Development of predictive rotation models for ITER-relevant plasma conditions on the ASDEX Upgrade and DIII-D tokamaks

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In recent years, significant work has been carried out on the ASDEX Upgrade (AUG) and DIII-D tokamaks to validate our theoretical understanding of momentum transport. This has resulted in the development of the first reduced, validated, analytical model capable of predicting the rotation in the core of tokamak plasmas, as demonstrated by the predictions in Fig. 1. These advancements will impact predictions of impurity transport, turbulence stabilization, and mode locking in future fusion devices, while also opening new avenues for integrated modeling and real-time control.

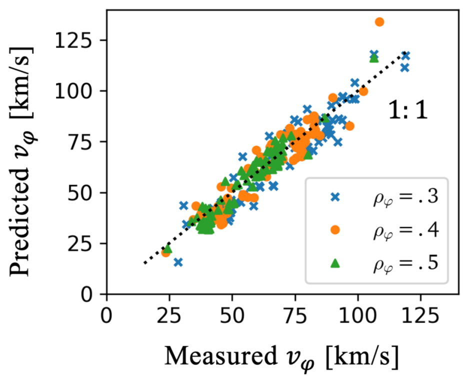

Figure 1: Comparison between the measured (x-axis) and predicted (y-axis) toroidal rotation for different radii. Unity is shown as black dotted line. Data set is constructed from various AUG H-mode discharges. Adapted from [7].

The foundation for validating the momentum transport theory was established on AUG through the development of a new analysis methodology based on the TRANSP [1] and ASTRA [2] codes. This methodology extracts diffusive, convective, and residual stress momentum transport coefficients from torque perturbation experiments performed using neutral beam injection (NBI) modulation [3,4].

First investigations of the isotope dependence of momentum transport revealed no impact of different isotopes on the transport coefficients, consistent with gyrokinetic theory [5]. This indicates that the validated models are broadly applicable to fusion reactors with mixed fuel compositions.

Scaling laws for the normalized momentum diffusivity (Prandtl number) and convective velocity (pinch number) were developed and validated based on AUG data. This was achieved by applying the methodology to a set of AUG discharges in a predominantly ion-temperature-gradient-dominated turbulence regime, with the extracted Prandtl and pinch numbers compared to predictions from linear, local gyrokinetic theory, computed using the GKW code [6]. For the first time, this comparison resulted in quantitative agreement between theory and experiment in terms of absolute magnitudes, profile shapes, and trends with plasma parameters [4]. This breakthrough facilitated the development of validated scaling laws for the Prandtl and pinch numbers [7]. Additionally, gyrokinetic parameter scans provided valuable insight into the physical mechanisms behind the observed trends.

The corresponding measurements of residual stress are consistent with current theoretical understanding [7]. Residual stress, a non-Fickian, off-diagonal transport term unique to momentum transport, generates intrinsic torque and can spin up the plasma from rest. On AUG, the measured intrinsic torque is typically small in the inner plasma core and becomes stronger toward the pedestal top, a pattern also observed on DIII-D. In the inner core, intrinsic torque is most strongly correlated with the logarithmic density gradient. In the outer core, the intrinsic torque shows a stronger correlation with the local pressure gradient. These findings suggest that different mechanisms drive intrinsic torque in the core and edge regions of the plasma. The observed trends align qualitatively with the concept of profile shearing [8] and turbulence intensity gradients influencing the inner core, while ExB-shearing effects become more prominent at the edge.

Building on the insights from this study, a reduced momentum transport model was developed to capture the essential contributions to momentum transport in the plasma core while significantly reducing computational complexity compared to gyrokinetic calculations [7]. This reduced model incorporates gyrokinetic scalings for the Prandtl and pinch numbers, combined with experimental scalings for intrinsic torque. It has been implemented in the ASTRA code and is published, making it available for broader use and further development. It accurately predicts rotation profiles for a database of discharges, confirming that it captures the most critical contributions to momentum transport, as illustrated in Fig. 1. Recent efforts have shown that the experimentally measured dependencies of intrinsic torque can be unified with the theoretical concept of the so-called profile shearing effects [8], providing a normalized, machine-independent, and extrapolatable formulation of the reduced model.

This work was extended to more reactor-relevant conditions by analyzing AUG discharges with an ITG-TEM mixed-mode turbulence regime. The application of strong ECH modifies the density gradient profiles and induces residual stress, which generates a counter-current intrinsic torque in the inner plasma core. Combined with momentum diffusion and convection, this mechanism leads to hollow rotation profiles, as shown in Fig. 2(a). This outcome is potentially undesirable for the stability of future fusion devices. Notably, the reduced transport model accurately reproduces these hollow rotation profiles, as demonstrated in Fig. 2(a).

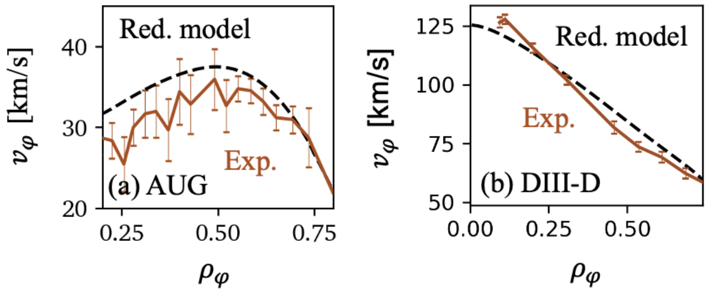

Figure 2: Predictions of the reduced momentum transport model for (a) a AUG discharge with hollow rotation profiles due to an ITG-TEM mixed-mode regime (#29216, P_NBI = 3 MW, P_ECH=3.4 MW, n_e=7.2*10^{19} m^{-3}), (b) a DIII-D discharge in a TEM-dominated turbulence regime (#200416, P NBI = 2.2 MW, P ECH=3.2 MW, n e=2.7*10^{19} m^{-3})

In recent experiments, the momentum transport analysis scenario was adapted to the DIII-D tokamak, and a corresponding analysis framework was established. To advance the validation efforts and further develop the reduced model for reactor-relevant conditions, the experiments were conducted to investigate turbulent momentum transport in low-torque and, consequently, low-rotation regimes, where turbulence growth rates exceed the ExB-shearing rates. These experiments involved thorough scans of the turbulence regime by varying the electron cyclotron resonance heating. During these experiments, it was possible to explore a TEM-dominated turbulence regime. Preliminary analysis shows that the hollow rotation profiles disappear in strong TEM conditions, indicating a co-current intrinsic torque. As shown in Fig. 2(b), the reduced transport model successfully explains the peaking of the rotation profile under these conditions.

The new DIII-D dataset, along with the specific implementation of the analysis technique, will provide further opportunities to adapt and refine the presented models. Ultimately, the existing implementation of the reduced transport model in ASTRA, together with the usage of quasi-linear gyrokinetic codes, will allow a more comprehensive understanding of turbulent momentum transport in the plasma core. This will enable mapping out the core rotation profiles of ITER based on assumptions about the rotation boundary. Altogether, this will give the community greater confidence in the extrapolation of rotation profiles for future tokamak devices and consistently incorporate the effects of rotation into scenario development for the stable operation of future fusion devices.

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