Observation of the Generalized Neoclassical Toroidal Viscosity Offset Rotation Profile and Implications for ITER*

S.A. Sabbagh[1], Y.S. Park[1], J. Kim[2], J. Ko[2], W.H. Ko[2], K.C. Shaing[3], Y. Sun[4], S.H. Hahn[2], Y. In[2], Y.M. Jeon[2], H.H. Lee[2], J.H. Lee[2], S.G. Lee[2], Y.K. Oh[2], J. Seol[2], J.W. Yoo[3]

[1] *Dept. of Applied Physics and Applied Mathematics, Columbia U., New York, NY, USA*

[2] *National Fusion Research Institute, Daejeon, Republic of Korea*

[3] *National Cheng Kung University, Tainan, Taiwan*

[4] *ASIPP, Hefei, Anhui, China*

Neoclassical Toroidal Viscosity (NTV) due to non-ambipolar particle diffusion that occurs in tokamaks due to low magnitude ($\delta\mathbf{B}/B_0 \sim O(10^{-3})$) 3D applied fields [1,2] is often used for positive purposes including modification of the plasma toroidal rotation profile, V_ϕ, to stabilize MHD modes and for ELM suppression at plasma rotation speeds characteristic of unbalanced neutral beam injection. However, tokamak devices aiming to produce high fusion power output, including ITER, are expected to rotate much more slowly due to relatively small levels of momentum injection and larger plasma mass compared to present machines. Therefore methods of producing and altering plasma rotation on these devices are highly desired. Understanding how plasmas intrinsically rotate is of primary interest to confidently extrapolate this effect to ITER-scale plasmas as it may provide significant rotation. A potentially beneficial NTV effect that may be important in slowly rotating plasmas such as envisioned in ITER is the NTV offset rotation [1,3]. Past experimental research has only considered that the NTV offset rotation can occur in the direction opposite to the plasma current (counter-I_p). In the experiments described in this paper, the NTV offset rotation profile, V_0^{NTV}, was directly measured and studied in the KSTAR superconducting tokamak in a parameter regime that has shown for the first time controlled rotation in the co-I_p direction at high electron temperature, T_e. This result is expected when considering generalized NTV theory allowing for torques generated by both electron and ion channels, the balance of which yields the V_0^{NTV} profile (electron/ion NTV torque scales as $(m_i/m_e)^{0.5}(T_e/T_i)^{3.5}$ indicating that the electron channel can be dominant) [1,4]. Co-I_p plasma rotation and shear in the plasma outer region has significantly exceeded ITER projections [5].

The present experiments aimed to directly measure the V_0^{NTV} profile in plasmas not utilizing NBI heating, doing so for the first time in plasmas expected to have V_0^{NTV} dominated by the electron channel. Figure 1 illustrates the plasma current, line-averaged density, core plasma rotation, and heating used. Long pulse plasmas (up to 8s I_p flattop duration) allowed

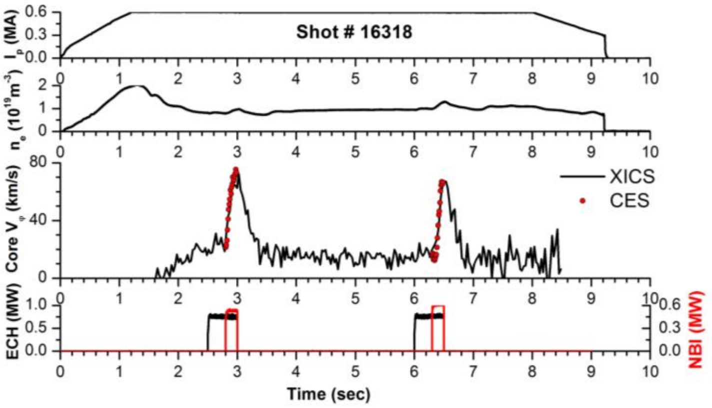

Figure 1. Target plasma experimental setup for measurement of the NTV offset rotation profile (3D field not applied).

quasi steady-state conditions to be produced at two measurement times per discharge. A prime objective of the experimental setup was to avoid the use of NBI to heat the plasma. The co-I_p directed NBI system in KSTAR would produce plasma rotation approximately an order of magnitude larger than V_0^{NTV}, so NBI use would obscure its measurement. Experiments were therefore conducted in plasmas heated ohmically and also by the addition of up to 0.8 MW of 140 GHz second harmonic electron cyclotron heating to increase T_e. The plasma rotation profile was measured using charge exchange spectroscopy (CES) by utilizing a single NBI source running at derated voltages (50 – 60kV as opposed to normal operation at 90 – 95 kV) just for the purpose of allowing plasma rotation and ion temperature profile measurement. Figure 1 shows the relative timing of the ECH and NBI pulses, along with core plasma rotation as measured by CES during NBI (in red). The V_0^{NTV} measurement was made only at the start of the NBI pulse, either using the earliest available measurement interval, or by making a small time extrapolation (~ 10ms) back to the NBI start time (2.8s, 6.3s). An X-ray imaging crystal spectrometer (XICS) channel shown agrees with the core CES V_ϕ measurements. Applied 3D fields were added to these plasmas to generate the NTV effect utilizing in-vessel control coils configured to deliver a predominantly n = 2 field. Density feedback was utilized to maintain density control. To study its effect on V_0^{NTV}, variations to plasma temperature were made by varying density at fixed applied 3D field strength.

To clarify the V_0^{NTV} profile measurement approach, consider a simple and often-used torque balance equation $dL/dt = T_{NTV} + T_{NBI} + T_{ECH} + T_{Intrinsic} – L/\tau_{2D}$, where L is the plasma angular momentum, T_j terms are torques due to NTV, NBI, ECH, and a base “intrinsic” torque in an ohmic plasma, and τ_{2D} is the plasma momentum confinement time before adding the 3D field. We then consider a highly-simplified expression for $T_{NTV} = C_1\delta B^2(V_\phi - V_0^{NTV})$, where δB is the 3D field magnitude. The multiplicative term C_1 is a function of plasma parameters, especially temperature [1]. Replacing L by IV_ϕ/R where I is the plasma moment of inertia, and considering that the intrinsic plasma rotation is generated by T_{ECH} and $T_{Intrinsic}$ without any applied 3D field, the torque balance equation in terms of velocities is

$$C_1\delta B^2\left(V_\phi - V_{0-NTV}\right) + \frac{I}{R\tau_{2D}}\left(V_\phi - V_I\right) = 0$$

where V_I is the plasma intrinsic toroidal velocity profile due to all sources other than NTV. When $\delta B = 0$, $V_\phi = V_I$ which is measured at the quasi-steady-states times 2.8 and 6.3s. As δB is increased, the V_ϕ profile moves away from V_I and toward V_0^{NTV}. With δB sufficiently large, V_ϕ approaches V_0^{NTV} and saturates at that profile. This dynamic was observed under various conditions in these experiments. An example is given in Figure 2, showing the measured V_I profile, and two profiles that saturate when the current, $I_{n=2}$, used to generate the applied $n = 2$ field reached 3.2 kA/turn. Values of $I_{n=2}$ less than this value generated V_ϕ between V_I and V_0^{NTV}. Several characteristics of the V_0^{NTV} profile in Figure 2 are important. The V_0^{NTV} is in the co-I_p, rather than the counter-I_p direction found in past work [3] and thought to be the sole direction for V_0^{NTV} by simplified theory. However, the present result is expected when NTV theory is considered more generally, as the direction depends on the balance of the electron and ion non-ambipolar fluxes [1,4]. Being EC heated, the core plasma has (T_e/T_i) greater than 4. Since the electron to ion NTV torque ratio scales as $(T_e/T_i)^{3.5}$, the electron channel should be dominant here, consistent with the co-I_p direction of V_0^{NTV}. Also, while V_ϕ in the plasma edge region (which equates to more than 12 krad/s) is not large compared to core V_ϕ values generated by NBI, it is quite large compared to projections for ITER, which for a range of conditions are approximately 2 krad/s in the pedestal region [5]. The shear that is created in V_0^{NTV} is also very large – 15 times greater than the shear measured for the V_I profile shown, due to the co-I_p direction of V_0^{NTV} at larger R.

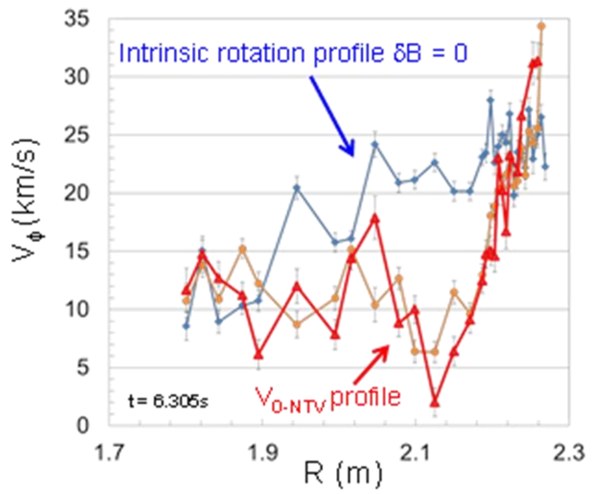

Figure 2. Measured intrinsic rotation profile V_I, and saturated V_0^{NTV} profile in an EC heated plasma.

Plasma conditions were varied to determine the dependence of the V_0^{NTV} profile on plasma temperature. Figure 3 shows a progression of V_ϕ profiles in ohmic plasmas and an ECH plasma producing a V_0^{NTV} profile. The V_I profile (no applied 3D field) shown under ohmic heating has V_ϕ near zero in the core region, increasing to about 7 km/s at large R. When the $n = 2$ applied field is added (at a level somewhat smaller than needed to saturate the V_ϕ profile at V_0^{NTV}), the V_ϕ in the outer region approximately doubles to 15 km/s. This shows that the rise is due the 3D field and not simply ECH. However, when ECH is added, the heating in the outer region leads to a strong increase of V_ϕ, again more than doubling it to 35 km/s. $I_{n=2}$ is large enough to saturate the rotation profile here, producing the V_0^{NTV} profile. While the characteristic strong co-I_p rotation is found in the outer region, the core region now shows rotation in the counter-I_p direction as is expected if the NTV torque is dominated by the ion flux (due to a higher density and somewhat lower core T_e/T_i ratio). A comparison of V_0^{NTV} profiles is shown for various T_e, T_i and constant $I_{n=2}$ in Figure 4 by changing density. The highest temperature plasma (lowest density) yields a V_0^{NTV} profile in the co-I_p direction in both the core and outer regions, with strong rotation shear in the outer region. The middle T_e produced with a line-averaged density feedback setting of $1.5x10^{19}/m^3$ has

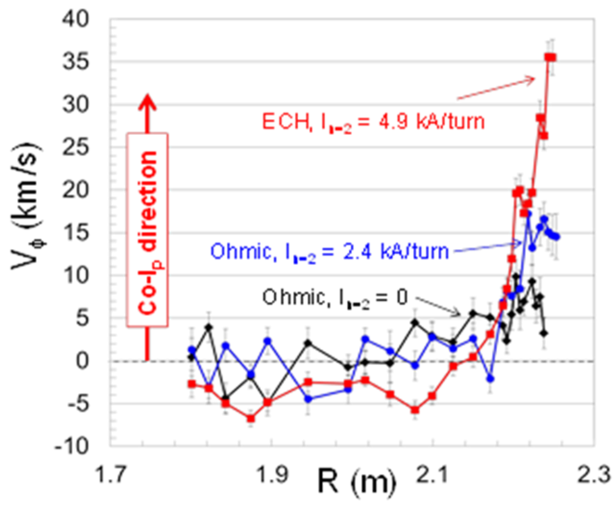

Figure 3. Comparison of plasma rotation profiles in ohmic and ECH plasmas at varied 3D field levels.

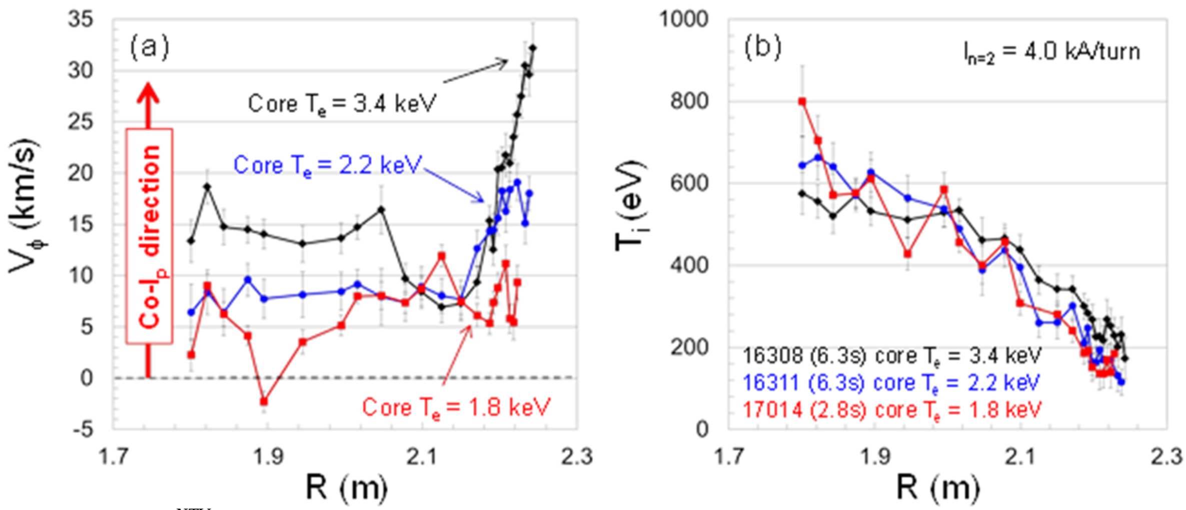

Figure 4. (a) V_0^{NTV} profiles at different plasma temperatures, and (b) Ti profiles for these variations.

lower V_ϕ in the core and outer regions. The lowest T_e has density set to $2.0x10^{19}/m^3$ and V_ϕ in the outer region drops to levels found in the lowest rotation ohmic plasma in Figure 3.

*Supported by U.S. DOE grants DE-FG02-99ER54524 and DE-SC0016614.

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