Effects of Localized Neoclassical Toroidal Viscosity Effects on the Toroidal Rotation Profile in KSTAR

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Abstract. KSTAR provides a great environment to carry out the NTV study in that the intrinsic error fields and the toroidal field ripples are very small in magnitude, and asymmetric magnetic fields can be added by the in-vessel coil current on demand. In this paper, we report both theoretical and experimental studies on NTV in KSTAR. It is shown that the radial transport of the toroidal angular momentum, $mnR\mathbf{e}^{\zeta}\cdot\mathbf{V}$, is also proportional to the first order of gyro-radius. In this work, we introduce a different method of the NTV torque estimation, that includes the usual toroidal angular momentum transport besides the NTV torque. It may resolve some known discrepancies between theories and experiments and reveal unknown puzzles at the same time. We show that the inherent neoclassical toroidal viscosity induced by the intrinsic error fields and toroidal field ripple in KSTAR is small enough not to deform the pedestal structure in toroidal rotation profiles, always observed uniquely in H-mode KSTAR plasmas.

I. INTRODUCTION

The plasma flow has been an important issue for several decades since it plays a crucial role in magnetohydrodynamics (MHD) stability and plasma confinement. In 1990s, the polodal flow received particular attention due to the close relation between its shear and L-H transition. In early 2000, the toroidal plasma flow became a highly interesting topic when the spontaneous toroidal rotation was measured in C-Mod [1] and a supporting theory [2] was developed. In 2003, it was shown that the neoclassical toroidal viscosity (NTV) is enhanced significantly in the presence of the nonaxisymmetric magnetic fields [3]. Since then, the NTV has been studied intensively as a toroidal flow control knob.

KSTAR provides a great environment to carry out the NTV study in that the intrinsic error fields and the toroidal field (TF) ripples are very small in magnitude [4], and asymmetric magnetic fields can be added by the in-vessel coil current on demand. In this paper, we report recent progress of both theoretical and experimental studies on NTV in KSTAR.

II. TOROIDAL ANGULAR MOMENTUM TRANSPORT WITH NON-AXISYMMETRIC FIELDS

In [3,5,6], the covariant component of the plasma flow speed vector, $\mathbf{e}_{\zeta}\cdot\mathbf{V}$, is adopted to demonstrate the toroidal rotation damping by asymmetric magnetic fields since it gives a neat form of the toroidal viscosity $\langle\mathbf{e}_{\zeta}\cdot\nabla\cdot\mathbf{\Pi}\rangle$ and the plasma really flows in $\mathbf{e}_{\zeta}$ direction instead $\nabla\zeta$ direction. Here, $\mathbf{e}_{\zeta}=g^{-1/2}\nabla\psi\times\nabla\theta$, $g^{1/2}=(\nabla\psi\times\nabla\theta\cdot\nabla\zeta)^{-1}$, ψ is the poloidal flux function, θ and ζ are the poloidal and the toroidal angle respectively. Since what we measure in the experiments is close to the toroidal angular momentum, $mnR\mathbf{e}^{\zeta}\cdot\mathbf{V}$, rather than $mnR\mathbf{e}_{\zeta}\cdot\mathbf{V}$, it is essential to see if the contribution of the toroidal viscosity to the radial transport of the contravariant component, $\mathbf{e}^{\zeta}\cdot\mathbf{V}$ is also significant. It is shown that the radial transport of the toroidal angular momentum, $mnR\mathbf{e}^{\zeta}\cdot\mathbf{V}$, is also proportional to the first order of gyro-radius [7]. It implies that the toroidal flow damping in the presence of asymmetric magnetic field can be described appropriately regardless of the toroidal direction chosen.

III. TRANSPORT ANALYSIS TO OBTAIN THE NTV FROM THE EXPERIMENTS

In the past, the NTV torque is inferred from the rate of change of the measured toroidal rotation, which is thought to give the ratio of the viscosity term to the inertia term in the momentum equation on the local flux surface. Since this commonly used method does not properly include the diffusion and the convection of the toroidal momentum, the local NTV torque can be frequently misestimated. The validity of this method can be examined with a simulated case. The temporal evolution of the toroidal rotation profile (V_ϕ) due to the local NTV torque can be simulated by solving a simplified (effective) momentum balance equation as

$$\frac{\partial L_\Phi}{\partial t} + \nabla \cdot \left(-\chi_\Phi^{\mathrm{eff}} \frac{dL_\Phi}{dr} \right) = T_{\mathrm{NBI}} + T_{\mathrm{add}}$$

where $L_\phi \equiv mnRV_\phi$ is the momentum density, χ_ϕ^{eff} is the effective momentum diffusivity, T_{NBI} is the torque density driven by NBI and T_{add} is the additional torque density, which can be regarded as the NTV torque density here. Figure 1 shows an example of the simulation result on the toroidal rotation damping by the local NTV torque density. Figure 1(a) shows the time traces of the toroidal rotation velocities at several locations. It is simulated that the toroidal rotation is reduced by the local NTV torque from 1000 to 1500 ms. The input NBI and NTV torque density profiles are shown in Fig. 1(b). The temporal change of the toroidal rotation profile during the addition of the local NTV torque is shown in Fig. 1(c).

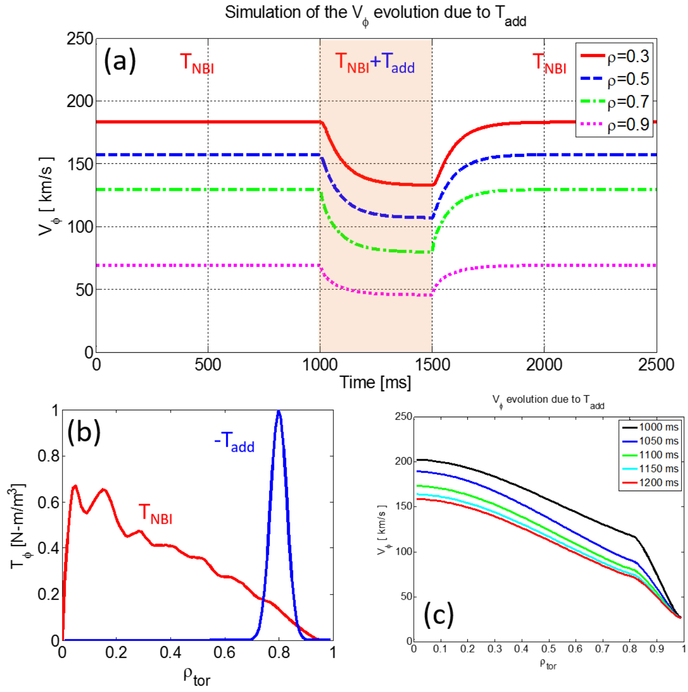

Figure 1 Simulated test case: (a) the temporal evolution of the toroidal rotation at several locations, (b) the input NBI and NTV torque density profiles, and (c) the temporal chanse of the toroidal rotation profile during the addition of the NTV torque

Then, we have tried to estimate the additional NTV torque density from $\frac{\partial L_\phi}{\partial t} \sim T_{NTV}$ for this case. Actually, one usually needs to fit the toroidal rotation data over finite time to deduce $\partial L_\phi / \partial t$ in real experiment condition. In addition, the time range for the fitting can be varied by researchers. Here, we have estimated the NTV torque density by fitting the data over 30 ms, 50 ms, and 100 ms as shown in Fig. 2. Note that the start time for the time range is set to be the time (at 1000 ms) when the NTV torque is applied to plasma. Finally, we found that $\partial L_\phi/\partial t$ cannot represent the NTV torque density profile as shown in Fig. 3.

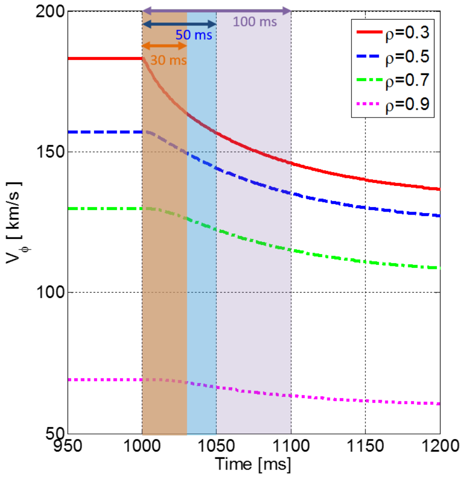

Figure 2 Time ranges for estimating $\partial L_\phi/\partial t$

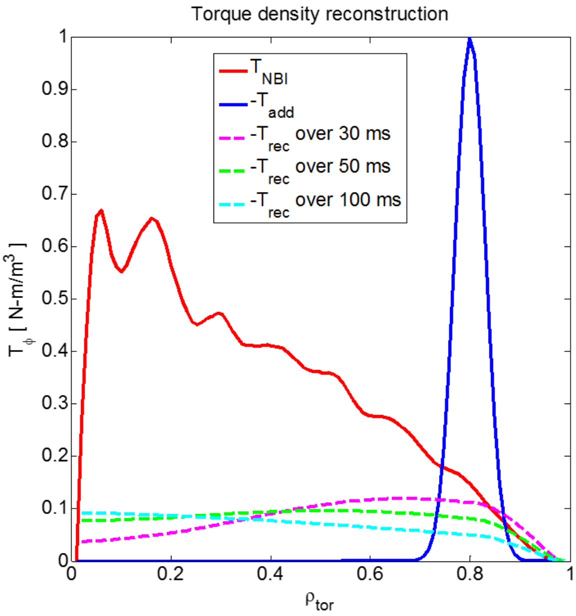

Figure 3 The reconstructed torque density profiles from $\frac{\partial L_\phi}{\partial t} \sim T_{NTV}$

In this work, we introduce a new method of the NTV torque estimation, that includes the usual toroidal angular momentum transport besides the NTV torque. It is possible to estimate the unknown torque density profile by solving the momentum balance equation directly while χ_ϕ^{eff} profile and $\partial L_\phi/\partial t$ are known. In principle, this method can provide an exact solution for the unknown torque from $\partial L_\phi/\partial t$ as long as it solves the momentum balance equation which describes the real momentum transport physics in plasmas. Figure 4 clearly shows that the reconstructed torque density profile obtained by this method represents the input NTV torque density profile accurately except for the numerical errors at the boundaries (ρ → 0 and ρ → 1). Note that it does not necessarily need to apply this method to the transient phase only. It provides a same answer with the $\partial L_{\phi}/\partial t$ profiles at two-time points. In addition, it is applicable to the time-varying torque density profile. It may resolve some known mismatches between theories and experiments and reveal unknown puzzles at the same time.

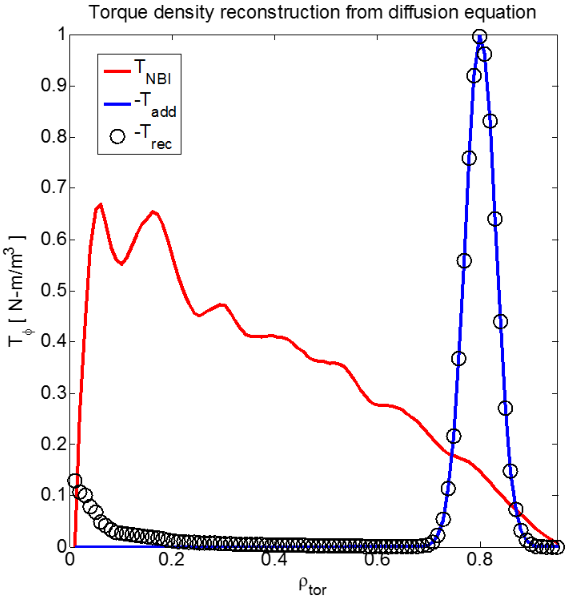

Figure 4 The reconstructed torque density profile (T_{rec}) obtained by solving the momentum balance equation represents the input local torque density profile (T_{add}) very well

IV. PEDESTAL STRUCTURE IN THE TOROIDAL ROTATION PROFILES

We show that the inherent neoclassical toroidal viscosity induced by the intrinsic error fields and toroidal field ripple in KSTAR is small enough not to deform the pedestal structure in toroidal rotation profiles, always observed uniquely in H-mode KSTAR plasmas [8] as shown in Fig. 5. We also find that the inherent neoclassical toroidal viscosity obtained from the typical levels of the intrinsic error fields and toroidal field ripple in other tokamaks is not negligible when the plasma is rotating in the co-I_p direction, thereby reducing the toroidal rotation significantly and making the pedestal structure hard to be observed as shown in Fig. 6. It implies that important physics phenomena related to the momentum transport whether by collisions or turbulence can be hidden by a large toroidal flow modification by NTV. On the other hand, the pedestal structures are more likely to appear in tokamak plasmas that is rotating in the counter-I_p direction since the magnitude of the radial electric field can be large in the whole range.

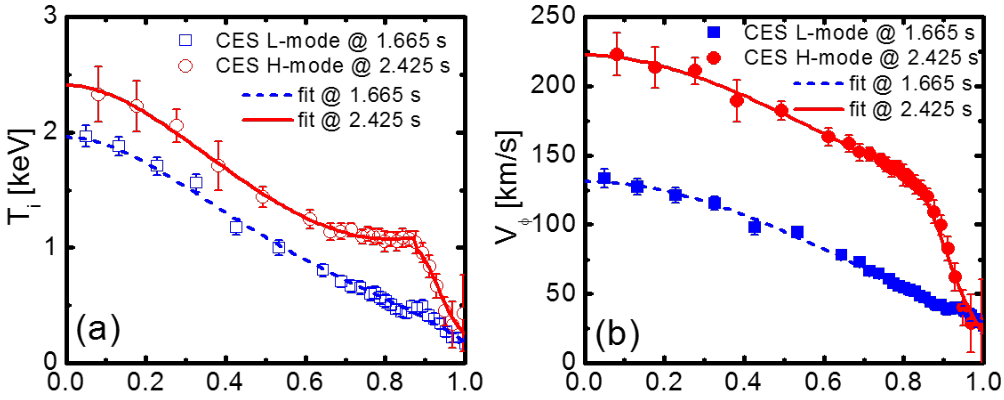

Figure 5 (a) The ion temperature and (b) toroidal rotation profiles between L- and H-modes in KSTAR

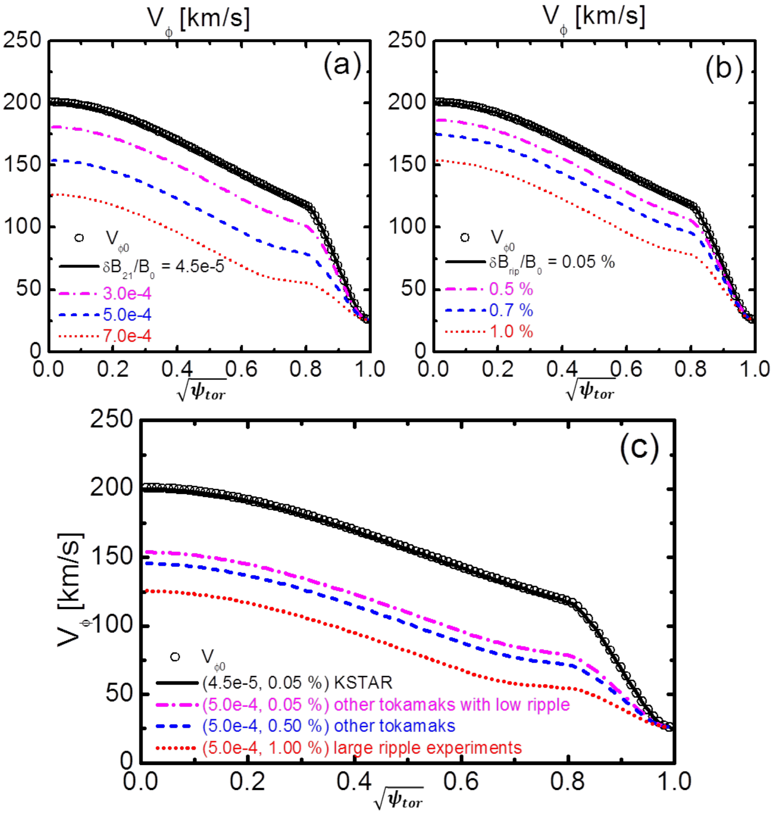

Figure 6 Toroidal rotation profiles according to (a) intrinsic error field, (b) toroidal field ripple, and (c) intrinsic error field + toroidal field ripple levels

V. SUMMARY

In this study, we show that the radial transport by non-axisymmetric magnetic fields is not negligible regardless of the toroidal direction choice. We also show that the pedestal structure can be deformed by intrinsic or applied non-axisymmetric magnetic fields. To show this, the NTV term is added in the momentum balance equation. In such a process, it was found that the toroidal rotation profile evolution time scale is comparable to the confinement time scale. It implies that the NTV can be overestimated when the momentum diffusion effects are not considered.

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