Peak neoclassical toroidal viscous force in the DIII-D tokamak

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Observation of a theoretically-predicted peak in the neoclassical toroidal viscosity (NTV) force as a function of toroidal plasma rotation rate Ω is reported. The NTV was generated by applying $n = 3$ magnetic fields from internal coils to low Ω plasmas produced with nearly balanced neutral beam injection. The peak corresponds to a toroidal rotation rate Ω_0 where the local radial electric field E_r is near zero as determined by radial ion force balance.

Understanding the influence of non-axisymmetric (NA) magnetic fields on toroidal plasma rotation remains a fundamental challenge of fusion plasma science. In this paper we investigate the toroidal rotation dependence of NTV driven by NA magnetic perturbations. Breaking toroidal symmetry introduces mirror and curvature forces with toroidal components that when crossed with the equilibrium magnetic field generate non-ambipolar radial particle and heat fluxes. In a fluid moment approach [1] toroidal forces arising from symmetry breaking modify the parallel stress tensor which gives a *toroidal* viscous force that is absent in perfect axisymmetry.

When the NA magnetic field amplitude is much less than the poloidal mirror trapping, i.e., $\delta B/B_0 \ll \varepsilon = r/R_0$, poloidal and *toroidal* plasma flows on magnetic flux surfaces can be determined successively [1]. First, on the ion-ion collision timescale $1/\nu_i$ ($\sim$ ms), the parallel force balance equation describes the damping of poloidal flow to a diamagnetic-like rate given by $\langle q\vec{V}_i \cdot \vec{\nabla}\theta \rangle \simeq (c_p/Z_i e)dT_i/d\chi$. Here $\vec{V}_i$ is the ion fluid velocity, T_i is the ion temperature, $Z_i e$ is the dominant ion species charge, χ is the poloidal magnetic flux function, θ (ζ) is a poloidal (toroidal) angle, c_p is a number of order unity, and $\langle \dots \rangle$ denotes a flux surface average. Second, on a longer transport timescale roughly of order $[\nu_i(\delta B_n/B_0)^2]^{-1}$, the NA magnetic fields damp the *toroidal* component of plasma flow to an "offset" rotation rate $\Omega_*(\nu_i, E_r) = [(c_t + c_p)/(Z_i e)]dT_i/d\chi$, where c_t is a number of order unity. The NTV damping rate is [2]

$$\frac{\partial \Omega}{\partial t} = -\mu_{\parallel}(\nu_i, E_r)\left(\frac{\delta B_n}{B_0}\right)^2 \left[\Omega - \Omega_*(\nu_i, E_r)\right] \quad . \tag{1}$$

Here $\delta B_n/B_0$ is the relative amplitude of the NA fields, $\Omega \equiv \left\langle R^2\vec{V}\cdot\vec{\nabla}\zeta\right\rangle/\left\langle R^2\right\rangle$, and $\mu_{\|}(\nu_i, E_r)$ is the NTV damping rate.

Experiments on DIII-D [3], JET [4], NSTX [5], and MAST [6] have all observed toroidal flow damping by applying external NA fields in general agreement with the form given in Eq. (1). With the recent introduction of both co- and counter-I_p neutral beam injection, the DIII-D tokamak is now able to access low toroidal rotation states and observe both toroidal flow damping and spin-up [7], to an offset value in qualitative agreement with Ω_*.

In this paper, we expand on previous work by performing a rotation scan of the NTV torque applied by external non-resonant $n = 3$ fields from the I-coils [8] on the DIII-D tokamak. Varying the toroidal $\vec{E}\times\vec{B}$ precessional drift relative to other characteristic frequencies of interest causes a change in the level of NTV damping [9, 10, 11]. Time scales longer than compressional Alfvén wave times ($\sim\mu$s) require radial force balance, which yields [1]

$$\omega_E = \frac{\left\langle qR^2\vec{V}_i\cdot\vec{\nabla}\theta\right\rangle}{\langle R^2\rangle} - \frac{1}{Z_i e n_i}\frac{dp_i}{d\chi} - \Omega \equiv \Omega_0 - \Omega \quad , \tag{2}$$

where $\omega_E \equiv d\phi/d\chi \simeq E_r/(RB_\theta)$ is the toroidal $\vec{E}\times\vec{B}$ precessional drift frequency. If the plasma profiles are assumed to remain fixed, then Eq. (2) indicates that scanning Ω will cause a concomitant change in E_r. This will in turn vary the critical collisionality ratio ν_i/ω_E, and cause transitions between the relevant NTV regimes.

For DIII-D H-mode plasmas, the relevant NTV regimes are the $1/\nu$ [9], $\sqrt{\nu}$ [10], and the superbanana-plateau (sbp) [11] regimes. We connect the three regimes by Padé approximation:

$$\mu_{\|\mathrm{P}}(\Omega) = \frac{0.21|n|v_{ti}^2\sqrt{\varepsilon\hat{\nu}}}{\langle R^2\rangle\left[|\omega_E|^{3/2} + 0.30|\omega_{\nabla B}|\sqrt{\hat{\nu}} + 0.04\hat{\nu}^{3/2}\right]} \quad , \quad \Omega_*(\Omega) \equiv \frac{c_p + c_t(\Omega)}{Z_i e}\frac{dT_i}{d\chi} \quad . \tag{3}$$

Here $|\omega_E|$ should be expanded via Eq. (2), $\hat{\nu} \equiv \nu_i/(|n|\varepsilon)$ for compactness, and n is the toroidal mode number of the applied NA field. The toroidal offset rotation number $c_t(\Omega)$, is a weakly varying function of Ω. The grad-B drift frequency for superbananas is $\omega_{\nabla B}$, estimated for thermal particles as $|\omega_{\nabla B}| \equiv T_j/(|Z_j e|)\,|d\varepsilon/d\chi|$ [11], and $v_{ti} \equiv \sqrt{2T_i/m_i}$ is the ion thermal speed. The damping rate $\mu_{\|\mathrm{P}}(\Omega)$ is strongly peaked around Ω_0, where $E_r \simeq 0$. Integrating Eq. (1) with Eq. (3) over the plasma volume in the large aspect-ratio limit yields

$$-T_{NTV} = 4\pi^2 R_0^3 \int_0^a r dr \rho_M \mu_{\|\mathrm{P}}^{\mathrm{cyl}} \left(\frac{\delta B_n}{B_0}\right)^2 (\Omega - \Omega_*)^{\mathrm{cyl}} \quad . \tag{4}$$

Here the superscript "cyl" denotes we have approximated $\Omega \equiv \left\langle R^2\vec{V}\cdot\vec{\nabla}\zeta\right\rangle/\left\langle R^2\right\rangle \sim V_\phi/R$ along the outboard midplane in what follows.

To investigate the existence of the peak in the total NTV torque predicted by the combination of Eqs. (3) and (4), NA magnetic field perturbations are applied to DIII-D plasmas using the I-coils: a set of 12 picture-frame coils toroidally distributed at two poloidal locations, six above and six below the midplane [8]. For this experiment, the I-coils are configured in “odd-parity” to apply predominantly non-resonant $n = 3$ magnetic fields. These DIII-D plasmas are high $\beta_N \sim 1.6 - 1.7$, H-mode discharges, and have similar lower single null diverted cross sections.

The total NTV torque dependence on toroidal plasma rotation is observed by making several plasmas with similar profiles but different toroidal rotation Ω. To measure the dependence of Eq. (4) on toroidal rotation the neutral beams are operated in rotation feedback mode, attempting to hold the observed charge exchange recombination carbon toroidal impurity rotation, Ω_C, at the $\rho = 0.68$ surface constant. The I-coils are rapidly switched on at $t \simeq 2050$ ms to 3 kA, and the NTV torque thus generated can be observed as a jump in the total beam torque: $\Delta T_{NBI} = -T_{NTV}(\Omega)$ as seen in Fig. 1. This torque measurement procedure is repeated for several similar discharges. The resultant total NTV torque as a function of the deuterium toroidal rotation rate, Ω_D, (calculated from Ω_C using NCLASS [12]) at the $\rho = 0.68$ surface is shown by the diamonds plotted in Fig. 2.

To compare the NTV torque predicted by (4) with the experimental data, NCLASS profiles along the outboard midplane are calculated for each shot. The non-resonant magnetic perturbation profile $\delta B_n(r)/B_0$ from the applied $n = 3$ fields is assumed to be a *vacuum* cylindrical profile $(\delta B_n)^2/B_0^2 = 2(|b_{m3,\theta}(a)|^2/B_0^2)(r/a)^{2m-2}$ for a single $m, n = 3$ perturbation. For simplicity, we assume a single $m = 2, n = 3$ magnetic perturbation, and find a coefficient of $|b_{23,\theta}(a)| = 3.6 \times 10^{-3}$ Tesla gives a good fit to the data. This yields $\delta B_n(a)/B_0 \sim 2.6 \times 10^{-3}$ for the typical toroidal field on the magnetic axis of $B_0 = 1.94$ Tesla.

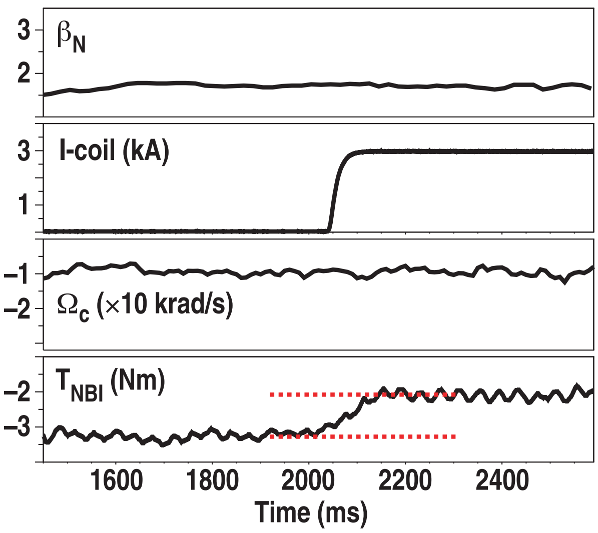

Figure 1: Time traces for shot 138574, showing β_N, I-coil current, rotation rate at $\rho = 0.68$, and total injected neutral beam torque. Positive rotation and NBI torque are co-I_p.

A theoretical NTV torque scan is also performed with (4) using the NCLASS equilibrium for shot 138574 at 1905 ms. The profiles are held fixed, while the deuterium toroidal rotation profile is scanned self-similarly, i.e., $\Omega(\rho) = \Omega f(\rho)$, where $-30 \leq \Omega \leq 15$ krad/sec and $f(\rho) \equiv$

$\Omega(\rho)/\Omega(0.68)$ is a normalized rotation profile from shot 138574 at 1905 ms. The computed torque as a function of Ω is shown by the solid line labeled "model" in Fig. 2. In addition, the NTV torque (4) is calculated for each NCLASS plasma equilibrium independently and plotted (triangles) in the same figure. In all cases, the profiles are integrated from $\rho = 0.1$ to 0.9. The point NTV rotation scan (triangles) is calculated by taking the average of the computed torque profile $\sim$ 100 ms before and $\sim$ 400 ms after the I-coil switch-on. Good agreement between the model (line), the theory points (triangles), and the data (diamonds) for the location of the peak in Fig. 2 is obtained by fitting the unknown value of the equilibrium neoclassical poloidal rotation constant c_p to a value of $c_p = 1.5$.

In summary, this paper reports the first observation of a theoretically-predicted peak in the NTV torque for low toroidal rotation rates in DIII-D by applying external NA magnetic fields with the I-coils. The experimental peak is found to be in good agreement with a simple Padé approximant connection formula. These results are significant in demonstrating that the $\vec{E} \times \vec{B}$ and diamagnetic-level poloidal and toroidal flows and the torques on them are as predicted by a combination of axisymmetric and NA neoclassical theory.

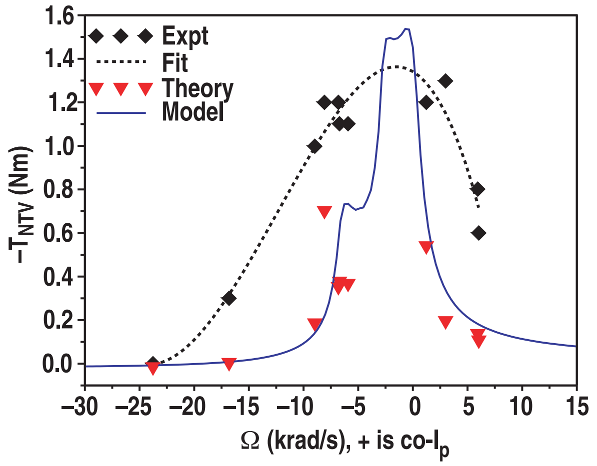

Figure 2: Measured NTV (diamonds) and torque model (line) versus deuterium toroidal rotation rate (from NCLASS) at $\rho = 0.68$. A least-squares spline fit (dashed) is shown for data.

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