Experimental validation of momentum transport theory in the core of a tokamak plasma


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Motivation

• Understanding of momentum transport **crucial to predict toroidal plasma rotation**, which
  • impacts impurity transport (see talks from F. Reimold and D. Fajardo)
  • stabilizes turbulence via $E \times B$ shear $\rightarrow$ **influences confinement**
  • **provides stability** against MHD events $\rightarrow$ **avoids disruptions**

• **No fully validated theoretical model** for momentum transport available
  $\rightarrow$ no predictive capability for rotation profiles of a future reactor

• **Momentum transport studies are challenging** due to a third transport mechanism
  $\rightarrow$ Strong assumptions or **simplifications usually made** in previous exp. works

• To be presented: method to **assess** the momentum **transport coefficients purely from experimental data** and **validate theoretical predictions**
Outline

• Introduction

• **Background** of the Methodology: Equations and Modeling

• Comparison of **Gyrokinetic Predictions and Experimental Results**
  • **Parameter and Isotope Dependence** of Momentum Transport

• Summary and Outlook
Momentum Transport Equation

\[
m \frac{\partial}{\partial t} n_R v_\Phi = -\frac{1}{V'} \frac{\partial}{\partial \rho} V' \Gamma_\Phi + S_{\text{NBI}}
\]

→ Problem underconstrained in a steady-state analysis

NBI modulation

Time average

Fourier analysis

Steady-state

Amplitude

Phase

→ Problem constrained if modulation of turbulence can be compensated
Momentum Transport Modeling

\[
m \frac{\partial}{\partial t} n R \nu_\varphi = - \frac{1}{V'} \frac{\partial}{\partial \rho} V' \Gamma_\varphi + S_{NBI} \Gamma_\varphi = -mnR \left( \chi_\varphi \frac{\partial \nu_\varphi}{\partial \rho} + V_c \nu_\varphi \right) + \Pi_{RS}
\]

**Mom. transport equation**

Exp. \( \nu_\varphi \) boundary at \( \rho_{\varphi} = 0.8 \)

\( S_{NBI}, Q_i \) from TRANSP

\( \chi_\varphi(t), V_c(t), \Pi_{RS}(t) \)

**ASTRA forward-models \( \nu_\varphi \)**

**Optimization versus experimental \( \nu_\varphi \)**

**Prandtl number:** \( Pr = \chi_\varphi / \chi_i \)

**Pinch number:** \(-R \cdot V_c / \chi_\varphi \)

**Intrinsic torque:** \( \tau_{int} = V' \Pi_{Rs} \)

**Uncertainties**

→ First model to retain time dependencies (via \( \chi_i \)) in all transport coefficients and channels
→ Concept has been validated on a broad set of discharges [Zimmermann et al. PPCF. 64. 2022]
Fitting of the reference case #40076 at 1.8-4.2s (ELMy H-mode)

Experimental data vs. successful ASTRA modelling

Steady-state vs. successful ASTRA modelling

Transport Coefficients:

- Prandtl number
- Diffusivity
- Pinch number
- Torque

Colormap of the parameter space

→ unique solution obtained
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Validation of Gyrokinetic Predictions

- Performed quasi-linear, local gyrokinetic calculations via GKW

- Coefficients are predicted to be stable despite modulation, $\chi_i$ time dependence valid

- Good agreement of Gyrokinetic Predictions and Experimental Results for ITG dominated plasma
  - First time to quantitatively validate this kind of theoretical predictions
  - Retaining time dependencies is crucial to obtain best solution
Parameter Dependence of Momentum Transport

[Zimmermann et al. NF Letter. 2023. Submitted.]

Compared ITG dominated discharges with variation in plasma current, density, and density gradient:

Experiment vs. GKW prediction

→ Technique opens the door to further theory validation and physics-based parameter scalings

→ Coriolis pinch, deformation of the eigenfunction & $k_\parallel$

Experiment at $\rho_\varphi = .35$

vs. GKW prediction

Experiment at $\rho_\varphi = .7$

vs. Stolzfus-Dueck model

→ deeper $E_r$ well, smaller turbulence decay length?
Isotope Dependence of Momentum Transport

[Zimmermann et al. NF. 63. 2023]

- Comparison of hydrogen and deuterium plasma
- Matched fluxes, dimensionless parameters, and heat transport to isolate isotope dependence
- Theory predicts negligible isotope dependence
- Very similar transport coefficients assessed: no isotope dependence observed
- Variation of $\tau_{int} \sim -\nabla p$ at edge,
  \[ \frac{-RV_c}{\chi_\varphi} \sim \text{gradients in core} \]

→ Increases confidence when applying theory to other main ion species and mixtures
Summary and Outlook

• Developed a code framework to extract momentum transport coefficients purely from experimental data

• First methodology to disentangle all three momentum fluxes simultaneously, key requirement is retaining the time dependencies

• Validated gyrokinetic predictions for ITG dominated plasmas, studied theory scalings on convection, intrinsic torque, and isotope dependence

• Expand this validation to more discharges (→ TEM), compare to a GKW data base
• Apply this technique to other tokamaks as JET and KSTAR to analyze $\rho_s$ dependence (A. Kirjasuo)
• Develop physics-based scaling laws, to be used for example in integrated modeling approaches
References

• Momentum transport equation: [Fable. PPCF. 2017]
• GKW code: [Peeters. CPC. 2009]
• ASTRA code: [Pereverzev. MPI. 2002]
• Coriolis pinch: [Peeters. PRL. 2007]
• NUBEAM/TRANSP code: [Beslau. PPPL. 2018] [Pankin. CPC. 2004]
• Prandtl number: [Strintzi. PoP. 2008]
• Stoltzfus-Dueck model: [Stoltzfus-Dueck. PRL. 2012]
• IMEP: [Luda. NF. 2021]