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Experimental demonstration of an up-down asymmetry effect on intrinsic rotation in the TCV tokamak


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Abstract

A new mechanism has recently been proposed that generates a radial flux of parallel momentum in toroidal plasmas. Namely, by considering up-down asymmetric flux surfaces, the symmetry following the magnetic field can be broken and an additional contribution to the turbulent momentum flux arises, potentially changing the intrinsic rotation profile. These predictions are tested with specific experiments on TCV. The intrinsic toroidal rotation is observed to change by roughly a factor of two when changing the up-down asymmetry of the plasma. More precisely, the toroidal rotation gradient changes in the outer part of the plasma, where the flux surface asymmetry is the highest. The experiments were performed for all combinations of the toroidal magnetic field and plasma current directions, that affect the sign of the predicted up-down asymmetry flux. In each case the variation of the intrinsic rotation profile with the up-down asymmetry is observed in the direction predicted by the theory.

(Some figures in this article are in colour only in the electronic version)

Introduction

For more than 20 years now, the theory of momentum transport in tokamak plasmas has been trying to catch up with always more challenging experimental observations. It was first realized that as the momentum confinement time is comparable to and scales with the ion confinement time [1], momentum transport is likely to be dominated by turbulent processes. The theory of ion temperature gradient (ITG) turbulence was thus revisited and shown to predict momentum
diffusivity comparable to ion heat diffusivity [2]. Subsequent experimental investigations [3] further pointed at turbulence being responsible for the radial transport of momentum. A couple of years later, an exciting observation was made: peaked toroidal rotation profiles can be sustained even in the absence of externally applied torque. This phenomenon, usually described as ‘spontaneous’ or ‘intrinsic’ rotation, has been observed in many tokamaks and under a large variety of plasma conditions [4–12]. It demonstrates that momentum transport must include contributions not proportional to the rotation gradient (sometimes called non-diffusive or non-diagonal contributions). The observation of intrinsic rotation has stimulated and led to considerable development of the theory, backed up by new experimental observations. We are now at the stage where, although the wealth of experimental observations cannot all be explained, the theory of turbulent transport has made sufficient progress to make predictions that can be tested experimentally. In this work, we focus on the recent prediction that up-down asymmetric plasma shapes induce a non-diagonal turbulent momentum flux potentially large enough to modify the intrinsic rotation [13, 14]. A detailed investigation of the effect in the TCV tokamak [15] is presented, developing and building on a prior short communication of the results [16]. In the first section of the paper, the link between momentum transport and intrinsic rotation is emphasized and a brief summary of the present state of turbulent momentum transport theory is presented. The methodology adopted for the experimental test of the up-down asymmetry effect is described in section 2 and the experimental results presented in section 3, before concluding.

1. Theoretical and experimental framework

1.1. Transport equation

In an axisymmetric device, the toroidal angular momentum density obeys a conservation equation:

$$\sum_{\text{species}} \frac{\partial (n \rho m R v_{\theta})}{\partial t} + \nabla \cdot (\Gamma_{\theta} + m R v_{\theta} \Gamma) = S_{\theta}, \quad (1)$$

where \(n\), \(m\) and \(v_{\theta}\) are the species density, mass and toroidal fluid velocity, respectively, and \(R\) is the major radius at the considered position. The total flux of toroidal angular momentum density is separated into two parts, \(\Gamma_{\theta}\) and \(m R v_{\theta} \Gamma\), to underline the contribution arising from a finite particle flux \(\Gamma\). The momentum sources and sinks \(S_{\theta}\) are accounted for in the right-hand side of the equation. Quasi-neutrality was assumed which implies that the contribution to the toroidal angular momentum density proportional to the poloidal flux cancelled when summing over the species. A 1D transport equation is obtained by performing a flux surface average of equation (1):

$$\sum_{\text{species}} \frac{\partial (n \rho m R v_{\theta})}{\partial t} + \frac{1}{V} \frac{\partial}{\partial r} \left[ V' \langle \Gamma_{\theta} \cdot \nabla r \rangle + V' \langle m R v_{\theta} \Gamma \cdot \nabla r \rangle \right] = \langle S_{\theta} \rangle. \quad (2)$$

The flux surface average is indicated by the angle brackets \(\langle \cdot \rangle\) and \(V' = \partial V/\partial r\) is the radial derivative of the plasma volume enclosed by a flux surface. The radial coordinate (flux surface label) is chosen to be \(r = (R_{\text{max}} - R_{\text{min}})/2\), with \(R_{\text{max}}\) and \(R_{\text{min}}\) the maximum and the minimum major radius of the flux surface being labelled, respectively. Equation (2) governs the evolution of the toroidal rotation profile \(v_{\theta}\) in an axisymmetric device (no MHD, no ripple). In the case of steady-state scenarios and intrinsic rotation (no particle and no momentum sources in the region under investigation), as in this study, the transport equation reduces to

$$\sum_{\text{species}} \Gamma'_{\theta} = \sum_{\text{species}} \langle \Gamma_{\theta} \cdot \nabla r \rangle = 0, \quad (3)$$
simply stating that the contravariant radial component of the flux surface averaged toroidal angular momentum density flux is zero.

1.2. Turbulent momentum flux decomposition

The most relevant candidate for momentum transport in tokamaks is small-scale (ion Larmor radius) turbulence, or said differently, in most conditions $\Gamma_\psi$ is expected to be dominated by the momentum flux arising from plasma turbulence. As demonstrated in the framework of the gyrokinetic theory, a breaking of the symmetry around the low field side midplane and following a magnetic field line is required to get a finite turbulent momentum flux [17]. If symmetry is enforced, the momentum flux in the upper part and lower part of the plasma exactly compensates, resulting in zero net radial transport. Several symmetry breaking mechanisms have been found to generate a sizeable contribution to the turbulent momentum flux and we choose to decompose $\Gamma_\psi$ according to these mechanisms. This is done here for one species:

$$\Gamma_\psi = nmR_0[\chi_\parallel R_0\omega_\phi + V_{co}R_0\omega_\phi + M\gamma_E + C_{FS} + C_{\rho\ast}].$$

The toroidal angular frequency $\omega_\phi$ of the plasma is counted positive for toroidal rotation clockwise when viewed from the top and $R_0$ is a reference major radius. The first term in the equation above describes the diagonal momentum flux which tends to relax the rotation gradient $\omega_\phi' = -\partial\omega_\phi/\partial r$ and is characterized by the parallel momentum diffusivity $\chi_\parallel$. It has been first evidenced in an analytical work on the fluid ITG turbulence [2] and then thoroughly studied in the fluid [18–20] and gyrokinetic [17, 21–24] framework. The second term is the Coriolis pinch [25], proportional to the toroidal rotation $R_0\omega_\phi$ (lowest order flow [26]) and which usually tends to increase the rotation profile peaking (inward pinch). It arises from the phase shift between density and parallel velocity fluctuations generated by the Coriolis drift [25]. The Coriolis pinch appears as a curvature effect [27–30] in the laboratory frame and can be decomposed into a turbulent equipartition pinch (TEP) and a thermoelectric pinch [27, 31, 32]. Recent gyrokinetic simulations demonstrated that including the kinetic electron response is essential to correctly capture the Coriolis pinch physics [32–34]. The third term in equation (4) is the residual stress part which is neither proportional to $\omega_\phi'$ nor to $\omega_\phi$. Residual stress can arise from the symmetry breaking due to perpendicular sheared flows (term proportional to the $E \times B$ shearing rate $\gamma_E = -\partial E_r/\partial r$) [35], due to up-down asymmetric flux surfaces (term $C_{FS}$) [13] or due to global effects ($\rho_\ast$ effects, term $C_{\rho\ast}$) [22]. The most studied mechanism so far has been the effect of $E \times B$ shearing [19, 21, 23, 36–38]. The up-down asymmetry effect $C_{FS}$ was described in [14] and recently, various contributions to $C_{FS}$ have also been discussed [37,39–41]. Residual stress plays a particular role in the physics of intrinsic rotation, as it provides a seed rotation that can be convected by the Coriolis pinch to balance the diagonal contribution and sustain a rotation gradient over the whole profile [23, 42]. Finite flows at the plasma boundary can also provide the seed rotation from which the profile develops.

There is naturally some freedom in the choices made in equation (4) to decompose the momentum flux. The present ones are made to emphasize the symmetry breaking mechanisms at play and separate the diagonal, pinch and residual stress contributions which all play a distinct role in intrinsic rotation. The decomposition is motivated by the formulation of the problem in the co-moving plasma frame with pure toroidal rotation, which corresponds to the lowest order flow (in $\rho_\ast$) of a collisional tokamak plasma [26]. It is interesting to note that in the case of pure toroidal rotation, the poloidal components of the parallel and $E \times B$ flows cancel each other and hence $\gamma_E$ (defined in the rotating frame) is proportional to $\omega_\phi'$. This means that to lowest order in $\rho_\ast$, the effect of $E \times B$ shearing can totally be included in the
diagonal part of the momentum flux, leading to values of an effective momentum diffusivity typically 20% smaller than $\chi_\parallel$ \cite{23, 38}.

Finally, we note that the decomposition used in equation (4) does not necessarily imply that the coefficients $\chi_\parallel$, $V_{co}$, $M$, $C_{FS}$ and $C_{\rho*}$ are independent of the plasma parameters, including $\omega'_\phi$ and $\omega_\phi$. The momentum flux can, however, always be locally linearized as a function of $\omega'_\phi$ and $\omega_\phi$. Experimentally, perturbative studies can be used to estimate the coefficients, similarly to what is done for heat transport \cite{43}. Experiments based on neutral beam injection (NBI) modulation \cite{44–49} and magnetic perturbation breaking \cite{50, 51} have evidenced the existence of a momentum pinch and led to values of $R_0 V_{co}/\chi_\parallel$ in rather good agreement with the Coriolis pinch theory. Some experiments have also evidenced the existence of residual stress terms \cite{48, 52}, but the comparison with the theory is much less advanced. This study aims at an experimental investigation of the residual stress induced by the up-down asymmetry of the flux surfaces.

1.3. Relationship between intrinsic rotation and momentum flux

The role of the various momentum flux contributions in sustaining the intrinsic rotation gradient can be emphasized by combining equations (2) and (4) into

\[
R_0 \omega'_\phi = -[V_{co} R_0 \omega_\phi + M \gamma_E + C_{FS} + C_{\rho*}] / \chi_\parallel,
\]

In the following, equation (5) is used to make the link between the predicted up-down asymmetry residual stress $C_{FS}$ and the observable intrinsic toroidal rotation gradient.

2. Design of the experiments

2.1. Principle

The mechanism under investigation is based on the fact that an up-down asymmetry of the magnetic configuration leads to a partial compensation of the radial flux of momentum caused by the turbulence in the upper and lower part of the plasma, resulting in net radial transport of momentum across the flux surface \cite{13, 14}. As one may expect, the subsequent momentum flux $C_{FS}$ is predicted to change sign when the up-down asymmetry of the plasma is reversed, i.e. when the plasma cross-section undergoes a mirror transformation with respect to the horizontal midplane. Symmetry considerations also imply that $C_{FS}$ changes sign if the direction of the toroidal magnetic field or plasma current is reversed. These changes in the sign of $C_{FS}$ are expected to modify the intrinsic rotation gradient, as discussed in the previous section. To test this prediction, a plasma configuration for which $C_{FS}$ is large and decays slowly towards the magnetic axis (i.e. the asymmetry penetrates deeply into the plasma core) has first been designed by performing a series of gyrokinetic simulations with the flux-tube code GKW \cite{53, 54} for various magnetic equilibria. The two chosen asymmetric magnetic configurations have then been achieved in the TCV tokamak, see figure 1, with the plasma limited on the high field side wall of the vacuum vessel fully coated with carbon tiles (which means that carbon is the main impurity in the plasma). The principle of the present experiments consist in the comparison of the intrinsic rotation profiles for the two asymmetric configurations of figure 1 for all combinations of magnetic field and plasma current directions. The magnetic configuration is labelled $s^+$ or $s^-$ when the top triangularity is positive or negative, respectively. The direction of the magnetic field $b^{+/-}$ and plasma current $j^{+/-}$ is defined with respect to the toroidal direction, positive when clockwise from above. The same convention is adopted for the toroidal rotation $v_\phi$. 

4
2.2. Measurement of the intrinsic toroidal rotation

The experimental test reported here relies on the precise measurements of the toroidal rotation profile over the plasma minor radius. A charge exchange recombination spectroscopy (CXRS) diagnostic [55] is used for that purpose. The toroidal rotation is obtained from the Doppler shift measurement of the carbon VI ($n = 8 \rightarrow 7, 529.1 \text{ nm}$) line emitted after charge exchange recombination between fully ionized carbon impurity and neutral hydrogen atoms. A diagnostic neutral beam (DNBI) [56] is used to inject the hydrogen atoms and provide proper illumination along the whole plasma radius. The quasi-perpendicular injection and relatively low power of the beam ($E \sim 50 \text{ keV}$ and $I = 3 \text{ A}$) ensure that the DNBI imparts negligible torque to the plasma and that the measured rotation is indeed intrinsic (the effect of the DNBI on the toroidal rotation is found to be less than $2 \text{ km s}^{-1}$ [57]). The CXRS provides up to 20 local measurements along the plasma minor radius, with a radial resolution $\Delta r < 1.4 \text{ cm}$ determined by the radial extent of the light collection volumes. This corresponds to a radial resolution $\Delta \rho_\psi < 0.06$ when using the normalized square root of the poloidal flux $\rho_\psi$ as a radial coordinate. The measurement relies on the knowledge and subtraction of the background emission spectrum that is determined by modulating the DNBI in 50 ms pulses, with 1/3 duty cycle. The resulting uncertainties are down to less than $2 \text{ km s}^{-1}$ accounting for wavelength calibration and statistical errors.

3. Experiments

The investigation of the up-down asymmetry effect on intrinsic rotation would ideally be done by changing the plasma shape with all other parameters kept constant and looking at the impact on the rotation profile. Naturally, ideal experiments of this type are almost always impossible in a tokamak where the number of actuators is limited and many parameters are strongly coupled. In addition, it is never guaranteed that the experimental set-up is as expected. In the present case, one could, for instance, wonder what would be the effect of a slight asymmetry in the vacuum vessel or toroidal magnetic field. It is, nevertheless, possible to first approach the ideal case by keeping constant as many plasma parameters as possible and then conduct additional tests to discard other potential mechanisms. This approach is adopted here and we
first focus on the effect of the up-down asymmetry for a specific case $b^− j^+$, then extend the
tudy to the other orientations of magnetic field and plasma current and finally perform a few
additional experiments to close the case.

The effect of the up-down asymmetry is looked at in deuterium L-mode plasmas for the
magnetic configurations presented in figure 1 with total current $I_p = 340 \pm 3$ kA, magnetic
field $B = 1.4 \pm 0.02$ T and edge safety factor $q_{95} = 2.9 \pm 0.05$. The evolution of these
parameters during the plasma pulse is shown in figure 2 for the two configurations ($s^+ b^− j^+$
and $s^− b^− j^+$). The line-averaged plasma density, $\bar{n}_e = 4.1 \pm 0.1 \times 10^{19}$ m$^{-3}$, is maintained
constant by feedback on the gas injection. Once stationary conditions are reached, the density,
temperature and rotation profiles are collected over a time window larger than 450 ms (shaded
area in figure 2), which corresponds to more than 12 energy confinement times. The electron
density and temperature are obtained from a Thomson scattering diagnostic and CXRS is used
to measure the $C^{6+}$ density, temperature and toroidal rotation. Figure 3 shows the density

![Figure 2. Temporal evolution of the plasma current $I_p$, toroidal magnetic field $B_T$, edge safety factor $q_{95}$, line-averaged density $\bar{n}_e$ and loop voltage $V_{loop}$ for the $s^+$ (red) and $s^−$ (blue) configurations of figure 1 with $b^− j^+$. The temperature, density and rotation profiles are collected over more than 450 ms once stationary conditions are reached (shaded area). (Colour online.)](image-url)
Figure 3. Left: electron temperature (top) and density (bottom) from Thomson scattering. Right: carbon temperature (top) and density (bottom) from CXRS. The profiles are shown for the $s^+$ (red) and $s^-$ (blue) cases of figure 2. The vertical dashed line indicates the sawtooth inversion radius. The carbon density profile is multiplied by a factor of 10 to fit on the same scale as the other profiles. (Colour online.)

and temperature measurements over the whole collection window as a function of the radial coordinate $\rho_\psi$, together with the error bars and a cubic spline fit with tension. The sawtooth inversion radius estimated from soft x-ray measurements with a multiwire chamber operated in the proportional regime [58] is also indicated in the figure by a dashed line. The spatial resolution of the soft x-ray measurement is $\Delta \rho_\psi < 0.05$ at the midplane of the vacuum chamber. As usually observed, the profiles are strongly flattened inside the inversion radius while a gradient develops in the outer part. In both magnetic configurations, the same density and temperature profiles as well as inversion radius are obtained within the error bars, to the exception of the $C^{6+}$ density which is 20% higher in the $s^-$ than in the $s^+$ configuration (the normalized carbon density gradient is however similar in both configurations). This indicates that in the present regime, heat, particle and impurity transport are largely insensitive to the orientation of the asymmetric shape $s^+/^-$. As we will see, the opposite is true for momentum transport.

Examples of the active CXRS spectra (i.e. the spectra during a DNBI pulse) are shown in figure 4 at three radial positions: one central $\rho_\psi = 0.17$, one outside the inversion radius $\rho_\psi = 0.6$ and one just before the last measurement point $\rho_\psi = 0.83$. The height, width and shift of the spectra with respect to $\lambda = 529.1$ nm are related to the $C^{6+}$ density, temperature and
toroidal rotation, respectively. The first observation is that high-quality spectra are obtained along the whole minor radius and that carbon density is slightly higher for the $s^-$ configuration as already mentioned. While the Doppler shift is similar for $s^+$ and $s^-$ at $\rho \psi = 0.83$, a sizeable difference builds up when moving towards the magnetic axis. Once the spectra are processed, they translate into the toroidal rotation profiles shown in figure 5 (top left plot). At matched edge rotation values, the $s^+$ configuration develops a steeper toroidal rotation gradient than the $s^-$ configuration outside the inversion radius, resulting in a stronger counter-current rotation in the first case than in the second one.

From a theoretical perspective, the up-down asymmetry flux $C_{FS}$ is predicted to be of the same sign as $-s_is_j s_b$ [14] with $s_i$ used here to denote the sign of the quantity $i$. According to equation (5), it follows that the toroidal rotation gradient $v'_\psi = -\partial v_\psi/\partial r$ should be more positive when $s_is_j s_b > 0$. This is expected to apply in the region where the up-down asymmetry of the flux surfaces is sizeable, i.e. in the outer part of the plasma, and where turbulent transport is the dominant process in setting the rotation profile, i.e. outside of the inversion radius and away from the edge (sink-free region). The observation of more positive values of $v'_\psi$ in the $s^- b^- j^+$ case compared with the $s^+ b^- j^+$ one therefore matches the theoretical prediction.

The next question to arise is ‘Is this observation really due to the up-down asymmetry residual stress?’ Answering this question unambiguously is extremely challenging and would require to measure the correlation between radial and parallel fluid velocity perturbations in the plasma core for the two magnetic configurations. This is not foreseeable in the near future, but it is possible to look at the problem under a slightly different angle and answer ‘Could a known effect other than the up-down asymmetry residual stress be responsible for the change in the rotation profile?’ To this end, the same experiments are repeated for all the magnetic field and plasma current orientations $b^+/b^- j^+/j^-$ and the resulting toroidal rotation profiles are shown in figure 5 (remaining plots). In all cases, a different rotation profile is obtained in the $s^+$ and $s^-$ configurations, with values of $v'_\psi$ more positive when $s_is_j s_b > 0$, thus still in agreement with the theoretical prediction of the up-down asymmetry residual stress. This observation allows one to discard any other mechanism whose effect on the toroidal rotation profile does not follow the $s_is_j s_b$ dependence.

Interestingly, in the $b^+ j^-$ configuration the plasma core rotates in the co-current direction, while it rotates in the counter-current direction for the other three configurations. In TCV L-mode plasmas, a reversal of the toroidal rotation direction from counter-current to co-current is usually obtained by ramping up the density [59–61]. Here the density was similar in the four magnetic configurations $b^+/j^+ b^-/j^-$ and the proximity to the point of rotation reversal was tested.
by changing the density by ±20% in dedicated cases. It is not understood why the $b^+ j^-$ cases rotate in the co-current rotation, but this has little importance for the effect under investigation, which is a differential effect. Actually, it is even beneficial for the study as it demonstrates that the differential effect of the up-down asymmetry is a very robust phenomenon that is still observed in the direction predicted by the theory, independently of whether the rotation is co-current or counter-current.

So far, we have been describing the effect of the up-down asymmetry on the rotation profile of the carbon impurity, which is the measured quantity. Provided the impurity concentration is not very high, the main part of the turbulent momentum flux is however carried by the bulk ions (deuterium) and it is therefore important to check that the same behaviour is obtained for deuterium. The difference between carbon and deuterium rotation is obtained from the force balance equation assuming that the poloidal rotation is neoclassical. The poloidal rotation is calculated with the neoclassical transport code NEOART based on the Hirshmann and Sigmar formalism [62] with the viscosity coefficients being equivalent to NCLASS [63] and retaining the high collisionality limit of the Pfirsch–Schlütter transport [64]. The resulting deuterium toroidal rotation profiles are shown in figure 5 (dashed lines). As expected in a medium-sized device like TCV where the diamagnetic velocity is relatively large, the deuterium toroidal
rotation is significantly more co-current than the carbon rotation. The variation of the deuterium rotation with the up-down asymmetry nevertheless follows the variation of the carbon rotation, a direct consequence of the similar pressure profiles obtained in the \( s^+ \) and \( s^- \) configurations, figure 3.

The modification of the toroidal rotation profile induced by the up-down asymmetry is quantified by calculating, for each configuration, the quantity \( \Delta v_\phi = v_\phi |_{\rho_\psi=0.65} - v_\phi |_{\rho_\psi=0.85} \) which provides an estimate of the average toroidal rotation gradient \( \bar{v}_\phi' \) in the outer part of the plasma. The range \( \Delta \rho_\psi = 0.65–0.85 \) corresponds to a variation in minor radius of \( \Delta r = -5.55 \text{ cm} \) with a difference of less than 5% between the configurations. It covers a region from well outside the sawtooth inversion radius to just inside the last CXRS measurement points. The values of \( \Delta v_\phi \) obtained for the deuterium and carbon species are summarized in table 1. Note that in the reversed rotation cases (i.e. co-current core rotation), the rotation profile is no longer monotonic and as a consequence the values of \( |\bar{v}_\phi'| \) are smaller than those for the non-reversed cases. Within each set (reversed or non-reversed) larger values of \( |\bar{v}_\phi'| \) are obtained when \( s_i s_b s_j \) sign \( (\Delta v_\phi) > 0 \), consistently with the profiles shown in figure 5 and the dependences of \( C_{FS} \) on \( s_i s_b s_j \).

It is important to realize that the whole intrinsic rotation profile depends on the rotation value at the plasma edge and, experimentally, a significant correlation between edge and central rotation is usually observed. From a theoretical perspective, the edge rotation value determines the momentum pinch in this region, which in conjunction with the residual stress then builds up the rotation gradient over the whole minor radius, equation (5). The mechanisms that set the edge rotation are far from being understood but one important player is found to be the magnetic configuration. The edge rotation (and the scrape-off layer flows) indeed depends on the position of the X-point (diverted configurations) \cite{61, 65, 66} or of the plasma–wall contact point (limited configurations) \cite{67}. It is likely that similar effects are at play in the present experiments and it could explain part of the scatter in table 1 (i.e. the slightly different values of \( |\bar{v}_\phi'| \) obtained in configurations that ‘should’ lead to the same value). It should be stressed, however, that a change in the boundary condition cannot be responsible for the effect reported here, as the variation of \( |\bar{v}_\phi'| \) with the up-down asymmetry can be obtained at matched edge rotation values, as shown in figure 5.

Finally, a couple of additional tests were performed to check that the intrinsic rotation profile of an up-down symmetric case lies between the profile obtained for \( s^+ \) and \( s^- \) and that the effect of the up-down asymmetry is still observed with a reduced or non-existent sawtooth inversion radius. These tests are detailed in the appendix.

### 4. Discussion and conclusions

Following the prediction of the up-down asymmetry effect on turbulent momentum transport \cite{13}, dedicated experiments have been conducted in the TCV tokamak to test the impact on
the intrinsic rotation profile. The toroidal rotation gradients of the carbon impurity (measured) and the main ion (calculated) are observed to depend on the up-down asymmetry of the plasma flux surfaces. In the case of up-down asymmetric plasmas, the rotation gradient in the outer part of the plasma changes with the shape $s^+/-$, magnetic field $b^+/-$ and plasma current $j^+/-$ orientations. Larger values of $|\bar{v}_\phi^\prime|$ are obtained when $s_s s_p s_j \text{sign}(\bar{v}_\phi^\prime) > 0$, in agreement with the theoretical prediction. The change in the gradient reflects on a change by a factor of 1.5–2 in the central rotation and the effect is observed independently of whether the plasma core rotates in the co-current or counter-current direction. The effect of the boundary condition (edge rotation), MHD activity, magnetic field ripple, slight asymmetry in the device (vacuum chamber, toroidal magnetic field and/or plasma–wall interactions) or torque from the DNBI cannot explain the full set of experimental observations. To our knowledge, the only mechanism that can account for all the observations is the turbulent up-down asymmetry residual stress. Preliminary quantitative comparisons with the theory have been made in [16]. Here, we focused on the experimental results and leave fully quantitative comparisons to a further study, which will require non-linear simulations including the effect of collisions and the electron dynamics.

Interestingly, the fact that similar temperature and density profiles are achieved in spite of the different toroidal rotation indicates that the toroidal rotation profile has little impact on confinement in the present experiments. This might look odd with the, now classical, picture that sheared toroidal rotation is beneficial to energy confinement but is not necessarily inconsistent. First, sheared perpendicular flows stabilize primarily the long wavelength instabilities (ITG) while in TCV the trapped electron mode is usually found to be the most unstable mode. In addition, flow shearing might well be important close to confinement bifurcations and have much less pronounced effect far from the transition. One way to address this issue would be to repeat the experiments closer to the conditions where confinement transitions are observed (eITB or H-mode), to see whether it is possible to induce a bifurcation by changing the rotation profile through the up-down asymmetry effect.

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Appendix. Effect of the up-down asymmetry at lower current and dynamical evolution of the plasma shape

A few more tests are described in this appendix. First, the plasma shape was varied dynamically in the same plasma pulse starting from an up-down symmetric plasma of positive triangularity and evolving towards the configuration $s^+$ or $s^-$ (with $b^+ j^+$. Because the shape evolution involves a change in the plasma–wall interaction, the line average density was not as well controlled as in the previous cases and dropped from $\bar{n}_e = 4.5 \pm 0.1 \times 10^{19} \text{m}^{-3}$ in the symmetric configuration to $\bar{n}_e = 4.1 \pm 0.1 \times 10^{19} \text{m}^{-3}$ in the $s^+/-$ configurations. Separate checks showed that this density variation has a negligible impact on the rotation profile in the present scenario. As shown in figure A1 the toroidal rotation profile in the symmetric case is found to lie between the profiles of the $s^+/-$ cases, as expected from the fact that $C_{FS} = 0$ in an up-down
symmetric configuration. Note that the initial up-down symmetric case is not identical in the left and middle plot. This might be due to the fact that the up-down symmetric configuration is achieved at the beginning of the pulse, not long after the current ramp-up, therefore in a phase where it is more likely to get some variations from shot to shot. Note also that the shaping of the $s^-$ configuration was not as pronounced as the $s^+$ configuration due to an unexpected disruption that shortened the plasma pulse. These results are therefore clearly not at the same level as the rest of the study but we nevertheless think they are useful in showing how the symmetric case behaves in comparison with the asymmetric ones. The $s^+/-b^+ j^+$ configuration was also repeated at lower plasma current $I_p = 190$ kA for which the sawtooth inversion radius is strongly reduced or non-existant. Again, the effect of the up-down asymmetry on the rotation profile is observed, figure A1, but is slightly less pronounced than at higher currents.

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