Topic: EX-S, or EX-C (crosses boundaries)

Physical Characteristics of Neoclassical Toroidal Viscosity in Tokamaks for Rotation Control and the Evaluation of Plasma Response*

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Favorable use of low magnitude ($\delta B/B_0 \sim O(10^{-3})$) three-dimensional (3D) magnetic fields applied to tokamak devices has been demonstrated by the mitigation or suppression of ELMs [1] and Alfvenic modes [2], and by altering the plasma rotation profile, ω_ϕ, to strongly affect the stability of disruption-producing modes in tokamak plasmas, such as neoclassical tearing modes and resistive wall modes [3]. Neoclassical Toroidal Viscosity (NTV) [4] caused by non-ambipolar diffusion inherently due to the 3D field has been associated with such rotation alteration. Research in the past few years by various groups worldwide has examined further details of NTV theory and experiment which have raised critical questions for extrapolation to ITER and future devices, including the dependence on collisionality, 3D field spectrum, the plasma response to the applied 3D field, and rotation profile hysteresis. Our present work focuses on these questions with new analysis of yet unpublished experimental results from the low aspect ratio ($A \sim 1.3$) National Spherical Torus Experiment (NSTX), with complementary research from dedicated experiments at relatively high aspect ratio ($A \sim 3.5$) in the long-pulse superconducting KSTAR device. This new research includes analysis of experiments from the extensive NTV database of both devices to evaluate new aspects of the physical characteristics of NTV, and to quantitatively address the critical questions stated above.

Experiments conducted on NSTX utilizing rapid changes (significantly faster than the momentum diffusion time) of the applied 3D field, $\delta\boldsymbol{B}$, best isolate the torque profile exerted on the plasma by NTV. The measured angular momentum damping and the theoretically computed NTV torque density profiles, T_{NTV}, created by a range of experimentally applied 3D field spectra are analyzed, including configurations with dominant $n = 2$ and $n = 3$ field components. Fig. 1 compares the theoretically computed T_{NTV} profile vs. minor radial coordinate to the measured change in the plasma angular momentum density, dL/dt, as $\delta\boldsymbol{B}$ is rapidly changed. The analysis computes $\delta\boldsymbol{B}$ in full 3D, and uses the complete Shaing formulation of T_{NTV} valid for all collisionality regimes and the superbanana plateau regime [5] for both ions and electrons as implemented in the NTVTOK code [6]. The calculation includes the effect of flux surface displacement derived from the assumption of a fully penetrated $\delta\boldsymbol{B}$ (the "vacuum field assumption"). A standard decomposition of $\delta\boldsymbol{B}$ into in-surface and normal components is made to first order in the displacement, $\delta B = \vec{b} \bullet \left(\vec{B}/B\right) + \left(\vec{\xi} \bullet \nabla B\right)$. The large radial variations of the theoretical T_{NTV} shown are due in part from this, and appear in similar published models of $\boldsymbol{\xi}$. In contrast, such large radial variations of T_{NTV} are not readily observed experimentally. Rather, T_{NTV} is experimentally found to be radially extended, without strong localization of the torque as is

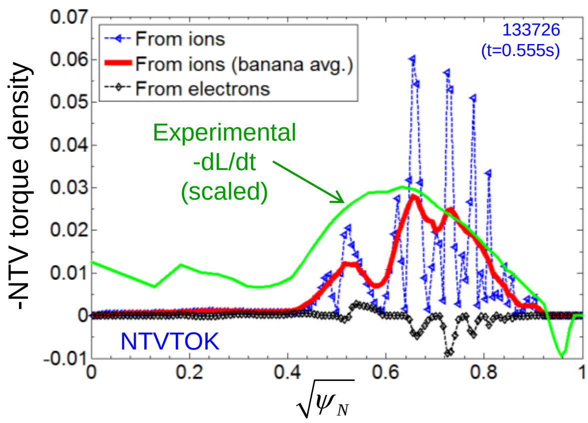

Fig. 1: T_{NTV} profile components for an n = 3 field configuration in NSTX, computed from (i) ions using the vacuum field assumption, (ii) ions using banana width-averaging, (iii) electrons. The measured (-dL /dt) profile is shown in green.

observed in resonant braking by magnetic islands. Solution of the momentum diffusion equation shows that details of the ω_ϕ evolution related to these strong radial variations may be discerned from the charge exchange recombination spectroscopy diagnostic. Experiments at low A yield unique information, as the strong field gradient at small major radius yields a small computed displacement $|\xi| \sim 0.3$cm, which is smaller than either the ion banana width or gyroradius. This result suggests that the computation should include averaging of T_{NTV} over such spatial scales. Fig. 1 shows the result of averaging the ion T_{NTV} profile over the banana width, which more closely matches the measured *dL/dt* profile. This work directly supports the near-term application of NTV for model-based, closed-loop ω_ϕ control in NSTX-Upgrade. Results from a state-space rotation controller that has been designed and tested using applied 3D fields as an actuator will be shown. When applied to the solution of the momentum diffusion equation, the controller clearly illustrates the detailed action of the NTV on the time-evolved ω_ϕ profile versus the longer timescale momentum diffusion.

A further important and favorable observation for ω_ϕ control is the lack of hysteresis on the ω_ϕ profile when altered by non-resonant NTV, as it reaches the same steady-state profile for a given applied field independent of the initial ω_ϕ. Dedicated long-pulse experiments in KSTAR clearly illustrate this (Fig. 2). The rotation profile pedestal is reduced, altering ω_ϕ toward an L-mode profile shape while maintaining H-mode energy confinement. Analysis of these experiments also finds the expected theoretical scaling of T_{NTV} with $\delta \boldsymbol{B}^2$, and strong dependence on ion temperature ($\sim T_i^{2.5}$).

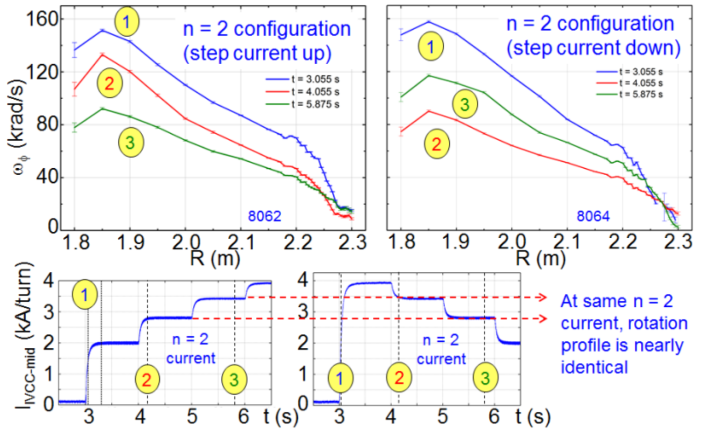

Fig. 2: Rotation alteration in KSTAR using an n = 2 field configuration shows no strong hysteresis (error bars shown).

Another critical and advanced area of research regarding T_{NTV} profile computation is the evaluation of the plasma response, with increased importance in plasmas with moderate to high beta. A major issue is that the plasma displacement ξ and its plasma-induced amplification are not directly measured in detail in any experiment and the development of first-principles models is still an active research area. Enabled by the large database of measured T_{NTV} profiles (e.g. Fig. 1), the present study takes a unique approach in verifying plasma response models. Due to the strong theoretical dependence of the T_{NTV} profile $\propto \delta \boldsymbol{B}^2$, the quantitative T_{NTV} profile measurements significantly constrain the allowable field from ξ and its plasma induced amplification. Models presently being tested against experiment include the vacuum field assumption for ξ, and various physics models in the M3D-C[1] resistive MHD code. Fig. 3 shows the computed averaged $|\delta \boldsymbol{B}|$ from M3D-C[1], compared to the banana width-averaged vacuum field assumption model for the NSTX plasma in Fig. 1. Initial analysis shows the M3D-C[1] single-fluid model produces a flux surface-averaged $|\delta \boldsymbol{B}|$ magnitude consistent with the experimentally measured T_{NTV}. Analysis in the next several weeks will compare theoretical and experimental T_{NTV} profiles quantitatively using the M3D-C[1] generated fields.

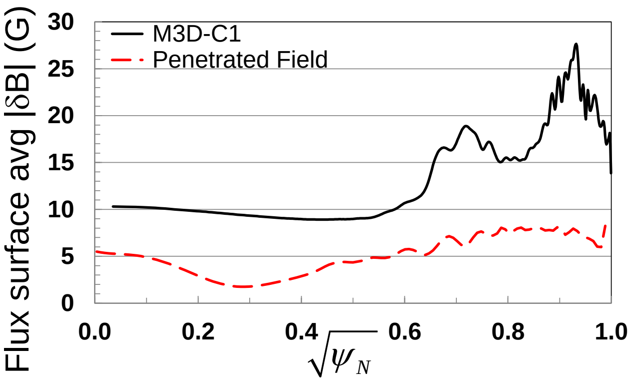

Fig. 3: Flux-surface averaged $|\delta B|$ for fully-penetrated field model, and the M3D-C[1] single fluid model.

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