Evidence of Neoclassical Toroidal Viscosity on the Neoclassical Tearing Modes in TCV tokamak

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Abstract. The interplay between the plasma toroidal rotation and the onset of magnetohydrodynamics instabilities, such as the Neoclassical Tearing Modes (NTMs), is an important issue for tokamak performance. An interesting mechanism characterizing this interaction is the breaking of axisymmetry due to the NTM helical structure, which is the source of a magnetic viscous drag parallel to the toroidal field. This effect, known as Neoclassical Toroidal Viscosity (NTV) depends on magnetic island width, and is responsible of the nearly global slowing down of the toroidal velocity across the profile. In the TCV tokamak the spontaneous plasma toroidal rotation profile, observed even in absence of other external momentum sources [1], can be modified by nearly central electron cyclotron heating (ECH) with a slight poloidal asymmetry and current drive (ECCD) [1,2,3]. The evidence of NTV effect on the plasma toroidal velocity profile of TCV is apparent as a pronounced flattening at the onset of m/n=3/2 and 2/1 tearing instabilities in the neoclassical regime in TCV discharges (I_p~150 kA, n_e_av~2 10^{19} m^{-3}, T_e~3 keV) with 1.5 MW EC ramp up/down phases. Comparison of the measured and calculated toroidal plasma velocity is performed using the NTV formulation [4,5] applicable in the collisionless regimes. The different aspects of the NTM onset associated both with the ECH-coECCD effect on the current profile and with NTV observed in several TCV discharges are discussed, in the frame of classical and neoclassical tearing modes theory applied to 3/2 and 2/1 modes.

1. Evidence of NTV braking

The damping of the plasma toroidal rotation at the onset of magnetohydrodynamics instability, such as the NTMs, is an interesting effect expected when either or both resonant and nonresonant magnetic perturbations break the toroidal symmetry. The general fluid equations for electrons and ion species, include viscous force terms, given by the divergence of the viscous stress tensor that depends significantly on the collisionality regime and on the structure of the magnetic field. In the important special case of axisymmetric magnetic equilibria (e.g. tokamaks) there is no toroidal viscosity and the poloidal and perpendicular (radial) viscosities damp the plasma (ion) flow. Conversely, in non axisymmetric configurations there are both poloidal and toroidal viscous forces braking the flow in those
directions. The perpendicular diffusion of the toroidal momentum is a transport effect depending on the collisional or turbulent regime, while the toroidal magnetic viscosity (NTV) depends both on collisionality and on the amplitude of the magnetic perturbation. New experimental evidence of the interplay between the plasma rotation and the presence of \( m/n=3/2 \) and \( 2/1 \) tearing instabilities in the neoclassical regime is observed in a series of highly reproducible TCV discharges in the same plasma conditions \( (I_p \sim 150 \text{ kA}, n_{e,av} \sim 1.5 \times 10^{19} \text{ m}^{-3}, T_e \sim 0.25 \text{ keV}, q_{95} \sim 5.8) \) with slightly different 1.5 MW EC ramp up/down phases. The evolution of the \( 3/2 \) modes is characterized, initially, by a conventional growth rate driven by the ECH modifications of the plasma current profile, followed by a neoclassical behaviour during the EC power ramp, with subsequent onset of a \( 2/1 \) mode. Evidence of an associated neoclassical toroidal viscous torque is observed as a pronounced flattening and global braking of plasma rotation at the onset of these tearing instabilities \( 3/2 \) and \( 2/1 \). In Fig.1(left) the EC power evolution is shown for 2 sets of shots: #45225, #45226 with slow ramp up power along \( \sim 1 \text{ sec} \) and #45246, #45247 with faster ramp up in \( \sim 0.2 \text{ sec} \) and a slow ramp-down: the \( 3/2 \) onset is observed at 0.8 MW and the \( 2/1 \) onset at 1.25 MW in all these shots. Self-stabilization occurs at less than 0.4MW. In Fig.1(right) the spectrograms of \#45226 \ and \#45247 indicate the \( 3/2 \) (light lines around 11-12 kHz and the \( 2/1 \) (intense lines) at 4.5-5 kHz evolutions. In the latter one at the ramp down (\( \sim 1.2 \text{ sec} \)) the mode frequency slightly increases until the turn off of the power at \( \beta_p < 0.5 \).

![Image](image.png)

**Figure 1.** (left) EC power time traces and \( 3/2 \) (dotted lines), \( 2/1 \) (dashed lines) onset for \#45225, #45226, #45246, #45247. (right) Spectrogram of \( 3/2, 2/1 \) modes in \#45226 and \#45247 shots.

The time evolution of the toroidal \( v \) profiles and of \( v \), at different radial locations are shown in Figs.2-3 for \#45225 and \#45247, respectively. The natural intrinsic counter rotation in absence of external drive (\( t<0.3 \text{ s} \)) changes when central EC heating and co-ECCD are added (\( t>0.3 \text{ s} \)), as already observed in TCV [1]: the plasma is accelerated in the co-\( I_p \) direction and the toroidal rotation is reduced. At the onset time of \( 3/2 \) mode (\( t=0.605 \text{ s} \), \( t=0.555 \text{ s} \) for \#45225, \#45247 respectively) the rotation is significantly modified and changes in sign. At this stage, the mode growth appears as a conventional tearing evolution driven by co-ECCD. When the mode appears, it creates a extremum near the mode surface (helping also to determine the mode location), which results in a local flattening. This interplay between the plasma toroidal rotation and the tearing onset is observed in the modification of the rotation profiles \( v \), evolving in co-current direction, in particular outside the mode location. It is seen
that the gradient inside the mode location reverses sign [1]. At the triggering of 2/1 mode (t=1.18 s, t=0.555 s for #45225, #45247) a global rotation braking towards the counter direction with the strongest deceleration at q=2 location is present as well. These kinds of braking affecting the whole v\phi profile could be related to the NTV effects. The aim of this paper is to attempt to describe the plasma rotation braking at the 3/2 and 2/1 positions as due to the NTV torque, expressed mainly through magnetic field resonant radial perturbations associated to the presence of magnetic island, in the TCV collisionless regime.

**Figure 2.** (left) v\phi profiles versus time for #45225. (right) v\phi evolution versus radii for #45225.

**Figure 3.** (left) As **Figure 2** (left) for #45247. (right) As **Figure 2** (right) for #45247.

2. Interpretation model of NTV effect
The observed damping of toroidal rotation in these TCV experiments can be mainly related to the action of resonant helical magnetic perturbations, with magnetic islands formation, with some contribution of non resonant perturbations. Such symmetry breaking magnetic perturbations ‘modulate’ the tokamak magnetic field, taking into account the tokamak
magnetic field modulus. The magnetic field modulus, decomposed into helical harmonics, can be expressed in the Hamada coordinates by \[7,8,9,10]穥

\[
|B(r + \delta r)| = |B_0(r)| + \delta r \cdot \nabla B_0 + ...
\]

\[
\approx B_0 \left( 1 - \varepsilon \cos \theta + \frac{1}{B_0} \sum [b_{m,nc} \cos(m \theta - n \phi) + b_{m,n} \sin(m \theta - n \phi)] \right)
\]

(1)

where \( \delta r \) is the fluid displacement vector, \( \varepsilon = r/R_0 \), \( R_0 \) the major radius, \( b_{m,nc} \) and \( b_{m,n} \) are the even and odd Fourier coefficients of the magnetic perturbations. The magnetic field toroidal non-uniformity \( \partial B/\partial \phi \neq 0 \) due to the perturbed field causes a non-ambipolar current in the minor radius \( r \) direction and a toroidal braking force proportional to the square of the fluid displacement \( |\delta r| \). In a fluid description the effect appears as a neoclassical toroidal viscous force (NTV) proportional to \( \sim <B \cdot \nabla \cdot \pi_i> \) \[4,8\]. The contribution of the NTV effect to the evolution of the toroidal flow velocity \( v_\phi \) is given by \[6,7\]:

\[
\frac{\partial v_\phi}{\partial t} = \frac{1}{\rho_m} \langle e_\phi \cdot v_\phi \rangle = -\frac{1}{\rho_m} e_\phi \cdot \nabla \cdot \pi_i = v_\phi^\lambda \langle (b^\lambda)^n (v_\phi - v_{\phi,0}^\lambda) \rangle
\]

(2)

where \( e_\phi \) is unit vector in the toroidal direction, \( \rho_m \) the mass density, \( \pi_i \) the ion viscous stress tensor, being \( \langle \ldots \rangle > \) the flux surface average. The term \( v_{\phi,0}^\lambda \) is a frequency linked to the ion NTV viscosity and \( v_{\phi,0}^\lambda \) indicates the neoclassical toroidal flow velocity. This neoclassical rotation profile is comparable to the gradient of the ion temperature \( T_i \) of the ion species. The term \( b^\lambda \) represents the dimensionless effective magnetic field perturbation proportional to the \( b_{m,n} \) in eq.(1). The terms \( v_{\phi,0}^\lambda \), \( v_{\phi,0}^\lambda \) and \( b^\lambda \) refer to a given collisionality regime \( \lambda \) characterizing the plasma. The NTV force brakes the plasma momentum in the toroidal direction with a mechanism different from the traditional perpendicular diffusion. Non resonant helical perturbations (with kink-like displacement \( |\delta r|/R_0 \sim b_{m,n}/B_0 \)), without formation of magnetic islands, cause a global toroidal torque proportional to \( (b^\lambda)^2 \) with \( \alpha = 2 \), while resonant helical perturbations, with magnetic islands formed of full width \( w \) (where the displacement is \( |\delta r| \sim w \)), provide a toroidal braking proportional to \( (b^\lambda)^2 \propto (w/R_0)^2 \) with \( \alpha = 1 \) \[10\], more localized near the \( q \) rational surfaces.

In the TCV experiments the relevant low collisionality appears to be in the banana regime\( \lambda = \nu \) with frequencies in the range \( \nu_{iv}/\varepsilon \leq \omega_{OE} \) \[7\], as shown in Figs. 4(a),(b),(c),(d), where \( \omega_E \) is the ExB drift frequency, \( \nu_{ii} \) the ion-ion collision frequency, \( \varepsilon \) the inverse local aspect ratio. In very few narrow time intervals the other banana regime \( \lambda = 1/\nu \) appears as well, with \( \nu_{iv}/\varepsilon < \omega_{OE} < \omega_{th,i}(R_0q) = (T_i/m_i)^{0.5}/(R_0q) \) the ion transit frequency and \( \omega_{th,i} \) the ion thermal speed.

In this regime, where the particles trapped in the banana orbits are collisionless and the ion neoclassical toroidal viscosity is dominant, the effective toroidal damping rate \( v_{//} \) in eq.(2) is given by \( v_{//} = \nu_{ii} \omega_{ii}^2 / \omega_E^2 \), taking for the effective dimensionless amplitude \( b^\lambda \) of the field perturbation the expression:

\[
(b^\lambda)^2 \propto \sum_{m,n} \left( \frac{b_{m,n}(r)/B_0}{B_0} \right)^2 + \sum_{m,n} (b_{m,n}(r)/B_0)
\]

(3)
In eq.(3) \( m', n' \) are the poloidal and toroidal mode numbers of non resonant perturbations, while \( m, n \) are those of the resonant perturbations associated to the full island width \( w_{m,n} = 4(b_{m,n})^{0.5}(R_0 L_q q /m)^{0.5} \) of an \((m/n)\) mode. The \( b/\nu \) term is calculated taking into account the experimental measured Mirnov signals and the experimental safety factor profile \( q \). Since the temperature of the main deuterium ion species is considered equal to the temperature of the carbon ions, the radial profile of the carbon rotation is used for the evaluation of the experimental offset velocity \( v_{\nu,0} \), comparable to the ion diamagnetic rotation speed \( v_d \), proportional to the ion temperature gradient through the constant \( k_c = v_{\nu,0} / v_d \):

\[
v_{\nu,0}(r) = k_c v_d(r) = k_c \frac{1}{ZeB_0} \frac{dT}{dr}
\]

with \( Z_i = 1 \) is the charge of the main deuterium species and \( B \), the poloidal magnetic field. In this \( \nu \) regime the theoretical limit of the value of \( k_c \) is 0.92 [7]. This offset velocity \( v_{\nu,0} \) is comparable with the measured rotation near the zero torque \( dv/\nu \). In particular, it should be noted that \( v_{\nu,0} \) is experimentally observed to be zero near the resonant \( q \). Both these offset velocities \( v_{\nu,0} = k_c v_d \) and \( v_{\nu,0} = v_{d,p} \) have been considered in eq.(2) to model the plasma toroidal rotation evolution. Tests of local rate of decay of \( v_\phi(r_s) \) according with the NTV model of eq.(2) are performed near the rational surfaces \( r=r_s \).

### 3. Simulations of NTV braking
Magnetic braking of the NTV kind, associated to the appearance of few low order tearing modes, seems to affect significantly the plasma toroidal rotation profile in presence of tearing mode in these experimental TCV scenarios. In Figs.5-9 we show the satisfactory agreement between the toroidal velocity decay rate \( dv/\nu \), using eq.(2) including the 2 expression (4)-(5) for \( v_{\nu,0} \), and the experimental one. In our calculations the best simulations have been obtained with \( k_c = 0.12-0.35 \) to be compared with the theoretical value \( k_c \approx 0.92 \) [7] in the \( \nu \) regime limit. Our values fall below the neoclassical collisionality \( \nu \)-regime limit confirming that our estimation is consistent with the neoclassical prediction. It should be noted that in these
experiments the plasma toroidal velocity $v$, and the neoclassical toroidal flow velocity (offset rotation) $v_{\nu,0}$ are typically in the co plasma current direction (negative sign) in the plots. We found that the offset rotation ($\sim -2-4$ km/s) is comparable to the ion diamagnetic speed, as predicted by the neoclassical theory. In Figs.5-6 the evolution rate at 2/1 resonant location are shown for #45225 and #45226, respectively. Both resonant helical magnetic perturbations from 2/1 mode and non resonant from 3/2 island contribute in eq.(2) to the NTV torque using eq.(3). Before 2/1 onset only the non resonant perturbation by 3/2 instability plays a role, while after this onset both resonant and non resonant perturbations can contribute. The measured $dv/dt=0$ gives an estimate of the equilibrium plasma rotation in terms of an offset toroidal rotation comparable to the ion diamagnetic speed, in agreement with [7].

Figure 5. (a) Measured (solid line) and calculated by ion NTV drag (dashed, dotted lines) evolution rate of $v$, at q=2 for #45225. (b) Experimental time velocity evolution $v$, at q=2 and offset rotations by eqs.(3)-(4) for discharge #45225.

Figure 6. (a) As Figure 5 (a) for discharge #45226. (b) As Figure 5 (b) for discharge #45226.

In Fig.7 the growth/decay rate of the toroidal velocity is shown at 3/2 resonant position. The NTV model of eq.(2) reproduces well the measured evolution rate and the offset $v_{\nu,0}$ is still observed in co plasma current direction (negative sign). A very interesting feature appears
modeling the \( v_\phi \) rate for the \#45246 (with 3/2) and \#45247 (with 2/1) where the modes occur on the fast EC ramp up phase and evolve from the power plateau until the end of the ramp down phase. The mode dynamics is different from the evolution of instabilities in the previous shots. Before the EC ramp down the toroidal rotation profiles are decelerated towards the counter direction up to a nearly zero rotation (\#45246, \#45247), while in the ramp down phase the rotations are pushed to other constant velocities, in counter direction for \#45246 and co direction for the \#45247, as shown in Figs. 8-9. So, different offsets seem to characterize the plasma in the EC ramp up and plateau phase and in the power ramp down. Best fits of the evolution rate of the toroidal velocity are obtained using both co- \( v_{\phi,0} \) and \( v_{\phi,0} = 0 \) in the former phase and \( v_{\phi,0} \neq 0 \) with co/cntr \( v_{\phi,0} \) in the latter one.

**Figure 7.** (a) As Figure 5 (a) for discharge \#45226 at \( q=3/2 \). (b) As Figure 5 (b) for discharge \#45226 at \( q=3/2 \).

**Figure 8.** (a) As Figure 7 (a) for discharge \#45246 at \( q=3/2 \). Effects of \( v_{\phi,0} = 0 \) (dotted line) and \( v_{\phi,0} \neq 0 \) (dashed-dotted line). Best fit (dashed line) with \( v_{\phi,0} = 0 \) before the EC ramp down. (b) As of Figure 7 (b) for discharge \#45246 at \( q=3/2 \). The different offsets are shown: co \( v_{\phi,0} \) and \( v_{\phi,0} = 0 \) before ramp down and \( v_{\phi,0} \neq 0 \) in cntr direction during the ramp down.
Figure 9. (a) As Figure 8 (a) for discharge #45247 at q=2/1. (b) As Figure 8 (b) for #45247 at q=2/1 with $v_{\phi,0} \neq 0$ in co direction in ramp down.

4. Conclusions

In low collisionality TCV discharges with just tearing and neoclassical tearing instabilities, but no external fields, it has been found that within the uncertainty of the measurements ($\pm 2$ km/s) the evolution of the toroidal rotation profile is consistent with the effect of a NTV torque proportional to the difference between the toroidal velocity and the neoclassical toroidal flow velocity $v_{\phi,0} \neq 0$ (offset speed), evaluated in steady state conditions $\frac{dv}{dt} \sim 0$. In some cases, when the mode is triggered on the fast EC power ramp up, the toroidal offset rotation $v_{\phi,0} = 0$ is used to better simulate the experimental evolution rate of the toroidal rotation velocity before the EC ramp down. It should be noted that in our simulations we best fit the experimental $v$ evolution taking into account an offset in co-plasma current direction (as well shown in the plots for evolution), despite the usual counter offset from the neoclassical theory. This can be perhaps due to the presence of resonant magnetic perturbations changing the toroidal rotation sign and further experimental investigations should be performed.

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