Non-Diffusive Momentum Transport and Intrinsic Rotation in Tokamaks

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This presentation will focus on using state-of-art gyrokinetic simulations which exploit high performance computational resources to understand toroidal momentum transport and flow generation. There are complex transport phenomena of great importance in magnetic confinement fusion [1]. An optimized plasma flow is believed to play a critical role in both controlling large-scale (macroscopic) plasma stability and in reducing energy loss due to plasma microturbulence and thereby achieving high quality performance in plasma confinement, particularly for ITER. The strong coupling between toroidal momentum and energy transport universally observed in fusion experiments suggests that micro-turbulence is a key player in determining plasma rotation, as well. The strong momentum-energy transport coupling via microturbulence as a "medium" was predicted by theory [2] and confirmed by gyrokinetic simulations [3]. Unlike energy transport, however, the toroidal momentum transport exhibits a non-diffusive nature, which is responsible for the amazing phenomenon of intrinsic rotation observed in nearly all tokamaks; i.e., toroidal plasmas can self-organize and develop rotation without an external torque [4]. Note that intrinsic rotation in tokamaks is an example of "negative viscosity phenomenon" in which an up-gradient component of the momentum flux organizes a structured mean flow. Negative viscosity phenomena are of broad interest in the context of atmospheres, oceans, stellar interiors, and other rotating fluids. The key results of our simulations include the identification of nonlinear flow generation by the residual stress (a non-diffusive element of the momentum flux) produced by electrostatic turbulence of ion temperature gradient (ITG) modes and trapped electron modes (TEM). This residual stress is shown to drive intrinsic rotation as a type of wave driven flow phenomenon which operates via wave-particle momentum exchange. The characteristic dependence of non-diffusive momentum transport has been studied over a wide range of experimentally-relevant parameters for the purpose of developing predictive capability for plasma rotation in ITER. Specifically, the "intrinsic" torque associated with residual stress is shown to

increase close to linearly with the plasma pressure gradient. This result is consistent with experimental trends observed in various tokamaks including C-MOD where the central flow velocity scales linearly with the edge pressure gradient [6]. Further, the momentum pinch [7], another non-diffusive element, is also identified in the simulation of TEM turbulence. Finally, high performance computational resources are shown to play a critical role in leading to scientific discovery in this study in two key aspects: (i) the Cray XT4, Franklin system at NERSC and the Cray XT5, Jaguar petascale system at OLCF have enabled global kinetic simulations encompassing both the meso- and micro-scales as well as with the multi-scale resolution needed to deal with both ion and electron dynamics – a true scientific grand challenge; and (ii) advanced HPC software tools including the major services from the End-to-end Framework for Fusion Integrated simulation (EFFIS) [8], ADIOS[9], have provided the capability needed to easily generate and analyze the huge amount of data from these fluctuation simulations and to compare with experimental data – functions which are essential for elucidating the physics picture of nonlinear residual stress generation. Work supported by the SciDAC project for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas.

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