Topic: EX-S

Isolation of Neoclassical Toroidal Viscosity Profile Under Varied Plasma and 3D Field Conditions in Low and Medium Aspect Ratio Tokamaks*

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The phenomenon of Neoclassical Toroidal Viscosity (NTV) due to non-ambipolar particle diffusion in a three-dimensional (3D) field has been proposed in theory [1], with the first quantitative validation by experiment [2] performed a decade ago. The effect has been used for positive purposes in tokamak experiments, including alteration of the plasma rotation profile, ω_ϕ, using low magnitude ($\delta B/B_0 \sim O(10^{-3})$) 3D fields. This ω_ϕ alteration can strongly affect the stability of disruption-inducing modes in tokamak plasmas, such as neoclassical tearing modes and resistive wall modes [3]. These, and other uses of 3D fields in tokamaks (i.e. suppression of ELMs and Alfvénic modes), benefit from broader experimental investigations of the dependence of NTV on key plasma parameters and 3D field spectra [4-6]. This understanding is especially important to accurately extrapolate NTV effects to low collisionality plasmas in ITER when using 3D fields.

The present work quantitatively analyzes and compares a formidable combination of databases from two tokamak devices of significantly different aspect ratio. This new and uniquely extensive collection of data allows testing of NTV theory over a broad scope of important plasma variations including aspect ratio, q_{95}, collisionality, temperature, normalized gyroradius ρ^*, plasma rotation speed and profile, as well as applied 3D field strength and spectrum in both devices. First, a new database was generated in late 2015 in a dedicated joint international experiment to isolate and measure the NTV profile for the first time in the KSTAR superconducting tokamak at medium aspect ratio ($A \sim 3.5$). Over 360 different variations of the parameters mentioned above were produced from this experiment alone. These results are compared with new analysis of complementary experimental results from the extensive NTV database of low aspect ratio ($A \sim 1.3$) National Spherical Torus Experiment (NSTX) plasmas. In addition, a new dedicated experiment approved to run on the recently upgraded and operational NSTX-U device is expected to provide additional key data on the NTV dependence at lower plasma collisionality (potentially 10x lower than NSTX) and with new 3D field spectra allowed by independent control of the six 3D field coils on the device. NSTX-U has already reached normalized beta of 4 and peak electron temperature of 1.5 keV, indicating that the device will support the proposed experiment in spring of 2016. This dataset is quantitatively compared to the combined NTV theoretical formulation by Shaing, et al., applicable for all plasma collisionality. The theory is presented in detail in a recent comprehensive review [7].

Isolation of the NTV torque profile, T_{NTV}, is accomplished experimentally by applying the 3D magnetic field faster than the momentum diffusion time of the plasma, yielding a perturbation equation that balances the experimentally measured dL/dt profile against the theoretical T_{NTV} [2]. Figure 1 shows a full quantitative comparison of these profiles in NSTX, with T_{NTV} using a plasma response consistent with the applied 3D field (often used in theoretical calculations of T_{NTV}), emphasizing the comparison to the ion T_{NTV} profile averaged over the banana width, which as shown more accurately matches the measured dL/dt profile. Experiments at the low aspect ratio and high q of NSTX yield unique

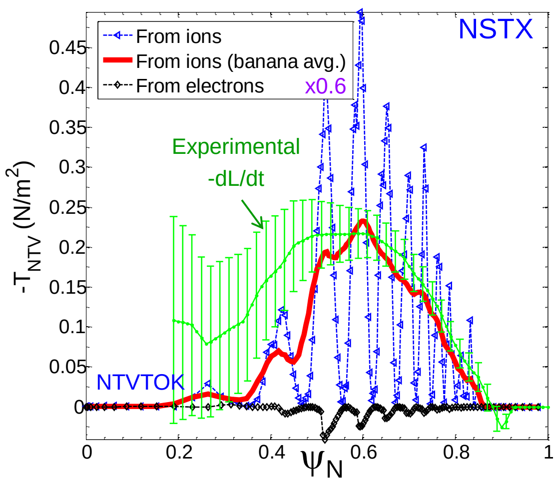

Fig. 1: T_{NTV} profile components for an n = 3 field configuration in NSTX (x0.6) computed for (i) ions using "vacuum field assumption", (ii) ions using banana width-averaging, (iii) electrons. The measured (-dL /dt) profile is shown in green.

information in this regard, as the maximum computed theoretical plasma displacement $|\xi| = 0.3$cm is smaller than the ion banana width, showing that finite-orbit effects will average T_{NTV} over such spatial scales. Further analysis of T_{NTV} will compare this to the analogous experiment at smaller ρ^* in KSTAR for which the influence of rational surfaces is also not readily apparent in the measurements (see next section). The computed magnetic field used to compute T_{NTV} includes full detail of the coils in 3D and retains the full toroidal, n, and poloidal spectral decomposition in the calculations. A change in L is not found outside of error bars in the core of NSTX plasmas for analysis intervals much less than the momentum diffusion time. In contrast, measurements of L at later times clearly show diffusion of the NTV toward the core, spoiling the measured T_{NTV} profile isolation. This emphasizes the importance of the experimental approach used here in isolating T_{NTV}.

The KSTAR experiment provides both unique results and key comparisons to the NSTX data. The large database was created in a single experiment by leveraging the long pulse (20 second plasma duration) and new (for 2015) fast power supply capability (IPS) of the device that allowed up to 18 experimental data points per pulse in 20 discharges. Six different 3D field spectra were run, which included dominantly $n = 2$, $n = 1$ field pitch-aligned, $n = 1$ field pitch non-aligned configurations, and the superposition of these $n = 2$ and $n = 1$ configurations. Several key plasma parameters were varied in the study including the applied 3D field strength, plasma collisionality (via divertor gas injection), plasma rotation speed and profile, T_i up to 3 keV, and $5.0 < q_{95} < 8.2$. Figure 2 shows the experimental evolution of the ω_ϕ profile (error bars shown) as measured by charge exchange spectroscopy (CES) diagnosis before and after the application of three primary 3D field spectra, isolating the non-resonant T_{NTV} profile. Measurements showed that strong resonant MHD modes were absent. As expected by theory, the measured rotation profile change due to the 3D field, $\Delta\omega_\phi$, (Fig. 2, bottom row) does not change sign, and is close to zero at the plasma boundary. All cases show broader $\Delta\omega_\phi$ (which represents the measured T_{NTV}) than found in NSTX, which is thought to be caused by the closer proximity of the coils to the plasma. The ability to change the relative pitch alignment of the applied 3D field to the equilibrium field adds a new capability compared to NSTX, yielding a clear and unexpected result: the non-pitch-aligned field configuration produces a stronger change to the ω_ϕ profile than the pitch-aligned case. The pitch-aligned field was expected to yield larger T_{NTV} as the amplification of δB by the plasma should be stronger in this configuration. Further analysis will determine the reason. The $\Delta\omega_\phi$ is global and non-resonant, with no strong indication of localized resonant effects, similar to NSTX results in different field configurations. The full analysis of the experimental and theoretical T_{NTV} profiles for KSTAR (analogous to the NSTX analysis (Fig. 1)) is underway. While this analysis is required for a quantitative conclusion, the NTV magnitude presently appears to be understood by simple superposition of the separate applied 3D field spectra. The full T_{NTV} analysis will include a significant improvement to the reconstructed equilibria, including for the first time CES T_i profile data, motional Stark effect measurement of the magnetic field pitch angle, and Thomson scattering for T_e and n_e, which are available for all plasmas created in these experiments.

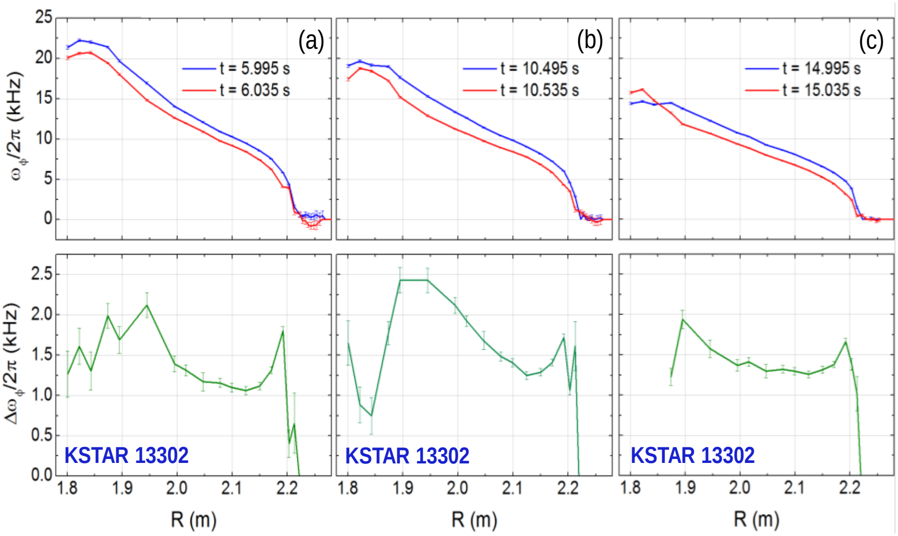

Fig. 2: Rotation profile alteration in KSTAR using (a) n = 2, (b) n = 1 pitch non-aligned, and (c) n = 1 pitch aligned 3D field configurations.

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