LETTER TO THE EDITOR

Evidence for the neoclassical nature of the radial electric field in the edge transport barrier of ASDEX Upgrade

E. Viezzer, T. Pütterich, C. Angioni, A. Bergmann, R. Dux, E. Fable, R. M. McDermott, U. Stroth, E. Wolfrum and the ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany

E-mail: Eleonora.Viezzer@ipp.mpg.de

Abstract. Experiments have been performed on ASDEX Upgrade to clarify the nature of the radial electric field, E_r, in the edge transport barrier of tokamak plasmas. Highly resolved radial profiles of E_r have been diagnosed spectroscopically through the radial force balance of impurity ions. We show that in the fully developed edge pedestal the nature of the radial electric field is neoclassical. This requires, in particular, that the main ion poloidal rotation is at neoclassical levels. Both main ion and impurity ion poloidal rotation profiles have been measured in deuterium, hydrogen and helium plasmas with main ion pedestal top collisionalities, $\nu_{*,i}$, between 1.2 and 12. These profiles have been compared to a hierarchy of neoclassical models and are found, in all cases, to be in good agreement demonstrating that inside the edge transport barrier the E_r well is sustained by the gradients of the main ion species.

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1. Introduction

After the discovery of the high confinement mode (H-mode) on the ASDEX tokamak [1] sheared $\mathbf{E}\times\mathbf{B}$ plasma flow was identified as a key component for the suppression of turbulent transport and the formation of transport barriers [2]. At the onset of the H-mode, the edge turbulence level is significantly reduced and a steep edge pressure gradient ∇p develops which is responsible for the improved H-mode confinement. This pressure gradient as well as the concomitant turbulence stabilization are sustained throughout the H-mode by the presence of a sheared plasma flow perpendicular to the magnetic field caused by a local radial electric field, E_r. Therefore, the size and the nature of E_r and the accompanying flow have been the subject of intense research for several decades [3, 4]. One obvious source for E_r is non-ambipolar transport [5], which also provides the possibility of bifurcation phenomena [6]. The flows parallel and perpendicular to the helical magnetic field lines are the physically relevant parameters and are related to E_r via $v_\perp = \mathbf{E}\times\mathbf{B}/B^2 - \nabla p\times\mathbf{B}/qnB^2$ and $v_\parallel = v_\theta B/B_\theta + RB_\phi(E_r - \nabla p/qn)/B$ [7] (charge q, density n, local major radius R, poloidal and toroidal magnetic field B_θ and B_ϕ). In axisymmetric geometry, for a particular poloidal flow, an arbitrary combination of perpendicular and parallel flows can be prescribed since E_r is a degree of freedom of the system. This is the reason why neoclassical transport in tokamak plasmas is often considered as intrinsically ambipolar [7]. In a tokamak, however, toroidal flows are damped by field inhomogeneities (ripple) and neutral gas friction, and must also comply with momentum conservation. Therefore, the toroidal flows are constrained as well and especially close to the separatrix, where the H-mode transport barrier develops, also in a tokamak a well defined value for the ambipolar radial electric field, E_r^{amb}, can be expected [8].

Due to the importance of the electric field for the H-mode, E_r measurements have already been compared to neoclassical theory but the overall picture is not yet conclusive. Early studies on the edge plasma of the DIII-D tokamak found a disagreement between experimental and neoclassical poloidal rotation [9] ; here the measured main ion poloidal rotation deviated by one order of magnitude from the neoclassical prediction. In dedicated studies of the L-H transition, the evolution of E_r was decoupled from that of the ion pressure gradient [10].

The core electric field was studied in many experiments and confinement regimes including internal transport barriers. In many cases very large discrepancies between experiment and theory were found [11–14]. In other cases the poloidal flow measurements agreed with neoclassical theory within the experimental uncertainties [15–22]. These measurements have been mostly performed on impurity ions.

Based on detailed spectroscopic measurements of the plasma flows in ASDEX Upgrade (AUG), this letter presents for the first time direct evidence that neoclassical theory can account for the main features of the edge radial electric field in tokamaks. In case of a negligible toroidal flow, which is shown to be a good approximation in the pedestal region of AUG, neoclassical theory yields the simple expression $E_r^{\mathrm{amb}} \approx \nabla p_i/en_i$, where E_r is mainly determined by the ion pressure gradient (elementary charge e, ion density n_i). This relation corresponds to the cancellation of the poloidal components of the ion diamagnetic and $\mathbf{E}\times\mathbf{B}$ drifts up to small neoclassical correction terms. High quality edge poloidal rotation data of impurities have been measured in deuterium and hydrogen plasmas, and, for the first time, of main ions in helium plasmas at AUG and show consistency with neoclassical theory. This demonstrates the validity of this picture and the applicability of the simple approximation of E_r^{amb}.

2. Experiment

The most common method to measure the rotation of the plasma is active charge exchange recombination spectroscopy (CXRS) [23]. A combination of poloidal and toroidal views allows for a direct evaluation of E_r using the radial force balance equation. In general, poloidal flow measurements are challenging due to their relatively small

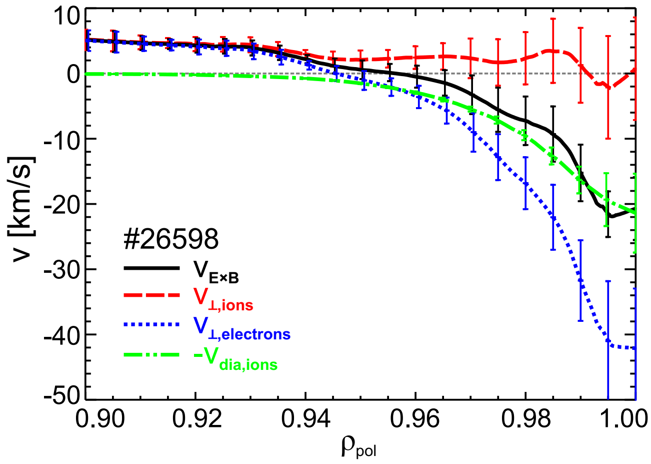

Figure 1: **E**×**B** velocity (black), perpendicular velocity of main ions (red) and electrons (blue) and main ion diamagnetic fluid velocity (multiplied by -1, green) measured in an H-mode discharge with a toroidal magnetic field on-axis of B_ϕ = -2.5 T, plasma current of I_p = 1 MA, 5 MW of neutral beam injection (NBI), 0.8 MW of electron cyclotron resonance heating (ECRH) and a central line-averaged density of $8\times10^{19}\,\mathrm{m}^{-3}$.

magnitude. At AUG the poloidal rotation velocity is measured using active CXRS on a heating beam [24]. Due to the energy dependence of the CX cross-sections several atomic physics effects [25] may arise when measuring CX emission and can give spurious temperature and rotation measurements. The effect of the gyro-motion of the impurity along with the finite lifetime of the excited state of the transition [26, 27] can become important when measuring in the plane of the gyro-orbit, i.e. in the poloidal direction. The corrections arising from the atomic physics effects have been calculated for the geometry of the poloidal CXRS system and are found to be small [24]. For the main ion poloidal rotation measurements in helium plasmas that are presented in the following the maximum correction due to the atomic physics effects is 0.2 km/s which is well within the experimental uncertainties. The corrections have been calculated using a lifetime of 2 ns for the He^+ ($n = 4 \rightarrow 3$) transition. This value has been determined from the Einstein coefficients calculated using the Cowan code [28]. To reduce systematical uncertainties in the rotation measurements the wavelength calibration is performed on a shot-to-shot basis using a neon lamp [24]. This enables a quite accurate determination of the wavelength calibration with uncertainties smaller than 1 km/s.

Recent AUG results [29] have shown that using the radial force balance of impurity ions the CXRS measurements yield the same edge E_r profile independent of the trace impurity used for the evaluation. Comparing the E_r profile to the gradients of the main ion species allows us to obtain information on the perpendicular main ion flow indirectly. This is done in figure 1 which shows the perpendicular velocity of the main ions (red) and electrons (blue), the **E**×**B** velocity (black) and the ion diamagnetic drift velocity (multiplied by -1, green) measured in an H-mode plasma. Combining all measurements of the edge kinetic profiles provides experimental evidence that perpendicular to the magnetic field the ion fluid is almost at rest (below 5 km/s) in the lab frame, while the magnitude of both the $\mathbf{E}\times\mathbf{B}$ and diamagnetic flow is up to 22 km/s in the edge pedestal. If the toroidal rotation is small at the plasma edge, the balance between the ion diamagnetic and $\mathbf{E}\times\mathbf{B}$ flows indicates that the poloidal rotation velocity of the main ions, $v_{\theta,i}$, may be approximately neoclassical. In the following, we present the first measurements of $v_{\theta,i}$ in the edge transport barrier of AUG and compare the measured profile to neoclassical calculations.

3. Main ion and impurity ion poloidal rotation measurements and comparison to neoclassical models

In order to quantify whether the main ion poloidal rotation is neoclassical, we measured $v_{\theta,i}$ directly in helium plasmas which provide the opportunity to obtain information on the main ion species via CXRS on He^{2+} ($n = 4 \rightarrow 3$, $\lambda = 468.571$ nm). For the application to deuterium, which is usually the main ion species at AUG, background emissions and the beam halo prevent a simple interpretation of the spectra.
Figure 2 shows the measured main ion (a) temperature, (b) density, (c) toroidal and (d) poloidal rotation velocity profiles along with spline fits in black. In the presented discharge the main ion collisionality $\nu_{*,\mathrm{He}}$ at the pedestal top ($\rho_{pol} = 0.97$) is $\sim$12, i.e. deep in the Pfirsch-Schlüter regime ($\nu_* > \epsilon^{-3/2}$ with ϵ being the inverse aspect ratio). In the data analysis the plume effect [23] has not been taken into account. The helium plume is caused by He^+ ions, excited via electron impact (or ion impact), which gyrate along the magnetic field lines and thus, lead to polluting emission in the spectrum. However, at the plasma edge the contribution of the helium plume is expected to be small [23], which is supported by independent electron density measurements: the helium density is half the electron density and the edge gradients are well matched, i.e. $\nabla n_{\mathrm{He}} = \nabla n_e/2$, (see figure 2(b)).
The sign convention used in this paper is as follows: poloidal rotation velocities, which are vertically upward at the low-field side, are negative, i.e. in the electron diamagnetic drift direction. In the standard magnetic configuration of AUG B_ϕ is negative (clockwise viewed from above) and B_θ is positive (pointing downward at the outer midplane). I_p and the NBI are pointing into the positive toroidal direction (counter-clockwise viewed from above).
The main ion poloidal rotation is 1–3 km/s (of the order of $\lesssim 0.03$ of the thermal velocity) and is in agreement with the neoclassical prediction obtained with the neoclassical code NEOART [30] shown in red in figure 2(d). NEOART incorporates a fluid model based on the calculation of collisional transport coefficients for a given number of impurities and includes collisions between all species. The code solves a set of linearly coupled equations for the parallel velocities in an arbitrary toroidally symmetric geometry and calculates neoclassical transport parameters for all collisionality regimes. The consistency between the neoclassical calculation and the experiment shows that the main ion poloidal rotation is driven predominantly by the ion temperature gradient [31]. The red dashed lines in

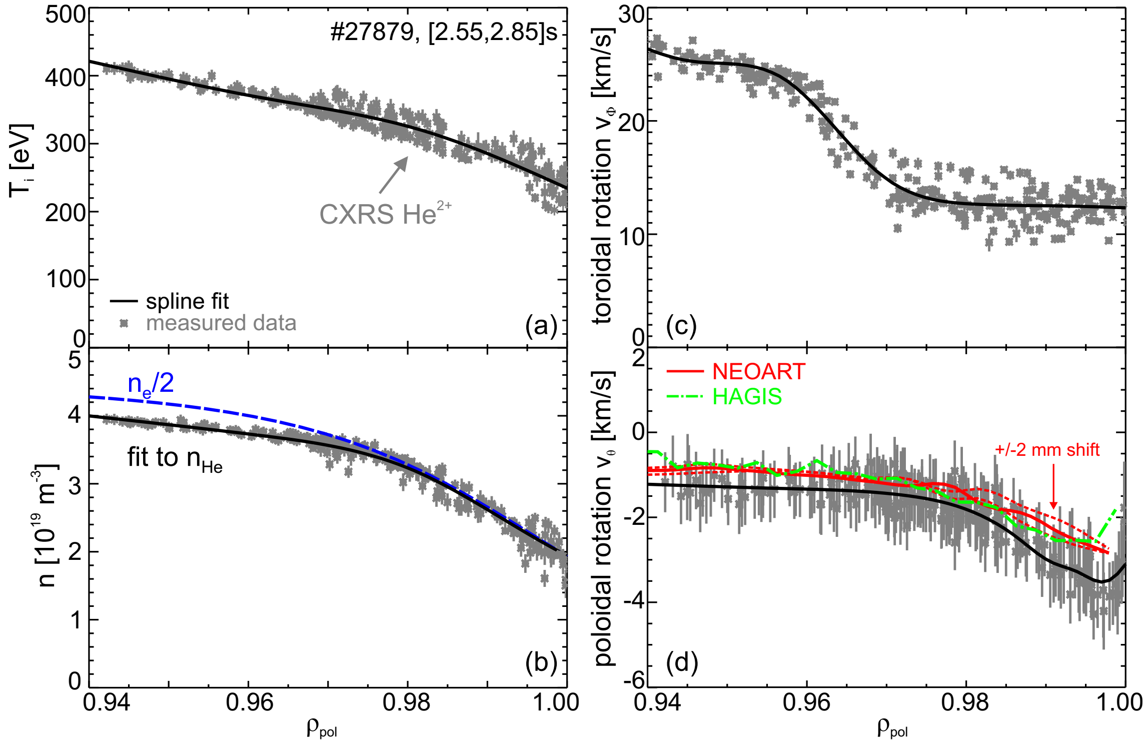

Figure 2: Main ion CXRS measurements in a helium plasma: (a) temperature, (b) density, (c) toroidal and (d) poloidal rotation velocity. The fit to the measured data is shown in black. In (d) the neoclassical prediction of the main ion poloidal rotation obtained with NEOART and HAGIS is shown in red and green (dashed-dotted line). The data were measured in an H-mode plasma with B_ϕ = -2.5 T, I_p = 1 MA, 0.5 MW ECRH, 9.2 MW deuterium NBI heating and a central line-averaged density of 1.1×10^{20} m^{-3}.

figure 2(d) show the effect of a radial shift of ±2 mm between the ion and electron profiles which are used as input for the neoclassical simulations. The green dashed-dotted line shows the neoclassical poloidal rotation profile as calculated with the HAGIS code [32, 33]. HAGIS is a kinetic particle code with a Monte-Carlo pitch angle collision model that simulates a three-species plasma and includes the effects due to finite orbit sizes. The good agreement between the measurement and both neoclassical predictions also demonstrates that in these plasmas the orbit-squeezing effect [34] is negligible.
Compared to the helium plasmas performed at DIII-D, where the ion collisionality at the plasma edge varied from 0.1 to 0.3 [9], the main ion collisionality in our experiment is two orders of magnitude higher. This might explain the opposite direction of the main ion poloidal rotation velocity measured at AUG and DIII-D. At DIII-D $v_{\theta,i}$ was positive, i.e. in the ion diamagnetic drift direction, and reached values of up to 40 km/s in the plasma edge, which was far off from the neoclassical estimate ($v_{\theta,i} \approx$ 0–2 km/s). In the neoclassical treatment, $v_{\theta,i}$ is strongly dependent on the edge ion parameters. Depending on the ion collisionality the main ion poloidal rotation can be in the electron or in the ion diamagnetic drift direction, or be close to zero. The experiments at DIII-D indicate

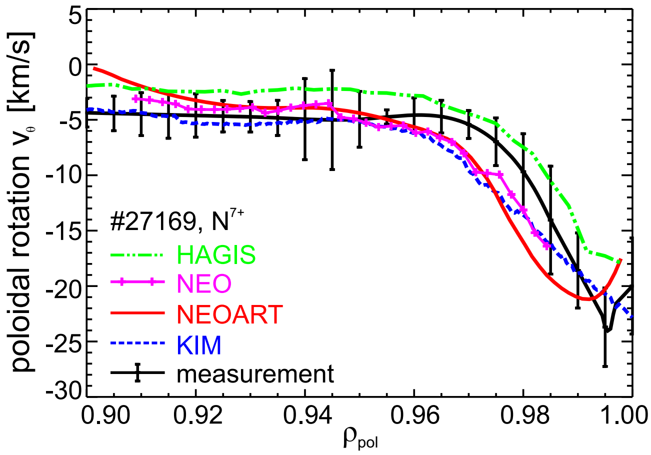

Figure 3: Impurity ion poloidal rotation velocity measured on N^{7+} in a D plasma, along with the conventional neoclassical prediction [31] in blue (dotted line) and the simulated profile using NEOART (red, solid line), NEO (purple, crosses) and HAGIS (green, dashed-dotted line).

that in the low collisionality regime the neoclassical prediction might not be sufficient to characterize the measured profile. This was also reported in recent DIII-D experiments using indirect measurements of $v_{\theta,i}$ [35]. The presented data based on CXRS on He^{2+} show that in the Pfirsch-Schlüter regime $v_{\theta,i}$ is well described by neoclassical theory.
The comparative analysis has been extended to several different impurities and to a hierarchy of models which describe neoclassical transport theory, i.e. from a conventional neoclassical model [31] to a more comprehensive description, such as that allowed by the HAGIS code, that includes finite orbit width effects. In an H-mode discharge performed in deuterium the poloidal impurity rotation velocity was measured on the N^{7+} ($n = 9 \rightarrow 8$) spectral line at $\lambda = 566.937$ nm and compared to conventional neoclassical predictions based on the analytic model by Kim et al. [31]. Here, the calculation is based on a fluid model with simple viscosity coefficients derived using the Hirshman and Sigmar moment approach [36]. Figure 3 shows the spline fit to the measured poloidal rotation data in black, and in blue (dotted line) the neoclassical prediction using the analytic model [31]. In addition, the neoclassical profiles obtained with the numerical codes NEOART, NEO [37] and HAGIS are shown in red (solid line), magenta (crosses) and green (dashed-dotted line). NEO is a drift-kinetic code that uses a δf expansion of the fundamental drift-kinetic Poisson equations and a first-principles approach to calculate the neoclassical transport coefficients directly from the solution of the distribution function f. As shown in figure 3 all of the models agree reasonably well and are consistent with the measured profile. This also demonstrates that kinetic effects, which are included in HAGIS, play only a minor role in the plasmas considered here. It should be noted that at the very plasma edge the gradient scale length approaches that of the poloidal ion gyroradius ($\sim$1 cm for a D ion at the top of the pedestal), thus breaking the order assumed in the theory and the neoclassical approximation is

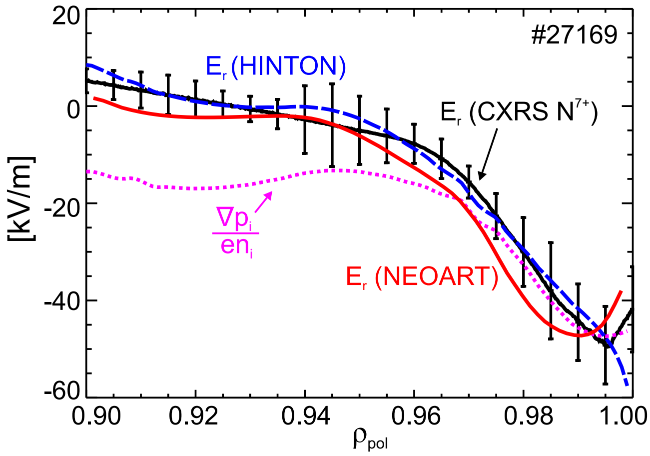

Figure 4: E_r profile as measured with CXRS in black, estimate of $\nabla p_i/en_i$ in magenta (dotted line), E_r calculated using the Hinton-Hazeltine formulation [7] in blue (dashed line) and from NEOART (red, solid line).

less valid in this region. In this plasma, the main ion collisionality $\nu_{*,\mathrm{D}}$ is in the banana regime ($\nu_{*,\mathrm{D}} < 1$) for $\rho_{pol} < 0.96$ and approaches the plateau regime ($1 < \nu_{*,\mathrm{D}} < \epsilon^{-3/2}$) at $\rho_{pol} \approx 0.96$, while the impurity collisionality $\nu_{*,\mathrm{N}}$ is deep in the Pfirsch-Schlüter regime. In the edge transport barrier of helium (as presented above) and deuterium plasmas [38], the toroidal main ion flow is observed to be small (of the order of $\lesssim 0.25$ of the thermal velocity). Thus, the agreement between the measured poloidal rotation and the neoclassical simulations also indicates that the edge radial electric field behaves as expected from neoclassical theory.

Figure 4 shows the E_r profile derived from the CXRS measurements in black and an estimate of the main ion pressure gradient term $\nabla p_i/en_i$ in magenta (dotted line). In the edge pedestal ($\rho_{pol} > 0.97$) the E_r profile matches $\nabla p_i/en_i$. The profile shown in blue has been calculated using the Hinton-Hazeltine formulation [7] of E_r, while in red the profile calculated using NEOART is shown. At the plasma edge the poloidal rotation velocity is at neoclassical levels and, for small toroidal rotation velocities, the radial electric field is well described by the simple approximation of $\nabla p_i/en_i$.

For a further validation of this result different impurity species, including He^{2+}, B^{5+}, C^{6+} and N^{7+} measured in deuterium and hydrogen plasmas, have been analyzed. Figure 5 shows the minimum of the poloidal rotation velocity measured in the edge transport barrier plotted against the minimum of the neoclassical profile as simulated with NEOART of both impurities (black/coloured squares correspond to D plasmas, black triangles to H plasmas) and main ions (red circles) as measured in He plasmas. In these plasmas, the main ion collisionality at the pedestal top ($\rho_{pol} = 0.97$) varied from 1.2 (plateau regime) to 12 (Pfirsch-Schlüter regime). In H-mode, both the sign and the magnitude of the neoclassical poloidal rotation are consistent with the measurement. Since friction between main ions and impurities is the dominant term in the impurity parallel momentum balance, the poloidal impurity rotation is mainly determined by the

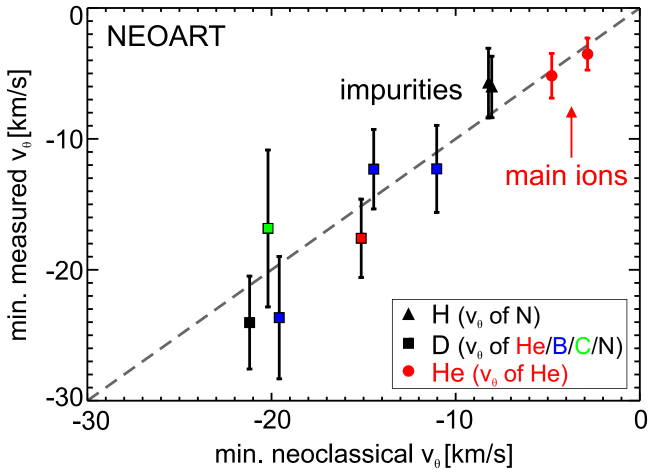

Figure 5: Minimum of measured poloidal rotation velocity versus minimum of neoclassical profile for various species including He^{2+}, B^{5+}, C^{6+} and N^{7+} (impurities are highlighted in black, main ions in red) in H-mode plasmas with different main ion species (H, D and He).

main ion pressure and temperature gradient scale lengths, while the contribution from the impurity pressure gradient scale length is small as it is scaled by Z_i/Z_α [31] (Z being the charge state of the main ion i and the impurity α, respectively).

4. Summary and Conclusions

Measurements of the edge radial electric field and the poloidal rotation of both main ions (in helium plasmas) and impurities (obtained in deuterium and hydrogen plasmas) have been compared to neoclassical theory. The experiments provide evidence that in the fully developed edge transport barrier of an H-mode the radial electric field is neoclassical. This is closely connected to the finding that the main ion poloidal rotation is at neoclassical levels. These results are also in keeping with the poloidal impurity rotation term typically being the dominant contribution for the evaluation of the depth of the E_r well. In H-modes with pedestal top collisionalities ranging from the plateau to the Pfirsch-Schlüter regime, the measured poloidal rotation of both main ions and impurities are found to be consistent with neoclassical predictions; both the sign and the magnitude of the experimental and simulated profiles are in quantitative agreement. These results show that in the established H-mode the driving mechanism for the main ion poloidal rotation at the plasma edge is given by the ion temperature gradient (viscous damping). This implies that corrections to the main ion poloidal flow due to parallel flows (friction) or turbulence are negligible in the plasma regimes considered here.
The measurements presented here give hints on the nature of the main ion transport in the edge transport barrier and are in line with the impurity particle transport being neoclassical [39]. The mechanism responsible for damping the toroidal rotation velocity to small values at the plasma edge remains an open issue [40] and requires a more

detailed understanding of the toroidal momentum transport in the edge pedestal region which is the subject of future work.

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