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A Gyrokinetic Moment Model of the Plasma Boundary in Fusion Devices

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A comprehensive understanding of the turbulent transport processes occurring in the boundary region, which encompasses the edge and scrape-off layer (SOL) regions, is of primary importance for the future development of magnetic confinement fusion devices. The boundary plays a crucial role in regulating the heat and particle fluxes on the machine wall, impurity concentration, helium ash removal, and neutral dynamics. However, modelling the turbulent plasma dynamics in the boundary is challenging due to the wide range of plasma parameters present, in particular the plasma collisionality. The presence of regions of low collisionality can limit the use of fluid models, requiring a gyrokinetic (GK) description. At the same time, the use of first-principles GK simulations is challenged by their high computational cost.

This presentation introduces a GK boundary moment designed to efficiently simulate the plasma dynamics in the boundary region [1]. The GK moment model is based on a moment expansion, referred to as the gyro-moments (GMs), of the full gyrocenter (full-F) distribution function onto a Hermite and Laguerre velocity-space polynomial basis. The GM hierarchy equation derived for the GMs is valid at an arbitrary level of collisionality, provided that a first-principles GK Coulomb (Fokker-Planck) collision operator is considered [2,3]. In order to assess the properties of the GM model developed herein and the role of collisional effects, several numerical and analytical investigations will be presented, with comparisons with well-established models and numerical codes. In particular, the numerical implementation and the closed analytical expressions of a linearised GK Coulomb collision operator allow for a comprehensive comparison with other approximated collision operator models [3,4,5]. This comparison demonstrates that simplified collision operator models can lead to significant deviations from the GK Coulomb operator in predicting linear growth rates of microinstabilities [5,6] and zonal flow damping [6]. These results call into question the accuracy of previously-used simplified collision operators. Furthermore, the capability of the GM approach to describe efficiently both the high and low collisionality regimes is also demonstrated. Analytical results and comparisons with well-established numerical codes demonstrate that fluid predictions are well recovered with a low number of GMs, while increasing the number of GMs allows for the description of microinstabilities in the collisionless limit [6], such as trapped electron modes. Finally, the first full-F and turbulence simulations based on the GM approach will be presented in the case of a linear plasma device [7]. The present results offer new avenues for efficient and high-fidelity simulations of turbulence in the boundary region, which is a key milestone for the success of ITER.

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