the intrinsic rotation may provide the necessary velocity, which has been observed in many tokamaks. The common feature is that the change in toroidal rotation velocity increase with the change in stored energy normalized to the plasma current during the transition from the L-mode to the H-mode phase (Rice Scaling \[1\]). The mechanism driving intrinsic rotation is still a mystery, leading to a very rapid development both in theory and modeling. Many effects influence the evolution of toroidal flow in tokamaks plasmas, such as radial transport of toroidal flow due to collision-induced and microturbulence-induced anomalous processes, which is usually considered within the context of an equilibrium axisymmetric magnetic field model. Recently, there has been increasing interest in the effects of small three-dimensional magnetic field perturbation effect on tokamak plasmas. Although the magnetic field of a tokamak is designed to be toroidally symmetric, there is always a slight non-axisymmetric magnetic perturbation (NAMP) due to intrinsic error field, MHD perturbations in the plasma and external magnetic perturbation applied to control edge localized modes (ELMs) and RWMS. An understanding of the plasma braking mechanism with a helical magnetic perturbation becomes an important issue for an optimization for the application of magnetic perturbations. Recently, the neoclassical toroidal viscosity (NTV) torque induced by non-axisymmetric magnetic perturbation in the collisionless regimes in tokamaks has been explored in modeling and experiments, both confirmed the NTV theory developed by Shaing \[2-4\]. Recently, the perturbed distribution is solved numerically from the bounce-averaged drift kinetic equation, and the numerical solutions are in good agreement with the analytic results in different asymptotic limit of the collisionless regimes \[5, 6\]. Strong magnetic braking effect without mode locking during the application of NAMP (so-called non-resonant magnetic braking) has been observed in the experiments in tokamaks. The NTV torque may explain the observed braking effect.

Another concern is related to ELMs. Understanding and control of ELMs are essential for the H-mode operation, which is baseline operating scenario for the ITER tokamak experiment. ELMs may originate from a combination of current and pressure gradient driven MHD modes, and are usually identified by $D_\alpha$ radiation from the plasma edge. With recent advent of fast cameras, the spatial structure of the ELMs has been observed and it is now widely believed that ELMs result in a medium number of filaments, localized in the perpendicular plane and extended along the magnetic field and expelled from the plasma edge into the scrape off layer (SOL). MHD activity of ELMs generates magnetic fluctuations, and such measurements have been performed by magnetic pickup coils close to the vessel wall or on insertable probes. There are two fast reciprocating Langmuir probe (FRLP) systems inserted through two horizontal ports at the outer midplane separated by 89° from each other in the toroidal direction \[7\]. They can provide information on electron temperature, electron density, floating potential, Mach number, heat flux, radial electric field and Reynolds stress at the plasma edge with 5 MHz sampling rate. Also, they can provide magnetic fluctuation during ELMs. This measurement provides us general information of the magnetic perturbation magnitude, which can be used for further modeling.

Spontaneous rotation has been widely observed in Ohmic H-mode plasma on Alcator C-Mod and DIII-D, in ICRF H-mode plasmas on JET and Alcator C-Mod, and in ECH H-
mode plasmas on DIII-D. It has been observed that type I ELMs induce a loss of toroidal rotation in NBI H-mode plasmas on DIII-D and JET. In recent campaign, spontaneous rotation has been observed in LHCD H-mode plasmas with type III ELMs on EAST and it is firstly observed that type III ELMs initially induce the loss of the core and edge spontaneous rotation, and then the core reaches a steady state with low rotation velocity. The basic idea in this paper is, ELMs bring in magnetic perturbation, which can also induce NTV torque, thus can affect the rotation. The magnetic perturbation generated by ELMs can be modeled considering their filamentary nature, and the NTV torque can be obtained using the recently developed numerical method [5, 6].

2 Observation of rotation braking during ELMs

The first H modes with type-III edge localized modes (ELMs) were obtained on EAST superconducting tokamak with lithium-wall coatings heated by lower-hybrid current drive (LHCD) in the recent experimental campaign. Two imaging 2-D x-ray crystal spectrometers and fast reciprocating Langmuir probe diagnosis have been developed for measuring the toroidal rotation at the core and edge regions, respectively. The changes of toroidal flow (TF) under the conditions of LHCD have been observed both at core and edge regions, and it was found both the edge and core toroidal rotation velocity decreased every time ELMs appeared, indicating that type III ELMs can induce the loss of core and edge toroidal rotation (FIG. 1).

FIG. 1: Time histories of (a) $D_\alpha$ brightness, (b) central argon toroidal rotation velocity change relative to 3.10s (L-mode phase), (c) the edge plasma toroidal rotation

3 NTV theory

The toroidal symmetry breaking, induced by the non-axisymmetric magnetic perturbation, will cause a nonambipolar radial particle flux. The radial currents of the nonambipolar diffusion will cause a toroidal viscosity, which is called NTV, and its equivalent
torque is called the NTV torque. A common used form of the magnetic field strength $|B|$ can be written as

$$B = B_0[1 - \epsilon \cos \theta - \sum_n (\cos \theta) e^{in\alpha}] \equiv B_{eq} + \delta B \quad (1)$$

where $B_0$ is the magnetic field strength on the magnetic axis, $\epsilon$ is the amplitude of the $\cos \theta$ component, $n$ is the toroidal mode number of the helical perturbation, $\alpha = q\theta - \zeta$ is the drift angle, $q$ is the safety factor, $\theta$ and $\zeta$ are the poloidal and toroidal angles, respectively, in Hamada coordinate. The magnetic field can be expressed as

$$\vec{B} = \frac{d\Psi_p}{dV} \hat{V} \times \nabla \alpha \quad (2)$$

where $2\pi \Psi_p$ is the poloidal magnetic flux, $\hat{V} \equiv \frac{V}{4\pi}$, and $V$ is the plasma volume enclosed by the flux surface. $(\hat{V}, \theta, \zeta)$ are the Hamada coordinates with Jacobin $J \equiv (\nabla \hat{V} \times \nabla \theta) \cdot \nabla \zeta |^{-1} = 1$, which can significantly simplify the expressions with $\nabla$ operator. The linearized bounce-averaged drift kinetic equation can be written as

$$\omega_{d\alpha} \partial_\alpha f_1 + \omega_{d\hat{V}} \partial_{\hat{V}} f_M = \frac{\nu_d}{2\epsilon} \langle L(f_1) \rangle_b \quad (3)$$

where $\omega_{d\alpha}$ and $\omega_{d\hat{V}}$ are the bounce-averaged drift frequencies of the particles in the $\alpha$ and $\hat{V}$ direction respectively. The general form of the magnetic flux surface averaged particle flux $\Gamma$ can be written as

$$\Gamma_j = \rho_j R_0^2 \frac{\sqrt{\epsilon q^2 \omega_{lj}^2}}{2\sqrt{2\pi^{3/2} \epsilon_j (d\hat{V}\Psi_p)}} \sum_n \lambda_{1,n}(\omega_\zeta - \omega^j_{n,c,n}) \quad (4)$$

According to the relationship between the viscosity and the particle flux, the general form of the induced toroidal NTV torque density can be written as

$$T_{NTV} = -\sum_j \langle R^2 \nabla \phi \cdot (\nabla \cdot \vec{\Pi}_j) \rangle_\Psi = -\tau_{NTV}^{-1} \langle R^2 \rangle_\Psi \rho_i \omega_\phi \quad (5)$$

where $\phi$ is the geometric toroidal angle.

Recently, NTV torque induced by non-axisymmetric magnetic perturbation in the collisionless regimes in tokamaks is modeled by solving the bounce-averaged drift kinetic equation numerically, and here is a general result showing the dependence of the ion NTV torque on the plasma rotation and collisionality (Fig. 2).

4 Filament structure of ELMs

Recently, several large tokamaks have discovered the filamentary structure of ELMs, such as MAST, ASDEX-U, JET, DIII-D, NSTX and C-Mod. ELMs evolve into filaments when the instability is saturated and the transport effects become pronounced. It revealed that
FIG. 2: The dependence of the ion NTV torque on the plasma rotation and collisionality

the ELMs are filamentary perturbations of positive density formed along the local field lines close to the LCFS. As the ELM induces a significant loss of current, it is reasonable to assume that at least part of the current is lost in the filaments. There is already work using such filament model to determine key parameters for the evolution of the ELM filaments [8]. Currents flowing in the filaments induce magnetic perturbations, which can also break symmetry of magnetic field strength and lead to deformation of magnetic surface, thus generate NTV torque that affects toroidal rotation. Our work is to identify if this magnetic perturbation of ELMs is sufficient to brake the rotation.

5 Modeling and results

The key problem in NTV calculation is the proper identification of the deformation of magnetic surface. In fact, plasma response always exists and it is difficult to determine the final form of the magnetic perturbation in real tokamaks. Such importance of plasma response to nonaxisymmetric perturbations has been addressed [9]. The variation of the magnetic field strength should be evaluated on the distorted magnetic surface, which means the Lagrangian variation in the field strength should be calculated. This Lagrangian variation in the magnetic field strength is given by

$$\delta_L = \delta_E B + \delta_\xi B$$

The first term in the right-hand side of equation is the Eulerian variation, which is almost independent on the plasma response; the second term is the contribution from plasma response and it usually plays more important role, as can be larger by an order of magnitude. To simplify, here we adopt the second part as the perturbed magnetic field. The
magnetic surface displacement has the form \( \xi = \xi + 0\cos(m\theta - n\zeta) \), and \( m = qn \). The safety factor is of the magnetic surface where ELMs take place, 2.5cm in pedestal near the LCFS. Also, \( \xi_0 \) here can have a poloidal distribution, as the filament current has been reported to be centered poloidally at the outboard midplane with a Gaussian decay in several tokamaks [8]. Here, we assume the single mode structure of ELMs, that is to say, filaments of ELMs are located evenly in space, see Fig. 3. The maximum displacement of

\[ \text{FIG. 3: The perturbed magnetic surface model} \]

the magnetic surface in pedestal is assumed to be 0.02cm, as it was observed on KSTAR [10]. The corresponding magnetic perturbation is \( 10^{-3}T \). The core rotation velocity is 14km/s, and the edge 4km/s. The plasma parameters used in NTV code [5, 6] is listed in FIG. 4. With all these experimental data and assumptions, The NTV torque is then

\[ \text{FIG. 4: The spatial profiles of (a) the electron temperature, (b) the electron density and (c) the rotation velocity vs. normalized radius} \]

calculated, see Fig. 5. Next, we estimate torque using the relationship \( T_t = \partial_t \langle m, n RV_t \rangle \). At the edge, \( m \sim 1.67 \times 2 \times 10^{-27}kg \), \( n \sim 2.5 \times 10^{19}m^{-3} \), \( R \sim 2.27m \), \( \Delta V_t \sim 10km/s \), \( \Delta t \sim 0.5ms \), the expected \( T_t \sim 1N/m^2 \), this is nearly in accord with the calculation.

Previous work on EAST has suggested that there is a mechanism at the edge that breaks the rotation, while the core rotation change is mostly likely related with momentum
transport to the edge. In other words, NTV torque should have little impact on the core but great on edge, which is in accord with the calculation as well. To emphasize, overall evaluation including using transport code with our torque calculation is needed, to analyze the time-varying behavior of the rotation profile [11], and compare the momentum transport time scale from core to edge with the experimental observation.

In our calculation, we found that the core has little dependence on the magnetic surface displacement, while the edge relies on it heavily. Also, the mode number affects the NTV; mostly it changes the profile of the edge torque. The exact profile of the edge torque has uncertain that comes from the exact edge displacement profile and the accurate mode number. However, the magnitude of the edge NTV torque is still nearly $0.1 - 1 N/m^2$, in accord with the experimental observation. Further calculation and analysis are needed, and later we may use the plasma displacement calculated from ELITE code in our calculation to compare with that here.

6 Summary

Both plasma rotation and ELMs are important issues in tokamak physics, and they are related to each other in many aspects, such as effect of ELMs on rotation in JET [11] and effects of rotation on the stability of type-I ELMs [12]. Thus, exploring the mechanism of how they affect each other is essential in further experiment and modeling. In this paper, we make the first attempt to identify the NTV torque induced by ELMs which brakes the rotation. With proper assumptions and the recent developed NTV code, it is shown that the ELMs-induced NTV torque is significant enough to make a difference to rotation. Previous work analyzed that the loss of core rotation is related to a momentum transport to edge, and here we found the loss of edge rotation may be related to the NTV torque. The exact structure of ELMs is complex, here we used a simplified single mode number. Further work using perturbations generated by other codes such as ELITE is planned, to additionally identify the significance of the ELMs-induced NTV torque in rotation braking events.
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