Effects of ECH/ECCD on Tearing Modes in TCV and Link to Rotation Profile

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Abstract. The Tokamak à Configuration Variable (TCV) has extensive rotation profile measurements together with a flexible electron cyclotron heating and current drive system (ECH/ECCD). A wide variety of carbon toroidal rotation profiles have been measured in TCV in a wide parameter range, in L-mode plasmas without an external momentum source. New specific experiments have been performed to better separate the momentum transport properties that can be attributed to micro-instabilities and those related to MHD activity. Additionally, the effect of ECH/ECCD is also analyzed in some detail. It is shown that MHD modes are not only responsible for increased viscosity, but can lead to significant local toroidal rotation gradients. This is due to a torque related to the sawtooth crash activity with m=1/n=1 [B. P Duval et al, this conference]. Modes at higher rational surfaces also slow the plasma and a combination of 3/2 or 2/1 modes and sawteeth can lead to non-monotonic rotation profiles. These studies confirm that the $1/I_p$ dependence of the central toroidal rotation is mainly due to the sawteeth activity, at least in L-mode, rather than to intrinsic turbulent transport properties. The momentum transport properties outside the sawtooth mixing radius do not depend on plasma current. It is also shown they do not depend on ECH, so long as ECH does not influence the sawtooth activity. Once ECH is injected near, or inside, the $q = 1$ radius, then it has a significant effect on the toroidal rotation profile. The poloidal rotation remains small, (near neoclassical), for all cases analyzed to date. These effects are observed with, to within experimental limits, self-similar kinetic profiles n_e, T_e and T_C, showing that the heat and particle transport properties of these L-mode plasmas do not depend on the ExB shearing rate.

1. Introduction

The role of plasma rotation in the performance and stability of tokamak plasmas is significant. A major difference between present machines and ITER, will be the lack of momentum driven by the NBI beams. Thus, intrinsic rotation, the level of toroidal rotation in the absence of external momentum input, and its projection to ITER [2] remains an important research topic. This has also triggered significant advances in both experimental and theoretical studies of momentum transport [3]-[9]. The effect of MHD modes on plasma rotation have usually been observed to slow the rotation profile across the whole minor radius [10], indicating a significant contribution of the $m = 0$ neoclassical viscous terms. The present analysis focusses on the effect of rotation damping due to internal MHD modes [[11] and references therein] and their relation to NTV theory [12].

In this paper we present new experimental results that better distinguish the momentum transport properties in the absence of external source and possible effects of MHD modes. These modes comprise both the internal kink activity, related to the sawteeth and the low m/n neoclassical tearing modes, where m, n are the poloidal and toroidal mode numbers respectively. Recent results showed that sawteeth accelerate the core plasma at each sawtooth crash [13], confirming previous TCV conclusions that the core plasma rotation was limited mainly by sawteeth activity [[14] and references therein]. At that time, the role of MHD activity was not fully distinguished from intrinsic momentum transport properties [14]. Herein, we have developed plasma scenarios to avoid modifications of the MHD activity during the stationary phase, or used ECCD to stabilize a tearing mode in order to assess its role on toroidal plasma rotation. The aim is to also better understand the rotation reversal mechanisms observed in L-mode plasmas [15, 4]. These experimental results are presented as follows: in Sec. 2.we re-assess the role of the sawtooth activity and the mixing radius on the overall rotation profile in both limited and diverted plasmas; in Sec. 3 significant effects of ECH deposition outside or inside the $q = 1$ surface are presented in plasmas with positive and negative triangularity, together with the role of counter-CD; and in Sec. 4 the effects of $2/1$ and $3/2$ modes are described.

2. Plasma current effects on toroidal rotation profiles in TCV limited and diverted L-modes

The main effect of increasing plasma current was shown to *flatten* or rather *bulge* the toroidal rotation profile inside the sawtooth inversion radius. This effect is sufficient to limit the maximum toroidal rotation and directly results in the observed $1/I_p$ scaling, at least in L-mode [14]. An opposite sign was, however, sometimes observed for rotation gradient in between limited and diverted plasma configuration [16]. The goal here is to compare the intrinsic toroidal rotation gradients observed in limited and diverted plasmas with greater precision. Since the effect of sawtooth activity is significant, a plasma current scan in both limited (Fig. 1(a)) and diverted (Fig. 1(b)) plasmas was performed. Using previous techniques to create a diverted plasma, where the diverted configuration is formed after the plasma current has been established, it was difficult to avoid MHD activity or a non-stationary current density profile. As the limited plasma is moved out from the inner wall, it usually shrinks radially with a rapid toroidal cross-section decrease. This effectively increases the plasma current density and significantly decreases the edge safety factor where $q_{95} = 3$ was often approached. Current diffusion is relatively slow and, even if no modes are triggered, this transient phase can affect the plasma evolution during a significant part of the discharge flat top, especially as it is often accompanied by an overshoot of the plasma density (to avoid MHD modes). We therefore developed a new scenario in order to form the divertor configuration for q_{95} values higher than 4.5-5 with relatively low density. We have also performed discharges where half of the plasma flat top was in limited and half in diverted configurations, by lowering the plasma current during the X-point formation phase. In all cases, we observed similar behavior for the toroidal rotation profiles as shown in Fig. 1. The plasma current is negative in all these cases and the toroidal rotation is essentially counter-current. A finer scan was performed in the limited configuration and we note that the main gradient is self-similar during the current scan (Fig. 1(a)). At higher plasma current, local gradients can become zero or of opposite sign if inside the mixing radius. Note that, at low plasma current, the toroidal reversal is small and a significant pinch is observed to sustain a peaked counter-current rotation profile. This scan confirms that the properties of the turbulence sustaining the pinch do not change with plasma current. Note that the case #40122 has a lower plasma density and a different rotation profile. It is interesting to link these observations to impurity transport studies [17]. There, it is shown that the carbon density profile can be very peaked at low plasma current and is significantly affected by sawtooth activity (Fig. 2 of Ref. [17]). Nevertheless, the logarithmic carbon density gradient stays the same outside the mixing radius showing that the local transport properties are not affected either by increasing the plasma current.

This result is similar for a diverted configuration i.e. counter-current rotation at low plasma current. Fig. 1(b) shows that, at higher current, we obtain a full profile reversal, as described in [15, 14]. These diverted shapes have usually very high triangularity and plasma shaping so sawteeth tend to couple further out in radius. This may be seen from the carbon density profiles. As presented in [17], the flattening of the carbon density profile is significant due to sawtooth activity and can act as a "indicator" of the region affected by sawtooth activity. This is extremely helpful to our discussion and the carbon density profiles for the diverted shape are shown in Fig. 2 (Note: the profiles for the limited shape are shown in [17]). Fig. 2(b) in particular shows that already at $I_p = -207$kA ($q_{95} = 4.3$) sawtooth activity obliterated the strong carbon density peaking observed at the lowest current. This indicates that the rotation profiles are affected outside the inversion radius, which is why we shall refer to the mixing radius in the following. It should be noted that the 1/1 mode extends up to the plasma boundary in present

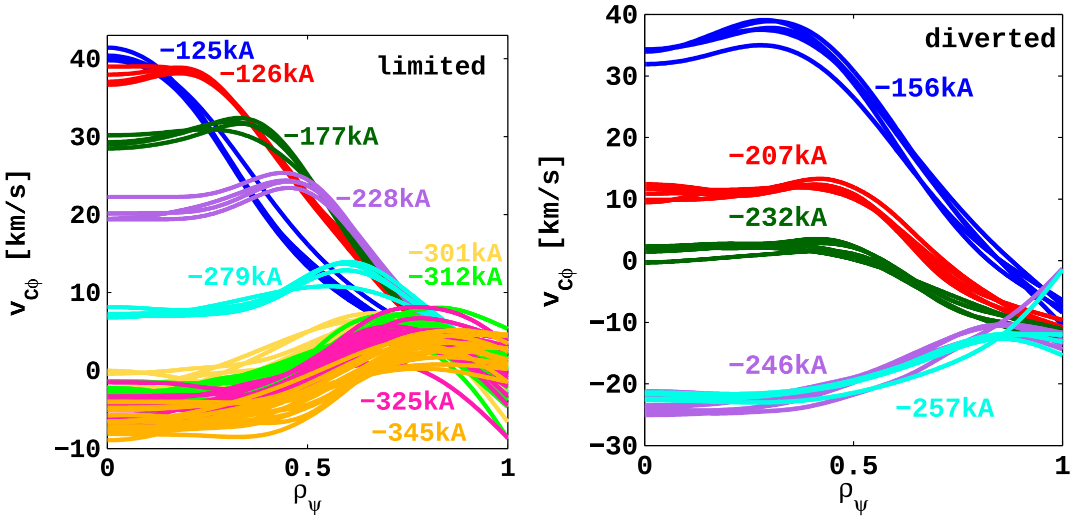

FIG. 1. a) Carbon toroidal rotation profile in a limited plasma versus plasma current: 40122/-125kA; 40117/-126; 40118/-177; 40119/-228; 40130/-279; 41385/-301; 41388/-312; 41386/-325; 41387/-345. The line-averaged density n_{el} is about 2.3e19m^{-3}, except for 40122 which has 1.2e19. b) I_p scan in a diverted configuration: 40161/-156kA; 40160/-207; 40162/-232; 40530/-246; 40159/-257, with $n_{el} \sim$ 3e19m^{-3}.

shaped plasmas. The effect of shaping is not directly assessed here, but it is expected that higher plasma shaping leads to increased toroidal coupling, which could explain why diverted cases tend to have a more significant reversal than the limited cases and that they occur at slightly higher q_{95} values. The plasma shapes corresponding to Fig. 1 are shown in Fig. 3. The limited plasmas have low shaping characteristics. We also note that the ion temperature profiles are similar during each plasma current scan.

3. Effects of off-axis and on-axis ECH power deposition on the toroidal rotation profiles

A slow scan of the ECH power deposition from far off-axis to central location was performed for two plasma discharges with positive and negative triangularity. The effects on the toroidal rotation profiles are given in Fig. 4. The soft-X ray emission central chord shows a sharp increase when the deposition location is near $q = 1$ and inside. We may thus clearly differentiate profiles obtained when ECH is outside (dashed lines) or inside (solid lines) the sawtooth mixing radius. With external deposition, the profiles remain self-similar and momentum transport is not affected. However, with deposition inside the mixing radius, the whole rotation profile descends (with a transient compensation observed at the plasma edge). The final profiles are very similar to those obtained when increasing the plasma current described in the previous Section. Thus, the main effect has been to increase the co-rotation contribution with sawtooth activity, such that even the gradients near $\rho \sim 0.7$ are flattened. Note that the carbon density profiles are relatively flat, implying a wide mixing radius. This is consistent with observations described in the previous Section since $q_{95} \sim 3.6-4$ and these are relatively high plasma current cases (similar to the -228kA case in Fig. 1). In order to better assess the transport properties outside the mixing radius, such a scan should be performed at much lower plasma current.

The main effect of on-axis ECH appears, again, to be strongly linked to sawtooth activity. This was further examined by additional ECH, cntr- and co-CD at two levels of power, 215kW and 730kW, into a low current low density limited discharge similar to #40122 (Fig. 1(a)). Since we know that central current drive can change significantly the q profile inside the $q = 1$ region and the sawteeth [18], we can measure the effect on the toroidal rotation profile. Fig. 5 compares the central ECH case (a) and the central counter-CD case. The low power phase is shown by

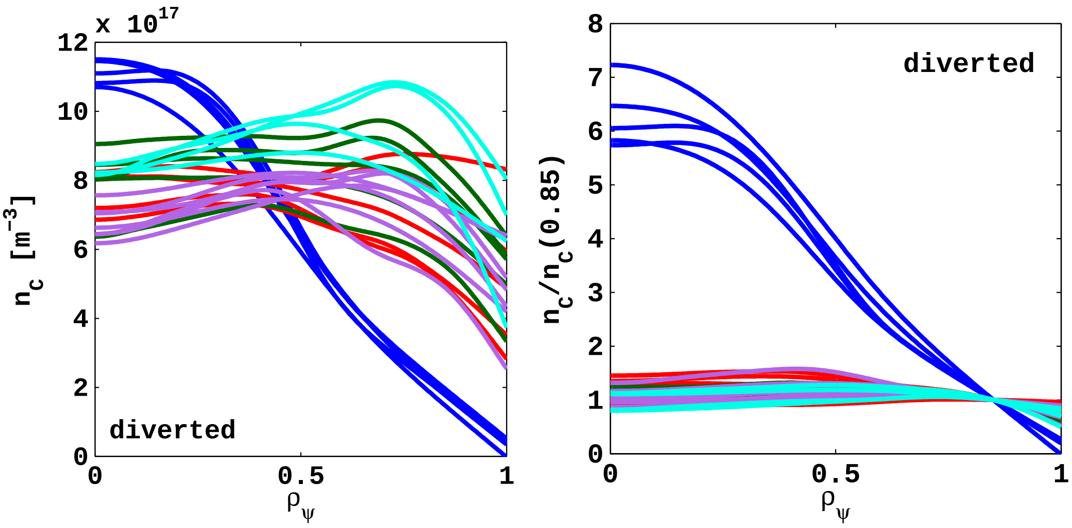

FIG. 2. a) Carbon density profiles for the current scan in the diverted shape as in Fig. 1(b) (same color code). b) Same as (a) but normalized by the value at $\rho = 0.8$. Except for the lowest current, the sawteeth affect the carbon density profile essentially across the whole minor radius.

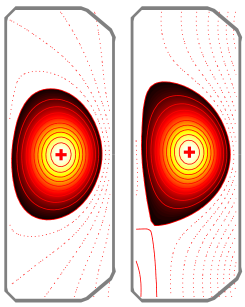

FIG. 3. (a) and (b): Plasma shapes corresponding to the limited and diverted shapes used in Fig. 1(a) and (b) respectively.

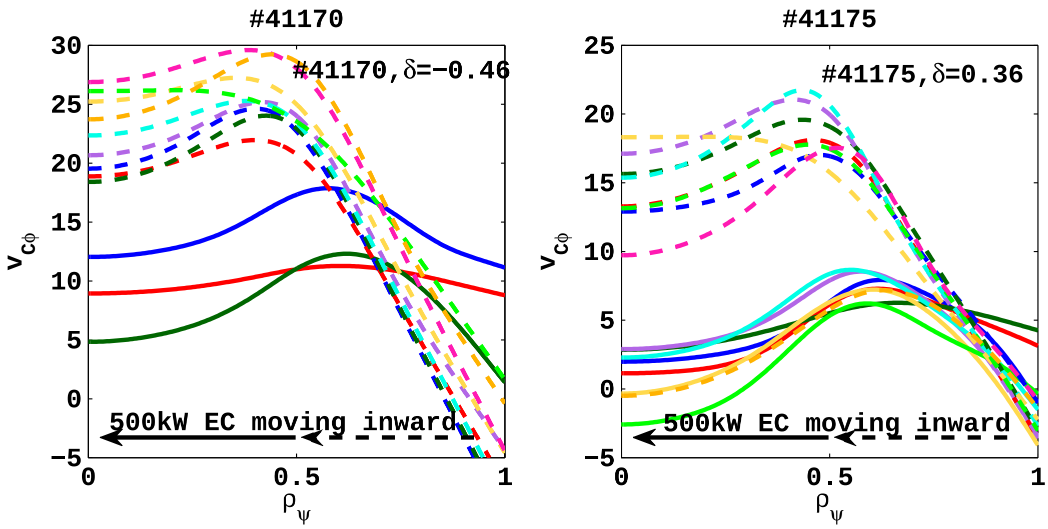

FIG. 4. ECH deposition scan from $\rho \sim 0.9$ to $\rho \sim 0.$ in (a) a negative ($\delta = -0.45$) and (b) a positive triangularity ($\delta = 0.36$) plasma shape. The dashed lines represent cases when the deposition is still outside the sawtooth mixing radius and solid lines when it is inside.

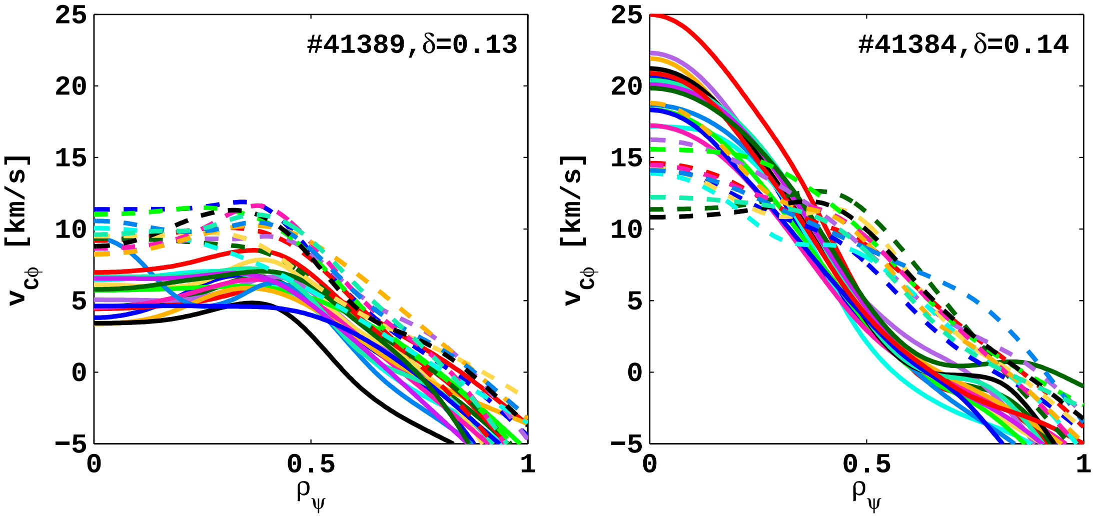

FIG. 5. Toroidal rotation profiles for a central ECH case (a) and a central counter-CD case (b). The phase with 215kW is shown with dashed, while solid lines correspond to 730kW injected power. Note that the counter-CD case leads to twice the on-axis electron pressure in the high power phase due to improved confinement.

dashed and the higher power phase by solid lines.

Clearly, the whole profile is reduced compared with the peaked ohmic profile, which would obtain ∼40km/s near the plasma center, Fig. 1(a). The ECH case shows that this effect is stronger with increasing power. On the other hand, the counter-CD case shows that the profile in the central region can also be modified. With low power, the co-current bulge is slightly reduced, while with increased power a peaked counter-current rotation profile is sustained in the core. This demonstrates that changing the central q profile can change significantly the toroidal rotation profile, as both cases have the same EC power. The counter-CD case develops an improved confinement region inside $\rho_\psi = 0.4$ similar to [19], with 6keV on-axis, and the absence of the co-current bulge could be attributed to an absence of sawtooth activity. This requires further investigation and is out of the scope of this paper. The effect of co-CD is discussed in the next Section as a 3/2 mode was triggered by the high power phase.

4. Effects of tearing modes on toroidal rotation profiles in ohmic and EC-heated plasmas

Here, two cases of profiles with and without a tearing mode in the plasma are compared. In the first, a tearing mode happened to be unstable for a given ohmic low current scenario, with low shaping, and was stabilized it by injecting EC at the mode location ($q = 2$). In the second, a 3/2 mode was destabilized during central co-CD deposition permitting a comparison of the effect of EC and of the mode.

The first case featured a 2/1 tearing mode that was unstable at the beginning of an ohmic discharge, at about 0.5s, and that remained throughout the discharge (#40537 in Fig. 6). Adding 200kW of EC at the $q = 2$ surface, near $\rho_\psi = 0.75$, partially stabilized the mode whose width decreased by about ∼2 (#40539). As both the mode and EC power can influence the rotation profile, a direct comparison is not possible. In #40543, we first added 500kW at the rational surface, to fully stabilize the mode, and then maintained a long stationary phase at 200kW, without modes for comparison with #40539. Finally the mode was fully stabilized with 500kW that was then turned off. The mode was not triggered for at least 0.2s and the corresponding profiles are shown (#41405). It should be noted that the latter case is not fully stationary and the plasma current was 10% higher.

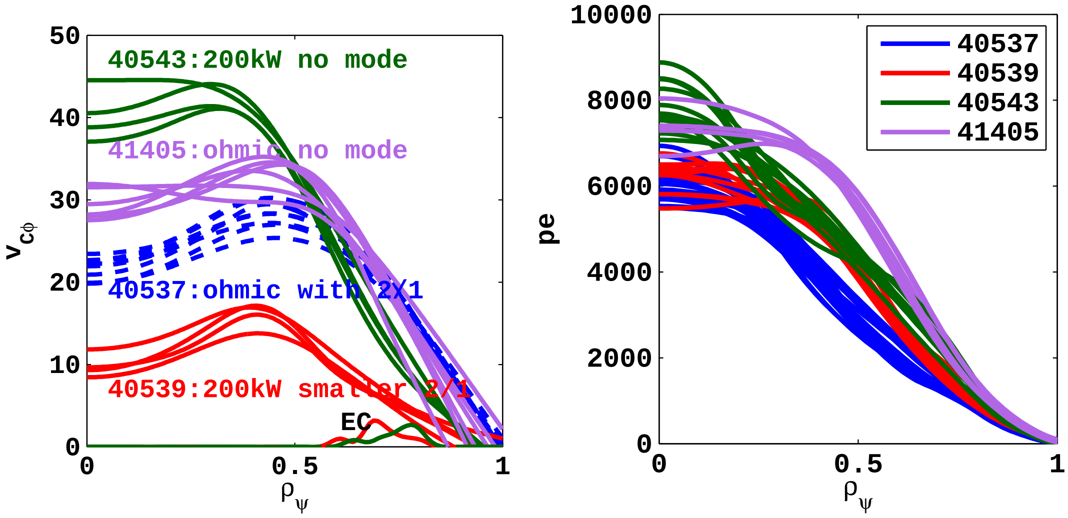

FIG. 6. (a) Toroidal rotation profile for two ohmic cases (#40537 with a 2/1 mode and #41405 without) and two co-ECCD cases with 200kW (#40539 the mode partially stabilized and #40543 without) . $I_p \sim 200$kA and $q_{95} \sim 5$.

Several interesting effects are observed. Adding off-axis co-CD to stabilize the mode, #40543, leads to a considerable more peaked rotation profile than for the ohmic case with the mode (#40537). Conversely, #40539, with the same EC power but a partially stabilized mode, has a much reduced rotation, even smaller that the ohmic case with a larger mode. If the rotation damping is due to NTV and the tearing mode, this indicates that a heated island significantly increases the toroidal damping. This could be due to collisionality effects since the local T_e value is ~2 times larger in the EC heated case and needs to be analyzed in greater detail. The pressure profiles are shown in Fig. 6(b), with the main differences due to temperature changes since the n_e profiles are relatively similar, except for #41405 that is more peaked. The pressure profiles show a large difference between the ohmic case with and without the mode, the latter leading to a significant confinement degradation, as expected. Note, again, that #41405 has a slightly (10%) higher plasma current.

In the second example, the effect of on-axis co-CD, in a low plasma current discharge is considered, completing the series shown in the previous Section. A 3/2 mode is destabilized in the latter phase of the discharge, midway through the higher power phase. This allows a comparison between the low and high power phases without modes and the high power phase with a 3/2 mode, Fig. 7(a). The ohmic shot with a similar plasma current and density is shown for reference, #40122 (also shown in Fig. 1(a)). This clearly shows an overall reduction of the rotation profile, as discussed above, even with only 215kW added in the center (red lines). The profiles at 730kW, before the mode is triggered, are similar to the ECH case shown in Fig. 5(a). However once the 3/2 mode appears, an opposite gradient of the toroidal rotation forms as indicated by the dashed line. This could be due to a coupling between the sawteeth and the 3/2 mode, or simply to sawteeth induced acceleration, modified by the presence of the 3/2 mode, itself modifying the profiles inside the $q = 1.5$ surface.

5. Conclusions

The new experimental results obtained by a more detailed comparison of the difference between limited and diverted plasmas, show that both behave similarly with respect to the plasma current. At low plasma current, the toroidal rotation is counter-current in both cases with a significant pinch sustaining a peaked profile. The momentum transport properties sustaining this pinch are not modified by increasing the plasma current, outside the sawtooth mixing radius. At higher

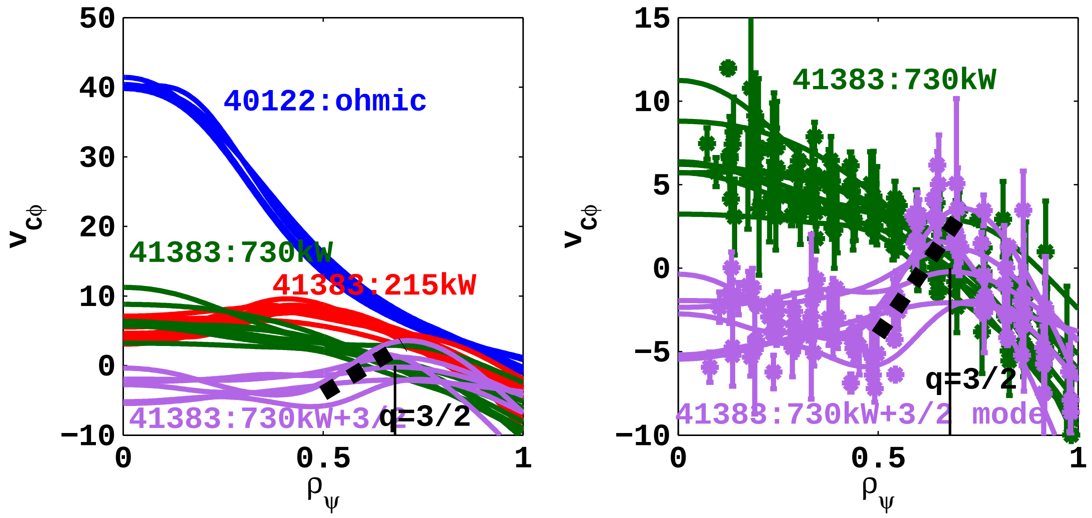

FIG. 7. a) Similar cases as in Fig. 5 but with central co-CD. The ohmic reference case is also added (#40122). In the middle of the high power phase, a 3/2 mode appears. Profiles before and after the mode onset are presented. b) Same as (a) but with only the profiles in the high power phase, including the data points.

plasma current, local gradients of the toroidal rotation profile can be modified significantly, and even change sign. These effects are, however, observed when the sawtooth activity influences the whole minor radius. A useful metric of this effect is the flattening observed on the carbon density profile [17]. For cases where the mixing radius extends close to the plasma boundary, small changes of the profiles or plasma density can affect significantly the rotation profile. The exact role of the 1/1 internal kink is not fully understood.

The toroidal rotation profiles are not affected significantly by ECH when deposited outside the mixing radius. However when the deposition is inside, up to the plasma center, a significant reduction of v_ϕ is obtained (or a significant enhancement in the co-current torque). It has been shown to be similar to the effect of increasing the plasma current. Injecting counter-CD in the center can, however, lead to a strong counter-current peaking of the rotation profile. Further studies are needed to determine if this is attributable to the disappearance of the sawteeth or to the improved confinement that is sustained. Adding co-CD in the center does not lead to confinement improvement and profiles similar to central ECH deposition are obtained.

The presence of a tearing mode can further affect the toroidal rotation profile. Two cases in the presence of a 2/1 and a 3/2 modes were analyzed in detail. The 2/1 mode does not alter significantly the plasma rotation for the ohmic case but has a strong effect when heated, albeit with a smaller width. This could be related to the NTV effects and also requires further study. On the other hand, a 3/2 mode, with strong central co-CD, has sustained a significant gradient in between the $q = 1$ and $q = 1.5$ surfaces. Again, this bulge of the toroidal velocity in the co-current direction is similar to the effect of the sawteeth activity observed in the plasma current scan. The physics mechanisms relating the 1/1 internal kink with momentum transport therefore require detailed study.

Acknowledgements

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