Experimental validation of momentum transport theory in the core of the ASDEX Upgrade tokamak

C. F. B. Zimmermann[1 2 *], R. M. McDermott[1], C. Angioni[1], B. P. Duval[3], R. Dux[1], E. Fable[1], A. Salmi[4], U. Stroth[1 5], T. Tala[4], G. Tardini[1], T. Pütterich[1], and the ASDEX Upgrade[6] team

[1] Max Planck Institute for Plasma Physics, 85748 Garching, Germany
[2] Department of Applied Physics and Applied Mathematics, Columbia University, New York 10027, USA
[3] Ecole Polytechnique Fédérale de Lausanne, SPC, CH-1015 Lausanne, Switzerland
[4] VTT, P.O. Box 1000, FI-02044 VTT, Finland
[5] Physik-Department E28, Technische Universität München, 85747 Garching, Germany
[6] see the author list of H. Zohm et al, 2024 Nucl. Fusion, 10.1088/1741-4326/ad249d
[*] E-mail: benedikt.zimmermann@ipp.mpg.de

Introduction

Toroidal plasma rotation in tokamaks is a critical parameter influencing stability and confinement, particularly through its role in avoiding magnetohydrodynamic instabilities, such as locked modes. Understanding momentum transport, driven by diffusion, convection, and residual stress, is essential for predicting this rotation. Residual stress, a non-diffusive mechanism, generates intrinsic torque that can spontaneously spin up the plasma. However, uncertainties in modeling these mechanisms hinder accurate rotation predictions for future fusion reactors. This work presents a methodology developed on the ASDEX Upgrade tokamak (AUG) to experimentally separate the contributions to core momentum transport. Previous approaches lacked consistent treatment of time-dependent effects and interaction between transport channels, leading to discrepancies with theory. This analysis resolves those issues, enabling the derivation of scaling laws for momentum transport coefficients and corresponding reduced transport models.

Methodology

The method relies on modulating neutral beam injection (NBI) to introduce perturbations in plasma rotation measured via charge exchange recombination spectroscopy. The advantage of a controllable rotation perturbation lies in the ability to use Fourier decomposition to analyze the rotation profiles. This enables the extraction of transport coefficients and the separation of their contributions based on their temporal dependencies. Since modulation also alters the heating, and the resulting ion temperature responses affect turbulence, and consequently the turbulence-driven momentum transport, these cross-channel couplings must be accounted for by scaling the transport coefficients with the time-dependent ion heat diffusivity. The analysis was conducted using TRANSP [1] and ASTRA [2, 3]. TRANSP, with its NUBEAM module [4], models NBI-driven torque and heating, while ASTRA solves the momentum transport equation using experimental boundary conditions at the pedestal top. A global optimization routine adjusts transport

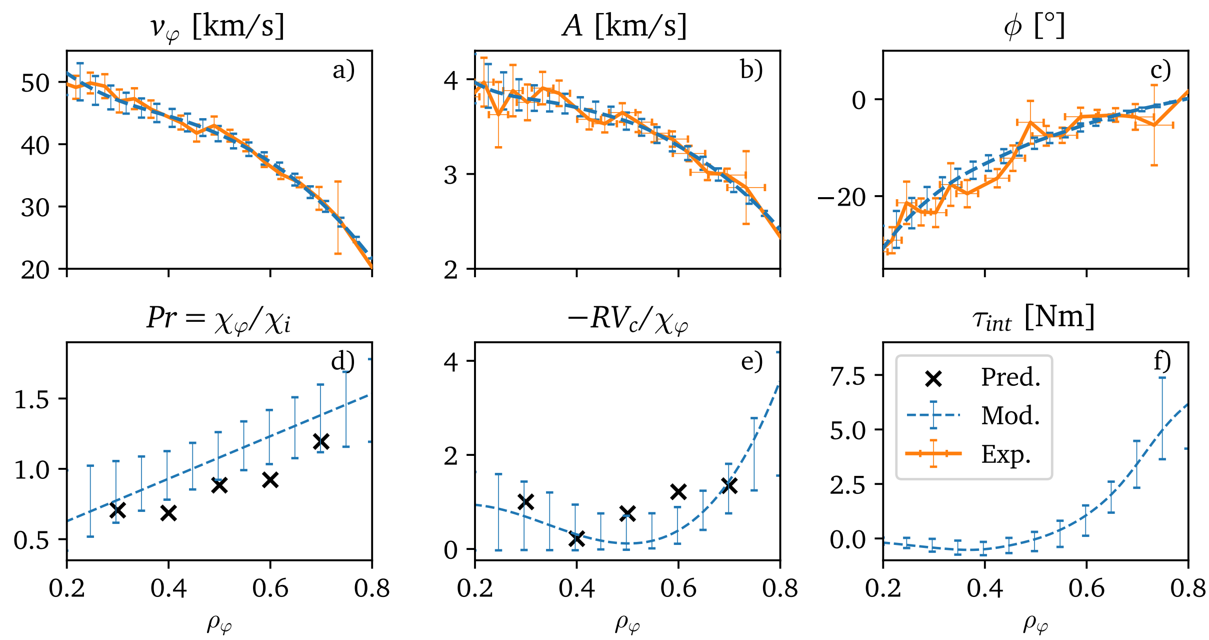

Figure 1: Momentum transport analysis of the AUG discharge #40076, 2.0 − 4.2s. Shown are (a) the time-averaged, (b) the amplitude, and (c) the phase profile of the toroidal plasma rotation over the normalized radius ρ_φ. Experimental (orange) and modeled (blue) data are in good agreement. The associated Prandtl, Panel (d), and pinch number, Panel (e), are consistent with gyrokinetic predictions, shown as black symbols. Panel (f) shows the measured intrinsic torque.

coefficients to best match experimental data. Key outputs are the Prandtl number $Pr = \chi_\varphi/\chi_i$ (momentum diffusivity over ion heat diffusivity), pinch number $-RV_c/\chi_\varphi$ (with the major radius R and the convective velocity V_c), and intrinsic torque τ_{int}, with associated uncertainties.

Results

Numerous experiments in the AUG tokamak were conducted to validate the methodology and investigate how plasma parameters influence momentum transport. A key requirement was developing a modulation scenario with high-quality, low-noise data, and unique solutions from Fourier profile analysis. To identify the best setup, NBI power, frequency, duty cycle, and geometry were varied. The results showed that reduced power, off-axis beams at low frequencies provided the best compromise between clear rotation signals and minimal heating perturbation [5]. With an optimized scheme, various modeling approaches were tested to extract momentum transport coefficients. A linear Prandtl number and cubic polynomials for pinch and residual stress provided a good balance between accuracy and computational cost. The best agreement with experimental data was achieved when including intrinsic torque and time-varying transport terms [6], as shown in Panels (a)-(c) of Fig. 1. Omitting these led to significantly worse fits. Error analysis confirmed that solutions corresponded to global minima in parameter space. The transport effects can be ordered by their strength, showing that the convective momentum flux is small compared to both the diffusive flux and the intrinsic torque in the outer-core of the plasma. Experimental Prandtl and pinch numbers were then compared to predictions from linear, local gyrokinetic theory using the GKW code [7], see Panels (d) and (e) of Fig. 1. For the first time, good agreement was found in absolute values, profile shapes, and parameter trends [6]. This resolved long-standing discrepancies, which likely resulted mainly from omitting intrinsic torque and time dependencies. These results underscore the importance of cross-channel couplings and consistent modeling. As a first application, the methodology was used to examine isotope effects on momentum transport [8]. Gyrokinetic theory suggests diffusion and convection do not strongly dependent on isotope mass, although heat fluxes may be affected due to the mechanism of equipartition. Experiments with deuterium and hydrogen plasmas with matched heat fluxes showed no isotope effect in momentum transport, confirming theoretical expectations. This validates the applicability of the corresponding models to future fusion devices like ITER with different isotope fuels. For a thorough comparison to gyrokinetic theory, isolated parameter scans were performed using the GKW code [7]. Previous simplified gyrokinetic models were found to differ from more realistic calculations involving collisions, non-circular equilibria and simultanous variation of input parameters. Parametric scans were conducted numericalley to develop and test scaling laws. The Prandtl number was found to depend mainly on trapped particle dynamics, with inverse aspect ratio ε serving as a key ordering parameter. The pinch number scaled best with the logarithmic density gradient R/L_{n_e}, consistent with the concept of the Coriolis pinch [9]. These scaling laws were validated against experimental trends derived from the experiment, showing good agreement. This confirmed the theoretical predictions for the NBI-heated, Ion Temperature Gradient mode (ITG)-driven H-mode plasmas studied [10]. Measured intrinsic torque was low in the plasma core and increased toward the pedestal, see Panel (f) of Fig. 1. In the core, it correlated with the logarithmic density gradient. In the outer core, it aligned more with the pressure gradient, suggesting different torque-driving mechanisms in core and edge regions. While detailed predictions would require global nonlinear simulations, the trends align with theoretical concepts relating to profile shearing [11] in the core, and $E \times B$ shearing towards the edge [12]. In recent work, the methodology was applied to study the emergence of hollow rotation profiles in the presence of strong electron cyclotron resonance heating, see Panel (a) of Fig. 2. It was found that such hollow rotation profiles can result from a counter-current intrinsic torque (see Panel (b) of Fig. 2) in a mixed mode regime between ITG and Trapped Electron Mode (TEM), demonstrated in Panel (c), and in agreement with previous findings [13]. For the stability of future fusion reactors such hollow rotation profiles should be avoided. Based on these insights, a

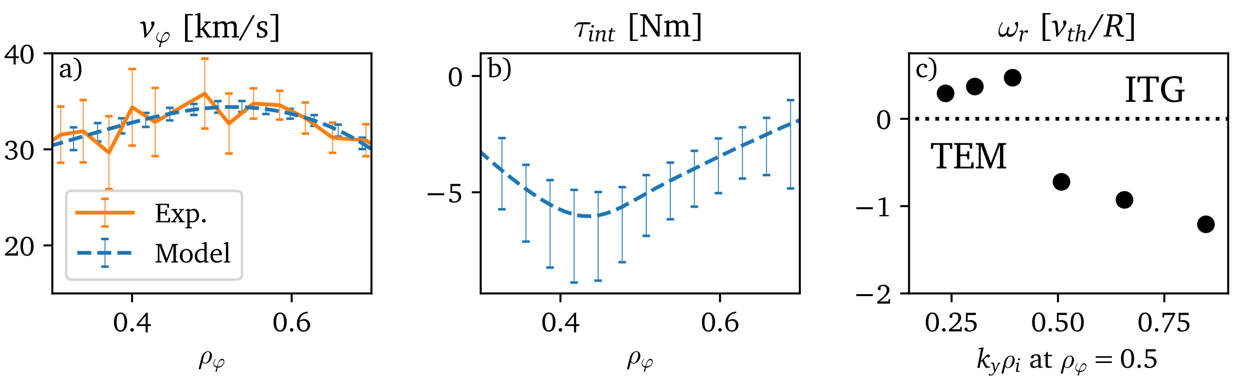

Figure 2: Momentum transport analysis of the AUG discharge #29216, $5.5-7.0$s with strong electron heating, $P_{ECRH} \approx 3.4$ MW versus $P_{NBI} \approx 3.0$ MW, at high line-averaged density of $n_e \approx 7.2 \cdot 10^{19}$ m^{-3}. Panel (a) shows the measured and modeled hollow rotation profiles. These are caused by a counter-current intrinsic torque, see Panel (b). A gyrokinetic analysis at mid radius, Panel (c), suggests a mixed mode regime between TEM, mode frequency $w_r < 0$, and ITG, $w_r > 0$, over the wave number range $k_y\rho_i$ tested with the GKW code.

reduced momentum transport model was developed. It combines gyrokinetic scaling for Prandtl and pinch numbers with empirical scalings for intrinsic torque. Implemented in ASTRA, the model was validated against an independent dataset, accurately predicting core rotation profiles over a large range of discharges. This opens avenues for various applications, including integrated modeling approaches and real-time control, and will provide a foundation for predictions of rotation profiles in future reactors.

Outlook

The results presented on resolving the mismatch between experimental observations and gyrokinetic predictions in the plasma core, together with the published methodology, and the first versions of a reduced rotation model for the core, have resulted in renewed interest within the community in this transport channel and in experiments of this kind. Future work will address transport regimes in strongly electron-heated plasmas with low input torque, study momentum transport in the plasma edge, and explore experiments on non-turbulent sources of intrinsic torque, such as neoclassical toroidal viscosity. Further development of reduced rotation models should incorporate these new insights and take into account the role of the normalized gyroradius in scaling momentum transport coefficients to future reactor conditions.

[1] J. Breslau et al. 2018 *Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*. [2] G. Pereverzev and P. N. Yushmanov. 2002 *MPI for Plasma Physics, Garching, Germany*. [3] E. Fable et al. 2013 *Plasma Phys. Control. Fusion*. 55. [4] A. Pankin et al. 2004 *Comput. Phys. Commun.* 159. [5] C. F. B. Zimmermann et al. 2022 *Plasma Phys. Control. Fusion*. 64. [6] C. F. B. Zimmermann et al. 2023 *Nucl. Fusion*. 63. [7] A. G. Peeters et al. 2009 *Comput. Phys. Commun.* 180. [8] C. F. B. Zimmermann et al. 2023 *Nucl. Fusion*. 63. [9] A. G. Peeters et al. 2007 *Phys. Rev. Lett.* 98. [10] C. F. B. Zimmermann et al. 2024 *Phys. Plasmas*. 31. [11] Y. Camenen et al. 2009 *Phys. Plasmas*. 16. [12] G. M. Staebler et al. 2013 *Phys. Rev. Lett.* 110. [13] C. Angioni et al. 2011 *Phys. Rev. Lett.* 107.